An Advanced Tool for Evaluating the Probability of Failure of Existing Tailings Dams

A Scientific Approach Supporting the Prioritisation of Mitigating Measures and Minimise Risk within the 'As Low As Reasonably Practicable' Principle

L. de Haan

RWTH AACHEN UNIVERSITY
TU Delft
Aalto University

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by

L. de Haan

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	RWTH Aachen University	426512
	Aalto University	904782
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Thesis Committee	Dr.Ir. A.A.M. Dieudonné	Delft University of Technology
	Dr. M.W.N. Buxton	Delft University of Technology
	Dr. J.P. Aguilar-López	Delft University of Technology
	Dr. B. Lottermoser	RWTH Aachen University
	Dr. R. Serna	Aalto University
	Ir. B. Russell	BGC Engineering
	Ir. J. Whittall	BGC Engineering

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Abstract

The frequent occurrence of catastrophic tailings dam failures underscores the urgent need to improve safety practises and minimise associated risks. While various risk assessment methods exist, a systematic approach to evaluate the total Probability of Failure (PoF) of existing tailings dams is lacking. Current methods do neither offer swift and straightforward guidance for directing mitigation measures to reduce risk to 'As Low As Reasonably Practicable' (ALARP), a requirement of the Global Industry Standard on Tailings Management (GISTM). To bridge this gap, this study introduces an advanced tool for evaluating the total PoF of existing tailings dams systematically and swiftly, supporting the rational prioritisation of mitigation efforts and minimise risk within the ALARP principle.

The tool utilises a semi-quantitative approach, combining observation frequency and expert judgment. A baseline PoF for each dam construction method and failure category is established using a database of 450 tailings dam incidents and accidents developed in this study. This baseline PoF is subsequently modified based on site-specific factors influencing failure prevalence.

A total of 255 key contributing factors are identified based on a fault tree analysis, the GISTM and experts in the field These factors encompass site conditions, design elements, and the Level of Practice (LoP), which address all major credible failure modes and mechanisms. The factors are linked to the failure categories they influence and assigned relative weights through the analytical hierarchy processing method for each dam construction method and failure category. Subsequently, the weights are multiplied by modifiers to account for the effects of site-specific conditions (favourable: 0.2, neutral: 1, adverse: 5, and unknown: 2). Users can choose fulfilment conditions for each factor from drop-down menus. The selected inputs are linked to the modifiers. The adjusted weights are multiplied by the baseline PoF of each failure category, given the dam construction method. The summation of these products yields the total PoF of the investigated dam.

The results provide preliminary insight into factors significantly affecting the total PoF. This aids in evaluating whether the PoF reduction justifies costs, addressing the ALARP principle. Unlike conventional methods, a dam section can be analysed in a single day and considers all site conditions, design elements, LoP factors and credible failure modes.The tool can offer rational guidance for the allocation of mitigation measures, representing a novel addition to existing methodologies.

To validate the tool's capabilities, two case studies with available data are analysed: the Aznalcóllar failure to examine the ability to identify high-risk factors and a recently improved dam to evaluate if the mitigation efforts are adequately reflected. The studies demonstrate the tool's potential but also reveal uncertainties, inaccuracies and limitations. These stem from discrepancies in the baseline PoF, weightings, modifiers, and unaccounted factors. Therefore, caution is warranted in the tool's utilisation. Recommendations include various improvements and further verification and validation across a broader range of case studies. Value can be added by incorporating additional components and adapting the tool for new dams.

The tool has the potential to systematically and effectively asses the PoF of existing tailings dams. It complements sound engineering practices, offering swift insights into factors reducing PoF significantly. Accordingly, it facilitates preliminary, rational prioritisation of mitigation measures in accordance with the ALARP principle, contributing to ongoing efforts to improve tailings dam safety.

Preface

In front of you lies the master thesis 'An Advanced Tool for Evaluating the Probability of Failure of Existing Tailings Dams'. The thesis is presented in partial fulfilment of the requirements for the degrees of Master of Science in Applied Earth Sciences (European Mining, Minerals and Environmental Programme) at the Delft University of Technology, RWTH Aachen University and Aalto University and the Master of Science in Civil Engineering (Geo-Engineering) at the Delft University of Technology. The research is performed in the time span of one year, from December 2022 to December 2023.

Mining plays a vital role in the world and has always fascinated me. It is a complex, multifaceted industry that intertwines engineering, geology, environment, and even social and economic impacts. A critical facet of mining activities lies in the understanding of material behaviour, a concept explored within geo-engineering. The topic of tailings dams, which are an integral part of nearly every mining operation, encompasses crucial aspects of both mining and geo-engineering, highlighting their interdependence within the mining industry.

However, this is not my sole motivation for studying tailings dams. Tailings dams are complex structures with many challenges. Challenges naturally intrigue me and tailings dams represent significant, real-world issues. Tailings dam failures have far-reaching consequences, impacting the environment, communities, and the mining industry. To mitigate the risk of failure, proactive measures are essential, which I am eager to contribute to. The proposal from BGC Engineering for a thesis on tailings dams, in collaboration with enthusiastic experts, was an opportunity I could not decline.

Writing this thesis has been an educational process, providing an opportunity to apply and further develop the knowledge and skills acquired through my studies. This thesis marks the culmination of my master's journey.

I hope you enjoy reading my work.

L. de Haan
Delft, December 2023

Acknowledgements

After an intensive year, I am finalising my thesis with these words of gratitude. This period has been a profound learning experience, not just academically but also on a personal level. The process of writing this thesis has been demanding, and I could not have accomplished it without the support of those around me. I would like to express my heartfelt thanks to those who have supported me in my journey.

First and foremost, my deepest thanks go out to my graduation committee at Delft University of Technology. To my supervisors, Anne-Catherine Dieudonné and Mike Buxton, thank you for your guidance and for steering me in the right direction throughout this journey. I am also grateful to Juan Aguilar-López for his insightful feedback and fresh perspective on my work. Additionally, I appreciate the openness and discussions with other academics. A special acknowledgement to Marco Keersemaker for connecting me with BGC Engineering.

My gratitude extends to BGC Engineering for their collaboration, guidance, and the invaluable opportunity to visit their office in Vancouver, where I had the privilege of meeting various industry experts. I want to express particular thanks to Brad Russell for our enlightening discussions, and to John Whittall for initiating the project and handling logistical matters.

Finally, I would like to thank my family and close friends. I want to express a special appreciation to my parents for their unwavering support and guidance during the challenging times of this thesis, as well as for celebrating the enjoyable moments. I am also thankful to my friends for being there to discuss topics other than just the thesis, which was essential for me to navigate through this emotionally charged period. A special thanks to Hans van den Aker for proofreading my thesis.

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List of Abbreviations

AEP	Annual Exceedance Probability
AHP	Analytical Hierarchy Process
ALARA	As Low as Reasonably Attainable/Achievable
ALARP	As Low As Reasonably Practicable
ANP	Analytical Network Process
ART	Altered Rock Tailings
AZ/NZS	Australian/New Zealand Standard
CBA	Cost-Benefit Analysis
CI	Consistency Index
CL	Centreline
COBIT	Control Objectives for Information and Related Technology
COSO	Committee of Sponsoring Organizations
CPT	Cone Penetration Test
CR	Consistency Ratio
CSP^2	Center for Science in Public Participation
CST	Cycloned Sand Tailings
CT	Coarse Tailings
DBR	Design Basis Report
DH	Drill Hole
DS	Downstream
DSI	Dam Safety Inspection
E	Earthfill
EoR	Engineer of Record
EPRP	Emergency Preparedness and Response Plan
EQ	Earthquake Induced
ER	External Erosion
ETA	Event Tree Analysis
FEM	Finite Element Method
FMEA	Failure Modes and Effects Analysis
FN	Foundation Deficiency
FoS	Factor of Safety
FOSM	First-Order Second-Moment
FT	Fine Tailings
FTA	Fault Tree Analysis
GDP	Gross Domestic Product
GISTM	Global Industry Standard on Tailings Management
GTR	Global Tailings Review
HAZOP	Hazard and Operability Analysis
HRT	Hard Rock Tailings
HSE	Health, Safety and Environment
HT Manto	High-Temperature Manto
ICMM	International Council on Mining and Metals
ICOLD	International Commission on Large Dams
IEA	International Energy Agency
IPRB	Independent Peer Review Board
ISO	International Organization for Standardization
ITRB	Independent Tailings Review Board
LEM	Limit Equilibrium Analysis
LoE	Level of Engineering
LoP	Level of Practise
LOPA	Layer Of Protection Analysis
MCDM	Multi-Criteria Decision Making
MS	Mine Subsidence
MW	Mine Waste
NIST	National Institute of Standards and Technology
OMS	Operations, Maintenance and Surveillance
OT	Overtopping
PAG	Potential Acid Generating
PAR	Population at Risk
PC	Porphyry Copper
PGA	Peak Ground Acceleration
PLL	Potential Loss of Life
PoF	Probability of Failure
PPE	Personal Protective Equipment
PRI	Principles for Responsible Investment
R	Rockfill
RI	Random Index
RISM	Risk and Insurance Management Society
SAA	Shape Accel Arrays
SE	Excessive Seepage and Internal Erosion
SFAIRP	So Fas As Is Reasonably Practicable

SI Slope Instability
SQL Structured Query Language
SS Single Stage
SSC Sediment Hosted Copper
ST Structural Inadequacies
T Tailings
TARP Trigger Level and Response Plan
TSF Tailings Storage Facility
U Unknown
UFT Ultra-Fine Tailings
UNEP United Nations Environment Programme
US Upstream
USCOLD United States Committee On Large Dams
VMS Volcanic Massive Sulphide
VW Vibrating Wire
WISE World Information Service on Energy
WMTF World Mine Tailings Failures
WR Water Retention

Disclamer

This thesis report represents the culmination of research efforts conducted by the author within the thesis period. The author has strived to ensure the accuracy and reliability of the information presented. However, it is important to note that this report is not intended to provide professional or expert advice. No guarantee, either expressed or implied, is provided regarding the completeness, accuracy, reliability, or suitability of the content for any particular purpose.

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The scope of this report is confined to the specific outlined topic and objectives. It is not exhaustive and may not encompass all aspects or perspectives related to the subject matter. Developed methods are not a substitute for sound engineering practices and are not meant to replace expert-based risk assessment methods. Instead, their purpose is to facilitate risk-informed decision-making and provide preliminary insights into whether risks have been reduced to an As Low As Reasonably Practicable (ALARP) level. Readers are encouraged to consult qualified experts or authorities in their respective fields for specific guidance.

By accessing and reading this report, readers acknowledge and agree to the terms of this disclaimer.

I. Problem Formulation

The basis for the research is set, providing a comprehensive overview of the key elements that guide the study. A context for the research is provided, highlighting the background and relevance of the subject. The problem is stated and the pivotal elements of the research, such as research questions and objectives, hypothesis, scope of study and the adopted reach approach, are presented. Additionally, a roadmap is offered guiding the reader through the structure of the report.

1

Introduction

The escalating frequency and severity of tailings dam failures are raising concerns. As a response to this alarming trend, efforts are made to mitigate the associated risks. This study is also dedicated to advancing tailings dam safety by formulating a systematic and effective tool for assessing the Probability of Failure (PoF) in existing tailings dams to support the prioritisation of mitigation measures within the ALARP principle. This chapter serves as an introduction to the presented research.

1.1. Context

The mining industry produces billions of tonnes of waste each year by separating the fraction of ore from the gangue. This waste stream are known as tailings. Regardless of the commodity and processing method, they are often highly toxic and stored for permanent containment behind a so-called tailings dam. Some tailings dams tower dozens of meters high and reservoirs stretch for several kilometres. Therewith, they rank among the world's largest man-made structures (Islam & Murakami, 2021).

However, keeping the tailings dam safe and stable is one of the most challenging tasks in the entire mining process and tailings dam failures are not rare. In the past 50 years, 129 'major' tailings dam failures have been reported (WISE, 2023), accompanied by about 20 to 35 'minor' failures per annum (Adamo et al., 2020). Thereby an upward trend of high-consequence failure events has been observed since the turn of the century (Owen et al., 2020).

It raises concerns that more than 1 out of 7 tailings dams is classified as being at 'high risk' (Warburton et al., 2020), certainly considering the number of Tailings Storage Facilities (TSFs) across the globe. It is estimated that there are between 3,500 and 32,000 dams all over the world, although there is no complete inventory (Davies et al.,2000; WMTF, 2019). On top of that, the number of tailings dams is expected to increase. With the advancement of technology, mining is becoming economically viable at lower grades. Furthermore, the demand for minerals and metals is likely to increase due to the growing world population, their essential role in modern-day life, and their significance in the energy transition toward a low-carbon future (Meilli, 2016; Armstrong et al., 2019; Watari et al., 2021). Alternatives for tailings disposal are still in their infancy and often far-fetched, uncertain, and costly, preventing the industry from broadly utilising these yet (Van Zyl et al., 2002; Watson et al., 2010; Adams & Gerritsen, 2021).

Nonetheless, the growing concern is essentially based on the serious damage, environmental pollution, and fatalities caused by dam breakage, as recently illustrated by the Brumadinho dam collapse in 2019.

Upon failure, the loosely deposited solids have the ability to take on a slurry-like form again, increasing the flowability and downstream impacts. Around 12 million cubic meters of tailings were released from the pond of the Córrego do Feijão iron ore mine, contaminating the environment as far as 302 km downstream from the mine site and killing 270 people. (dos Santos Vergilio et al., 2020).

In the wake of this tragedy, the Global Tailings Review (GTR) conducted an independent multi-stakeholder review for safer tailings management for both future and existing dams, which was co-coinvented by the United Nations Environment Programme (UNEP), Principles for Responsible Investment (PRI) and International Council on Mining and Metals (ICMM). This resulted in the first Global Industry Standard on Tailings Management (GISTM) (GISTM, 2020) being launched in August 2020.

With the ambition of zero harm to people and the environment, it significantly raises the bar in tailings management safety standards and establishes consensus across the entire extractive industry. Thereby it represents a good start in the right direction (Islam & Murakami, 2021). Some complications arise upon the implementation of the standard; GISTM requires a risk management approach, however, it does not prescribe a specific methodology. Developing an auditable and specific risk management method for TSFs is an ongoing effort for mining companies, which is essential to prevent prospective catastrophic failures; before we have a dam(n) big problem!

1.2. Problem Statement

The GISTM (GISTM, 2020) state that the residual risks of tailings dams should be reduced to a level ALARP, a principle in risk management utilised for prioritisation of mitigation measures. The GISTM defines risks to be ALARP if 'all reasonable measures are taken with respect to 'tolerable' or acceptable risks to reduce them even further until the cost and other impacts of additional risk reduction are grossly disproportionate to the benefit'. At present, there is no established industry standard outlining how to demonstrate that the implemented risk reduction measures in tailings dams have effectively been decreased to the level of ALARP.

In some cases, it might be obvious to state when the risk is 'tolerable' or acceptable and when the mitigation measures are grossly disproportionate to the risk reduction. However, within complex risk scenarios like those found in TSFs, this distinction is often less evident. It demands subjective judgment and lacks clear delineation. Rational decision-making in such contexts is difficult and necessitates an unbiased assessment of the risk components (the PoF and the ensuing consequences) and the available risk mitigation options. This study is specifically directed at addressing the systematic and effective evaluation of the total expected PoF.

Current assessments for the PoF in TSFs are resource-intensive in terms of time, financial investment, and expertise. Besides, lacking standardised methods and industry-wide requisites, current PoF estimates often overlook crucial risk factors and failure modes. Quantifying the PoF proves to be a challenging task, yet it holds considerable value. Determining PoF efficiently is crucial for making informed decisions about mitigation measures and optimising resource allocation to address the most critical risks.

1.3. Research Design

This project aims to establish a transparent, auditable method for evaluating the PoF within the ALARP principle, ultimately enhancing tailings dam safety. This section outlines the research questions, objectives, hypothesis, scope, and the general methodology employed in the study.

1.3.1. Research Questions and Objectives

Arising from the problem statement, the core research questions and objectives guiding the investigation of this study are determined. The main research question, sub-questions and the associated objectives are presented in this section.

Research Questions

In the realm of tailings dam safety, a critical question arises:

How can the probability of failure of existing tailings dams systematically be evaluated to support the scientific, preliminary prioritisation of mitigating measures and minimise risk within the 'as low as reasonably practicable' principle?

To help answer this main research question, four sub-questions are developed:

- What are the primary concerns associated with the stability of existing tailings dams and what are the key contributing factors to their probability of failure?
- How do ordinary risk management methods and tools fall short in evaluating the 'as low as reasonably practicable' principle and probability of failure of tailings dams?
- What is an appropriate scientific method or tool to evaluate the Probability of Failure of existing tailings dams, supporting the prioritisation of mitigation measures within the 'as low as reasonably practicable' principle, and how can it be developed?
- What challenges and limitations remain while conducting evaluations for existing tailings dams with the developed method or tool?

Objectives

The primary objective is to address the need for and the development of a systematic and scientifically grounded method or tool for the evaluation of the PoF of existing tailings dams to enhance the prioritisation of risk mitigation measures within the ALARP principle. Each sub-question corresponds to a specific objective, collectively contributing to the broader goal.

- **Objective 1: Understanding Tailings Dams and Their Risks**
  This objective seeks to comprehensively identify the principal concerns associated with existing tailings dams and analyse the root causes and key contributing factors affecting the PoF, as well as their triggers. The complex interrelationships among these factors should also be mapped.
- **Objective 2: Identify Shortcomings in Risk Management Methods and Tools**
  This objective focuses on conducting a rigorous assessment of the limitations associated with conventional risk management methods. It should include an in-depth evaluation of the role and imperative of the ALARP principle and explore current applications in the tailings- and similar industries. Methods for ALARP demonstration also need to be identified. Furthermore, it should encompass the examination of existing methods and tools for determining the PoF. Lastly, the shortcomings and challenges in the current ALARP and PoF evaluation methods should be identified.
- **Objective 3: Developing a Scientific Method or Tool for PoF Evaluation**
  This objective is dedicated to the formulation and development of a scientifically sound method or tool for the systematic evaluation of the PoF across the wide range of existing tailings dams, aiming to provide a practical framework that facilitates the prioritisation of risk mitigation measures and allocate costs (in terms of time, money, resource, effort, etc.) within a single TSF of a large portfolio of dams. The requirements of the novel method or tool should be based on the challenges and shortcomings identified in the current practices.

- **Objective 4: Demonstrating Validity and Addressing Challenges and Limitations**
  This objective encompasses the validation and confirmation of the validity and reliability of the developed method or tool through real-world case studies, underlining the practical efficacy of the innovative solution. The remaining challenges and limitations of the proposed method and tool should be identified.

1.3.2. Hypothesis

The hypothesis is that a systematic and effective tool for the evaluation of the PoF can be developed and can enhance rational decision-making for risk mitigation within the ALARP principle. The fundamental belief is that risk should be minimised to the greatest extent possible, but it is acknowledged that a point may be reached where the costs outweigh the benefits, leading to disproportionality. Decisions need to be made since it is impractical to mitigate all risks. In industries like tailings management, where substantial investments and catastrophic consequences are at stake, the use of a tool can help make informed choices. A systematically and effectively evaluated PoF under specific site conditions offers preliminary insights into risks for further discussion and enables the early interception of high-risk scenarios. Implementing this solution is expected to steer operations and projects toward a rational, defensible, and transparent approach, a crucial step in improving tailings management and preventing future catastrophic tailings dam failures.

1.3.3. Scope of Study

The tool under development is exclusively focused on existing tailings dams and does not encompass criteria for prospective dams in its analysis. The study solely addresses the primary risks associated with conventional, identifiable failure modes at the specific case study site and does not account for exceptional behaviour. Additionally, it does not explore other risks at TSFs that might not directly lead to failure; these are considered subordinated to the risk of failure within this specific context.

The development of a perfect model is not feasible within the available one-year timeframe of the project. The study's objective is not to develop a perfect tool, but to present a potential solution that could serve as a foundation for further development within the industry. The aim is to develop a generalised solution applicable to various dams worldwide none of which are identical, encompassing all factors influencing the PoF of tailings dams.

The development of the tool is constrained by a literature review, publicly available data and software, and an analysis based on a case study of a TSF located in Canada. The name of the operator, the site and the specific location cannot be disclosed due to confidentiality reasons.

1.3.4. Research Approach

The project necessitates a structured approach comprising sequential, manageable steps. Initially, the concerns surrounding tailings dam instability and its underlying reasons for failure need to be identified. Subsequently, an assessment of existing risk assessment methods and tools for determining the PoF should be conducted to establish the necessary requirements. These steps will be conducted through a literature review. Based on the identified prerequisites, a concept for a potential tool needs to be established. This concept should be refined and worked out. Afterwards, the tool must be validated and sources for discrepancies should be identified. The exact methodology will depend on the nature of the tool's framework. The report adheres to this structured approach, as detailed in the following section.

1.4. Outline

This report comprises five main parts. Part I consists of this introduction, framing the problem at hand. Part II offers a theoretical foundation, crucial to understanding key concepts. In Chapter 2, tailings management and tailings dam design practices are examined, with an emphasis on safety concerns. It also provides an analysis of the primary risks of tailings dams and their influencing factors. Chapter 3 explores the general risk management process, identifying inadequacies in conventional methods and tools.

Chapter 4 details methods and tools for evaluating the PoF, while highlighting their challenges and limitations. Based on these challenges and limitations, it provides a concept of a tool and sets the stage for Part III, focusing on the tool's methodology for development. This part commences with Chapter 5, explaining the development of a database. Chapter 5 also analyses the main attributes within the developed database and highlights its opportunities, limitations and biases. Chapter 6 outlines the establishment of the baseline PoF, considering dam construction methods and failure categories. Chapter 7 examines the prevalence and established contributing factors affecting the baseline PoF. In addition, it delineates the weight determination process and fulfilment assessment.

Subsequently, in Part IV the resulting tool is presented. Chapter 8 presents the tool's operational mechanism through pseudocode, and describes the required inputs and resultant outputs. Instructions for downloading the product are also provided in this chapter. In Chapter 9 tool's potential and validity are demonstrated based on two case studies: one involving a failure and another focusing on a scenario where numerous mitigation measures were recently implemented. This investigation illuminates the remaining challenges and limitations of the tool.

The thesis concludes with an evaluation Part V, where Chapter 10 delves into a discussion of the tool's results, highlighting the tool's discrepancies and addressing limitations. Chapter 11 offers a conclusion of the research, and Chapter 12 provides recommendations for tool utilisation, improvement, further validation, verification, and eventual expansion. Figure 1.1 offers an overview of the report's structure, illustrating its alignment with the research objectives.

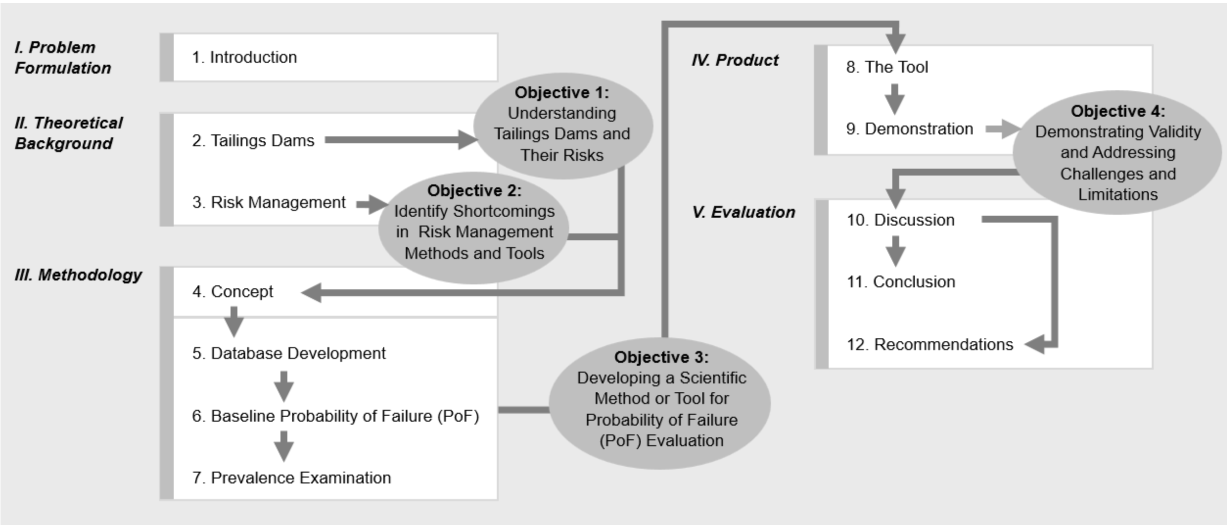

Figure 1.1: Report Structure

II. Theoretical Background

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- 2.1.1 Nature and Production of Tailings
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Objective 1: Understanding Tailings Dams and Their Risks

3. Risk Management

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Objective 2: Identify Shortcomings in Risk Management Methods and Tools

A comprehensive theoretical foundation for the research is provided based on an extensive literature review. Tailings management is thoroughly examined, including the production and properties of tailings and the disposal and storage methods, while also delving into dam design intricacies including construction methods, dam components, and the critical mass-water balance aspects. Safety concerns are extensively covered, discussing failure rates, categories, consequences, and a forward-looking safety perspective, providing a comprehensive understanding of tailings dams and associated risks. Furthermore, risk management basics are discussed, detailing terminology, the established process, popular assessment methods, and their practical implications. The ALARP principle is also examined, encompassing its definition, imperatives and application. The shortcomings in ordinary risk management methods and tools are determined.

2
Tailings Dams

Tailings dams serve as repositories for the vast volumes of by-products generated during mineral extraction processes and are an indispensable part of mining operations. However, they also pose some safety concerns. This chapter offers a comprehensive background on tailing management, tailings dam design and associated concerns.

2.1. Tailings Management

The fundamental aspects of tailings management will be explored, encompassing the nature and production of tailings, their properties and behaviour, as well as the methods employed for their disposal and storage.

2.1.1. Nature and Production of Tailings

During mining operations, a considerable amount of waste is generated, which includes overburden, waste rock, mine water, and tailings. Tailings are the by-products or leftovers resulting from the extraction of valuable minerals and metals from ore. (ICMM, 2021). They comprise ground-up rock, along with the chemical reagents and process water used in the commodity extraction process (Ridlen & Coffin, 2020). In some instances, tailings may also contain overburden. Although predominantly originating from mining activities, tailings can also arise from certain industrial and power plant operations, such as the refining of alumina from bauxite (Rana et al., 2021). In this study, tailings refer to both the solid grains and the interstitial (pore) water they contain.

Tailings constitute a significant waste stream, with an annual production surpassing 8,000 million metric tonnes according to the latest estimates in 2018 (Hatch, 2022). The cumulative global volume of stored tailings is estimated to be 300 billion tonnes, a quantity sufficient to fill a cube with a height of 6 kilometres (Elements Visual Capitalist, 2021). As an example, the daily tailings output from a large-sized copper mine is approximately 200,000 tonnes, generated during the process of producing just 1,750 tonnes of copper concentrate, as depicted in As an illustrative example, a large-sized copper mine produces approximately 200,000 tonnes of tailings daily during the process of generating just 1,750 tonnes of copper concentrate, as shown in Figure 2.1.

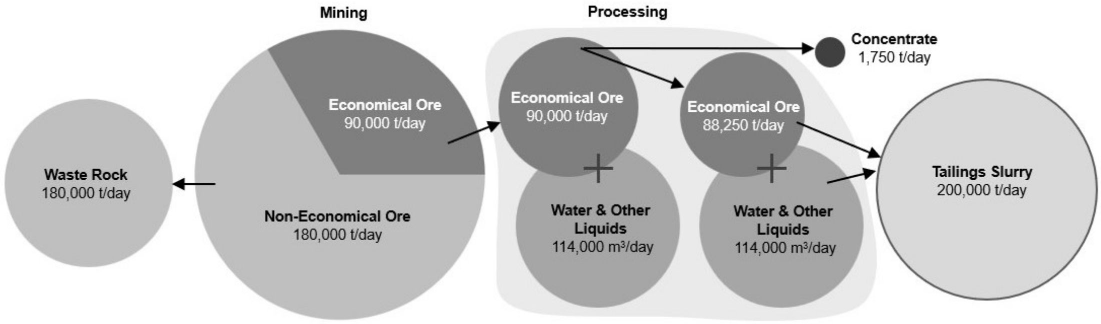


Figure 2.1: Tailings Production on an Average Day in a Large-Sized Copper Mine
(Modified after Roche et al. (2017), Based on Numbers from Mudd (2016))

2.1.2. Tailings Properties and Behaviour

Generally, tailings have characteristics similar to unconsolidated soils (ICOLD, 2019). However, due to their artificial nature, tailings exhibit distinct properties and behaviours (e.g. demonstrated by Vanden Berghe et al. (2009) and Vanden Berghe et al. (2011)). Various factors, including processing, grinding, transportation, and deposition, contribute to unconventional properties in tailings. The chosen processing method significantly alters the ore's characteristics, with techniques like gravity concentration, flotation, leaching, and oxidation leaving distinct imprints. Comminution, involving crushing and grinding, influences geotechnical properties as well. Further downstream in the process, physical activities such as thickening, pH adjustments, sulphide removal, and particle fraction separation also contribute to shaping the features of the tailings. During tailings deposition, segregation can cause changes in gradation, density, void ratio, and permeability. Lastly, the primary physical and chemical properties of mine tailings ultimately depend on the orebody and its mineralogy. (ICOLD, 2019; ICOLD, 2020). Variations arise based on distance from the discharge point, depth of the tailings deposit, and time (Blight & Bentel, 1983; Bjelkevik & Knutsson, 2005; Dimitrova & Yanful, 2012). Consequently, significant material differences exist both between sites and within a single site.

Despite their inherent variability, some general characteristics can be identified. Tailings typically have a high water content, ranging from 40-80% by weight during deposition, which may decrease to less than 20% after consolidation (Ridlen & Coffin, 2020). Furthermore, tailings are commonly deposited in a loose manner. The state parameter (ψ), defined as the difference between the void ratio and the void ratio at critical state, is mostly positive upon undrained shearing, indicating contractive properties. This contractive behaviour makes tailings susceptible to liquefaction (Vick, 1990; Martin & McRobers, 1999; Fourie et al., 2001; Blight, 2009; Morgenstern et al., 2016). This loose depositional state makes tailings also more compressible compared to most similar natural soils. Moreover, tailings grains exhibit high angularity due to the comminution process (Cho et al., 2006; Rodrigues & Edeskär, 2013). As a result, their drained strength is relatively high, with drained friction angles typically ranging from 30 to 35°. (ICOLD, 2001). However, the shear strength is usually low to moderate (ICOLD, 2001). Tailings commonly have lower plasticity compared to soils and usually do have a cohesion near zero (James et al., 2011). Generally, tailings sediments are considered to be in a normally consolidated state, with rare cases of over-consolidation (Vermeulen, n.d.; Zardari, n.d.). The stress-strain characteristics of tailings are similar to those of loose to medium-dense natural soils with similar gradation.

The (ICOLD, 2019) introduces five categories of tailings exhibiting similar properties, referred to as Coarse Tailings (CT), Hard Rock Tailings (HRT), Altered Rock Tailings (ART), Fine Tailings (FT), and Ultra-Fine Tailings (UFT), distinguished by their gradation. A comprehensive description of each category, along with relevant examples, is presented in Table 2.1.

Table 2.1: Categories of Tailings Exhibiting Similar Properties
(Modified after ICOLD (2019)) (CT: Coarse Tailings, HRT: Hard Rock Tailings, ART: Altered Rock Tailings, FT: Fine Tailings, UFT: Ultra Fine Tailings)

Tailings Type	Description	Examples of Mineral/Ore
CT	Sand or non-plastic silt-sized particles exhibiting sand-like behaviour; non-plastic; generally, a cohesionless angular soil exhibiting medium-high shear strengths and high hydraulic conductivity.	Uranium, gypsum, salt, tar sands, phosphate sand, coarse coal rejects.
HRT	Sand to sandy silt and may contain slime fractions which are non to low plastic; particularly those derived from igneous and metasedimentary rocks generally exhibit angularity, good shear strength and a hydraulic conductivity directly related to the grading; in case finer fractions are present, these dictate the properties, which may make them behave as altered rock tailings.	Copper, nickel, gold-silver, lead-zinc, molybdenum.
ART	Sandy silt with potentially a trace of clay; low plasticity; bentonitic clay content; derived from rocks that have undergone some alteration of e.g., feldspar minerals to clay minerals; moderate settling characteristics and shear strength dependent on quantity and type of clay faction; if there is >5% clay, these may exhibit similar properties to fine tailings.	Porphyry copper (with hydrothermal alteration), oxidised rock.
FT	Silt with trace to some clay and usually no or very small fraction of sand; low to moderate plasticity.	Iron ore fines, bauxite red mud, fine coal rejects, polymetallic ores.
UFT	Silty clay; high plasticity; low density and hydraulic conductivity; without intensive drainage, or exposure to evaporation in arid climates, ultra-fine tailing may take hundreds of years to consolidate.	Oil sands, phosphatic clays, kimberlite.

Lastly, tailings mostly contain hazardous substances, including sulphide, heavy metals, cyanides, radioactive material, phosphate, and bitumen wastes (Roche et al., 2017).

2.1.3. Tailings Disposal and Storage

In the early stages of tailings production during the Industrial Revolution, it was common to deposit tailings into rivers near the mine site (Vick, 1990). However, the inherent physical and chemical risks associated with tailings pose potential threats to both the environment and human well-being, necessitating appropriate treatment and secure storage solutions (Roche et al., 2017). This awareness and regulations have evolved over time. As a result, modern practices predominantly involve storing tailings in designated TSFs. They encompass engineered structures, components, and equipment dedicated to the management of tailings, other mine waste, and wastewater associated with mining operations (International Council on Mining and Metals (ICMM), 2021).

TSFs can be located on the surface, in underground mined-out voids (commonly known as backfill), or even on the seabed. The latter two are less common and also bring often high costs and additional risks (Roche et al., 2017). For this study, only surface-based TSFs are considered. Surface TSFs utilise multiple earth embankment dam sections to contain the tailings material, referred to as tailings dams (International Council on Mining and Metals (ICMM), 2021). Discharge from the dam can occur through various methods throughout its long lifespan.

Discharge Methods

Tailings are typically hydraulically discharged into the impoundment as a low-density slurry, comprising water and solids (Ridlen & Coffin, 2020). This practice is primarily driven by the existing water content in the tailings at the mill. In addition, the cost of dewatering and drying is usually prohibitive. Dry-stack of tailings occurs, but on a much smaller scale (MMSD, 2002). Various dewatering techniques are commonly employed once tailings have reached their storage location (Roca et al., 2019).

The preferred method of conveyance is gravity flow through pipes, although open launders may be used in some cases. Pumping may be required based on factors such as elevation differences and transport distance (Ridlen & Coffin, 2020). Common discharge methods for conventionally hydraulically filled impoundments include single point discharge, spigotting or deposition by hydrocyclones (ANCOLD, 2012; Fourie et al., 2022):

- **Single Point**: Tailings are discharged from a single point, mainly during flushing and maintenance campaigns. It is not recommended for regular operations due to potential irregular beach profiles. Thickened and paste storage tailings are typically discharged centrally.

- **Spigotting**: Spigotting involves closely spaced, independently controlled offtake pipes (spigots) for low-velocity deposition of tailings, improving particle segregation. Coarse tailings settle near the discharge point, forming a dense beach near the embankment.
- **Hydrocyclones**: Hydrocyclones are used to separate sand-rich tailings. The cyclone has no moving parts and utilises centrifugal forces to separate larger particles. It yields an 'overflow' of finer particles and water and an 'underflow' of partially dewatered coarser particles. The finer fraction is discharged into the impoundment, while the coarser tailings are often used for raising embankments.

Lifespan

During the entire operational life of a mine, tailings are continuously produced. The period when tailings are actively disposed of in the tailings dam, along with the construction of the embankment, is referred to as the "active" phase. Eventually, the dam enters an "inactive" state when construction, disposal, and other operations have temporarily or permanently ceased. Once officially decommissioned, a TSF is referred to as "closed." In some cases, active care may still be required after closure. A TSF is designated as "abandoned" when the entire mine site ceases all operations, and no further care is taken for the site (Rana et al., 2022). The lifecycle of a TSF is summarised in Figure 2.2. Note that the timescale varies based on factors like mine size, life span and available storage capacity. When the maximum capacity is reached (either due to permit, property or stability constraints) it can be decided to build a second TSF. It is most common to be in operation for about 5-70 years, aligning with the lifetime of most mines (Statista Research Department, 2013).

The primary objective of a TSF is to ensure the secure storage of tailings in perpetuity. This requires careful consideration of both their physical and geochemical stability upon closure. The TSF must not pose any hazard to public health and safety and harmful materials must not leach from or erode the site to prevent environmental damage (Roche et al., 2017).

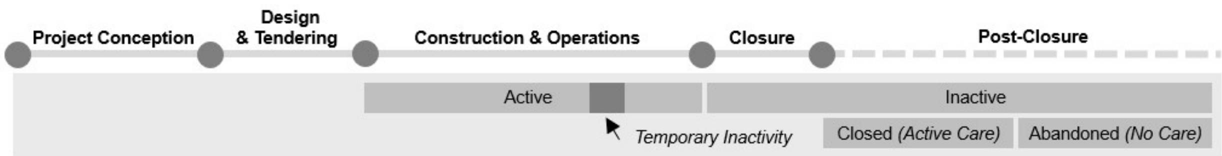


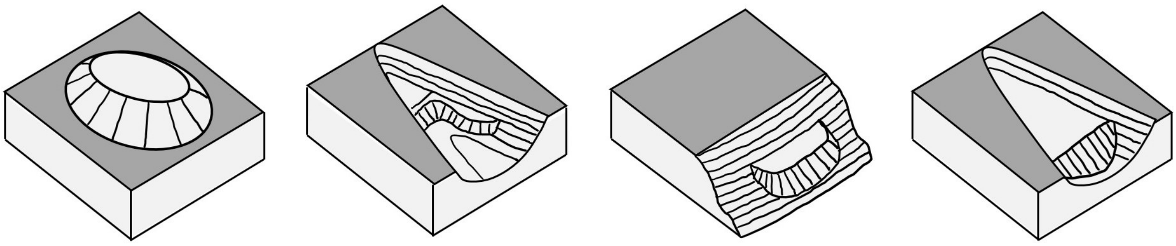
Figure 2.2: Schematic Overview of General Lifecycle of a Tailings Storage Facility (TSF) *(Based on Information from ICMM) (2021)*

2.2. Tailings Dam Design

Tailings dams range widely in size, from a few meters to several kilometers in length and hundreds of meters in height, influenced by factors such as tailings volume, mine lifespan, and regulatory requirements. These structures, among the largest man-made constructions on Earth, necessitate careful design. The spatial plan and construction methods, along with key components and the mass and water balance, are described.

2.2.1. Dam Construction Methods

TSFs are strategically located near the mining area, utilising layouts based on surrounding topography and project needs. Several spatial impoundment layouts can be distinguished, as illustrated in Figure 2.3. Common layouts include ring dikes on (near-)flat terrain that fully enclose the impoundments; partially enclosed impoundments on hillslopes, which are less than 10%; impoundments enclosed by a cross-valley embankment whereby the natural walls of a valley or topographic depression are utilised; and the storage of tailings below grade in e.g. abandoned open-pits or underground mines (also known as backfilling (Ridlen & Coffin, 2020). The below-grade impoundments are not considered in this work.

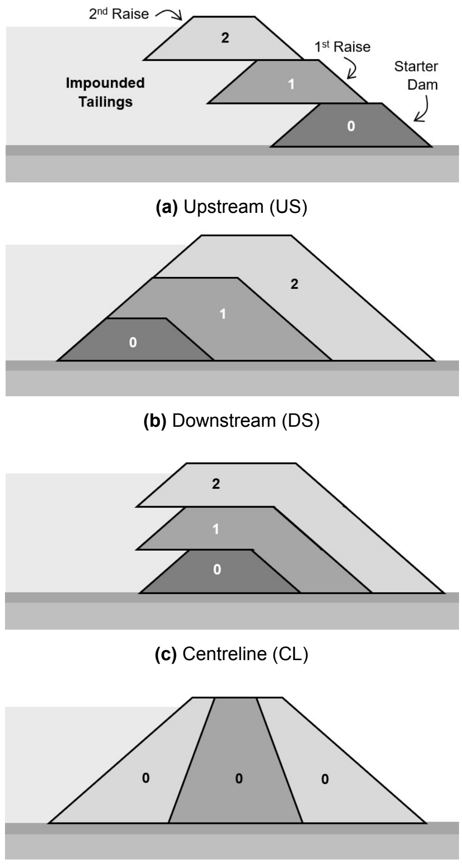


(a) Above-Grade **(b)** Below-Grade **(c)** Sidehill **(d)** Cross-Valley

Figure 2.3: Different Spatial Layouts of Impoundments
(Modified after Ridlen & Coffin (2020))

In contrast to regular water storage dams tailings dams are evolving structures. They are raised in successive stages as the tailings production continues over several years to decades, but often these periods extend more than 50 to even 100 years. The pace of raising depends on the project restrictions such as the expected consolidation time.

Three distinct raise methods are identified as Upstream (US), Downstream (DS), and Centreline (CL), shown in Figure 2.4. A combination of these methods is also possible. In US design, new levels of the dam are constructed over previously deposited tailings. Conversely, DS design involves building new levels outward from the tailings and atop previous raises. A CL dam combines features of US and DS dams, with new levels of raises constructed on both tailings and the existing embankment. Additionally, Water Retention (WR) dams can be distinguished, which are characterised by a clay core or other hydraulic barrier. Unlike other dam types, these dams are often constructed in one stage and designed to have standing water against the upstream dam face (Vick, 1990).



(a) Upstream (US)

(b) Downstream (DS)

(c) Centreline (CL)

(d) *Water Retention (WR)*

Figure 2.4: Common Dam Construction Methods

Vick (1990) provided a comparison between the different embankment types (see Table 2.2). One should note that the US design is widely favoured, constituting around 45% of all constructed dams (Piciullo et al., 2022). This preference is attributed to its high flexibility, cost-effectiveness, and minimal earthworks required. Notice that a DS dam construction requires approximately 6 times more earthworks than an US dam (Waldek, 2000). Additionally, a DS-constructed dam mandates a considerable amount of available space due to its outward design and necessitates stronger foundations to support the heightened weight. However, it is important to acknowledge that in the US design, the stability of subsequent raises heavily relies on the shear strength and drainage properties of the underlying tailings. This consideration becomes especially critical during seismic loading events, as loosely deposited tailings are susceptible to liquefaction. Besides, US dams are not suitable for significant water storage and high raising rates (Stark et al., 2022).

Table 2.2: Strengths and Weaknesses of Common Dam Construction Methods
(Modified after Vick (1990)) (US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention

Item	US	DS	CL	WR
Mill Tailings Requirements	At least 40-60% sand in whole tailings. Low pulp density desirable to promote grain-size segregation.	Suitable for any type of tailings.	Sands or low-plasticity slimes.	Suitable for any type of tailings
Discharge Requirements	Peripheral discharge and well-controlled beach necessary.	Varies according to design details.	Peripheral discharge of at least nominal beach necessary.	Any discharge procedure suitable.
Water Storage Suitability	Not suitable for significant water storage.	Good	Not recommended for permanent storage. Temporary flood storage acceptable with proper design.	Good
Seismic Resistance	Poor in high seismic areas.	Good	Acceptable	Entire embankment constructed initially.
Raising Rate Restrictions	Less than 4.5-9 m per year most desirable. Greater than 15 m per year can be hazardous.	None	Height restrictions for individual raises may apply.	Entire embankment constructed initially.
Embankment Fill Requirements	Natural soil, sand tailings or mine waste.	Sand tailings or mine waste if production rates are sufficient, or natural soil.	Sand tailings or mine waste if production rates are sufficient or natural soil.	Natural soil borrows.
Foundation Requirements	Consolidate tailings foundations before each raise for long-term stability.	Require a very strong and well-compacted foundation to support dam weight and resist deformation.	Strong and compacted foundation essential, with careful consideration for the stability of the central core.	Strong and well-compacted foundation needed, with impermeability to prevent water leakage.
Costs	Low	High	Moderate	High

Construction Materials

To construct tailings dams, easily accessible materials are used instead of concrete to manage costs. Earthfill (E) and Rockfill (R) fill are commonly used due to their relative stability. Moreover, the coarse fraction of the tailings can be utilised for embankment construction (Blight, 2009; Ridlen & Coffin, 2020). The coarse fraction (Cycloned Sand Tailings (CST)) can be effectively separated from the finer fraction by hydrocyclones (as explained in Section 2.1.3). However, it is important to note that construction with earth materials, while cost-effective, may present higher risks in terms of potential erosion and stability compared to using concrete (Adamo et al., 2020).

Slope Steepness

The gradient of constructed embankments usually falls within the range of 2.0H:1V to 4.0H:1V, contingent upon the material's strength and the pore pressure conditions in both the embankment and the underlying foundation. Flatter slopes offer enhanced stability and improved access. Ensuring the slope is not excessively steep is crucial to prevent failure, particularly for soft soils susceptible to contractive, strain-softening behaviour, or under extreme loading conditions (Ridlen & Coffin, 2020).

Advantages and Disadvantages Staged Raises

Staged construction provides the benefit of deferring capital costs throughout the mine's operational life. It also allows for the integration of experiential and knowledge-based insights from early stages and enables adjustments to address evolving conditions. Nevertheless, over time, there is a risk of losing original objectives and information about the early stages. Moreover, variations in construction quality due to different contractors, materials, and quality assurance procedures may be faced(Ridlen & Coffin, 2020).

2.2.2. Main Dam Components

A tailings dam has many key components, shown in Figure 2.5 and explained below (US EPA, 1994; Ridlen & Coffin, 2020; Oboni & Oboni, 2020). Each of these components plays a vital role in the safe and efficient operation of a tailings dam, ensuring containment and proper management. Nevertheless, the components are site-specific and dependent on dam design and construction.

- **Embankment**: The initial dam is referred to as the starter dam. Its stability is crucial as it acts as the foundation of the subsequent dam raises.
- **Foundation**: Beneath the tailings dam lies a bedrock or soil foundation, which should provide fundamental support for the entire structure. Note that the natural soil cover may not be removed. In US dams the deposited tailings are also part of the foundation.
- **Beach**: The top surface of the tailings near the dam face is known as the tailings beach. When well-managed, this develops into a relatively well-drained shell, serving as a structural zone. The beach slopes typically exhibit concave features, enabling hydraulic sorting of particles based on their size and specific gravity.
- **Decant Pond/Structure**: A decant pond may form as tailings settle, separating water from the sludge and should be considered in the design. A decant structure may be incorporated to release clarified water from the pond, managing water balance and preventing overtopping during heavy rainfall.
- **Freeboard**: The freeboard is the vertical distance between the designed or expected water level and the top of the dam. It provides a safety margin to prevent overflow and ensures unexpected surges or extreme weather events can be handled without compromising its structural integrity.
- **Liners**: Liner systems are employed for water containment and leachate collection at the surface, utilising materials like geomembranes and geotextiles, which may also serve as a cushion layer for the subgrade. Grout may also be injected into the foundation to improve the permeability characteristics, usually targeted to areas where potential seepage paths exist. However, they are expensive and low permeability fills are more frequently used instead.
- **Pipes**: Pipes are used for the transportation of liquids and tailings slurry, but also play a crucial role in drainage systems.
- **Drainage Structure**: Apart from the use of pipes for drainage, a well-designed internal drainage system is crucial for efficiently managing excess water within the dam. Proper drainage prevents the build-up of pore pressure and helps maintain the stability of the dam.
- **Spillway**: Spillways are essential to managing extreme flows, usually situated along the rim of the impoundment. The spillways can either be referred to as permanent or temporary. Permanent spillways are excavated channels through high bedrock locations with concrete control structures progressively raised over time. Temporary spillways are shallower channels, which are filled in upon dam raise to create a new one.
- **Monitoring/Surveillance Structure**: Tailings dams require continuous monitoring and surveillance systems to detect any potential issues early on. Instrumentation and regular inspections allow for timely response to any abnormal conditions.

When designing a tailings dam, it is crucial to consider various additional factors. These include but are not limited to, seepage collection, water treatment, vegetation or cover system, community engagement, and the development of an emergency preparedness and response plan (GISTM, 2020).

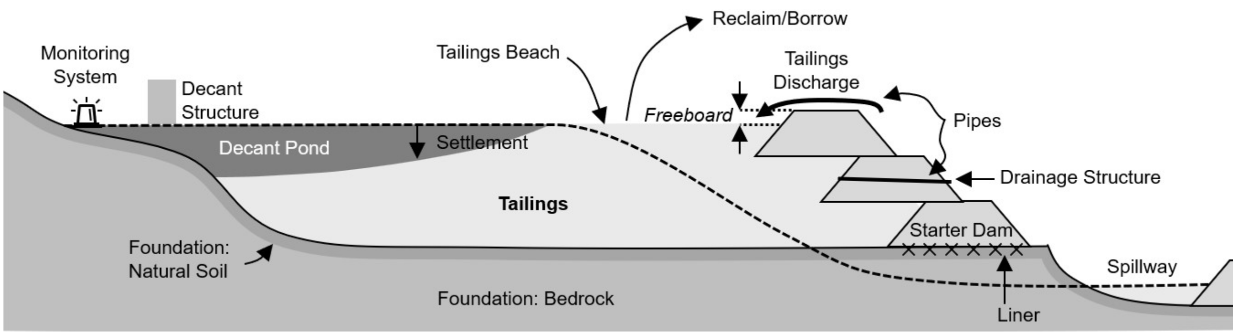


Figure 2.5: Main Components of a Tailings Dam

2.2.3. Mass and Water Balance

Tailings are generated throughout the entire mine operations and are continuously discharged upon their production. The design should take into account the deposition rates to appropriately plan raises and allow for sufficient consolidation time. The design should also consider the potential variations in tailings types. Sometimes, different types of tailings are produced and discharged in different (separate) sections of the TSF (International Commission on Large Dams (ICOLD), 2001).

Besides, re-excavating tailings can be contemplated for use as borrow material in constructing new dams or raises. Besides, the historical use of less efficient processing methods suggests the possibility of significant untapped resources remaining in these tailings, providing an additional rationale for their re-excavation. As a matter of fact, some tailings may even contain higher grades of valuable materials nowadays compared to the primary deposit. Such considerations should also be factored into the design process (Lottermoser, 2011; Araujo et al., 2022; Kinnunen et al., 2022).

Water is also a critical aspect of tailings dam design, given its extensive usage during processing and its association with most stability issues. The different components of the water balance are illustrated in Figure 2.6. As the tailings settle and consolidate, the water, initially trapped in the pores of the tailings, may rise to the surface. While some of the water of this decant pond evaporates, precipitation and surface runoff contribute to inflow. In addition, seepage may occur in the absence of preventive barriers, but it can be collected through a seepage collection ditch and eventually reclaimed. Whenever possible, water is decanted and reused in the mill. In certain instances, water may also be released back into the environment, after it has undergone eventual treatment (Jarvie-Eggart, 2015; Ridlen & Coffin, 2020; Cacciuttolo & Valenzuela, 2022).

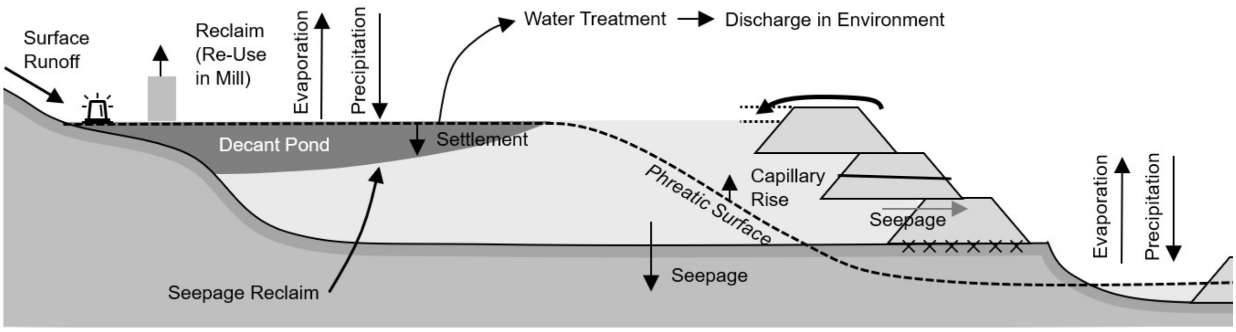


Figure 2.6: Water Balance of a Tailings Dam

2.3. Safety Concerns

Keeping the tailings dam safe and stable is one of the most challenging tasks in the entire mining process; tailings dam failures are not rare and consequences are catastrophic. This section defines the concept of failure and delves into the classification of failures within specific categories. Additionally, the study outlines the consequences stemming from such failures and offers insights into failure rates and the future perspective in this domain.

2.3.1. Definition of Failure and Failure Categories

Failure can be defined as 'an unacceptable difference between the expected and the observed performance' (Leonards, 1982). According to ANCOLD (2012), unacceptability is determined by deviations from the intended design. In the context of tailings dams, the design's primary objective is to prevent the dispersion of tailings and/or contaminated water into downstream environments and to comply with facility license conditions. Failure occurs when these objectives are not met.

A differentiation is frequently drawn between incidents and accidents. An incident encompasses any unforeseen event, occurrence, or circumstance that holds the potential to cause harm, damage, or disruption. On the other hand, an accident specifically refers to an unplanned and undesirable event that actually results in actual harm, injury, damage, or loss. While all accidents are incidents, not all incidents necessarily result in accidents (HSE, 2004). In this study, failures are specifically identified as accidents involving the release of tailings and/or contaminated water into downstream environments. Thus, failure is defined in this context as:

'An unacceptable deviation between the design intent, (encompassing facility licenses) and the observed performance, resulting in the release of tailings or contaminated water into the environment.'

The failures can encompass various scenarios, such as dam breaches, overtopping, excessive seepage without breach initiation, or the collapse of supplementary structures (Rana et al., 2022).

Failure Categories

The examination of historical dam failures in existing literature has led to the identification of 9 primary causes of failures. However, these encompass both failure root causes and failure mechanisms, making it more appropriate to refer to them as failure categories. The categories include: Earthquake Induced (EQ), Overtopping (OT), Slope Instability (SI), Foundation Deficiency (FN), Excessive Seepage and Internal Erosion (SE), External Erosion (ER), Structural Inadequacies (ST), Mine Subsidence (MS) and Unknown (U).

The subsequent list presents a comprehensive description of the different categories, which are illustrated in Figure 2.7. Note that the initial classification of failure categories originates from the International Commission on Large Dams (ICOLD) database. However, this document lacks detailed explanations for each category. Therefore, the failure descriptions are based on information later provided by other authors Roche et al. (2017), Roca et al. (2019), Lyu et al. (2019), Lin et al. (2022) and Rana et al. (2022), available incident descriptions, and with help the development of a Fault Tree Analysis (FTA), which is presented in Figure 2.8. Please be aware that the FTA may require additional refinement, yet it already illustrates the complexity of the failures.

- **Earthquake Induced (EQ)**
  All failures resulting from seismic events originating from earthquakes are classified within this category, potentially leading to total embankment collapse. Common failure mechanisms include:
  - **Dynamic Liquefaction**, occurring in loose, granular, saturated soils like tailings, subject to intense seismic shaking. Rapidly increasing pore water pressure acts as a lubricant between soil particles, reducing effective stress, and causing the soil or tailings to behave like a liquid. A high fines content, low permeability, and elevated material saturation exacerbate susceptibility, particularly in dams constructed in US fashion where the dam is built partly on top of the tailings.
  - **Sliding/Instability**, which occurs when seismic inertial forces induce dynamic stresses, potentially leading to slope instabilities like slumps or slides.
  - **Relative movement** of a **fault** beneath or near the dam, may potentially lead to instability of the embankment as well.
- **Overtopping (OT)**
  Overtopping occurs when water or slurry within the dam surpasses its crest or containment structure capacity, leading to spillage or flow over the top. It can cause direct dam collapse or head-cut erosion, eventually resulting in failure as well. Two primary mechanisms include:

  - **Surge overflow**, which is the continuous flow over the dam structure. It may result from material accumulation above the crest or settling of or under the dam core. Extreme weather events, poor water management systems, inadequate freeboard, and malfunctioning outlet systems are significant contributing factors contributing. Certain soil types, such as clay, silt, or organic-rich soils like peat, are prone to large settlements, further exacerbating the situation.
  - **Wave overwash** occurs when significant waves wash over the dam's crest and may be induced by strong winds or adjacent landslides. High water levels in the pond and insufficient freeboard contribute to wave overwash too. Besides, ice buildup can lead to blockage and overtopping.

- **Slope Instability (SI)**
  Slope instability refers to the susceptibility of a slope, or a portion of it, to movement or failure. This occurs when the forces acting on the slope exceed the inherent strength, resulting in slope displacement or collapse. Failures included in these categories are:

  - **Sliding/Instability**, which refers to the downward movement along a failure surface due to overriding forces surpassing material strength, often triggered by steep slopes, weak geotechnical properties, and/or excessive rainfall.
  - **Static liquefaction** failures occur in loose, saturated granular soils. A sudden increase in pore pressure reduces soil strength. Similar to seismic liquefaction, water acts as a lubricant between the soil particles, reducing the effective stress. This leads to slope instability, especially on steep slopes or poorly compacted granular soils.

- **Foundation Deficiency (FN)**
  Foundation failures encompass instances where the foundation fails to adequately support the dam's weight, potentially leading to the collapse of the dam structure. Distinguished types of failure include:

  - **Horizontal Sliding/Shearing**, whereby insufficient shear strength between foundation layers leads to sliding, compromising the dam support. The probability of shearing increases with the presence of weak or poorly compacted layers and excessive lateral forces.
  - **Settlement**, which refers to excessive vertical displacement of the foundation, resulting in uneven sinking of the dam structure, leading to cracks and instability. Factors like highly compressible layers, improper compaction, or excessive loading beyond design capacity contribute to settlement.
  - **Rotation** arises from the foundation's rotational movement, causing potential tilting or overturning of the dam structure. Uneven settlement or inadequate compaction of foundation materials often contributes to rotational failure.
  - **Static Liquefaction** happens when saturated loose granular soils in the foundation lose strength during sudden stress changes, resembling quicksand and reducing load-bearing capacity, exacerbated by high water content.

- **Excessive Seepage and Internal Erosion (SE)**
  Excessive seepage in dams results from uncontrolled water infiltration into the dam structure or foundation, releasing contaminated water downstream. Excessive seepage can also lead to the formation of erosion paths. Factors such as high permeability, high-pressure gradient, and high water content in the retained material contribute to this problem. Note that material saturation-related failures are classified under Slope Instability and Foundation Deficiency.

  Internal erosion is the seepage flow through soil or rock, leading to the migration of particles and the formation of tunnels or voids, causing potential seepage and/or instability of the dam's structure. A high water table, high permeability and internally unstable soils facilitate this phenomenon. Bonelli (2013) describes common mechanisms of internal erosion.

- **Backward erosion piping** initiates downstream of the dam at an unfiltered seepage exit with a high hydraulic gradient, enabling water to transport soil particles. A cavity forms, evolving into a pipe-like structure, usually in cohesive soil layers. As the eroded tunnel lengthens and reaches the reservoir, the water flow's erosive capacity increases, leading to further erosion.
- **A concentrated leak** forms when a large volume of fluid flows along an open seepage path, eroding the surrounding material. Seepage paths arise from cracks (e.g. differential settlement) or conduits that traverse through the embankment.
- **Suffusion** moves finer grains in widely graded or gap-graded soils (like glacial tills), increasing permeability as larger grains maintain soil structure. In contrast, during **suffosion** the soil volume decreases.
- **Contact erosion** takes place at the interface of two soil layers with different grain sizes and permeability, where water selectively moves through the coarser layer, transporting particles from the finer layer through the coarse layer, creating an open flow path.

• **External Erosion (ER)**
External erosion of the upstream or downstream dam face is a gradual process influenced by external factors such as **rainfall-runoff, waves, or wind**. This erosion weakens the slope surface, leading to potential overtopping, slope instability, and eventual failure. Deformations may also occur by ice drifting. Failures often occur due to unaddressed and unrepaired erosion gullies.

• **Structural Inadequacies (ST)**
This category encompasses **structural** failures involving the **collapse of components** such as spillway walls, outlet structures, decant systems, or tailings pipelines. Mechanical breakdown may result from factors like excessive subsidence, misalignment, loading, freezing/thawing, oxidation, weathering, and corrosion. Such failures can lead to flooding and loss of containment due to reasons like overtopping and dam rupture. It is crucial to emphasise that this category solely pertains to structural failures and excludes blockages of structures.

• **Mine Subsidence (MS)**
This category encompasses failures resulting from underground mine workings directly beneath or in close proximity to the tailings dam. Failures may stem from:

- **Excessive seepage** towards the underground mine, caused by suction forces, particularly under dewatering conditions. This may lead to the release of harmful substances into the mine.
- **Surface subsidence** due to the collapse of the underground mine workings or its nature (e.g., unsupported mining methods or selective extraction), exacerbated by weak host rock conditions. This is often a more catastrophic failure, potentially leading to a total dam collapse.

• **Unknown (U)**
This category encompasses dam failures where the **root cause** remains **unknown**. This scenario is prevalent for older dams that lack sufficient reporting and documentation.

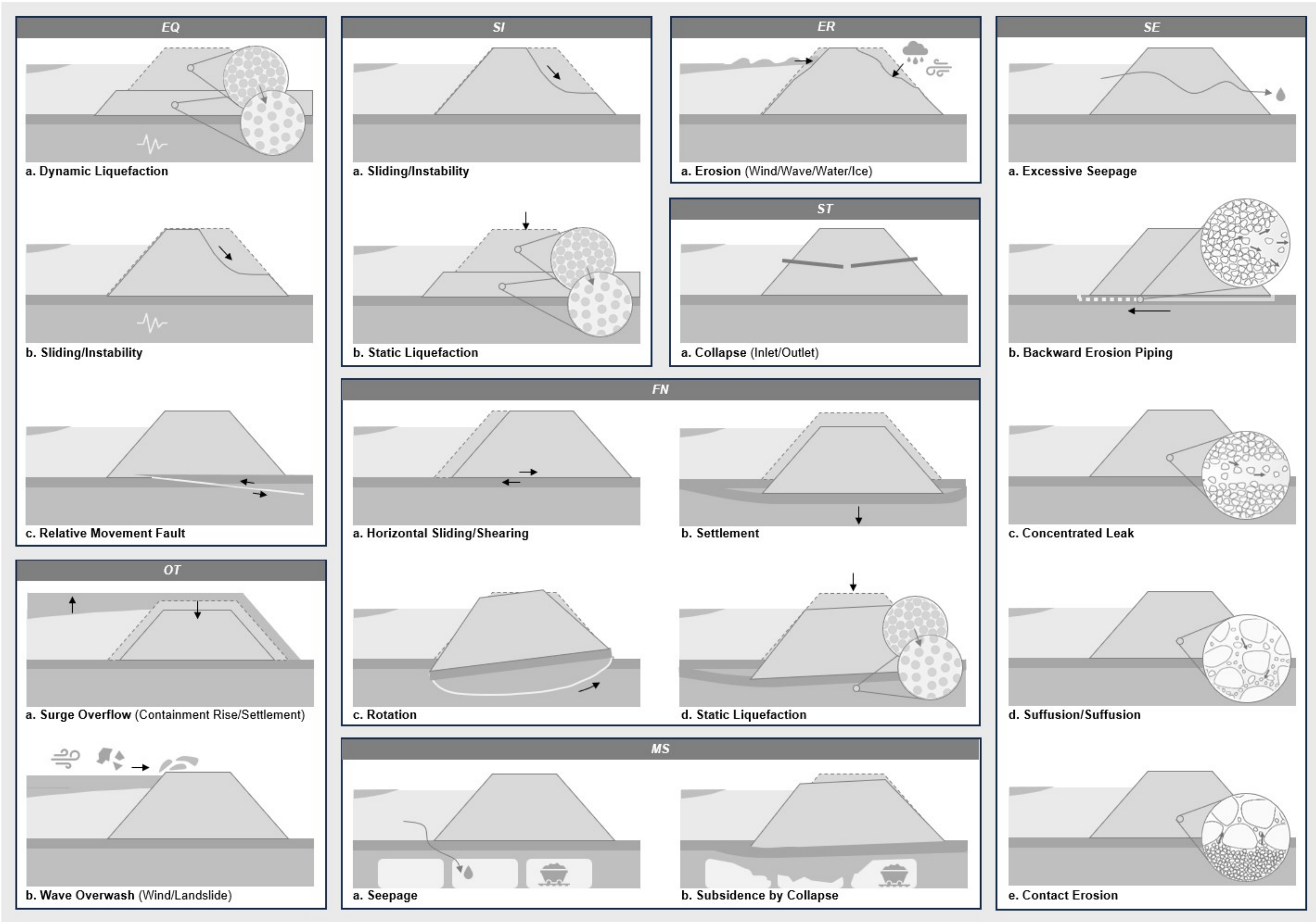


Figure 2.7: Schematic Overview of Different Failure Categories

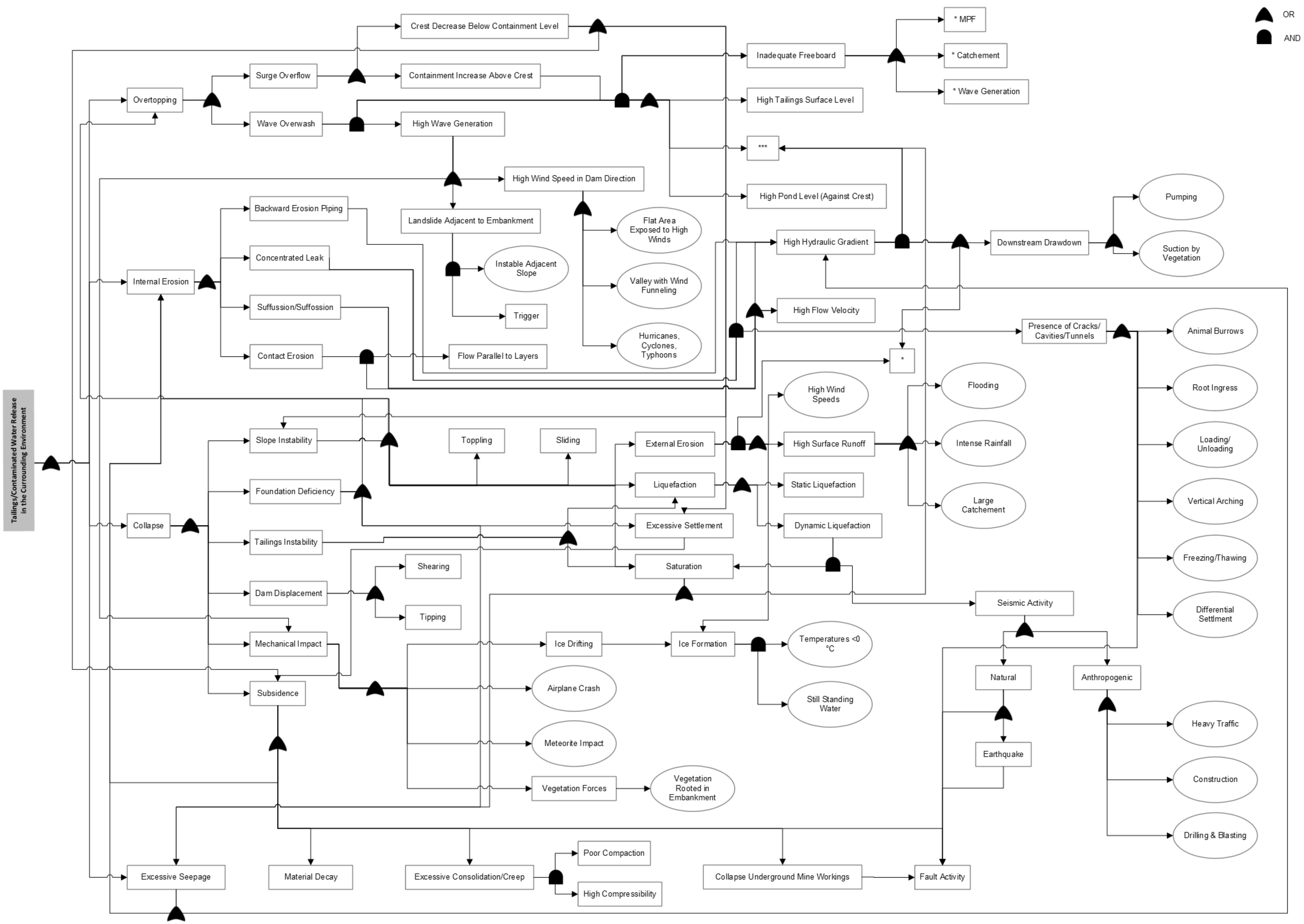
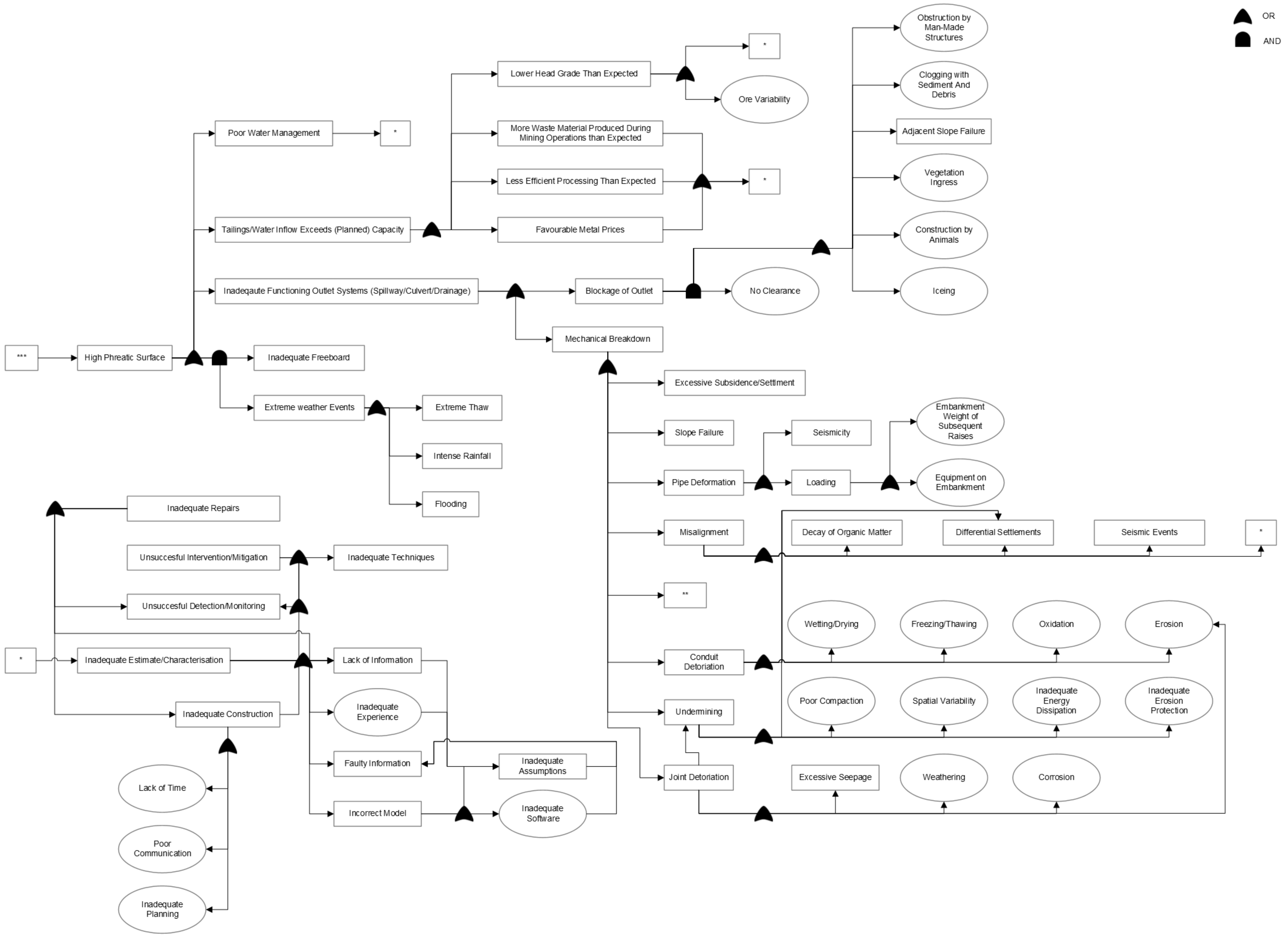


Figure 2.8: Fault Tree Analysis (FTA) *(Continuation on Reverse Side)*



OR
AND
***
High Phreatic Surface
Poor Water Management
*
Tailings/Water Inflow Exceeds (Planned) Capacity
Lower Head Grade Than Expected
*
Ore Variability
More Waste Material Produced During Mining Operations than Expected
Less Efficient Processing Than Expected
*
Favourable Metal Prices
Inadeqaute Functioning Outlet Systems (Spillway/Culvert/Drainage)
Blockage of Outlet
No Clearance
Obstruction by Man-Made Structures
Clogging with Sediment And Debris
Adjacent Slope Failure
Vegetation Ingress
Construction by Animals
Iceing
Mechanical Breakdown
Inadequate Freeboard
Extreme weather Events
Extreme Thaw
Intense Rainfall
Flooding
Excessive Subsidence/Settlment
Slope Failure
Seismicity
Pipe Deformation
Loading
Embankment Weight of Subsequent Raises
Equipment on Embankment
Misalignment
Decay of Organic Matter
Differential Settlements
Seismic Events
*
**
Wetting/Drying
Freezing/Thawing
Oxidation
Erosion
Conduit Detoriation
Poor Compaction
Spatial Variability
Inadequate Energy Dissipation
Inadequate Erosion Protection
Undermining
Joint Detoriation
Excessive Seepage
Weathering
Corrosion
Inadequate Repairs
Unsuccesful Intervention/Mitigation
Inadequate Techniques
Unsuccesful Detection/Monitoring
*
Inadequate Estimate/Characterisation
Lack of Information
Inadequate Experience
Faulty Information
Inadequate Assumptions
Incorrect Model
Inadequate Software
Inadequate Construction
Lack of Time
Poor Communication
Inadequate Planning

2.3.2. Consequences of Failure

The consequences of tailings dam failures are of great concern as well. Improperly designed, constructed, and managed tailings dams have a high potential to fail, resulting in catastrophic impacts on human life, health, safety, environment, infrastructure, and reputation. The consequences are often long-lasting and go hand in hand with high costs. The ICOLD (2020) and GISTM (2020) identify five primary categories of losses associated with such failures:

- **Population at Risk (PAR)**
  The PAR represents the count of individuals potentially exposed to the hazard, measured across the inundation area resulting from the failure.
- **Potential Loss of Life (PLL)**
  The PLL within the inundation area refers to the estimated number of individuals who may not survive the dam failure. There are several factors that influence the PLL, including flow depth, flow velocity, time of occurrence, advance warnings, topography, and transportation and mobility routes.
- **Environment**
  This category involves the destruction of surrounding natural environments, including aquatic and terrestrial habitats with possibly rare and endangered species. Water quality effects on groundwater, surface water, and fauna depend on geochemistry, especially when tailings are acid-generating, and long-term environmental consequences are lurking. Besides, the extent of the impact relies on the scale and type of the inundated area.
- **Health, Social and Cultural**
  The values of social and culture encompass implications for local businesses, services or social dislocation of individuals, as well as the potential impacts on regional recreational, heritage, and cultural assets fall within this category. The impact on human health is also considered within this category and may be affected by the toxicity of tailings and process water. This is especially a concern when tailings (seepage) contaminate drinking water resources.
- **Infrastructure and Economics**
  Failure could result in the loss of infrastructure, including bridges, highways, power stations, and commercial or residential properties, which is escalated when the infrastructure contains hazardous substances. Additionally, this category involves the impact on employment, economic compensation for individuals and properties, and the expenses associated with clean-up and rehabilitation.

One aspect not covered in the aforementioned categories is the potential damage a company may encounter. A company may face bankruptcy, legal litigation uncertainty, reputational damage and/or the loss of social licence to operate, as illustrated by some major dam collapse (Costa, n.d.).

Consequence Classification

The dimensions of failures and the magnitude of the consequences depend on various factors, such as the location of the tailings dam, the surrounding topography, the tailings rheology, the contained tailings volume, the failure mechanisms and the type and quantity of harmful substances present. The consequences can be classified according to Table 2.3, where the incremental losses of the five categories are described (GISTM, 2020).

Table 2.3: Common Form of a Consequence Classification
(Modified after GISTM (2020))

Consequence Classification	Incremental Losses				
	Population at Risk (PAR)	Potential Los of Life (PLL)	Environment	Health, Social and Cultural	Infrastructure and Economics
Low	None	None Expected	Minimal short-term loss or deterioration of habitat or rare and endangered species.	Minimal effects and disruption of business and livelihoods. No measurable effect on human health. No disruption of heritage, recreation, community, or cultural assets.	Low economic losses: area contains limited infrastructure or services. <US$1M.
Significant	1-10	Unspecified	No significant loss of deterioration of habitat. Potential contamination of livestock/fauna water supply with no health effects. Process water low potential toxicity. Tailings not potentially acid generating and have low neutral leaching potential. Restoration possible within 1 to 5 years.	Significant disruption of business, service, or social dislocation. Low likelihood of loss of regional heritage, recreation, community, or cultural assets Low likelihood of health effects.	Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes. <US$10M.
High	10-100	Possible (1-10)	Significant loss or deterioration of critical habitat or rare and endangered species. Potential contamination of livestock/fauna supply with no health effects. Process water moderately toxic. Low potential for acid rock drainage or metal leaching effects of released tailings. Potential area of impact 10 – 20 km^2. Restoration possible, but difficult and could take > 5 years.	500-1,000 people affected by disruption of business, services, or social dislocation. Disruption of regional heritage, recreation community or cultural assets. Potential for short-term human health effects.	High economic losses affecting infrastructure, public transportation, and commercial facilities, ore employment. Moderate relocation/compensation to communities. <US$100M.
Very High	100-1,000	Likely (10-100)	Major loss or deterioration of critical habitat or rare and endangered species. Process water highly toxic. High potential for acid rock drainage or metal leaching effects from released tailings. Potential area of impact > 20 km^2. Restoration or compensation possible, but very difficult and requires a long time (5 – 20 years).	1,000 people affected by disruption of business, services, or social dislocation for more than 1 year. Significant loss of national heritage, community, or cultural assets. Potential for significant long-term human health effects.	Very high economic losses affecting important infrastructure or services (e.g., highway, industrial facility, storage facilities, for dangerous substances), or employment. High relocation/compensation to communities. < US$1B.
Extreme	>1,000	Many (>100)	Catastrophic loss of critical habitat or rare and endangered species. Process water highly toxic. Very high potential for acid rock drainage or metal leaching effects from released tailings. Potential area of impact > 20 km^2. Restoration or compensation in kind impossible or requires a very long time (>20 year).	5,000 people affected by disruption of business, services, or social dislocation for years. Significant national heritage or community facilities or cultural assets destroyed. Potential for severe and/or long-term human health effects.	Extreme economic losses affecting critical infrastructure or services, (e.g., hospital, major industrial complex, major storage facilities for dangerous substances) or employment. Very high relocation/compensation to communities and very high social readjustment costs >US$1B.

Ideally, consequences should be described by such a classification. Alternative classification systems also exist. For instance, databases collecting historical failures (e.g. ICOLD (2001)) assessed the severity of consequences and assigned a severity score based on Table 2.4.

Table 2.4: Severity Classification
(Modified after WMTF (2019) and CSP2 (2023))

Severity Classification	Severity Code	Description
Very Serious	1	Multiple loss of life (~20) and/or release of ≥ 1,000,000 m^3 total discharge, and/or release travel of 20 km or more.
Serious	2	Loss of life and/or release of ≥ 100,000 m^3 semi-solids discharge and/or runout > 0.9 km.
Minor	3	Engineering/facility failures with release <100,000 m^3, other than those classified as Very Serious or Serious, no loss of life.
Potential	4	Other related facility tailings failures (e.g., sinkholes, pipelines), and non-tailings incidents (e.g., mine plug failures, waste rock failures, etc.) without release.
Not Assigned	-	Not assigned due to lack of information on toxicity of tailings known to be associated with beneficiation process.

2.3.3. Failure Rate

Several authors have recently analysed historical tailings dam failures (Azam & Li, 2010; Lyu et al., 2019; Rana et al., 2021, 2022; Lin et al., 2022; Piciullo et al., 2022). They report over 350 incidents throughout history, leading to public scrutiny due to the seemingly high frequency. Over the past 50 years, there have been 129 'major' tailings dam failures reported worldwide (WISE, 2023), accompanied by approximately 20 to 35 'minor' failures per annum (Adamo et al., 2020).

It is estimated that there are more than 3,500 - 30,000 dams all over the world, although there is no complete inventory (Williams, 2021). Assuming the 3,500 figure is correct, the average failure rate of tailings dams is about 1.2%, which is more than two orders of magnitude higher than conventional WR dams (Azam & Li, 2010). Even with tens of thousands of tailings dams worldwide, their failure rate remains several times higher than that of water storage dams (Lyu et al., 2019; Liang et al., 2021). Although the specific reasons behind these failures are not always clear, often involving multiple contributing factors, they can be categorised into different failure types based on root causes and failure mechanisms, as detailed earlier in Section 2.3.1.

The failure rate is alarming, especially as currently more than 1 out of 7 tailings dams is classified as being at 'high risk' (Warburton et al., 2020). Notably, about 10% of TSFs have experienced stability concerns during their operational history (Franks et al., 2021), and an upward trend of high-consequence failure events has been observed since the turn of the century (Owen et al., 2020).

Vulnerability Compared to Water Storage Dams

Tailings dams exhibit greater vulnerability compared to conventional water storage dams due to several factors. Firstly, unlike water storage dams, tailings dams undergo continuous elevation changes throughout their lifespan and experience ever-changing states of stress. The construction period spans at least 5 to 10 years, but is often extending over 50 to even 100 years. Secondly, the embankments of tailings dams are constructed using locally available materials such as E, R, or CST, in contrast to the concrete used in gravity dams. Note that there are also earth-filled dams utilised as water storage dams, constructed using situ materials as well. Nevertheless, tailings are not natural soils and may exhibit distinct behaviours (as elaborated in Section 2.1.2), which may make them more vulnerable to failure. Additionally, tailings dams frequently contain toxic substances that can pose significant hazards to both human health and the environment in the event of a release. Moreover, TSFs are not revenue-generating assets; instead, they represent ongoing burdens. Subsequently, the costs associated with monitoring and maintenance after mining activities cease are considerable. Furthermore, TSF owners often lack comprehensive familiarity with critical geotechnical issues, leading them to rely heavily on consulting designers. The original dam design and construction history are also frequently inadequately documented, and the passage of time may result in a loss of knowledge and expertise. Lastly, the absence of globally standardised regulations for specific design criteria and stability, construction, and operation requirements further contributes to the vulnerability of tailings dams (Davies, 2002; Rico et al., 2007; Vanden Berghe et al., 2011; Adamo et al., 2020).

Probability Classes

The PoF is often described by a rating, ranking from almost certain to close to non-credible. The rating is displayed in Table 2.5. Note that the qualitative interpretation guidance is based on the mining industry as a whole.

Table 2.5: Rating of the Probability of Failure
(Modified after Schafer et al. (2021))

Likelihood Rating	Qualitative Interpretation Guidance	Quantitative Interpretation Guidance	Annualised PoF
Almost Certain	Almost certain that an incident will occur given the circumstances. Very high probability of one or more occurrences per year.	Higher than 10% probability in a year	PoF ≥ 0.1
Likely	High likelihood. Commonly observed at similar facilities.	Higher than 10% probability in 10 years	PoF ≥ 0.01
Possible	Has occurred several times within the industry and at least once at the site (or similar facilities in the region).	Higher than 1% probability in 10 years	PoF ≥ 0.001
Unlikely	Has occurred before within the industry, but not at the site.	Less than a 1% probability in 10 years	PoF < 0.001
Rare	Low likelihood of occurrence, but not impossible. Has not occurred at the site but has occurred in industry.	Less than a 1% probability in 100 years	PoF < 0.0001
Very Rare	Very low likelihood of occurrence, but not impossible. Occurrence cannot be deemed non-credible	Less than a 1% probability in 1000 years	PoF < 0.00001
Close to Non-Credible	Extremely remote likelihood of occurrence. Although the mechanisms are technically plausible for the occurrence, it is seen as near non-credible.	Less than a 1% probability in 10,000 years	PoF < 0.000001

2.3.4. Future Prospect

In recent years, the number of tailings dam failures has been on the rise, together with their severity (Bowker & Chambers, 2015). Unfortunately, this trend is expected to continue. The safe storage of mine waste is becoming an ever more challenging task, especially considering the anticipated rise in the number of dams to be constructed, adding to the increasing scale and complexity of the tailings dams (Roche et al., 2017). To compound these challenges further, climate change predictions indicate a heightened occurrence of extreme weather events, which will exacerbate the situation (Franks et al., 2011). Another complicating factor is the existence of older dams that do not adhere to modern best practices, presenting a higher risk of failure. While newly constructed dams may follow better guidelines, there is no universally recognised global standard to which TSF need to adhere. While certain guidelines exist, adhering to them is not obligatory. Consequently, there is no standardised way to assess whether the risks have been sufficiently reduced.

Increasing Number of Tailings Dams

On top of that, the number of tailings dams is expected to increase. With the advancement of technology, mining is becoming economically viable at lower grades. Furthermore, the demand for minerals and metals is likely to increase due to the growing world population, their essential role in modern-day life, and their significance in the energy transition toward a low-carbon future (Meilli, 2016; Armstrong et al., 2019; Watari et al., 2021). Immensely, according to the International Energy Agency (IEA), demand for nickel and cobalt could increase 20-fold, and demand for copper could increase 6-fold by 2040 due to the growing electrification of the world (ICMM, 2022). In addition, it should be noted that alternatives for tailings disposal are still in their infancy and often far-fetched, uncertain, and costly, preventing the industry from broadly utilising these yet (Van Zyl et al., 2002; Watson et al., 2010; Adams & Gerritsen, 2021).

Given the risk related to the tailings material, their expected increase in production, the current tailings dam design practises, the failure mechanisms and the associated catastrophic consequences, it is crucial to take urgent action to mitigate the frequency and consequences of tailings dam failures. The future safety of these structures and the surrounding environment relies on proactive measures and effective risk management to address the growing challenges and uncertainties in managing mine waste. The current risk management practises and its challenges and shortcomings are described in Chapter 3.

3

Risk Management

Since its inception in the aftermath of World War II, the principle of risk management has undergone significant development and is now considered indispensable. While risk management has also gained attention in the TSF sector, the utilisation of traditional risk management strategies at TSFs still has its limitations. This section will provide an overview of the fundamentals of risk management and highlight how traditional strategies fall short, with a particular emphasis on the ALARP principle.

3.1. Fundamentals of Risk Management

Risk management refers to the process of identifying, assessing, and prioritising potential risks that an organisation may face, and taking actions to mitigate, avoid, or transfer those risks, something which is critical to the success of any organisation. This section defines the basic risk terminology and provides an explanation of the generic risk management process. Additionally, commonly used risk assessment methods are highlighted and their practical implementation is briefly described.

3.1.1. Basic Terminology

Risk, like love, is everywhere around us, playing a role in every consideration we make. However, similar to love, it is hard to define and different interpretations exist. Even though it may be inferred from the context of discussion what is meant by risk, in engineering it is necessary that we are precise and consistent in our understanding of the risk terminology (Elms, 1998). Various definitions of risk and associated risk management terms exist, as summarised by (Vlek & Stallen, 1980). The definitions vary across disciplines and time and are often tailored to the specific context. The herein-used definitions for risk and risk management are listed below, which are adopted from popular dictionaries, risk management guidelines and relevant articles that fit the context (Kaplan & Garrick, 1981; Oxford Languages, 2003; PMI, 2013; FERC, 2016; ISO:31000, 2018; CSA, 2022; APM, n.d.; Cambridge University Press, n.d.).

Risk

Risk can be defined as:

'A measure of the potential impact of uncertain events or conditions on the project objectives given a time period, typically expressed as the multiplication of the expected probability of the event, and the estimated consequences on public health, safety, property, environment, finances, and/or reputation'.

Note that throughout the remainder of this report, the term risk is used interchangeably with the risk of failure. Failure is defined in Section 2.3.1. The risk profile of a project is typically expressed with regard to the risk source, its probability, consequences and uncertainty, These elements play a crucial role in addressing the fundamental inquiries in risk management: 'What potential events might occur?', 'What is the probability of their occurrence?', and 'If they do occur, what are the resulting consequences?'. This conceptual framework was introduced by Kaplan & Garrick (1981).

- **Source**: Risks stem from a risk source: an element that, alone or in combination, has the inherent potential to generate risk. Risk sources are fundamental drivers, circumstances, or actions from which risks may originate. Examples of risk sources include employee errors, lack of policies and procedures, or changing environments.
  A risk source may result in a potential risk event, which is the occurrence(s) or change(s) of particular circumstances that can have various causes. The cause can be considered the reason for potential success or failure. The root cause is defined as the underlying, basic cause of failure. If the event pertains to something that goes wrong, there is often also a hazard in place. A hazard is anything that has the potential to cause harm to a valued asset, typically physical. A risk may arise if the risk source is induced by a trigger, which could lead to a threat.
- **Probability**: The probability of an event can be seen as the change of something happening, given the distribution of data. In contrast, the likelihood refers to finding the best distribution of data, given the particular data. Probability is a number between 0 and 1, where 0 is impossible and 1 is an absolute certainty. The concept of probability is simple, but its application can be complex.
  Two things need to be considered: the probability of a risk occurring and the probability of a risk having the expected impact and effect. Both are often difficult to determine in exact terms due to uncertainty and many dependency factors. The probability is often estimated with the help of statistics.
- **Consequences**: In addition to probability, risk is often defined by its consequences or results. The term "impact" is used to describe the degree of influence these consequences have. The effect of a consequence can be understood as the result of this influence. Different assets may be impacted by a risk's consequences, including the environment, public health and safety, and reputation.
  The severity of these consequences depends on various factors, such as the value at risk, vulnerability, degree of exposure, and risk velocity. For example, the impact of a dam failure is different if only one farm is downstream versus a large city like New York. Factors like the size of the tailings pond and the velocity of the dam failure can also impact the severity of the consequences.
- **Uncertainty**: Risk often arises due to uncertainty, which refers to the result of imperfect knowledge about the present or future due to a lack of information and/or understanding. Recognising and dealing with the degree of uncertainty is critical when outlining the risk profile, despite the difficulty involved in doing so.

Risk Management

Despite advancements in health and safety measures, the mining industry remains a dangerous profession. Given the high value at stake, effective management of risks is imperative. Risk management can be described as: *'A systematic and proactive process that involves coordinated activities to control and direct an organisation's risk with a primary objective to minimise threats and maximise opportunities to optimise the project's success'.* Risk management furnishes a foundation for sound decision-making, in which the following play a significant role:

- **Risk Appetite**: Signifies an organisation's willingness to embrace risk while pursuing strategic goals. It sets limits on acceptable risk exposure and guides decision-making. It is dynamic and shaped by industry, context, and values.

- **Inherent Risk**: Denotes the level of risk before implementing any mitigation measures. It reflects the potential impact and probability of adverse events occurring without considering risk controls. By assessing inherent risk, organisations identify their baseline exposure.
- **Residual Risk**: The level of risk that remains after applying mitigation measures. It represents the potential impact and probability of adverse events occurring despite implemented risk controls.

Roles within risk management should be clearly defined to ensure comprehensive risk assessment and mitigation. Engaging stakeholders throughout the process provides a holistic view of risks, identifies blind spots, and aids in developing effective mitigation strategies. Stakeholders include both internal and external parties, such as risk owners, employees, shareholders, regulators, local communities, industry associations, media, and special interest groups. Due to variations in project scale, complexity, and context, there is no universal solution for risk management. However, there are several common steps taken during the risk management process, as described in the next section.

3.1.2. Common Risk Management Process

Even though various definitions of risk management exist and the management approach differs from organisation to organisation, the risk management process shows similarities and is often characterised by a set of steps, of which an overview is presented in Figure 3.1. An explanation of each of these common components is presented below (Based on IRM (2002), PMI (2013) and ISO:31000 (2018)). It is essential to recognise that this is a continuous, cyclical process that repeats once it reaches its conclusion.

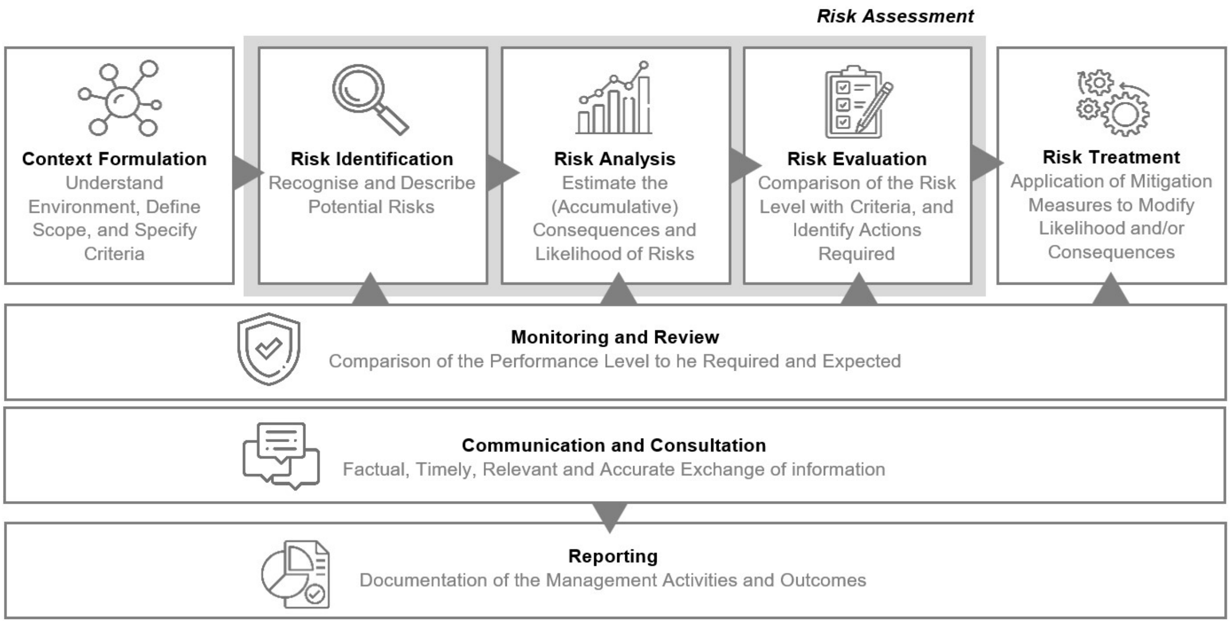


Figure 3.1: Generic Components of Risk Management Process
(Based on ISO:31000 (2018))

- **Context Formulation**
  It is essential to understand the internal and external environment, define the scope, and set clear objectives for a strong project foundation. Elements like the time, location, processes, systems, assets, as well as legislation, responsibilities and expectations of stakeholders should be specified.
- **Risk Assessment**
  Risk assessment aims to advise on the acceptability of current risks and the adequacy of measures. Comprehending uncertainties, adverse impacts, and opportunities is pivotal for goal attainment. assessment outcomes guide decisions and should entail collaborative, informed input.

- **Risk Identification**: The potential impact on the project objectives should be identified. This includes recognising risk sources, events, causes, and triggers, considering uncertainty and time. The key question is: 'What, how, why, where, and when might risks occur?', which could be answered by various methods including brainstorming, expert interviews and scenario analysis, among others. Projects often have a multitude of risks, which are often categorised by source, type, area, or phase. Risks can also be classified as external or internal, also known as systematic and unsystematic risk, respectively.
- **Risk Analysis**: Risk analysis assesses the real level of individual and combined risks. The central question to consider is: 'What are the (cumulative) consequences and probability?' A detailed description of the impact, elements at risk, vulnerability, exposure, velocity, and dose-response. Probabilities are assessed in detail. The analysis can be qualitative, quantitative, or mixed, contingent on assessment goals.
- **Risk Evaluation**: The final assessment step compares risk analysis results to contextual criteria. This comparison is carried out to determine whether additional action is necessary and where such action is required. It is important to consider the extent of control or influence over the risks when making these decisions and prioritise actions accordingly.

• **Risk Treatment**
For unacceptable risks or insufficient mitigation, action is needed via further treatment. Options to reduce the probability and or consequences are selected. Common methods (illustrated in Figure 3.2) include:

- **Elimination**: Physically removing hazard to prevent exposure.
- **Substitution**: Replacing hazard with less risky alternative.
- **Engineering Controls**: Isolating the risk via barriers.
- **Administrative Controls**: Altering practices to trim exposure duration, frequency or intensity.
- **Personal Protective Equipment (PPE)**: Using protective gear to minimise exposure.

The treatment options are arranged in descending order of effectiveness, but note that the most effective methods are often the most challenging.

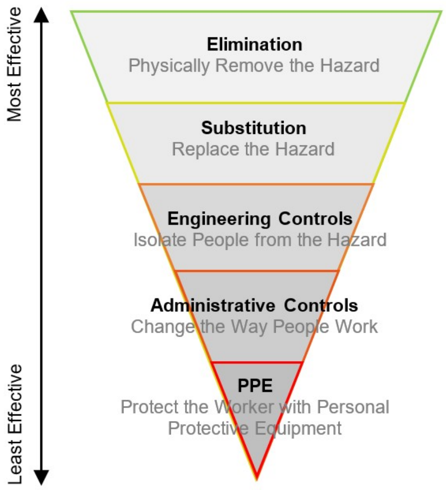


Figure 3.2: Hierarchy of Controls *(Modified after NIOSH (2023))*

• **Communication and Consultation**
Effective communication is vital to ensure that all involved parties know the risks and comprehend the decisions made. Maintaining an open dialogue with stakeholders facilitates the timely, relevant, and accurate exchange of information. To ensure the quality of risk management, it is crucial to consult experts who have practical experience in the type of activities under consideration. Communication and consultation are ongoing processes throughout the entire risk management process.

• **Monitoring and Review**
Continuous monitoring, review, and comparison of risks and risk management practices to the required or expected performance level are crucial to ensure and enhance the quality and effectiveness of risk management. In addition to known risks, new risks should be identified as they arise. Risk monitoring and review should begin at the onset of risk management and may extend beyond the project's completion.

- **Documentation**
  Documentation of all risk management activities is an integral part of the process and aims to support communication of activities and outcomes with stakeholders, provide information for decision-making, improve the current practices and preserve results for future use and reference. It also allows for validation and verification.

3.1.3. Popular Risk Assessment Methods

Risk can be assessed in a quantitative, semi-quantitative and qualitative manner. Quantitative risk assessment uses numerical data and models to assess the probabilities and consequences, whereas, in a qualitative approach, the risks are evaluated based on expert judgment to categorise the probability or consequences. Popular methods utilised for risk assessment in the mining industry are (Luko, 2014; Ostrom & Wilhelmsen, 2019):

- **Risk Matrix**: A visual representation that combines the probability and consequences of risks to assess their overall severity, aiding prioritisation in qualitative assessments. It is fast but may oversimplify risk interactions and be subjective in assigning scores.
- **FTA**: A deductive method that models the causes of an undesired event using a tree-like structure, identifying combinations of events that could lead to the undesired outcome. A FTA can be complex and resource-intensive; it may not account for all factors.
- **Event Tree Analysis (ETA)**: Complementary to FTA, ETA focuses on modelling the consequences that follow a specific initiating event, used to assess the potential outcomes. The drawbacks are similar to those of a FTA.
- **Bowtie Analysis**: A graphical method that illustrates the relationship between potential causes, preventative barriers, and consequences. It provides a visual representation of the risk scenario and its mitigation strategies. Bowties may simplify interactions and are challenging for complex scenarios. Besides, it provides limited quantitative insights.
- **Failure Modes and Effects Analysis (FMEA)**: A systematic approach to identifying potential failure modes in a process, system, or product, assessing their effects, and prioritising them based on severity, occurrence, and detectability. However, FMEA only focuses on single failure modes and does not capture interactions.
- **Hazard and Operability Analysis (HAZOP)**: Primarily for complex systems, HAZOP reviews process design methodically, detecting deviations and operational issues. A disadvantage is that it is often time-consuming and has the potential for subjective interpretations.
- **Layer Of Protection Analysis (LOPA)**: Quantifies risk reduction achieved by protection layers, assessing the adequacy of existing safeguards. It requires well-defined safeguards and complex scenarios may be oversimplified.
- **Cost-Benefit Analysis (CBA)**: Evaluation of the costs of (non-)monetary values against the benefits of a proposed project or action to determine the financial feasibility and desirability. It is a commonly used method in decision-making, especially when considering alternative options. However, accurately estimating these costs and benefits can be challenging, and valuing non-monetary factors may present additional difficulties.
- **Delphi Method**: A consensus-building technique involving expert panels, iteratively collecting and redistributing anonymous responses to reach consensus. It requires careful facilitation which is time-intensive and diverse opinions may not be well reflected.
- **Monte-Carlo Simulation**: Involves using random sampling techniques to model the impact of various input variables on a system's performance. It is particularly useful for assessing uncertainties and variability. Monte-Carlo simulations require extensive data and have a complex setup.

3.1.4. Practical Implementations and Implication

Regulatory frameworks and established methodologies guide the practical implementation of risk management. These frameworks vary across industries, countries, and specific contexts, ensuring a structured approach to risk assessment and mitigation. Risk-based management for tailings dams is a relatively recent concept, with methods and guidelines being adapted from other industries in the late 1980s to the 1990s (Singh & Herza, 2019).

A risk-based approach within the tailings industry is the GISTM, a guideline introduced by the GTR in 2020, after the Brumadinho dam failure. It outlines a comprehensive framework, which should systematically assess risks, devise effective mitigation measures, and ensure ongoing monitoring practices. Other, commonly used frameworks across various industries include International Organization for Standardization (ISO)31000, Committee of Sponsoring Organizations (COSO), National Institute of Standards and Technology (NIST), Control Objectives for Information and Related Technology (COBIT), Risk and Insurance Management Society (RISM) and Australian/New Zealand Standard (AZ/NZS).

However, while these frameworks provide valuable guidance, they frequently lack a definitive answer to the question 'How safe is safe enough?', which is rather an ethical and political question than an engineering decision. The answer is subject to multifaceted influences, including education, experience, norms, history, and cultural perspectives. The risk assessment techniques outlined in Section 3.1.3 do also not directly address this question. The majority of these methods focus on identifying potential outcomes, serving as an initial step toward answering the question and the CBA, for example, can also be employed to facilitate trade-off considerations, although no guidance is provided.

To achieve an objective answer to the question 'How safe is safe enough?', principles like As Low As Reasonably Practicable (ALARP) come into play. Alternatives for ALARP and objective evaluation exist (e.g. As Low as Reasonably Attainable/Achievable (ALARA) concept or So Fas As Is Reasonably Practicable (SFAIRP) principle), but these are not considered in this work, as the GISTM for tailings employs the ALARP principle. The forthcoming section delves into the nuances of the ALARP principle.

3.2. As Low As Reasonably Practicable (ALARP) Principle

The ALARP principle is a fundamental concept in risk management, used in the Health, Safety and Environment (HSE) concept to guide decision-making processes in numerous industries. This section navigates through the depths of this principle, beginning with its fundamental definition and branching into its components, methods of demonstration, application and challenges.

3.2.1. Definition of ALARP

Various definitions of ALARP exist, but they share similar theoretical and philosophical foundations. At its core, ALARP reflects the intent to mitigate risks to a level that is 'As Low As Reasonably Practicable', given the circumstances, whereby the risk is weighted against the cost of control. The principle acknowledges the reality that risks cannot be entirely eliminated but must be prudently managed to minimise potential harm while considering practical constraints. According to the GISTM a risk is ALARP if:

> *All reasonable measures are taken with respect to tolerable or acceptable risks to reduce them even further until the cost and other impacts of additional risk reduction are grossly disproportionate to the benefit (GISTM, 2020, p. 25) .*

This definition sets the stage for understanding the intricate interplay of tolerability, acceptability thresholds, and the balancing act between risk and costs central concepts in the ALARP principle.

Tolerance and Acceptability Threshold

To comprehend the ALARP principle, it is essential to recognise the delineation of three general risk regions: unacceptable risk, tolerable risk and broadly acceptable risk, shown in the 'carrot' model in Figure 3.4a. Each region signifies a different level of risk associated with the probability of an event occurring and its potential consequences:

- **Unacceptable Risk**: Positioned at the top, this region encompasses risks characterised by high probability and severe consequences. Such risks are deemed unjustifiable regardless of potential benefits, and should therefore be mitigated to the greatest extent possible.
- **Broadly Accepted Risk**: On the other end of the spectrum, broadly accepted risks are identified, having low probability and consequences. Such risks are generally broadly accepted and are typically trivial to daily life. Note that the theoretical ideal of absolute zero risk remains unattainable in practice.
- **Tolerable Risk**: The middle segment of the carrot model covers risks that fall between high and low probability, with consequences ranging from severe to negligible. Risks within this range can be deemed tolerable if they conform to the ALARP principle. This means that reasonable measures have been taken to minimise them further without disproportionate costs. This balancing of risk and costs and the concept of disproportionality is further explained below.

Hence, the ALARP principle aims to minimise tolerable and unacceptable risks (defined by thresholds) to a reasonable extent by balancing risk and costs.

Thresholds

The thresholds between the different regions should be set by the risk-responsible entities. These thresholds can be visually represented in so-called FN-Plots. The expected frequency of risk F is plotted against the expected consequences N (often expressed in statistical lives or monetary values), aiding in the communication of complex risk management decisions to various stakeholders. The results of the ALARP assessment can also be plotted in these graphs. An example of such a plot is provided in Figure 3.3, showing the thresholds of FERC (2016). Nevertheless, it is important to acknowledge that numerous sectors lack universally accepted criteria (Oboni & Oboni, 2013).

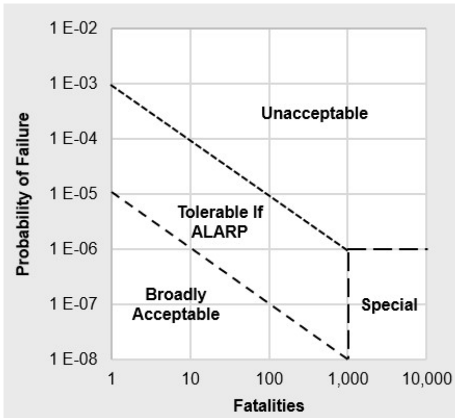
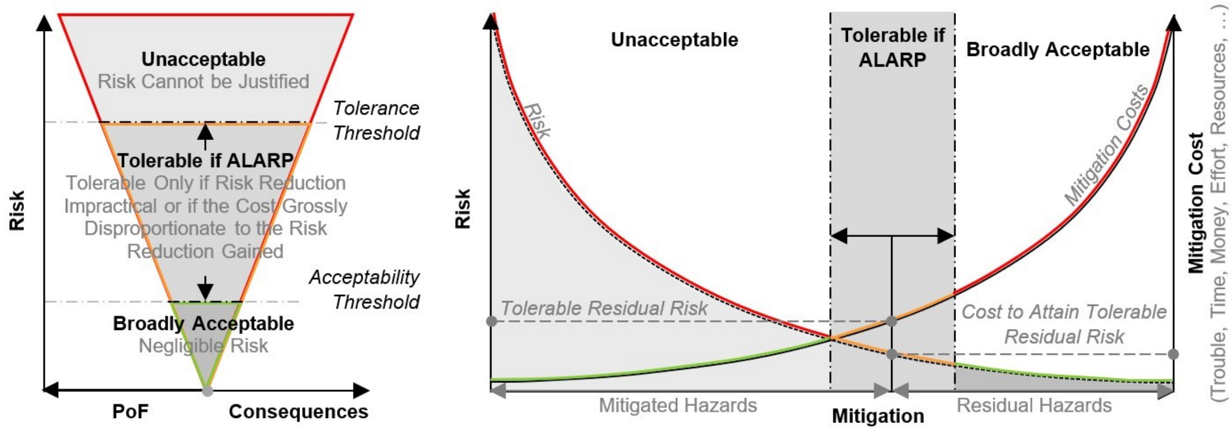


Figure 3.3: Example of a FN-Plot Showing Thresholds *(Based on FERC (2016)*

Balancing Risk Reduction and Costs

Although risk can never be completely eliminated, it may be significantly reduced by mitigation measures that decrease the probability and/or the consequences of the hazard. ALARP essentially involves the weighting of the cost to reduce a risk, against the resulting risk reduction. The costs do not simply refer to the monetary value of the risk reduction but should incorporate the trouble, time and money required (Hurst et al., 2019). Melchers (2001) also includes the physical difficulty of these cost components. Health & (HSE) (2001) describes the costs collectively as the 'sacrifice' to be made.

The relationship between risk reduction and mitigation costs is often exponential in shape; risk shows an exponential decay, while the costs show an exponential growth. For high risks, relatively modest investments can lead to substantial risk reduction, while further cost-intensive reduction yields diminishing returns (Oboni & Oboni, 2020), see Figure Figure 3.4b. The state of a risk being deemed ALARP is achieved when the risk falls below the tolerance threshold, and the costs associated with further risk reduction become disproportionately high in comparison to the potential reduction in risk.



(a) Risk Regions
(Modified after Health & (HSE) (2001))

(b) Relation Risk and Mitigation Costs
(Modified after Oboni & Oboni (2020))

Figure 3.4: As Low as Reasonably Practicable (ALARP) Principle

In some cases, it is obvious to state when the risk is 'tolerable' or acceptable and when the mitigation measures are grossly disproportionate to the benefit. For example, to spend 1 billion dollars on preventing a broken finger of 1 employee is unreasonable, but to prevent a tailings dam breach with catastrophic consequences for the whole community and environment for 1,000 dollars is undoubtedly proportionate. Nevertheless, while it may be apparent when mitigation costs are disproportional for some risk scenarios, the ALARP status for complex risks is often not straightforward and a careful demonstration is required.

3.2.2. Necessity of ALARP

The principle of ALARP has emerged as a foundational concept in modern risk management, which assists in making informed decisions. It provides a structured approach to risk assessment and mitigation and facilitates a framework for risk communication. It facilitates a non-binding approach to establishing objectives, encourages ongoing enhancements and provides guidance to the rather ethical and political questions: 'How safe is safe enough?'. This is especially indispensable in low-probability, high-consequence scenarios, such as the aviation, nuclear, oil and gas and TSF industries.

It can be argued that for risks with a high probability of occurrence and catastrophic outcomes, the precautionary principle can be applied. At its core, the precautionary principle suggests that when risk is uncertain and has the potential to cause significant harm to the public or environment, precautionary measures should always be taken (Bourguignon, 2015). Nevertheless, it is essential to approach this principle with caution, as emphasised by Maciotta & Lefsrud (2018). The avoidance of one risk often results in the increase of other risks (e.g. lack of employment, economic depression or insufficient power). The feasibility of further risk reduction will be dependent on the available sacrifice and the population's perception of risk.

Ultimately, a balanced choice should be made, resulting in residual risk levels that fall within the tolerability limits, without putting unnecessary strain on available resources. ALARP provides guidance to justify why further improvements should be made or should not be made Hurst et al. (2019). Risks having this low probability of occurrence and catastrophic outcomes are often the most worrisome risks and inherently difficult to quantify and therefore it is essential that ALARP thinking is applied (Oldenburg & Budnitz, 2016).

In cases where large populations or significant assets are at risk, demonstrating adherence to ALARP can enhance public and stakeholder trust. It shows that all reasonable efforts are being made to protect their safety and interests. Moreover, implementing the ALARP principles is not only a best practice but also a legal requirement in some cases.

3.2.3. ALARP Application and Demonstration

The ALARP principle finds application across various industries, including aviation, oil and gas, and nuclear sectors (Abrahamsen et al., 2018). Countries with strong safety standards have largely adopted ALARP or similar principles (Quddus et al., 2020). This is also expected to be the case for TSFs, although it is expected that the utilisation of ALARP will grow in the tailings industry due to its requirement in the GISTM. The specific application of these principles can vary significantly, both between industries and within the same country. There is limited available data on the precise practices of ALARP in industry.

In scientific literature, ALARP is described as a way of thinking. Although its principles are generally straightforward, its demonstration necessitates a considerable repository of information and substantial judgement in analysing it (Redmill, 2010). There is neither a simple formula to determine whether the risk is ALARP, nor a simple way to conclude whether the risk is unacceptable, leaving the ALARP region and tolerance threshold undefined. The balance of costs and the acceptability of risk depends on several factors, such as the severity of the risk, the elements at risk and the probability of a hazard causing harm, all of which contribute to the complexity of the evaluation process.

Generally speaking, ALARP can be demonstrated by asking two questions: (1) 'What more can I do? and (2) 'Why have I not done it?' (Beedle, 2021). To justify whether further improvements are reasonably practicable or not, several steps must be taken. These steps include hazard identification, establishing the range of minimum criteria, an assessment of the potential consequences and the probability that these consequences occur, identifying a comprehensive range of relevant risk reduction measures and assessment of reasonable practicality (Melchers, 2001; Risktec Essentials, 2018). ALARP thinking should be used throughout the entire project lifecycle and beyond (Hurst et al., 2019). The implementation of ALARP can be approached through qualitative, semi-quantitative, or quantitative methods.

While specific guidelines for demonstrating ALARP remain absent, Risktec Essentials (2018) describes several tools which are commonly employed. A brief list of these tools is provided below. The challenges and shortcomings are briefly discussed in the subsequent section (Section 3.2.4).

- **Codes and Standards**
  Codes and standards ensure systematic and aligned risk management by providing industry-specific guidance for assessing risks and determining ALARP levels in line with relevant industry norms, guidelines, and legal regulations. Risks meeting or falling within these standards may be deemed acceptable and ALARP. Deviations from these standards may indicate the need for additional safety measures.
- **Best Practise and Engineering Judgement**
  Drawing upon collective industry professionals and their individual engineering judgment, this approach relies on the consensus of professionals to evaluate and validate risk management decisions. Professionals in the field draw upon their extensive experience, deep subject knowledge, and industry best practices to evaluate risks and determine the most appropriate risk control measures within the ALARP framework.
- **Cost-Benefit Analysis and Quantitative Risk Assessment**
  CBA and quantitative risk assessments are systematic methods for evaluating the economic and safety implications of risk control measures, which are more frequently referenced in the academic literature than the other tools (e.g. Health & (HSE) (2001) and Jones-Lee & Aven (2011)). CBA quantifies the costs and benefits of various risk reduction options, helping decision-makers identify the most cost-effective approaches. Quantitative risk assessments employ mathematical models and data to assess the probability and consequences of specific hazards, aiding in the determination of risk levels and the need for mitigation measures.

They often involve the establishment of formulas to determine a certain cost-benefit ratio, which is used to describe the disproportionality between risk reduction and costs. An example of such a formula is given below (Risktec Essentials, 2018).

$$Implied\ Cost\ of\ Averting\ a\ Fatality\ (ICAF)\ (\$) = \frac{Net\ Cost\ of\ Option\ (\$)}{Potential\ Saving\ of\ Life\ (\$)} \quad (3.1)$$

where,

$$Net\,Cost\,of\,Option\,(\$) = Cost\,of\,Option\,(\$) - Reduction\,in\,Loss\,of\,Assests\,\&\,Production\,(\$) \quad (3.2)$$

Numerous other researchers have endeavoured to define a cost-benefit ratio, such as Cost Effectiveness (Bowles, 2004), and disproportion (HSE, 2001; FERC, 2016). They often offer recommendations regarding when a course of action is reasonably practical or when it appears grossly disproportionate. These provide guidance; however, it is believed that these specific numbers also depend on the risk appetite of the risk owner and the project constraints, costs, revenues, etc.

- **Peer Review and Benchmarking**
  Peer review involves independent experts or colleagues evaluating and providing feedback on the risk management strategies in place. This tool can help ensure that the chosen strategies are robust and effective. Benchmarking involves comparing an organisation's risk management practices against those of industry peers or best-in-class organisations to identify areas for improvement.
- **Stakeholder Consultation**
  Stakeholder consultation involves engaging relevant parties, such as employees, local communities, regulatory agencies, and other stakeholders, in the decision-making process. Their input can provide valuable insights into the perceived risks, potential consequences, and the acceptability of risk levels, all of which are crucial considerations in the ALARP demonstration.

3.2.4. Challenges and Shortcomings

Each of the tools described in the previous section can contribute to the comprehensive assessment of risks and the determination of whether the risks are reduced to a level that is ALARP. Despite their contributions, they have many challenges and fall short in several ways. These challenges and shortcomings are not unique to a specific industry but are rather widespread. The available conventional risk analysis also fall short for application within the tailings industry.

Absence of Clear Guidelines

There is a lack of consensus and clear guidance on how to carry out ALARP evaluations (Quddus et al., 2020). There is no standardised approach, primarily because each project or situation is often unique, making a one-size-fits-all solution impractical, though, there is often no guidance within the industry. The definitions for ALARP and related terms are often open for interpretation and lack clarity (Melchers, 2001), leading to subjective decision-making processes, which, in turn, result in inconsistencies in risk assessments and decisions.

Ethical Concerns

Ethical considerations complicate matters. What one group may deem an acceptable risk, another might find unacceptable, especially when different stakeholders are involved. Furthermore, Faber & Stewart (2003) highlight that preferences may change over time; for example, the public is more aware and concerned about environmental issues than two decades ago. Moreover, the acceptance criteria used in risk assessments are not always transparent and can seem influenced by negotiations, potentially raising questions about objectivity (Melchers, 2001). Besides, many risk assessment methodologies assume that all factors can be converted into monetary values. This is often problematic, particularly in the context of assessing risks to human life and well-being. Placing a specific economic value on human life (e.g. in a CBA) is a contentious issue, as life is often considered priceless (Jones-Lee & Aven, 2011).

Complexity of Risk Scenarios

The complexity of risk scenarios adds to the challenges. ALARP is dependent on numerous factors, including the financial state of the company, making it complex to evaluate. There are often complex interactions between different risks, making it hard to quantify the probability and consequences of failure, for instance, different types of losses, such as economic, non-monetary, and environmental, are not easily comparable (Faber & Stewart, 2003). Dynamic environments, where conditions are constantly changing, present additional hurdles. Assessing the PoF in such environments is complicated by the need to account for evolving likelihood over time. In addition, concerns may also change with time. Psychological studies show that the preferences of a decision-maker will change with time (Melchers, 2001) and individuals tend to play it safe when they might face losses, but become more willing to take risks when there is a chance for gains (Oboni & Oboni, 2013). Furthermore, the application of ALARP to emerging technologies can be problematic, as risks and treatments may not be well understood or known.

Resource Intensive Process

The process of applying ALARP is resource-intensive, demanding time, money, and expertise. Gathering the necessary information for ALARP analysis can be a laborious task, and the completeness of the information is not always guaranteed. Organisations may struggle to allocate the required resources for rigorous risk assessments.

Complications Conventional Analysis

Traditional risk analysis, whereby risk is quantified by multiplying the probability of an event by its potential consequences, faces challenges when applied to situations involving low PoF and high consequences, such as TSFs. This approach may yield an average risk rating that masks the severity of rare but high-impact events. Prioritising risks based solely on these average values is difficult, as acknowledged by Caldwell et al. (2015) and Oboni & Oboni (2016). Additional variables like costs and time should be investigated for effective prioritisation.

Additionally, there are difficulties in expressing the PoF and consequences. Several obstacles contribute to this, as mentioned earlier, encompassing ethical concerns and the complex nature of the risks. Conventional risk analysis lacks this complexity required for TSFs. Moreover, geotechnical expertise is required and on-site staff often lacks the expertise needed to understand the risk phenomena and their effects on the performance and stability of TSFs (Silva et al., 2009).

Although numerous tools are available for conducting risk assessments, a consistent, rational, and auditable approach to determine whether the risks of failure have reached an ALARP level is lacking and the GISTM (GISTM, 2020) does not provide a definitive framework for demonstrating ALARP. Addressing these challenges is essential to enhance risk management practices. A challenge within the ALARP demonstration, arising from the literature review, is the assessment of the PoF of TSFs. This study will focus on the development of a tool to access this PoF, excluding the determination of consequences. The upcoming chapter will delve into the ins and outs of determining the PoF, exploring the existing tools for this purpose, and outlining the necessity for new tools and their required features.

III. Methodology

Objective 3:
Developing a Scientific Method or Tool for Probability of Failure (PoF) Evaluation

The development methodology of the tool is detailed, focusing on the PoF estimation and the associated challenges and existing methods, as well as the necessity, requirements, and approach to tool development. The approach offers a scientific method for assessing the PoF. It consists of three steps: database development, the determination of the baseline PoF and a prevalence examination. The available data is examined and convergence and corrections made are highlighted. A simple analysis of the data attributes is performed and the opportunities, limitations and biases of the database are discussed. The baseline PoF is determined by dam construction method and failure category, considering available estimates in the literature and utilising distributions of the database. Lastly, the prevalence examination specifies factors affecting the baseline PoF and outlines the methodology for weighting and fulfilment assessment.

4

Concept Tool

This study focuses on developing an assessment tool for the PoF of tailings dams, addressing a gap identified in the preceding chapter's discussion of existing risk assessment methods for TSFs. This chapter summarises various approaches for assessing failure probability, existing tools, and their limitations and challenges. It then underscores the necessity for a new tool and outlines its requirements. Subsequently, it explains the tool's concept and the associated development process.

4.1. Probability of Failure (PoF) Estimation

This section continues the literature review and summarises various approaches for evaluating the PoF. Diverse methods and tools for assessing PoF are outlined, along with their challenges and limitations.

4.1.1. Common Methods

Vick (1994) and Morgenstern (1995), and others have identified three general, widely accepted methods for estimating event probabilities of earthen dams (including tailings dams):

1. **Frequency of Observations**: Based on historical failure data, the frequency of occurred failures is estimated, based on which the PoF can be estimated.
2. **Mathematical Modelling**: Computational analysis, like Finite Element Method (FEM) or Limit Equilibrium Analysis (LEM), could be used to estimate PoF, whereby various scenarios can be analysed.
3. **Expert Judgement**: Expert judgment relies on professional knowledge to estimate PoF for different failure mechanisms, offering insights into specific dam conditions and associated risks.

While calculating the PoF, several tools can be of assistance. Probabilistic models such as the First-Order Second-Moment (FOSM) method, Monte Carlo simulation, or reliability analysis methods are utilised to incorporate uncertainties in soil parameters, loads, and other variables affecting slope stability. The originally deterministic Factor of Safety (FoS) can also be utilised to perform a probabilistic analysis, describing input parameters as probability distributions instead of point values. In addition, methods like event tree analysis can contribute to defining the probability of failure. However, these conventional methods are often time-consuming and can involve substantial complexity and uncertainty (Tang et al., 1995). In the subsequent section, existing tools that have recently been developed to facilitate risk assessment for TSFs specifically in a cost-effective, user-friendly and time-efficient manner are described.

4.1.2. Existing Tools

The need for cost-effective, user-friendly and time-efficient risk assessments for TSFs has been ongoing for several decades. Efforts made often encountered challenges of defining reliable numbers within budget constraints, while also ensuring accessibility and efficiency. In contrast, Silva et al. (2009) introduced an alternative approach that involves the quantification of expert judgement to determine the PoF. This approach utilises a tool that takes into account the Level of Engineering (LoE) at the site.

Silva Method

The Silva method establishes a relationship between the FoS, PoF and LoE. This relationship is graphically depicted in Figure 4.1, which represents an updated version of the one initially introduced by (Lambe, 1985) and (Baecher & Christian, 2003). The plot is supported by 75 engineering projects of earth dams, tailings dams, natural and cut slopes and some earth retaining structures. Silva et al. (2009) classified earth structures based on the LoE in four categories:

- **Category I**: Facilities designed, built, and operated with state-of-the-art engineering. Generally, these facilities have high failure consequences.
- **Category II**: Facilities designed, built, and operated using standard engineering practice. Many ordinary facilities fall into this category.
- **Category III**: Facilities without site-specific design and substandard construction or operation. Temporary facilities and those with low failure consequences often fall into this category.
- **Category IV**: Facilities with little or no engineering.

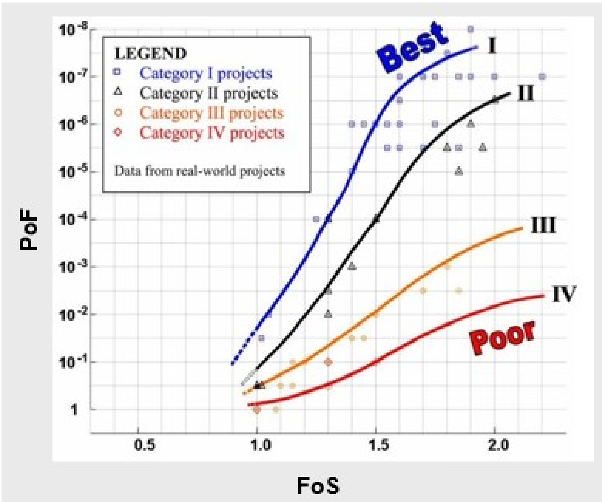


Figure 4.1: Relationship between Factor of Safety (FoS) and Probability of Failure (PoF) of Earthen Dams *(Silva et al., 2009)*

To determine in which category a certain structure falls, the practices followed for design (investigation, testing, analysis and documentation), construction, operation and monitoring are examined based on a set of criteria, with the different criteria assigned various weights.

Notably, a larger FoS does not necessarily imply a lower risk, as it can be offset by larger uncertainties, as illustrated in Figure 4.2 (D'Andrea & Sangrey, 1982; Tavares & Serafim, 1983; Christian et al., 1994; Kulhawy & Phoon, 1996). Furthermore, the flattening of the curves observed near a FoS of 2 signifies diminishing returns when it comes to over-engineering a constructed facility.

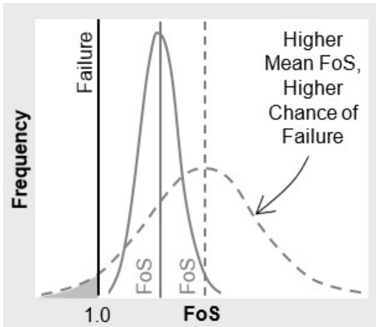


Figure 4.2: Probability of Failure (PoF) in Relation to Factor of Safety (FoS)

Modifications Silva Method

The Silva method has been modified by Chovan et al. (2021) to account for phased design and construction and the continuous operation over many years of observed performances and changing engineering practices. Modifications were made to the criteria of the different categories. Also, the weights were reviewed, shown in Table 4.1. The weights carry now equal weight, considering management and review systems that they integrated into engineering practice. Four modifications that may contribute towards a higher LoE are strong management; collaborative design, construction and operation; formal and thorough review processes; and effective documentation. In light of these modifications, the LoE is now referred to as Level of Practise (LoP). The resulting curves show similar results to those of Silva et al. (2009), see Figure 4.3.

Julien et al. (2019) have made similar attempts to modify and adapt this method to accommodate the latest practices and suit TSFs' risk assessment requirements. The adjustments by Julien et al. (2019) are also shown in Table 4.1. As can be observed, Julien et al. (2019) lowered the weighting of laboratory testing from 20% to 10% and increasing the operation and monitoring to 30%, aligning with the trend to rely on field monitoring (with piezometers, inclinometers, etc.). Chovan et al. (2021) and Julien et al. (2019) also provide methods for the determination of the consequences, which will not be elaborated upon as the consequence estimation falls outside the project scope.

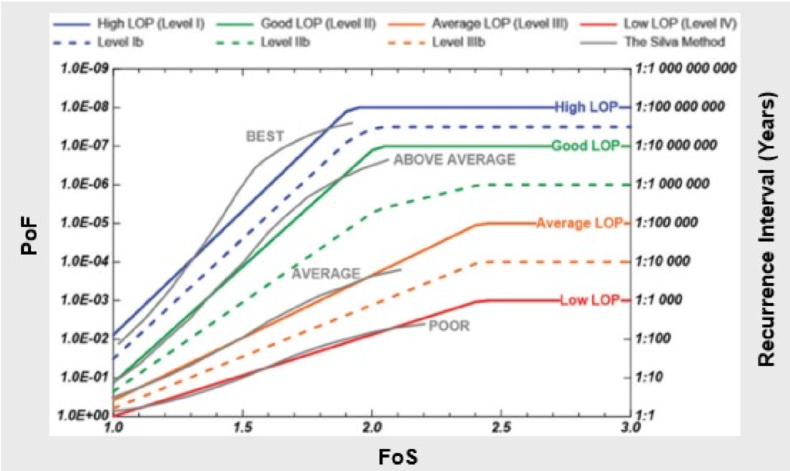


Figure 4.3: Relationship between Factor of Safety (FoS) and Probability of Failure (PoF) of Tailings Dams *(Chovan et al., 2021)*

Table 4.1: *Criteria and Weights for the Relationship between Factor of Safety (FoS) and Probability of Failure (PoF) of Earthen Dams by Various Authors*
((Silva et al., 2009; Julien et al., 2019; Chovan et al., 2021))

Method	Design			Construction	Operation and Monitoring
	Investigation	Laboratory Testing	Analysis & Documentation		
Silva et al. (2009) (Weights | Number of Criteria)	20% | 7	20% | 4	20% | 6	20% | 3	20% | 3
Julien et al. (2019) (Weights | Number of Crtieria)	20% | 9	10% | 6	20% | 7	20% | 8	30% | 13
Chovan et al. (2021) (Weights | Number of Crtieria)	20% | 9	13% | 6	18% | 8	18% | 8	31% | 14

Other Frameworks

Several other frameworks, relying on tools to generate semi-quantitative/quantitative results, have attempted to determine the PoF for tailings dams. Examples are Hansen et al. (2008) and Donnelly et al. (2016); however, the inputs are likely to be unavailable for most dams and the outputs do not align with the initial level of risk screening needs.

Singh & Herza (2019) have also introduced a framework for determining the probability of failure, producing relative risk profiles for storage facilities. Their approach aims for simplicity in results to ensure understanding among decision-makers and to minimise the risk of miscommunicating results. Based on 60 inputs the PoF is determined. However, it is not stated how this is obtained from these inputs. Singh & Herza (2019) also assess the potential consequences, but again, these are not discussed.

4.1.3. Challenges and Shortcomings

The above-mentioned tools have made quantitative risk assessments accessible to geotechnical engineers. However, it is important to acknowledge that these tools still have their challenges and limitations, some of which are discussed here.

New Concept

While risk management is not new in the tailings industry, it has gained increased attention in recent years. It is not yet perfect and further refinement is required. One of its central challenges involves addressing risks that span the extreme ends of the risk framework, characterised by low probability and high consequences. Besides, quantitative risk assessment methods are still not being fully developed, understood or accepted. For example, the methods described above only focus on slope and foundation failures. This is intensified with the uncertainties of inputs to adequately address the actual site, design and LoP decisions.

Limited Available Data

High consequence, low probability events are by definition rare. Limited data availability for tailings dams frequently necessitates the extrapolation or interpolation of information, leading to potential inaccuracies and eventually unreliable probability assessments. This is especially a concern for older dams and for dams other than US dams. Major tailings dam failures are rare occurrences, resulting in statistically insignificant base rates. Moreover, numerous variables that influence these base rates, such as the operating environment, design, and practices, are not captured in the statistical data. There is a lack of data that statistically represents the conditions that closely match conditions at existing dams. Relating these unique characteristics of each dam to an indicator of reliability for every potential failure mode is challenging. The probability estimates are presented in orders of magnitude from 10^{-3} to 10^{-8}, potentially leading to significant errors (Miller, 2018, 2019).

Complexity of TSFs

Tailings dams, as previously discussed, are complex systems operating in dynamic environments where conditions are in a constant state of change, resulting in risks that are continually evolving over time. Risk assessment methods often fall short of encompassing all relevant conditions and influential factors. Furthermore, the failure modes of different dam components are interrelated, with their failure probabilities not being simply additive; failure modes may share common root causes (Peter et al., 2003).

Difficulties in Probabilistic Analysis

Certain failure modes are amenable to probabilistic analysis. For instance, establishing probability-intensity relationships for seismic and flood hazards can be relatively straightforward. However, typically modelling allows the evaluation of only one failure mode at a time. Moreover, for some failure modes, no universally accepted industry-standard modelling method exists. As ICOLD (2005) has stated, "…there are issues with reliably quantifying the probability of failure particularly for those failure modes, such as internal erosion, that is not amenable to analysis". Complicating matters further, detailed information required for mathematical modelling is frequently unavailable, and the process of gathering such information can be resource-intensive, particularly when managing a large portfolio of dams.

Methods such as event/fault trees can become exceedingly intricate. One of the challenges with these methods is the necessity for completeness in capturing all relevant factors and similarly to mathematical modelling, they often focus on individual components, while the majority of risk assessment guidelines pertain to the overall probability of failure. As mentioned earlier, these components are unlikely to be mutually independent, making simple summation of their probabilities unfeasible.

Incompleteness of Existing Methods

Silva et al. (2009)'s, Chovan et al. (2021)'s, Singh & Herza (2019)'s solutions exhibit certain limitations. They primarily focus on slope instability and foundation failure categories, overlooking other potential failure modes. Additionally, they do not account for variations in dam construction methods, which, as indicated by the literature review, are likely exhibiting different behaviours. The solutions primarily provide information about the LoP in relation to the FoS and do not comprehensively address all site conditions and design elements. Also their LoP criteria may be incomplete. In comparison, the FTA, in Figure 2.8, for example, offers a more comprehensive perspective by identifying numerous other factors that could contribute to failure. The vast number of components and their complexity make it challenging to create a complete overview.

Uncertainties in Evaluations

As evident from the preceding discussions, numerous uncertainties emerge. The rarity of these events contributes to a high level of uncertainty. Further uncertainties are pervasive elements in various systems and processes, often arising from factors like variations in operating conditions, human influences, or the impact of external events. Managing uncertainty can pose a significant challenge when striving to accurately assess probabilities.

Subjectivity in Assessments

In the process of determining the PoF through expert judgment, the evaluation is frequently susceptible to the expert's opinions. This subjectivity can introduce variability and potential bias into the probability estimates. It can also offer valuable insights and experience-based assessments that quantitative models might overlook.

4.2. Tool Necessity and Requirements

To address the challenges and shortcomings related to the determination of the PoF and provide a solution for a clear, rational, and defensible prioritisation of risk management, a new tool is needed. This tool should identify bottlenecks and high-risk factors, indicating where further investigation and mitigation efforts are necessary while ensuring that resources, including time, effort, and money, are allocated efficiently.

While Silva et al. (2009), Chovan et al. (2021) and Singh & Herza (2019) have made valuable contributions. Their concept of quantifying expert judgment holds promise, as it aligns with the goal of making engineering decisions based on data, not just subjective opinions. Developing a practical method to perform quantified risk assessments for routine projects can have a positive impact on the safety of the facilities one designs and builds.

A new tool should address the diverse nature of dams, accounting for differences in design, construction materials, age, and purposes, as well as the dynamic changes these facilities undergo. All failure categories should be considered within the analysis. The tool should enable a quick and straightforward evaluation with minimal resource requirements, making it accessible even when detailed data is limited. It should not rely on parameters that are often unavailable or difficult to obtain. A robust database should limit uncertainties. The tool's guidance must be clear and unambiguous, minimising room for subjective interpretation. Ethical decisions should be avoided as much as possible. While recognising the inherent difficulty of determining the actual PoF, the tool should at least demonstrate relative correlations, for example, showcasing changes when evaluating with and without mitigation measures.

Figure 4.4 outlines the key considerations for developing a new tool that addresses the challenges and shortcomings of existing ALARP demonstration and PoF determination methods. While there may be other aspects to explore, this focused approach aims to provide a comprehensive solution for these challenges and shortcomings.

4.3. Tool Development Approach

The tool is built upon the foundational approach employed by Silva et al. (2009), Chovan et al. (2021) and Singh & Herza (2019), combining historical failure data with expert judgment. Below, an overview of the key components of the tool is provided. The tool's workflow encompasses the development of a robust database, the determination of baseline PoF, and a prevalence examination of the site. Other relevant considerations are touched upon as well. A similar strategy is presented by Porter et al. (2023), which is developed in parallel with this study.

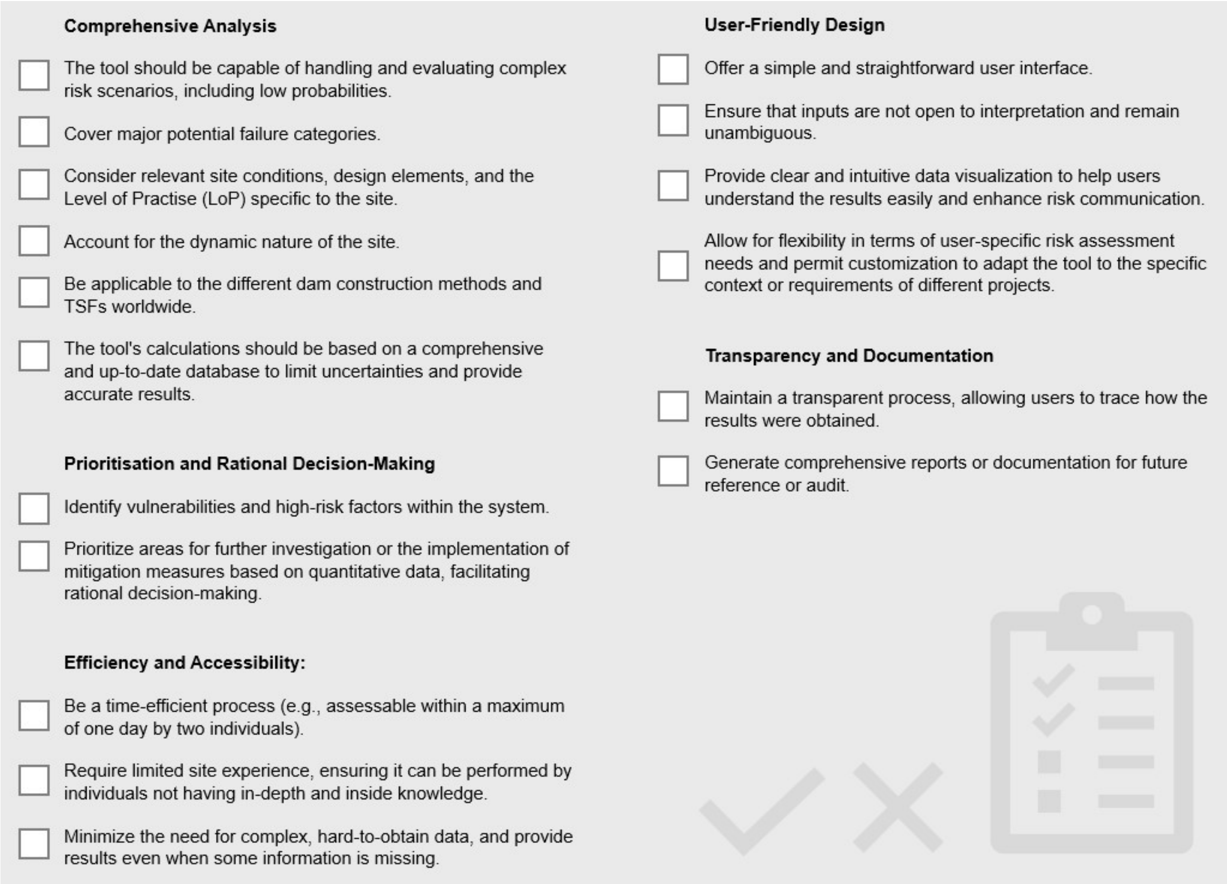


Figure 4.4: Overview of Requirements of the Tool

Database Development

The first step involves creating a comprehensive historical failure database. While multiple databases are available, they often contain limited information. The approach involves consolidating and refining these databases to ensure completeness. The database captures a range of attributes, including dam construction method and failure category.

Baseline Probability of Failure

In the subsequent stage, the baseline PoF is determined. This computation relies on two key factors: the number of existing dams and the failure frequency. Estimations for these factors are derived from a combination of literature sources and the refined historical failure database.

To account for different dam construction methods, the distribution of these methods within the database is determined. Using Bayes' theorem, a comparison is made between this distribution and the distribution of construction methods among existing dams. This comparison enables the determination of distinct baseline PoF rates for each construction method. Baseline PoF values specific to both dam construction methods and failure categories are established by analysing the relative distribution of failure categories for each construction method within the database.

Prevalence Examination

The baseline PoF will be used as basic input to the system. This baseline PoF will need to be adjusted based on the conditions of the site under investigation. This adjustment is facilitated by considering a set of factors, which are categorised into three main groups: site conditions, design elements, and the LoP. These factors collectively contribute to modifying the baseline PoF to create a site-specific assessment.

Tool users are required to input these factors via a drop-down menu. The tool then assesses the inputs and categorises their impact as adverse (increasing the baseline PoF), neutral (with no significant influence on the baseline PoF), or favourable (decreasing the baseline PoF). Modifiers are subsequently assigned to these factors and multiplied by their respective weights and the baseline PoF to generate an updated site-specific PoF. The weights of the different factors are determined by the Analytical Hierarchy Process (AHP) method.

Users can experiment with various inputs to observe how specific mitigation measures may change factors from adverse to neutral or favourable. Risks that are above the risk threshold, should be mitigated. For tolerable risks, ALARP has not been achieved if risk reduction is substantial when factors shift to more favourable conditions and the costs of mitigating that risk are not disproportionate. Once the risk reduction and associated costs become disproportionate, ALARP is achieved from the PoF standpoint. However, it is essential to recognise that a complete ALARP assessment necessitates the consideration of risk consequences.

Other Considerations

The initial results provided by the tool offer valuable insights, helping owners of storage facilities identify critical dams and specific failure mechanisms. For convenience, the risk assessment tool is designed in a spreadsheet format.

It is imperative to note that several factors require consideration before conducting a complete ALARP assessment. These include the evaluation of available mitigation measures, cost estimates for implementing these measures, and an assessment of the consequences associated with various failure modes and mechanisms.

> *Several authors have initiated promising efforts to establish the PoF of dam structures by combining the frequency of observations with engineering judgment. Nonetheless, these tools have their share of challenges and shortcomings. The creation of a novel tool, which aids in the estimation of the PoF and offers a rationale for prioritising risk reduction measures, is essential. The subsequent chapters offer an in-depth exploration of the development of the different components of the tool.* Chapter 5 *explains the creation of a robust database,* Chapter 6 *outlines the establishment of baseline PoF, and* Chapter 7 *addresses the prevalence examination. The tool is presented in* Chapter 8*.*

5

Database Development

This section presents the development of a new tailings dam failure database, building upon existing databases. First, an overview of the available databases is provided, followed by a description of their convergence and the corrections performed. Lastly, the data attributes within the new database are described and analysed, highlighting the opportunities as well as the limitations and inherent biases that are associated with utilising the database as a foundation for the tool.

5.1. Available Data

Numerous investigations worldwide gathered data on tailings dam failure events. Among these, four databases stand out as the most significant and frequently referenced sources: ICOLD (2001) (comprising of the USCOLD (1994) and UNEP (1996)), WISE (2023), WMTF (2019) and CSP2 (2023). The development of these four databases, and the information captured within each of the databases, are briefly described below.

1. **ICOLD** (ICOLD, 2001) : **USCOLD** (USCOLD, 1994) **and UNEP** (UNEP, 1996)
   The United States Committee On Large Dams (USCOLD) database collected a substantial amount of information on failure incidents from 1917 to 1989, gathered from publications, questionnaires and anecdotal information. The database, consisting of 185 failure events, was published in 1994. It has been supplemented by the UNEP in 1996, which identified an additional 26 independent failure events. In 2001, the ICOLD published the combined failure events in their 121 st bulletin, consisting of 221 entries. The information in this database follows a format similar to water storage dam reviews and includes details such as name/location, ore type, dam type, dam fill material, dam height, storage volume, incident type, dam activity, incident cause, incident date, release, runout, and a brief description of the incident.
2. **WISE** (WISE, 2023)
   The World Information Service on Energy (WISE) reviewed the ICOLD database. WISE focused on reporting significant tailings dam failure events since 1960 and WISE has provided information on 156 incidents on the location, parent company, ore type, type of incident, release, impacts, and incident date. While WISE may offer less comprehensive information than other databases, it is known for its up-to-date reporting on tailings dam failures.

3. **WMTF** (WMTF, 2019)
   The World Mine Tailings Failures (WMTF) database builds upon the foundation established by ICOLD while incorporating data acquired from WISE, supplemented by its own investigations. Missing descriptors were supplemented element by element using diverse sources, including legal documents and technical reports, while also other failures were identified. The resulting database contains a total of 352 incidents, that have occurred from 1915 to 2019. It encompasses a wide array of information; in addition to the information presented in ICOLD, it also reports on severity, locus of failure and economic history.
4. **CSP²** (CSP2, 2023)
   Analogous to the WMTF database, the Center for Science in Public Participation (CSP²) database expands upon the existing ICOLD and WISE datasets with its own analysis. It offers identical information to the WMTF database and also reports its first failure in 1915. Contrary to WMTF, CSP² covers tailings dam failures to date, capturing a total of 376 incidents.

Figure 5.1 presents a comprehensive timeline of the databases and summarises the information contained within each database. However, it is important to recognise that these databases are by no means complete; many failures remain unreported and significant gaps exist in the available information regarding the reported cases. A more detailed examination of these limitations is provided in Section 5.4.

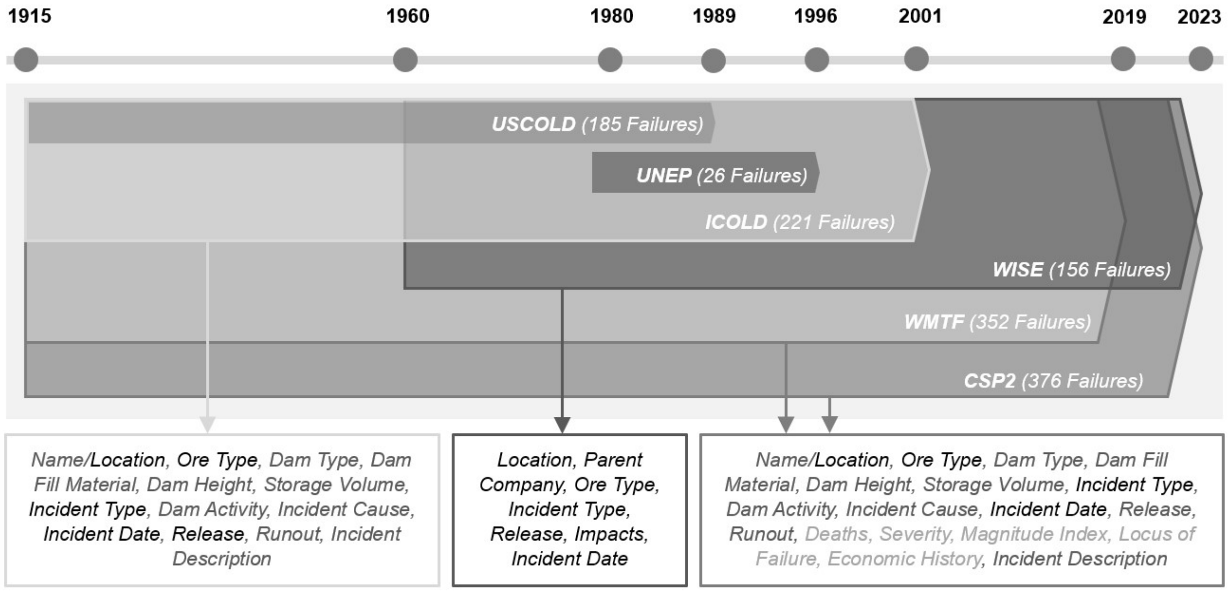


Figure 5.1: Overview of Existing Tailings Dam Failure Databases
(*Modified after* Piciullo et al. (2022))

5.2. Convergence and Corrections

To acquire a database with the largest number of reported failures with extensive information, the available databases, described in the previous section (Section 5.1), are merged. The databases have been revised and cross-checked with each other to enhance the reliability of the compiled database. To consolidate and rectify inconsistencies among the databases, corrections have been made; in the first place, by using primary bibliographic sources. However, if conflicting information was encountered or if it was not possible to obtain data from primary sources, one or more of the following revision strategies were implemented:

- Identification or assumption of a '**Human Error**' within the database
  If a mistake made by individuals was identified or suspected, it was considered a possible cause of the discrepancy and corrected accordingly.

- '**Averaging**' of values that were in the same order of magnitude
  When multiple values were available and they fell within a similar range, an average of those values was used as a representative estimate.
- Selection of the '**Most Reliable Source**' as the true value
  In cases where the credibility and accuracy of the sources varied, the information from the source with the highest level of trustworthiness (e.g. greatest expertise or most recent publication) was given priority and considered to be the true value.
- Acceptance of the value from the '**Majority of Sources**'
  If a particular value appeared more frequently across the variable sources, it was considered the most reasonable representation of the data and was accepted as the actual value, if the sources were of equal level of trustworthiness.
- Utilisation of other available information to make an '**Educated Guess**'
  When conflicting or incomplete information was encountered, additional contextual details or supplementary data were used to make an informed estimation or educated guess regarding the correct value.

Aside from the aforementioned corrections, effort was made to extract a maximum amount of information; gaps were filled where possible. The resulting database consists of 450 failure events, presented in Appendix A. The attributes include general details of the dam, its failure category and its impacts, based on the attribute information available in the parent databases. Nevertheless, modifications have been made to the field names due to certain names not adequately capturing the content they present. The subsequent section (Section 5.3) provides a more detailed explanation and analysis of attributes in the database.

5.3. Data Attributes and Analysis

Within this section, the various data attributes in the compiled database are described and the data distribution for each attribute is presented, accompanied by a concise analysis, and compared to the conclusions drawn by other authors studying tailings dam failure statistics. The opportunities of the database, are described in the next section (Section 5.4), along with the limitations and inherent biases.

5.3.1. General Dam Information

The first part of the database encompasses details concerning the dam and the material it holds. When available, the following fields are delineated: the dam's name, ownership details, geographical location and incident year; the deposit and ore type of the contained tailings, as well as the dam construction material; and the construction method, height, and storage volume of the dam. The definitions of these attributes, along with the data distribution and concise analysis, are presented below.

Name, Owner, Location and Year of Occurrence

Name, owner, location and year of occurrence are reported for each failure record. First of all, a distinct name is provided to differentiate the failed dam sections from others and each failure case is assigned a unique Failure ID, enabling easy reference to the specific failure instance. Secondly, the ownership attribute denotes the legal entity that possesses control over the tailings dam. The owner – often a governmental agency, private company or organisation – is responsible for the management, maintenance and regulatory compliance of the dam. In addition, the geographical location is presented, containing details about the region and country where the specific site is situated. Lastly, the year of occurrence provides a historical context of the tailings dam failures. If available, the date of failure is also provided.

Figure 5.2 illustrates the number of failure events by country. Among the total 450 instances in the database, there are 16 cases with unknown geographic locations, which are not represented in the figure. The location of the collected cases reflects the uneven distribution of mine exploitations and corresponding tailings dams, as well as the varying availability of information across different countries. Notably, nearly 30% of the reported failures occurred within the USA, likely influenced by these factors. This observation is further explained by the database's nature, which is sourced from instances with convenient access to the information within the USA. The USA is followed by Chile and Canada, each accounting for roughly 10% of the failures and about one-fifth of the failures within the database occurred in Europe. Similar conclusions were drawn by Azam & Li (2010), Lyu et al. (2019), Islam & Murakami (2021) and Halabi et al. (n.d.).

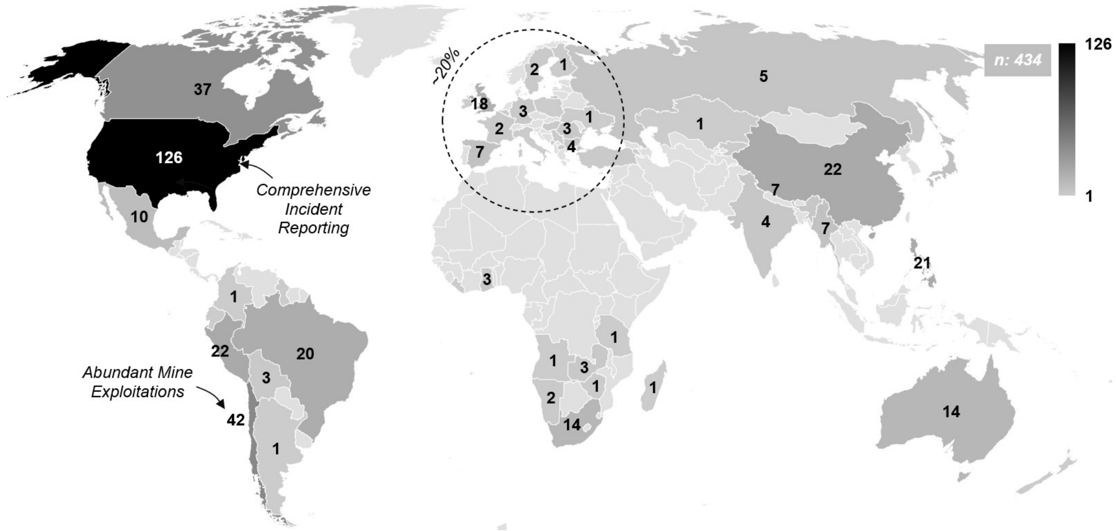


Figure 5.2: Geographical Distribution of Reported Tailings Dam Failures, Where Documented

In Figure 5.3, the reported tailings dam failures over time are shown. Prior to the 1970s, there were significantly fewer reported failures; it is believed that many failures remain unreported, but the limited number of tailings dams before this time (as Explained in Section 2.1.1) may also play a role, as well as the smaller scale mining operations and the shorter existence of the TSFs. Other authors, including Azam & Li (2010), Lyu et al. (2019), Piciullo et al. (2022) and Rana et al. (2022), observe the same trend. Although they acknowledge the reporting gaps, none of them attributes the lower number of tailings dams as a possible underlying reason, except for Azam & Li (2010). They propose that the higher failure rate in recent decades can be linked to increased mining activity following World War II, driven by the global demand for metals, minerals, and raw materials. Another striking feature, which may also have shed light on tailings dam failures, is the peak of failures in 1965, coinciding with the Valespario earthquake in Chile on March 28. This event led to the failure of multiple dam sections, as observed by other authors as well (Dobry & Alvarez, 1967; Villavicencio et al., 2014; Islam & Murakami, 2021).

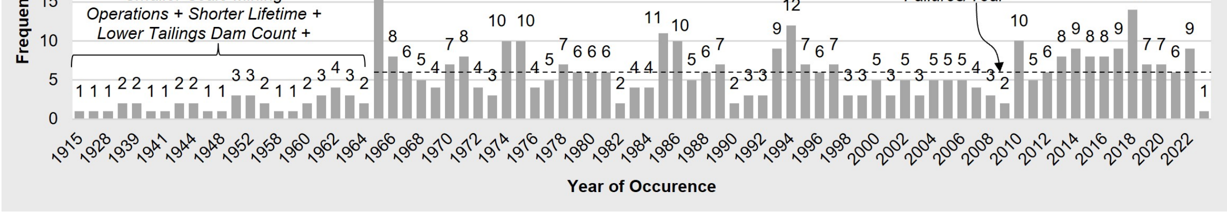


Figure 5.3: Timeline of Reported Tailings Dam Failures, Where Documented

After 1965, the number of failures per decade remained consistent, with an average of 6 reported failures per year. However, it is noteworthy that the actual frequency may be higher given the incompleteness of the database, and with 39 accidents lacking reported failure years. On the contrary, other scholarly sources, such as Lin et al. (2022), report even slightly lower frequencies, estimating 3 to 6 failures per year, which could be attributed to a lower number of reported failures in their dataset.

Deposit Type, Ore Type and Dam Fill Material

The database provides information on the deposit and ore type of the contained tailings. The deposit type refers to the geological origin of the contained materials, including stratified, vein, Volcanic Massive Sulphide (VMS), Porphyry Copper (PC), High-Temperature Manto (HT Manto), and Sediment Hosted Copper (SSC) deposits. Secondly, the ore type attribute refers to the valuable materials extracted from these deposits, such as aluminium, gold, coal or copper, providing insight into the primary mineral and metal content of the tailings. Moreover, the database includes details about the main construction material of the dams. As discussed in Section 2.2.1 the main dam fill materials identified in the database comprise Tailings (T), Mine Waste (MW), E, R, and CST.

Figure 5.4 displays the distribution of deposit types. Out of the 171 reported cases (for the remaining ones no deposit type is described), the majority (over 50%) are classified as stratified deposits, followed by PC deposits (15%) and vein deposits (7%). The remaining deposit types make up a smaller portion of the dataset. The underlying cause for this distribution remains uncertain, but it may be associated with the inherent variability in deposit types. Previous studies have not addressed the distribution of ore types.

In terms of ore type distribution, there is a diverse range observed among the 413 cases (Figure 5.5). Copper and gold account for the largest share, comprising 18% and 15%, respectively. They are followed by coal (8%), iron (6%), phosphor (8%), uranium (4%), and aluminium (3%). Other minerals and metals occur in less than 2% of the cases. The considerable natural variety emphasises the need for caution when drawing general conclusions about the PoF based on specific ore types. For example, the claim made by Halabi et al. (n.d.) regarding the higher vulnerability of copper tailings dams to failure is questionable, and likely oversimplifies the complexity of a tailings dam's structural stability.

Among the 211 cases (Figure 5.6), 40% of the failed dams are constructed using tailings material, which reflects the common practice of tailings-based dam construction. On the other hand, the use of tailings material in the dam poses significant safety concerns, as discussed in Section 2.3. E (28%), MW (11%), CST (10%), and R (7%) contribute to failures to a lesser extent. Combinations of different materials, although presumed to be commonly utilised in tailings dam construction, do not appear prominently within the database. No relevant literature was found on the relationship between dam fill material and the PoF.

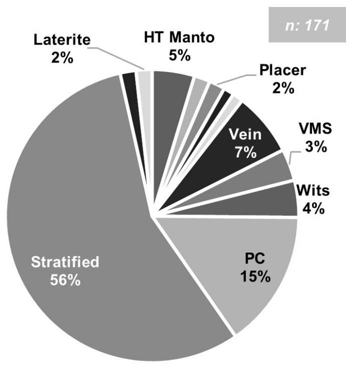


Figure 5.4: Distribution of Tailings Dam Failures by Deposit Type, Where Documented

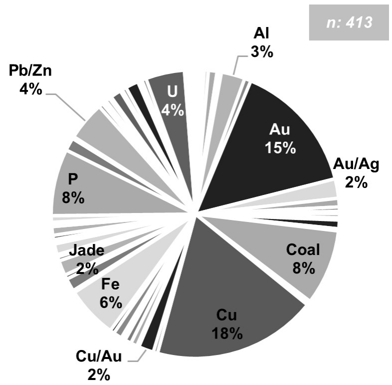


Figure 5.5: Distribution of Tailings Dam Failures by Ore Type, Where Documented

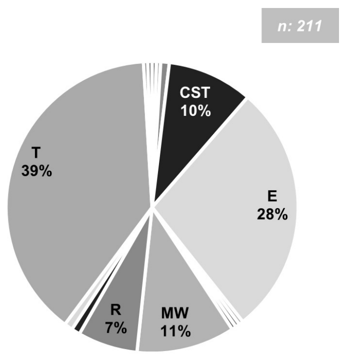


Figure 5.6: Distribution of Tailings Dam Failures by Dam Fill Material, Where Documented *(CST: Cycloned Sand Tailings, E: Earthfill, MW: Mine Waste, R: Rockfill, T: Tailings)*

Dam Construction Method, Dam Height and Storage Volume

The database also provides general information on dam construction methods, as well as details about dam height and storage volume. The dam construction method simply refers to the construction method employed for the tailings dam, with four main types being distinguished: US, DS, CL and WR, each exhibiting unique behaviour characteristics each with distinct behaviour characteristics (see Section 2.2.1). The dam height indicates the vertical extent or elevation of the tailings dam structure, while the storage volume indicates the capacity of the dam to hold the accumulated tailings material.

Figure 5.7 illustrates the distribution of tailings dam failures, with US dams accounting for the majority (57%) of reported cases. The high number of US dam failures is expected due to the abundance of US dams and risks associated with this geometry. Moreover, it is supposed that a considerable proportion of the 202 cases with unspecified dam types are likely to involve dams constructed in an upstream manner, making its share even bigger. Correspondingly, previous studies consistently show that over 50% of tailings failures occur in dams with an US geometry, except for Piciullo et al. (2022), who report a lower percentage of 32%. However, the construction type remains undisclosed for half of the failures in the database. Besides, approximately 15% of the failed dams are classified as DS dams, while another 15% are categorised as WR dams. CL constructed dams represent around 10% of the reported failures.

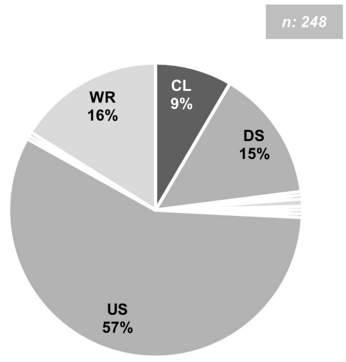


Figure 5.7: Distribution of Reported Tailings Dam Failures by Dam Construction Method, Where Documented

The dam height distribution shown in Figure 5.8 ranges from a few meters to 150 meters, but Rana et al. (2021), even report dam heights over 200 meters. Surprisingly, 70% of tailings dam failures occur in dams below 30 meters in height, contradicting the conventional belief that higher dams are less stable. This discrepancy can be attributed to the prevalence of lower-height dams and the larger population of older dams constructed without adherence to modern standards, while high dams are often well-designed. Although low dams are widely recognised as being a significant contributor to failure, this perspective is only shared by Strachan & Goodwin (2015).

Upon examining the storage volume of 127 cases depicted in Figure 5.9, notable variations become apparent. The median volume is around 1,500,000 m^3, with a 75th percentile of approximately 10,000,000 m^3. The maximum recorded volume exceeds 22,500,000 m^3, with some outliers beyond this threshold. The cumulative reported release volumes reach 1.3 billion m^3. However, caution should be exercised in drawing conclusions due to limited available information.

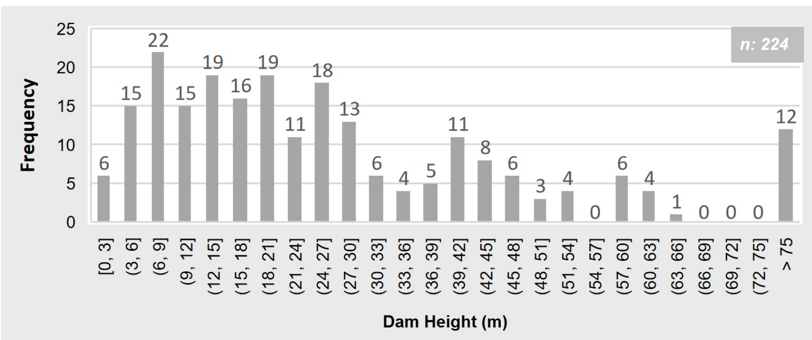


Figure 5.8: Distribution of Reported Tailings Dam Failures by Dam Height, Where Documented

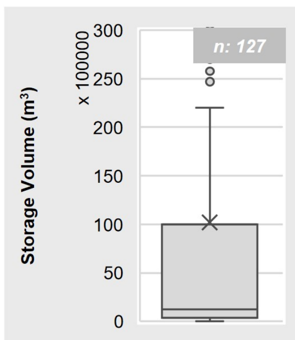


Figure 5.9: Distribution of Reported Tailings Dam Failures by Storage Volume, Where Documented

5.3.2. Failure Type

The second section of the database elucidates the failure type, encompassing event type, operational status of the dam during failure and the classification of failures into specific categories. This section presents a comprehensive description of these attributes and conducts a concise analysis of the distribution of data within the database.

Event Classification, Operational Status and Failure Category

As already stated, the database incorporates three fundamental indicators pertaining to the type of failure: event classification, operational status, and failure category. Initially, the database distinguishes between incidents (1), accidents (2) and groundwater issues (3), with incidents involving breaches of the dam resulting in loss of process water or tailings, accidents representing dam repairs without loss, and groundwater issues pertaining to excessive seepage or unintended impact on groundwater. Notably, within the defined scope of failure, exclusively incident types (1) and (3) are considered true failures, as per definition outlined in Section 2.3.1. Additionally, the database classifies the operational status of the dams at the time of failure as active or inactive. 'Active' dams are operational and receiving tailings material, while "inactive" dams have been decommissioned (see Section 2.1.1). Furthermore, the failures in the database are grouped into nine distinct categories: Earthquake Induced (EQ), Overtopping (OT), Slope Instability (SI), Foundation Deficiency (FN), Excessive Seepage and Internal Erosion (SE), External Erosion (ER), Structural Inadequacies (ST), Mine Subsidence (MS) and Unknown (U). Section 2.3.1 provides a detailed description of each category. Note that alternative categorisations may be preferred; however, for the purpose of simplicity, these specific failure categories have been adopted.

The event classification of the tailings dam failures in the database reveals that almost three-quarters of the records are categorised as incidents. Around one-fifth of the failures are classified as accidents. A smaller proportion, approximately 5%, is attributed to groundwater issues, while only 1% of the failures have an unknown classification, as shown in Figure 5.10 on the next page. The available literature does not yield definitive conclusions regarding the event classification. Nevertheless, it is expected that the dataset pertaining to accidents is notably more incomplete than that of reported incidents.

Figure 5.11 shows the number of failures based on the operational status at the time of failure. The majority, approximately 75%, of the failures occurred in active dams, while inactive dams accounted for 16% of the total failures. The operational status of the dam at the time of failure remains unknown in 11% of the cases. The exact reasons for the higher occurrence of failures in active dams are not fully understood; however, it is hypothesised that the dynamic changes in load imposed on the dam face during tailings deposition and subsequent dam-raising activities may play a significant role. At least, all authors agree on the fact that active dams fail considerably more frequently compared to inactive impoundments. As a matter of fact, often a more extreme distribution is observed (Davies, 2002; Rico et al., 2007; Rana et al., 2022; Piciullo et al., 2022).

The distribution percentages of each failure category are as follows: 18% for OT, 17% for SI, 13% for EQ, 11% for ST, 7% for FN, 3% for ER 1% for MS, and 20% for U. Figure 5.12 provides a visual representation of these percentages. The relatively large number of Unknown cases (90 cases) highlights the challenges in identifying and understanding the underlying causes of tailings dam failures. There is no prominent failure category that stands out significantly among the others, but a smaller percentage of failure cases are observed in the FN, ER and MS categories. Similar observations were made in other statistical analyses. The studies conducted by Haeri et al. (2021), Rana et al. (2022), Stark et al. (2022), Piciullo et al. (2022) and Halabi et al. (n.d.), reveal the following ranges for each failure category: 15 to 24% for OT, 15 to 22% for SI, 13 to 17% for EQ, 6 to 11% for ST, 5 to 10% for FN, 2 to 5% for ER 0 to 1% for MS, and 19 to 30% for U.

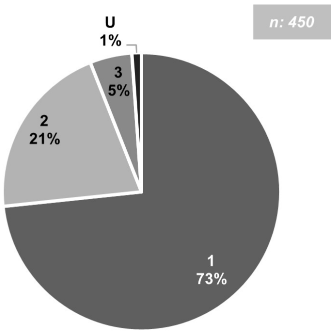


Figure 5.10: Distribution of Reported Tailings Dam Failures by Event Classification *(1: Accident, 2: Incident, 3: Groundwater Issues, U: Unknown)*

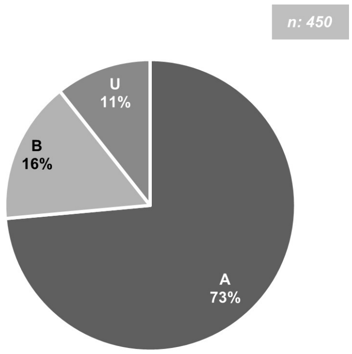


Figure 5.11: Distribution of Reported Tailings Dam Failures by Operational Status *(A: Active, B: Inactive, U: Unknown)*

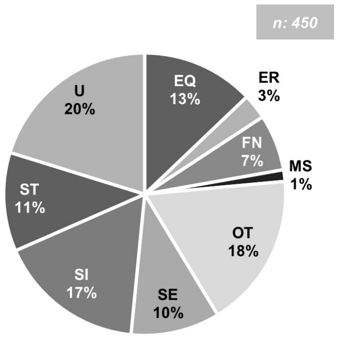


Figure 5.12: Distribution of Reported Tailings Dam Failures by Failure Category *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, U: Unknown)*

5.3.3. Impacts

The final section of the database addresses the impacts resulting from the tailings dam failures. It provides information on the release volume and run-out of the tailings material, as well as the number of fatalities and an estimation of the failure severity. This section is accompanied by a clarification of these terms and a concise statistical analysis of the findings.

Release Volume and Runout

The inclusion of release volume and runout in the tailings dam failure database provides information on the extent of the tailings material's dispersion in the environment. The release volume signifies the quantity of tailings material discharged during the failure. The runout distance denotes the distance travelled by the flowing or spreading tailings material from the point of failure.

The box and whisker plot in Figure 5.13 illustrates key statistics pertaining to the released volumes of 234 cases in the tailings dam database. The range of release volumes varies from zero to 1,000,000 m^3, with some outliers exceeding this threshold. The median release volume is approximately 75,000 m^3, and the upper quartile is around 45,000 m^3. The cumulative reported release volume in the database amounts to 325 million m^3. Yet, it is important to understand that a substantial portion of this total release volume is attributed to a small number of significant failures, e.g. the Mount Polley failure (2014) and the Brumadinho dam disaster (2019) Rana et al. (2022).

The runout analysis, displayed in Figure 5.14 shows a wide range of distances travelled by the tailings material, from zero to over 50,000 m, but there are also extreme cases where the tailings travelled more than 300 km into the downstream environment. The median runout distance is around 5,000 m, based on the 123 analysed records. These findings are in alignment with existing literature. Rana et al. (2022) also demonstrated that the runout distance is strongly influenced by the characteristics of the tailings and the downstream topography.

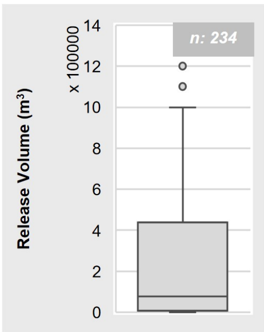


Figure 5.13: Distribution of Reported Tailings Dam Failures by Release Volume, Where Documented

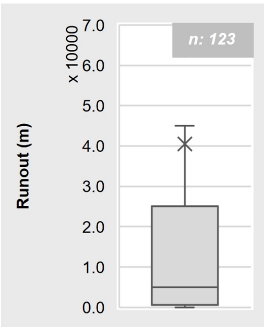


Figure 5.14: Distribution of Reported Tailings Dam Failures by Runout, Where Documented

Fatalities and Severity

Additionally, the tailings dam failure database includes information on the human impacts, providing insights into the human loss resulting from the failure. Furthermore, the severity of the failures is indicated using a scale ranging from 1 to 4, with 1 representing the most severe level. The specific definitions of the severity levels can be found in Section 2.3.2.

The examination of recorded fatalities demonstrates that the majority of tailings dam failures resulted in a relatively low number of casualties, typically fewer than three individuals, as can be seen in Figure 5.16. However, there are also cases of catastrophic events, that cost hundreds of people their lives. An example of such an event is the Brumadinho tailings dam failure in Brazil in 2019, which tragically claimed the lives of 270 people. Piciullo et al. (2022) recorded that approximately 80% of the reported cases did not result in any fatalities. In 8% of the cases, there were 1 to 10 deaths, in 5% of the cases, there were 11 to 50 deaths, and in 4% of the cases, the number of fatalities exceeded 50.

Figure 5.15 shows the estimated severity of all reported failure cases. 12% of the cases were classified as level 1 (most severe), 19% as level 2, and exactly 50% were classified as level 3. 9% was classified as a level 4 event and the remaining 10% were not assigned a severity level. The severity distribution within the literature remains inconclusive, but it is anticipated that numerous failures with low severity are unreported.

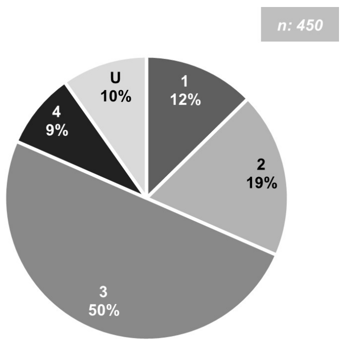


Figure 5.15: Distribution of Reported Tailings Dam Failures by Severity *(1: Very Serious, 2: Serious, 3: Minor, 4: Potential, U: Unknown*

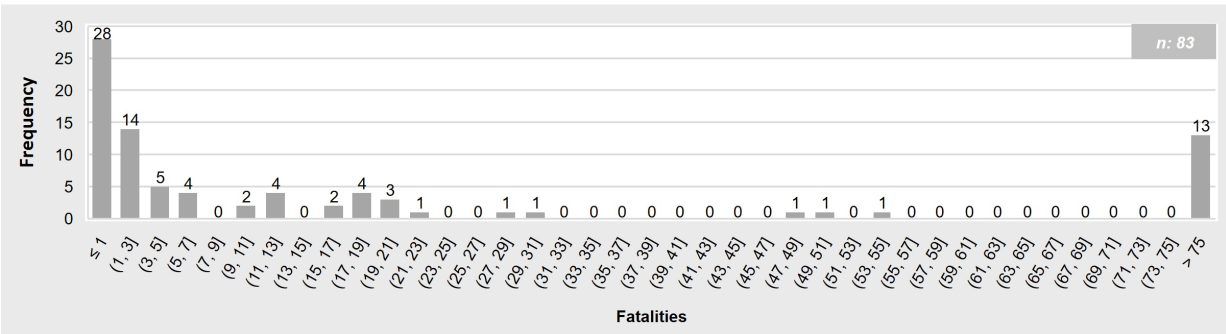


Figure 5.16: Distribution of Fatalities Reported Tailings Dam Failures by Fatalities, Where Documented

5.3.4. Notes

The ”Notes” field of the database contains additional information, comments, or explanations related to specific entries or incidents in the database. These notes may provide supplementary details that may not be captured in other fields or columns of the database. They offer contextual information, clarifications, or additional insights into the respective tailings dam failures.

Additionally, the database provides details on the sources of the data, where feasible. The traceability of these sources varies, with certain sources being readily identifiable, while others, such as institutional records, organisational data, and anecdotal accounts, pose challenges. A total of 110 cases in the database were traced back to publicly available, high-quality sources.

5.4. Opportunities, Limitations and Biases

This section explores the potential of incorporating the statistical data distributions from the database into the calculation of failure probabilities at specific mine sites. It also addresses the limitations of this application and identifies possible biases, to give a comprehensive understanding of the implications and considerations associated with utilising the statistical data distributions for the PoF assessments.

Potential Application in Tool

To determine the PoF at a mining site, historical statistical failure distributions incorporating key factors are valuable. These factors enable a more accurate estimation of the actual PoF. Once a baseline PoF is established, the impact of each attribute in the database on the overall probability can be assessed by analysing their respective distributions.

For example, if empirical evidence suggests that dams in the USA have a higher frequency of failures compared to other countries worldwide this can be taken into consideration when calculating the PoF of a specific site. For a dam section within the USA, adjustments reflect a higher PoF than a dam in another country, accounting for the specific risk associated with the country. However, note that the PoF goes beyond relying solely on this statistical distribution of historical data. In the case of the example, it is also important to consider the number of tailings dams in each country, as a higher quantity indicates greater exposure to potential failure.

Not all attribute distributions in the database may be suitable or significantly contribute to the estimation of the PoF. Further analysis and evaluation of each attribute distribution are necessary and will be discussed in-depth in the subsequent list, organised by the different segments of the database as presented in the previous section.

- **Name, Owner, Location and Year of Occurence**: The geographical representativeness in obtaining failure rate is inadequate, primarily due to the uneven information availability across countries. The USA is overrepresented in the database, primarily due to comprehensive incident reporting, compared to other nations. Determining the number of tailings dams in each country is challenging, and there are temporal variations in failure occurrences observed (Azam & Li, 2010; Lyu et al., 2019; Islam & Murakami, 2021). Evaluating the timeline of failure events, a consistent trend in failure rates has been observed over a period exceeding 50 years, suggesting a presumed continuation of this trend into the future. Considering the increasing number of tailings dams, the actual failure rate is likely to decrease. This observation highlights the need for careful consideration in calculating the baseline failure rate. Further details will be discussed in Section 6.1.2.
- **Deposit Type, Ore Type and Dam Fill Material**: The distribution of the deposit type is not well understood, but this is likely attributed to the natural variability of deposit types. Despite the distinct behaviours exhibited by different deposit types, which arise from variations in material characteristics and processing methods (as discussed in Section 2.1), no evidence is found in the literature that the ore type significantly influences the tailings dam stability. Treating this attribute as such would oversimplify the complex mechanisms involved in dam break events. However, the deposit and ore type present an opportunity to gain valuable insights into the potential consequences of a failure event, specifically regarding the flow behaviour and toxicity of the tailings. Nonetheless, these aspects are beyond the scope of this study.

  Conversely, the selection of dam fill material in tailings dams can exert a substantial influence on their stability; the dam fill material properties will influence the mechanical failure behaviour of the dam face. However, it is suspected that dam fill materials often consist of various materials, which are not explicitly indicated in the database. Therefore, caution should be exercised in drawing conclusions from this factor. Accordingly, this factor is not implemented in the tool.

- **Dam Construction Method, Dam Height and Storage Volume**: The inclusion of the dam construction method is valuable for assessing the PoF, as it provides insights into stability, performance, and vulnerability to various failure modes. The observed dam type distribution aligns with expectations and previous analyses and will be a relevant factor to implement in the tool.

  Furthermore, the dam height can be relevant in assessing the dam's stability and the potential failure consequences. While higher dam heights may pose additional challenges in terms of stability and containment of tailings material, the literature presents contradictory but justifiable, findings. However, the uncertainty surrounding the dam height of existing dams prevents its consideration in this study. However, it holds potential for implementation, and it could serve as a valuable attribute when estimating the consequences of failure.
- **Event Classification, Operational Status and Failure Category**: The event type itself does not provide direct information about thePoF. However, one may want to focus solely on true failures. These adjustments are discussed in Section 6.1.2.

  Differentiating between active and inactive dams provides valuable insights into whether the failure occurred during normal operation or during a period or non-operation. This distinction helps identify any operational or maintenance-related issues that may have contributed to the failure. However, the operational status of existing dams (over time) is unknown, which would be required for accurate implementation in the tool.

  The categorisation of failures by category plays a crucial role in understanding common factors or recurring issues across different cases. Consequently, it contributes to a comprehensive understanding of the failure mechanisms and facilitates the determination of appropriate mitigation measures. Therefore, considering event types is an important factor when calculating the various components of the PoFand the demonstration of ALARP.
- **Release Volume and Runout**: The release volume and runout of tailings material serve as indicators of the potential spatial extent of damage caused upon failure. They offer valuable information regarding the magnitude of environmental and socio-economic impacts and are thus significant factors in estimating failure consequences. However, it is important to note that these factors do not directly affect the PoF and, as such, are not within the scope of this study.
- **Fatalities and Severity**: Likewise, the fatalities and severity provide valuable information regarding the human and environmental impacts of a potential dam breach; however, do not contribute to the estimation of the PoF. On that account, these attributes are not discussed further within the context of this study.

In summary, the incorporation of dam type and failure category presented in the database can make a valuable contribution to the assessment of the PoF. Conducting an analysis between different data attributes can yield valuable insights and present additional opportunities for the database. Using joint probability distributions of site factors enables the calculation of cumulative failure probability, taking into account the combined effects of these factors. This approach provides a comprehensive assessment of site-specific failure probability, essential for decision-making, without necessitating a complete understanding of complex dam break mechanisms. Previous studies have explored relationships between data attributes, however, primarily focusing on the consequences of failure rather than the PoF.

Given the incomplete nature of the database, limited understanding of underlying distributions, and lack of information on non-failure cases, these factors are not considered in the present study. Instead, prevalence factors have been established to improve the accuracy of failure probability estimation based on the failure statistics of the individual attributes. This will be further explained in Chapter 7. In the subsequent sections, the incompleteness of failure records and distortions within the database are further discussed.

Incompleteness of Failure Record

The database utilised in this study is considered to be a subset of the total number of tailings dam incidents worldwide. Although the database used in this study is by no means complete, the current literature does not indicate a higher number of reported failures than what is captured in this database. The incompleteness of the database stems from various factors, which are briefly described below.

It is believed that numerous failures were not reported in the period prior to the 1970s. This idea is shared by Azam & Li (2010). Several factors may contribute to this phenomenon. Firstly, reporting failures may not have been deemed relevant or necessary. Secondly, the absence of comprehensive monitoring systems could have led to failures going unnoticed. Lastly, failures with legal or sensitivity implications are more likely to remain unpublished, which continues to be a concern in the present day.

Certain regions, particularly those with lax environmental legislation and limited oversight, may not diligently register all failure events. Failures occurring in remote areas or smaller mining operations, which receive limited attention, may go unnoticed or unreported. The reported failures in the database appear to be more satisfactory for the USA and Europe, but even in these countries, the completeness of the database can be questioned. For instance, in Europe, incidents related to mining activities were only included in the official database since 2003, following an amended directive, leading to a potential scarcity of reported historical incidents prior to 2003 (European Council, 2003).

Furthermore, there may be a scarcity of reporting for failure events with low severity. Regulations typically require reporting for significant or high-severity incidents, while lower severity events may not be subject to the same obligations, resulting in limited information about them. Tailings dam failures, particularly those with low severity, may not receive significant media attention. Companies may also choose not to externally report failure events with minimal risks and low severity to maintain a positive public image, leading to underreporting of less severe incidents.

The underreporting of failures becomes evident when comparing the level of mining activity with the number of reported failures. Take Australia as an example; it has only 14 reported failures. It seems unlikely that the number of failures is so low, especially considering that mining is a significant sector of Australia's economy, constituting 10.4% of its Gross Domestic Product (GDP) in 2020 (Casey, 2021). In contrast, mining in the United States, which reports 126 failures, represents only about 0.9% of its GDP (0.3% except oil and gas) (U.S. Bureau of Economic Analysis, 2023). The low number of incidents and accidents might be attributed to the extremely arid climate. It is evident that water frequently plays a significant role in failures. Additionally, other factors, such as good practices, might also play a role. However, the stark difference between mining activity (Figure 5.17) and reported failures (Figure 5.18) raises questions. In regions with substantial mining, such as western gold, iron ore, nickel, and diamond deposits, as well as coal deposits in the east, no failures are reported. Please note that in eastern Tasmania, a breach or incident involving a gold TSF has been reported, even though there are no currently operational gold mines in the area. This suggests that the number of TSFs is expected to be even higher, increasing the likelihood of both past and future failures.

Similar patterns may be observed in other countries. For instance, in countries like Chile, Peru, Mexico, Brazil, India, China, Russia, and parts of western and southern Africa, a higher number of failures are expected when comparing mining density (Figure 5.19) with the distribution of reported failures (Figure 5.20). Several other factors may contribute to the underreporting of failures. For instance, in countries like China and Russia, the political situation may also play a role in the scarcity of failure reporting.

However, in the approximately, last five years, it has become harder for companies to hide major problems because of the use of remote sensing and publicly available satellite data. This means that the record of failures will likely become more complete in the coming years, enhancing the reliability of the tool.

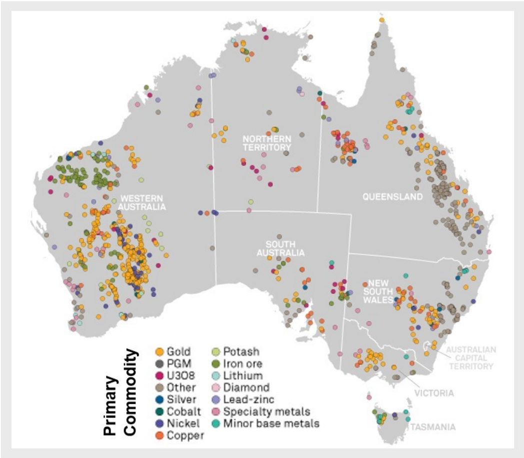


Figure 5.17: Active Mines in Australia by Primary Commodity *(DeCoff, 2022)*

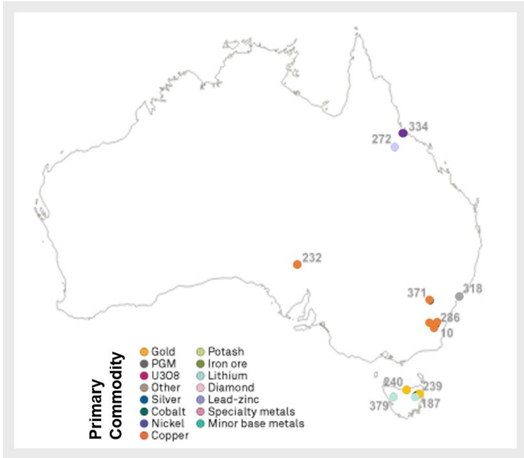


Figure 5.18: Failures in Australia in Database

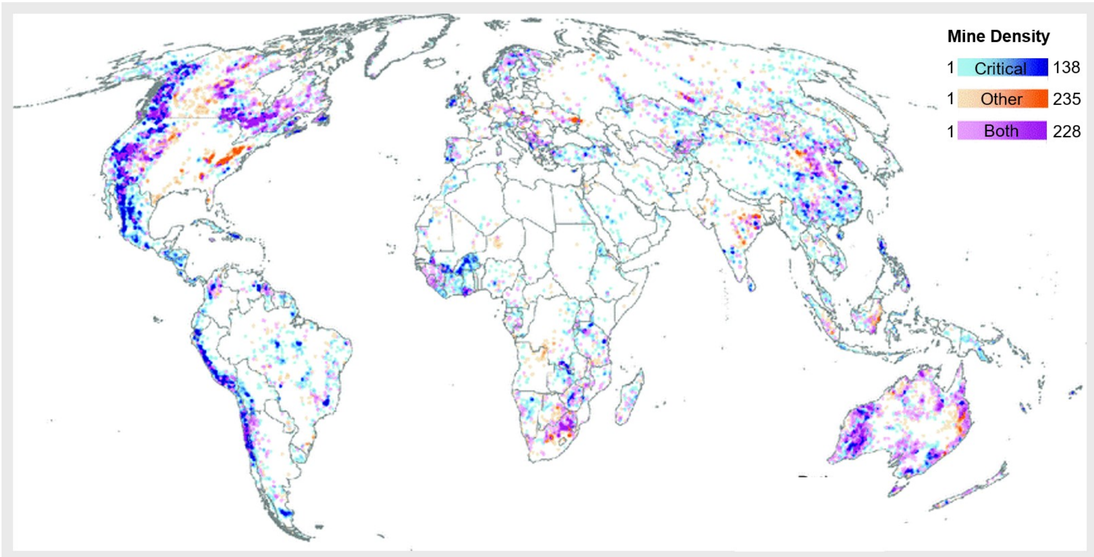


Figure 5.19: Global Mining Density – *Colour Scale: Critical Renewable Energy & Infrastructure Materials (Blue), Other Materials (Orange), Targeting Both (Pink). Shading (Light to Dark) Shows Mining Density in a 50-cell Radius / 1 km Cell. (Sonter et al., 2020)*

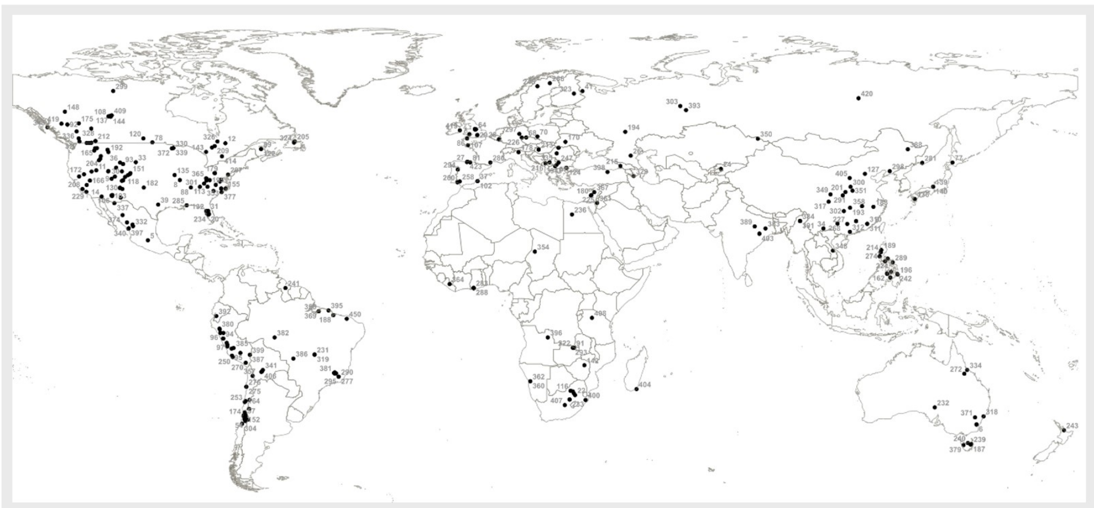


Figure 5.20: Geographical Distribution of Failures in the Database

It is noteworthy that there is variability in the level of detail provided for reported cases within the database. Not all fields are filled out, leading to differing levels of information provided for each reported failure case.

Distortions of Data Distribution

The database exhibits inherent biases, which are described below. The biases are important to acknowledge in order to avoid generating misleading or inaccurate results. Understanding these biases is crucial for assessing the reliability and applicability of the analysis outcomes, enabling informed decision-making and effective risk management. Additionally, this highlights the need for improved data collection efforts and enhanced data quality, emphasising areas where such improvements are preferred.

The incompleteness of the database significantly impacts its representativeness, since for example, the majority of the compiled cases originate from only a few countries. Furthermore, biases may arise from misreporting failure events within specific categories. Certain types of failures may be over or under-reported due to factors like detection biases. OT events, for example, with their visible and immediate consequences, are more likely to be reported compared to seepage-related failures, which may develop gradually and go unnoticed. This observation is particularly pertinent for failures classified as accident type (2), as some failure categories may show early warning signs, while others may not.

Moreover, the occurrence of multiple failures reported from a single event can initiate an incorrect predominance towards a failure mode. It is also possible for a single failure event to belong to different failure categories. Failures rarely have a singular cause, introducing additional complexity. The significant share of unknown failure causes (20%), underscores the challenges associated with identifying and understanding the underlying causes of these failures, suggesting the potential for errors in the database. In addition, the failure categories defined in the database, are likely not completely mutually independent.

Lastly, inaccuracies may have arisen due to variations in reporting by different individuals, employing different forensic methods, reporting at different times, and potentially diverse motivations and expertise. The latter is essential, considering the complexity of the failure mechanisms. The failure mechanisms are often oversimplified and it may be challenging to identify the root cause of failure. Often failure arises from a combination of multiple factors.

Despite these limitations, meaningful conclusions can be drawn through statistical analysis of the available dataset. The findings can inform future dam safety work and provide an indication of the baseline PoF by dam type and failure category, which will be discussed in the next chapter(Chapter 6).

6

Baseline Probability of Failure (PoF)

This chapter outlines the process for computing the overall baseline PoF. It also discusses how the baseline PoF by dam construction method and failure category is calculated, which are pivotal elements of the tool.

6.1. Overall

The overall baseline PoF is the average PoF across all existing dams. To calculate this baseline rate, one needs data on the global count of tailings dams and the average frequency of failures. The baseline PoF is obtained by dividing the failure frequency by the total number of dams.

6.1.1. Total Number of Tailings Dams

There is no complete inventory of existing tailings dams. The literature reports a wide range, spanning from a few thousand to approximately 35,000. Several researchers (Davies et al., 2000; Lyu et al., 2019; Liang et al., 2021) estimated a global count of 3,500 TSFs during the early 2000s. Franks et al. (2021) provide a more recent estimate of 3,400 to 8,100 TSFs that are constructed between 1965 to 2020. However, projections by Wei et al. (2013) indicate over 6,000 TSFs in China alone, while other authors propose figures of 12,000 TSFs exclusively in China (Yin et al., 2011; Pan et al., 2014; Wang et al., 2017). Hence, the estimates provided by the aforementioned authors are considered to be significantly underestimated, likely focusing on larger facilities and overlooking the potential existence of numerous smaller-scale TSFs.

This idea is shared by Spencer et al. (2021), who estimates 13,400 - 15,400 active and inactive TSFs by reviewing existing national inventories, and remarked that the true number of all existing TSFs worldwide could be in the order of 30,000 when accounting for abandoned TSFs and poorly reported countries. Additional studies, such as WMTF (2019), support this higher estimate. WMTF (2019) compiled inventories from 22 countries representing 60% of global mineral production, estimating 19,214 TSFs including active, inactive, closed and abandoned sites. To estimate the global count, they scaled this number up with 40%, resulting in a total of 32,000 TSF, with an uncertainty range of ±10% (29,000-35,000).

Furthermore, there are intermediate estimates that fall between the extremes mentioned above. For example, Azam & Li (2010) estimated a count of 18,401 TSFs, but did not disclose the specific methodology employed for this estimation. On the other hand, Rana et al. (2022) calculated a total of 20,230 TSFs by dividing the annual volume of tailings produced by the median volume per TSF based on Franks et al. (2021) inventory, which is considered to be incomplete. Rana et al. (2022) acknowledge the possibility that their estimate of 20,230 TSFs may still underestimate the global count.

An alternative approach considers estimating the number of TSFs based on the number of mine sites worldwide, assuming an average of 1.7 TSFs per site Rana et al. (2022). Maus et al. (2020) reported 6,000 mines, while NIOSH Mining (2021) estimated around 17,088 active mines in 1985. Using the latter figure, an estimate of approximately 29,050 TSFs can be derived. Nevertheless, substantial uncertainties surround this estimation, which will not be further explored in this context.

Figure 6.1 presents a summary of global TSF counts approximated in the literature. Acknowledging the inherent uncertainty in estimating the number of dams and considering the various estimates discussed, a conservative estimate of **25,000 existing tailings dams** is adopted for the subsequent analysis. This conservative approach is employed to err on the side of caution when assessing the PoF.

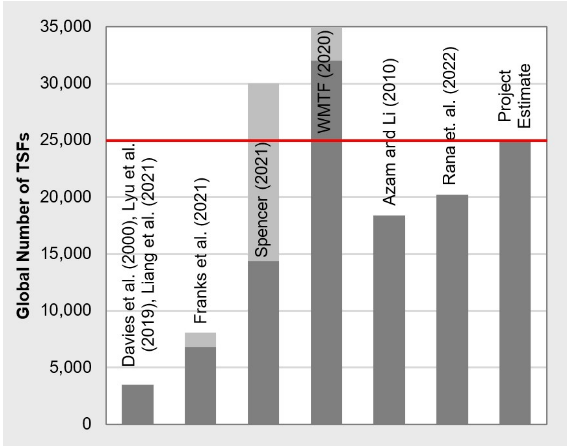


Figure 6.1: Reported Number of Existing Tailings Storage Facilities (TSFs) by Different Authors – *Colour Scale: Project Estimate (Red)*

6.1.2. Failure Frequency

Numerous studies have documented failure frequencies, and while minor discrepancies do exist, their findings generally fall within a similar range. Martin & Davies (2022) reported a failure frequency of 3.5 failures per year, while Azam & Li (2010) observed a rate of 5.0 failures per year in 1960, decreasing to around 2.0 failures per year in the 1980s. Consistent with these findings, Lyu et al. (2019) and Piciullo et al. (2022) estimated failure frequencies ranging from 3.5 to 5.0 events per year. Lin et al. (2022) conducted a comprehensive analysis, revealing specific failure frequencies over three periods: 2.9 from 1947 to 1970, 5.7 from 1972 to 1996, and 4.6 from 1997 to 2021. Overall, the average failure frequency from 1947 to 2021 estimated by Lin et al. (2022) was 4.4 failures per annum. Similar conclusions can be drawn from the developed database in Chapter 5. However, before analysing its data, it is necessary to make a few modifications:

- Accidents (Type 2 failure events) were excluded from the database as the focus is on true failures.
- Accidents related to groundwater issues (Type 3 failures) were removed, and the remaining Type 3 incidents (SE failures) were reclassified as Type 1 failures.
- Records with unknown incident or accident status are also removed from the database.

The resulting database comprises 351 entries, with 18 occurrences lacking the year of occurrence. The timeline of reported failures, along with the 10-year moving average and average failure frequency across specific time periods, is depicted in Figure 6.2.

The failure frequency prior to 1965 was relatively low at around 0.7 failures per year. However, after 1965, there was a significant increase, ranging from 3.3 to 5.2 failures per year. The reasons for these trends are explained in Section 5.3.1. In the last decade, the number of reported failures per year has shown a higher trend, suspected to be due to increasing awareness, reporting requirements and an increasing number of tailings dams (see Figure 6.16). Since 2010, there have been 94 reported failures, resulting in an average annual failure frequency of 7.2. Note that the 18 cases with unknown information are assumed to have occurred before 1965 or, at the latest, before 2001, as most were reported in ICOLD (2001).

The increasing failures in the past decade indicate that the current failure frequency of **7.2 failures per year** is the most relevant estimate at present. Although some uncertainty remains, this number will be utilised for the remaining analysis.

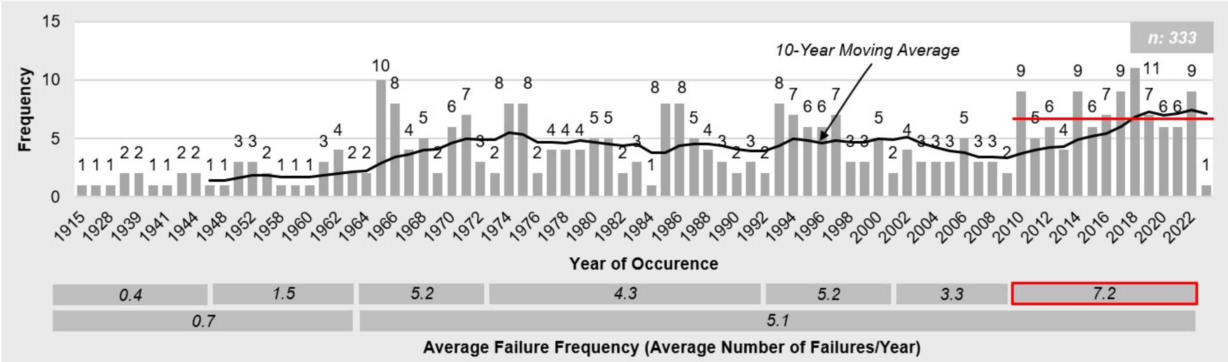


Figure 6.2: Timeline of Reported Tailings Dam Failures after Correction
Showing 10-Year Moving Average and Failure Frequency – *Colour Scale: Project Estimate (Red)*

6.1.3. Baseline PoF

The calculation of the overall baseline PoF involves a straightforward division of the failure frequency by the total number of dams. Based on the actual estimated global number of tailings dams of 25,000 and an actual annual failure frequency of 7.2, the calculated baseline PoF is approximately **2.9 E-04** (7.2/25,000). This falls within the expected range based on the existing literature (e.g. Lin et al. (2022)).

The strategy described above resembles the approach taken by Porter et al. (2023). They calculated a failure frequency of 4.4 failures per year among a population of 20,230 dams, resulting in an average annual PoF of 2.2 E-04. This figure is close to the estimate presented in this context.

6.2. By Dam Construction Method

After establishing the overall baseline PoF, an evaluation was conducted to assess the relative contribution of the four principal dam construction methods (Upstream (US), Downstream (DS), Centreline (CL), Water Retention (WR)) to this total probability. This requires examining the distribution of historical failures according to the construction method and this distribution within existing dams. The following sections will provide a more detailed explanation of how the baseline PoF by dam construction method is calculated.

6.2.1. Distibution Historical Failures

The distribution of dam construction methods for historical failures can be derived from the developed failure database (Chapter 5). Following the adjustments detailed in the bullet points in Section 6.1.2, this distribution is shown in Figure 6.3. Nonetheless, it is important to highlight that the database encompasses failures with dam construction methods that go beyond the primary ones identified in Section 2.2.1 and that the database lacks information on dam construction methods for 179 cases, both requiring adjustments. For the 9 cases in the database with dam construction methods other than US, DS, CL, and WR, the following corrections are made:

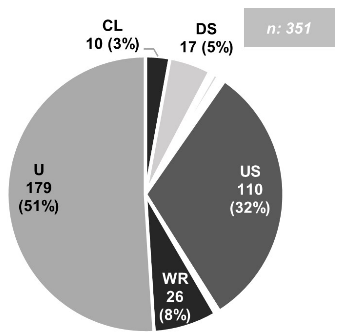


Figure 6.3: Dam Construction Method Distribution Failure Database *(US:Upstream, DS: Downstream, CL: Centreline, WR: Water Retention)*

- The 3 cases with construction methods 'open pit,' 'gravity,' and 'none' are removed from the database as they do not align with the tailings dams definition in Section 2.2.
- The other 6 construction methods not falling under US, DS, CL, or WR (e.g., 'Modified CL') are reclassified under the US category. This reclassification is based on the observation that these methods often include a significant US component, which is crucial for stability considerations.

To address the 179 cases with U construction types, several options were considered:

1. **Option 1**: Removing all failures with U construction methods from the database, relying on the known figures.
2. **Option 2**: Transferring all of the U construction methods (with the exception of those associated with MS failures) to the US category, as it is believed that many of these dams incorporate upstream components, which play an essential role in the tailings dams' stability. The 3 MS failures are equally distributed over the other dam construction methods, as this type of failure is not influenced by the specific method of dam construction.
3. **Option 3**: Distributing cases with unidentified construction methods to other dam types based on established associations between construction methods and failure categories, as follows:
   - Determining the relative contribution to the construction method for the different failure categories, for the 169 cases where both the construction method and failure category are known (shown in Figure 6.4a).
   - Utilise this known distribution to allocate the 179 failures with U construction methods (but known failure categories) across the dam construction methods (shown in Figure 6.4b. Similar to option 2, an exception was made for failures categorised as MS since only one known failure existed. In these cases, the U construction methods for MS were evenly distributed across the dam construction methods, as the type of dam is considered irrelevant when it comes to MS failures.
   - Add these cases of initially U construction methods to the known distribution.

28/31 = 90.3%

X	*Total*	US		DS		CL		WR	
EQ	*31*	28	90.3%	3	9.7%	0	0.0%	0	0.0%
OT	*32*	22	68.8%	2	6.3%	3	9.4%	5	15.6%
SI	*41*	36	87.8%	2	4.9%	0	0.0%	3	7.3%
FN	*12*	4	33.3%	1	8.3%	3	25.0%	4	33.3%
SE	*27*	11	40.7%	5	18.5%	1	3.7%	10	37.0%
ST	*13*	8	61.5%	2	15.4%	1	7.7%	2	15.4%
ER	*4*	1	25.0%	1	25.0%	0	0.0%	2	50.0%
MS	*1*	1	100.0%	0	0.0%	0	0.0%	0	0.0%
U	*8*	5	62.5%	1	12.5%	2	25.0%	0	0.0%
Total	*169*	*116*		*17*		*10*		*26*	

(a) Data Manipulation Obtaining the Construction Method Distribution on the Basis of the Known Relationship between Construction Method and Failure Category *(US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, U: Unknown)*

.

10 x 90.3% = 9.03

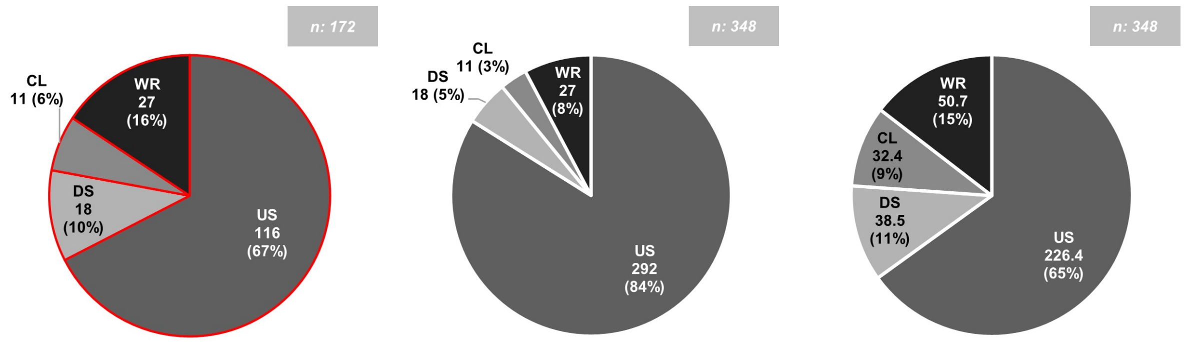
X	*Total*	US	DS	CL	WR
EQ	*10*	9.03	0.97	0.00	0.00
OT	*43*	29.56	2.69	4.03	6.72
SI	*13*	11.41	0.63	0.00	0.95
FN	*5*	1.67	0.42	1.25	1.67
SE	*22*	8.96	4.07	0.81	8.15
ST	*24*	14.77	3.69	1.85	3.69
ER	*5*	1.25	1.25	0.00	2.50
MS	*3*	0.00	1.00	1.00	1.00
U	*54*	33.75	6.75	13.50	0.00
Total	*179*	*110.41*	*21.47*	*22.44*	*24.68*

Equal Distribution for MS Failures

(b) Determining the Construction Method *Distribution of Unknown (U) Cases (US:Upstream, DS: Downstream, CL: Centreline, WR: Water Retention, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, U: Unknown)*

Figure 6.4: Methodology Data Manipulation (Option 3)

The distribution of construction methods within the database is represented in Figure 6.5. It illustrates the outcomes stemming from all three adjustment options for the U construction methods. Notably, there is a marked contrast between option 2 and the other two alternatives. Option 2 is considered less accurate, as it assumes that all dams with unknown construction methods are exclusively US dams, which is highly improbable. Options 1 and 3 yield relatively similar results. However, option 3 is intricate due to its substantial fabrication of data through data manipulation, which is a less desirable practice, having a relative share of **67.4% (US)**, **10.5% (DS)**, **6.4% (CL)** and **15.7% (WR)**, respectively.



(a) Option 1
(US:Upstream, DS: Downstream, CL: Centreline, WR: Water Retention) – Colour Scale: Project Estimate (Red)

(b) Option 2
(US:Upstream, DS: Downstream, CL: Centreline, WR: Water Retention)

(c) Option 3
(US:Upstream, DS: Downstream, CL: Centreline, WR: Water Retention)

Figure 6.5: Dam Construction Method Distribution Failure Database (After Corrections) – *Colour Scale: Project Estimate (Red)*

6.2.2. Distribution Existing Tailings Dams

The subsequent step involves the estimation of the distribution of construction methods of existing tailings dams worldwide to facilitate the calculation of conditional probability. The primary data source used is the 'Global Tailings Portal' (GRID-Arendal et al., 2020), recognised as the most comprehensive database encompassing global tailings dams, offering a reliable reflection of the distribution. This distribution is visualised in Figure 6.6. However, a correction is necessary due to the presence of construction methods not covered in this study. The distribution is adjusted as follows:

- 'In-pit' and 'dry stack' TSFs are excluded from the distribution since they do not fall under the definition of tailings dams within this study (see Section 2.2).
- Dams categorised as 'other' are entirely reassigned to the US dams category, as it is expected that these 'other' constructed dams incorporate an upstream component.

Consequently, the revised distribution reveals a total of 830 US dams, 500 DS dams, 124 CL dams, and 98 WR dams, having a share of **53.5% (US)**, **32.2% (DS)**, **8.0% (CL)**, and **6.3% (WR)**. This distribution is shown in Figure 6.7.

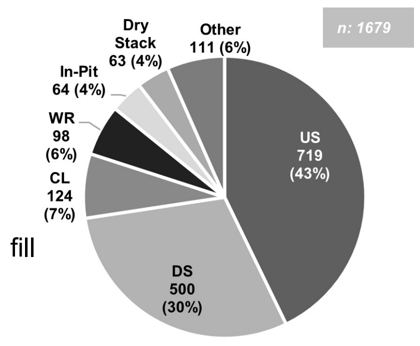


Figure 6.6: Dam Construction Method Distribution Existing Tailings Dams (GRID-Arendal et al., 2020) *(US:Upstream, DS: Downstream, CL: Centreline, WR: Water Retention)*

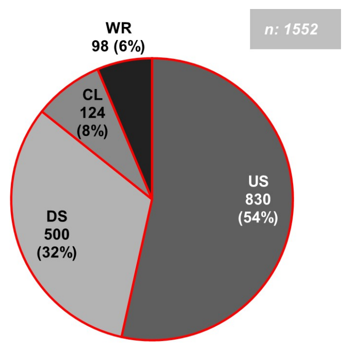


Figure 6.7: Dam Construction Method Distribution Existing Tailings Dams (After Corrections) *(US:Upstream, DS: Downstream, CL: Centreline, WR: Water Retention) – Colour Scale: Project Estimate (Red)*

6.2.3. Baseline PoF

To calculate the baseline PoF for a specific dam, it is insufficient to merely multiply the overall baseline PoF with the relative percentage of contribution derived from historical failure cases. The distribution of construction methods for existing tailings dams must also be considered to account for risk exposure. For instance, if the PoF for a WR dam constitutes 10% of the total recorded failures, but the number of existing WR dams accounts for only 5% of the total, the risk associated with this dam type is relatively high.
To address this, Bayes's theorem for conditional probability is employed. Equation 6.1 illustrates Bayes's theorem using the example of an upstream dam. In the equation, F represents the event of 'a dam failing this year', and US denotes 'the dam being a US dam'.

$$P(F|US)\ (1/Year) = \frac{P(F)\ (1/Year) \cdot P(US|F)\ (1/Year)}{P(US)\ (1/Year)} \tag{6.1}$$

Here, $P(F|US)$ is the PoF given that the dam is an upstream dam, which is the key aspect of interest. $P(F)$ denotes the probability of a dam failing, equivalent to the overall baseline PoF (as calculated in Section 6.1.3). Conversely, $P(US)$ is the probability of the existing dam being a US dam, determined by the distribution of existing dams (as defined in Section 6.2.2). Lastly, $P(US|F)$ is the probability of the failing dam being a US dam, indicated by the percentage of US dams among recorded historical failures (as estimated in Section 6.2.1).

In other words, considering a total of 25,000 dams, it is anticipated that approximately 53.5% (or $\sim$ 13,369 dams) will be US dams. Out of the projected 7.2 dams that will fail this year, it is expected that 67.4% (or $\sim$ 4.85 dams) are US dams. As a result, the PoF for an **US** dam this year is estimated to be **3.6 E-04** (4.85/13,369). The probabilities of failures for the other dam construction methods can be computed using the same approach. The estimated PoF for a **DS** dam is **9.4 E-05**, for **CL** dams it is **2.3 E-04**, and for **WR** dams it is **7.2 E-04**. An evaluation of the numbers is presented in Section 6.3.2. An overview is presented in Table 6.1, along with the results of Porter et al. (2023).

Porter et al. (2023) estimated PoF of 3.4 E-04 for US dams, 5.1 E-05 for DS dams, 1.1 E-04 for CL dams and 2.0 E-04 for Single Stage (SS) dams. Their strategy was to transfer all dams with U construction method to the US category (option 2). This explains why WR failures have a lower rate than reported in this study, but this method is considered inappropriate, as discussed earlier.

Table 6.1: Overview Baseline Probability of Failure (PoF) by Dam Construction Method *(US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention) – Color Scale: Lowest (Green) - Highest (Red)*

Results	US	DS	CL	WR
Results Study	3.6 E-04	9.4 E-05	2.3 E-04	7.2 E-04
Results Porter et al. (2023)	3.4 E-04	5.1 E-05	1.1 E-04	2.0 E-04

6.3. By Dam Construction Method and Failure Category

Unlike the PoF based on the dam construction method, the PoF attributed to a specific failure category can simply be determined by multiplying the relative occurrence of the failure category within the database with the baseline PoF. This assumption is grounded in the notion that the different failure categories are mutually exclusive and unrelated. The subsequent sections explain the process of calculating the baseline PoF by dam construction method and failure category. An in-depth explanation of the different failure categories is presented in Section 2.3.1.

6.3.1. Distribution Failure Categories

To calculate the relative distribution of the failures over the different failure categories, the failure database, developed in Chapter 5 is revisited. Prior to calculating the relative contribution of each failure category, the following modifications are implemented:

- Failures with U failure categories are excluded from the dataset. While these could serve as baseline failures unaffected by prevalence criteria, it is believed that the PoF for each failure category can be reduced through appropriate mitigation measures. Hence, their removal facilitates a clearer identification of the potential reductions in the PoF for each category.
- Where zero failures are reported for specific combinations of failure mode and raise method, 0.5 failures were added to avoid failure categories with probabilities of zero. Nonetheless, it is crucial to acknowledge that the inclusion of 0.5 additional failures has an impact on the distributions, especially in downstream dams, where originally only 8 failures were reported. However, this adjustment is deemed appropriate, given the expectation that such failures are likely to occur at DS dams.

A summary of the resulting distributions is illustrated from Figure 6.8 through Figure 6.12. Figure 6.8 displays the distribution encompassing all cases with a known failure category, whereas Figure 6.9 to Figure 6.12 exclusively represent cases where both the construction method and failure category are documented. Note that, especially for Figure 6.10, Figure 6.11 and Figure 6.12 the population size is limited. Figure 6.9 through Figure 6.12 serve as the foundation for computing the baseline PoF with respect to dam construction method and failure category. These form the fundamental data upon which the tool relies.

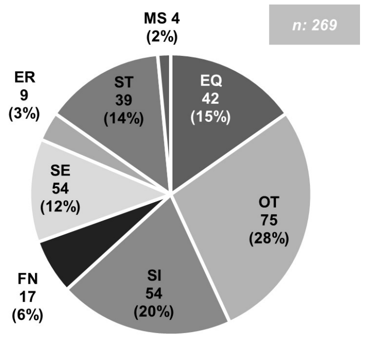


Figure 6.8: Distribution Failure Categories Database *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*

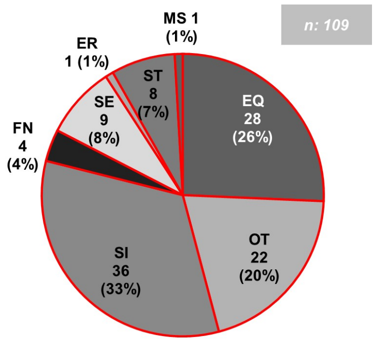


Figure 6.9: Distribution Failure Categories Upstream (US) Dams *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*

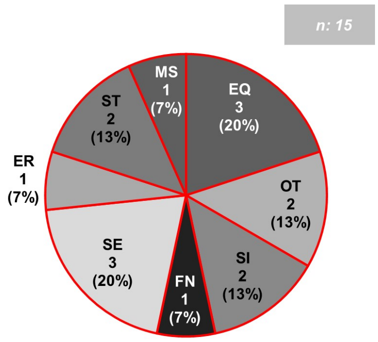


Figure 6.10: Distribution Failure Categories Downstream (DS) Dams *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*

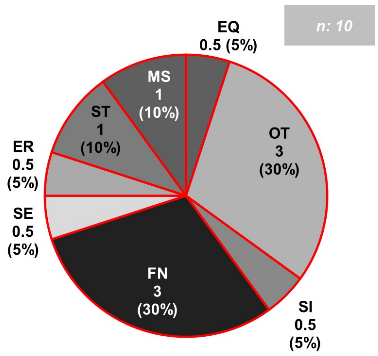


Figure 6.11: Distribution Failure Categories Centreline (CL) Dams *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*

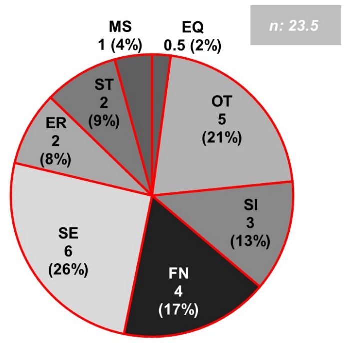


Figure 6.12: Distribution Failure Categories Water Retention (WR) Dams *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*

6.3.2. Baseline PoF

By assuming mutual exclusiveness between the different failure categories, the baseline PoF for each failure category can simply be calculated by multiplying the percentage of the distribution of the specific failure category by the baseline PoF. In Figure 6.13, the proportional distribution of various failure categories in relation to the baseline PoF categorised by dam construction methods is illustrated. Table 6.2 offers a summary of the associated numerical values.

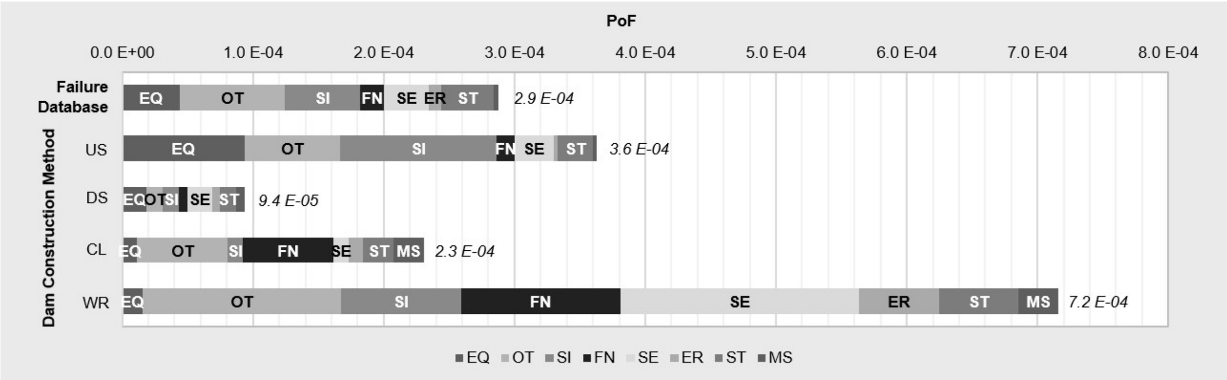


Figure 6.13: Overview Probability of Failure (PoF) by Dam Construction Method and Failure Category *(US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*

Several noteworthy observations can be drawn from the baseline PoF presented in Figure 6.13. It is essential to recognise that while the differences may appear substantial, they are, in reality, relatively small, often on the order of 10^{-4}. First of all, dams constructed using a DS method exhibit the lowest baseline PoF, they are often considered the most robust and stable dam types. Additionally, dams constructed using a CL method tend to have slightly lower PoF than the overall average, also having a relatively stable structure. In contrast, dams constructed using a US method display a slightly higher baseline PoF, which is also in line with literature expectations. Most notably, dams constructed with a WR method have the highest baseline PoF. This unexpected finding contradicts the general perception that WR dams are the most stable and are often engineered to the highest standards and, therefore should have a lower baseline PoF. This anomaly may be attributed to the fact that WR often have to bear the highest loads. Alternatively, it could stem from potential inaccuracies within the database, where the reported WR dams may not align with the definition of WR dams. It is conceivable that certain failures initially classified as WR dams may have been, in fact, starter dams. To better understand why WR dams have the highest baseline PoF, a more in-depth analysis of the specific data would be required.

Table 6.2: Probability of Failure (PoF) by Dam Construction Method and Failure Category *(US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy) – Color Scale: Lowest (Green) - Highest (Red)*

X	Overall	US	DS	CL	WR/SS
	P(F,X)	P(F|US,X)	P(F|US,X)	P(F|US,X)	P(F|US,X)
EQ	4.4 E-05	9.3 E-05	1.9 E-05	1.2 E-05	1.5 E-05
OT	8.0 E-05	7.3 E-05	1.2 E-05	6.9 E-05	1.5 E-04
SI	5.8 E-05	1.2 E-04	1.2 E-05	1.2 E-05	9.1 E-05
FN	1.8 E-05	1.3 E-05	6.2 E-06	6.9 E-05	1.2 E-04
SE	3.4 E-05	3.0 E-05	1.9 E-05	1.2 E-05	1.8 E-04
ER	9.6 E-06	3.3 E-06	6.2 E-06	1.2 E-05	6.1 E-05
ST	4.0 E-05	2.7 E-05	1.2 E-05	2.3 E-05	6.1 E-05
MS	4.3 E-06	3.3 E-06	6.2 E-06	2.3 E-05	3.0 E-05
Total	*2.9 E-04*	*3.6 E-04*	*9.4 E-05*	*2.3 E-04*	*7.2 E-04*

As anticipated, PoF for EQ failure category is higher in US dams than in other dam types. Similarly, SI failures are notably prevalent in US dams. Besides, CL dams exhibit a relatively high incidence of FN failures, likely attributed to their greater weight and height, which imposes higher loads on the foundation. This phenomenon is expected in DS dams as well, but data limitations, with only 15 DS dam failures reported, may explain its absence. Additionally, SE failures are relatively prominent in WR dams, consistent with expectations, as WR dams often have standing water against the dam face. Finally, it is worth noting that ER, ST, and MS failure categories collectively contribute a small proportion to the overall PoF. This pattern aligns with findings in earthen dams, where the primary contributors to failures are OT, and SE (Sharma, 2013).

Porter et al. (2023) adopted a similar approach. The findings from their study are presented in Table 6.3. While there are resemblances in the trends, certain disparities exist, primarily attributed to the limitations of the incomplete database utilised by Porter et al. (2023).

Table 6.3: Probability of Failure (PoF) by Dam Construction Method and Failure Category by Porter et al. (2023) *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*
– Color Scale: Lowest (Green) - Highest (Red)

X	Overall	US	DS	CL	SS
	P(F,X)	P(F|US,X)	P(F|US,X)	P(F|US,X)	P(F|US,X)
EQ	9.1 E-05	3.8 E-06	1.1 E-04	6.2 E-06	9.1 E-05
OT	8.0 E-05	2.3 E-05	1.1 E-04	1.0 E-04	8.0 E-05
SI	6.8 E-05	7.7 E-06	1.5 E-05	6.2 E-06	6.8 E-05
FN	2.6 E-05	1.5 E-05	4.3 E-06	1.2 E-05	2.6 E-05
SE	3.1 E-05	1.5 E-05	8.6 E-06	6.2 E-06	3.1 E-05
ER	2.7 E-05	3.1 E-05	4.3 E-06	2.5 E-05	2.7 E-05
ST	1.2 E-05	3.8 E-06	2.1 E-06	6.2 E-06	1.2 E-05
MS	1.7 E-06	3.8 E-06	2.1 E-06	3.7 E-05	1.7 E-06
Total	*3.4 E-04*	*1.1 E-04*	*5.1 E-05*	*2.0 E-04*	*3.4 E-04*

6.4. Remarks

The method detailed in this chapter for establishing the baseline PoF is not without its imperfections. Numerous discrepancies within the population have been touched upon in the preceding discussion. However, some additional concluding remarks are provided here. There are some points to note regarding the magnitude of the estimated PoF, mutual exclusivity and the influence of time on this baseline PoF.

Magnitude and Statistical Perspectives

The annual baseline PoF is on the order of 10 E-04/10 E-05, notably higher than the PoF for WR dams, which is typically estimated to be in the order of 10 E-05/10 E-06 (Lyu et al., 2019). While a higher failure rate is observed in tailings dams than in WR dams, the disparity exceeds expectations.

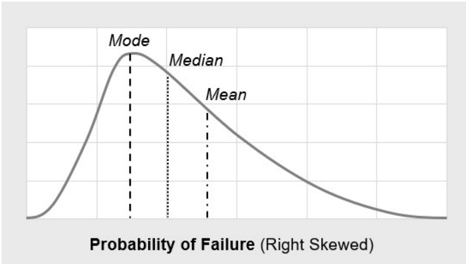


Figure 6.14: Mode, Median and Mean

A potential explanation lies in the calculation of the baseline PoF. The calculated baseline PoF is an average PoF, which may not conform to a normal distribution. Instead, it is more likely that the failure distribution shows a right-skewed pattern, leading to a considerably lower mode and median (Figure 6.14). The reported count is based on the number of TSFs rather than individual dam sections. As discussed in Section 2.2, TSF structures typically encompass multiple dam sections, and failures tend to impact only one or two sections, not the entire structure. It adds uncertainty to the analysis and is attributed to be one of the main reasons that the order of magnitude of the baseline PoF is relatively high.

Population Discrepancies

It is crucial to note the severe limitation in the sample size of failures with known dam construction methods and failure categories, particularly for DS (15 reported cases), CL (8 reported cases), and WR (23 reported cases) dams. This limitation leads to significant shifts in the distribution of failure categories when a single failure is introduced to the dataset.

Additionally, the significant uncertainties surrounding the number of existing tailings dams and the potential incompleteness of the database should be emphasised (as discussed in Section 5.4). These uncertainties have a profound impact on the overall baseline PoF, which serves as the foundation for the tool.

Mutual Exclusivity

Another essential assumption in this analysis is the assumption of mutual exclusivity among failure categories. This principle is demonstrated in Figure 6.15. However, it is important to acknowledge that dependencies and correlations likely exist among these failure categories. The tool and the calculation of the baseline PoF do not consider these dependencies, a factor that necessitates awareness.

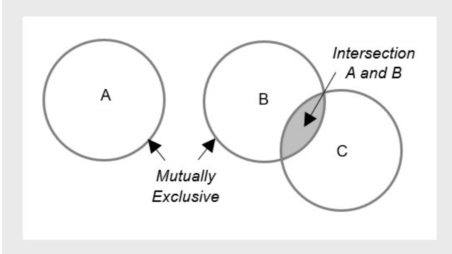


Figure 6.15: Mutual Exclusiveness

Temporal Insights

A noteworthy observation, while not directly impacting the results, pertains to the exponential growth in the number of tailings dams, see Figure 6.16 (Rana et al., 2022). Despite the increasing trend in failure frequency since 2010, this phenomenon suggests a potential decrease in the actual PoF over time. To ensure the most precise estimate, it is essential to calculate the annual baseline PoF based on the actual number of tailings dams and a recently observed failure frequency. Yearly updates will be required.

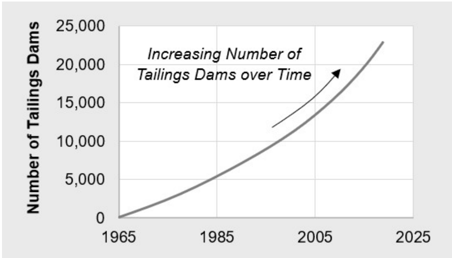


Figure 6.16: Estimated Number of Tailings Dam over Time *(Modified after (Rana et al., 2022))*

The baseline PoF based on dam construction method and failure category serves as the initial point for subsequent calculations within the tool. These probabilities are then adjusted through an evaluation of site-specific criteria, which may either increase or decrease the probability of certain failure categories occurring compared to these average probabilities. A detailed discussion on this topic is provided in Chapter 7.

7

Prevalence Examination

This section outlines the process by which the prevalence of various failure categories for the tailings dam under investigation is determined. This prevalence examination is based on the analysis of several contributing factors that may differ from dam to dam, encompassing site conditions, design elements, and the LoP. The quantification of the relative significance of each contributing factor and the fulfilment at a specific site is also detailed in this section.

7.1. Contributing Factors

Each TSF is unique, not only due to varying construction methods but also because of a multitude of other site-specific factors, which may impact the PoF. As a result, the baseline PoF, as presented in Chapter 6, is not directly applicable to every tailings dam, but necessitates appropriate adjustments to account for the site variations. The variations are captured in a set of factors that influence the predisposition of a TSF to experience failure category over another, referred to as contributing factors. These contributing factors can be broadly categorised into site conditions, design elements, and LoP, which are elaborated upon in the subsequent sections.

7.1.1. Site Conditions

The 'site conditions' refer to the physical conditions on, at or near or affecting the location where the tailings dam is built, including, but not limited to, weather, climate, hydrology, hydrogeology seismicity, subsurface geology and surface soil conditions. These conditions are often beyond human control given the site and project constraints, yet they may result in some failure categories being more or less likely to occur than they are on average. For instance, a tailings dam in a highly seismically active region is more prone to extreme loading and associated conditions that can lead to a failure related to earthquake events than one located in a seismically inactive area. Consequently, the PoF due to earthquakes is higher in seismically active regions and the baseline PoF needs to be adjusted for this increased probability.

The study presents a comprehensive identification of 31 specific site factors that influence the PoF. The site condition factors are derived from the FTA (Figure 2.8, Page 20) conducted, and from the incident descriptions available in the database (Appendix A.2). The factors are listed in Table B.1 in Appendix B. Importantly, the impact of the factors on the PoF varies across the different failure categories, and not all factors apply universally to each category and dam construction method. Table B.1 also indicates these variations in significance.

7.1.2. Design Elements

The design elements of a tailings dam govern all the physical components of the dam and the associated design decisions made. Key factors such as dam geometry and material selection are, among others, addressed in this process, which may significantly impact the dam's structural integrity and overall performance. Some design elements may increase the risk of specific failure categories, while others may decrease the PoF. For instance, dams of significant height may be more susceptible to foundation failures, while lower dams may reduce such risks. Thus, adjusting the baseline PoF is necessary to accommodate these design variations across projects. A robust tailings dam design takes into account all relevant elements, of which many positively affect the PoF and minimise potential risks.

The 54 specified design elements, pertaining to different failure categories, are presented in Table B.2 in Appendix B. Similar to the site conditions, these factors are derived from the FTA (Figure 2.8, Page 20), and the incident descriptions within the database (Appendix A.2), and not all of these factors exert a significant influence on the PoF for each specific failure category.

7.1.3. Level of Practise (LoP)

The concept of LoP pertains to the extent of proficiency, skill, and expertise employed throughout the lifecycle of a tailings dam. This LoP governs critical aspects regarding the degree of proficiency, such as the depth and quality of the hydrological and hydrogeological assessment. A higher LoP implies a greater focus on safety, environmental considerations, and adherence to best practices. Such elevated standards of practice have the potential to substantially mitigate risks associated with various failure categories. Consequently, it is imperative to adjust the baseline PoF in accordance with the LoP implemented.

Silva et al. (2009) and Chovan et al. (2021) have delineated factors pertaining to the LoP. However, their approach primarily focuses on SI and FN failure modes under static conditions, presenting limitations. The requirements laid out in the GISTM (GISTM, 2020) are also LoP indicators, intentionally established for a high LoP. Many operators are expected to have already evaluated their dam against the GISTM requirements, making it a convenient input for this tool.

Not all the requirements stipulated within the GISTM framework bear direct relevance to the assessment of failure probabilities. Out of the 219 requirements outlined in GISTM, 150 requirements hold particular relevance to the PoF analysis, which are listed in Table B.3 in Appendix B. The majority of these factors have some level of influence on almost all failure categories, although there may be exceptions where certain factors do not, or to a lesser extent, affect specific failure categories.

7.2. Adjustments to the Baseline Probability of Failure

Based on the assessment of various factors at the site under investigation, adjustments are required for the baseline PoF by dam construction method and failure category, which was introduced in the previous chapter (refer to Chapter 6). Firstly, it is essential to assign weights (W) to the distinct contributing factors, as they are expected to exert unequal influences on the PoF. It is crucial to emphasise that these weightings should be determined relative to one another to ensure proportionality in the adjustments. Additionally, there is a need to establish modifying factors (M) that accurately reflect the extent to which the contributing factors are satisfied in the context of the specific tailings dam being examined. These modifying factors should indicate whether the conditions are favourable, adverse, or expected to be average values. The baseline PoF is multiplied by the product of the weight of the contributing factor and its respective fulfilment score, yielding the contribution of that specific factor to the overall PoF. The total PoF can then be computed by taking the sum of all the PoF fractions of each contributing factor, see Equation 7.1.

$$PoF\ (1/year) = \sum_{n=1}^{n} (w_n\ (\text{-}) \times M_n\ (\text{-})) \times Baseline\ PoF\ of\ Failure\ Category\ (1/year) \quad (7.1)$$

The following sections outline the weight determination of the contributing factors and an overview of the resulting weights is presented. Moreover, it is explained how the fulfilment scores are obtained.

7.2.1. Weight Determination with Analytical Hierarchy Processing Method (AHP)

The weight determination presents a complicated challenge. Given the presence of more than 200 factors in total, it is crucial to employ effective problem-structuring techniques and use appropriate tools for evaluating these factors. Within the domain of Multi-Criteria Decision Making (MCDM), several methodologies exist to assign representative weights to criteria or factors. These methodologies differ in algorithm complexity, mathematical weighting techniques, possible evaluation, treatment of uncertain data, and the approach to data aggregation (Taherdoost, H. and Madanchian, M., 2023).

One of these methods is the Analytical Hierarchy Process (AHP) method, pioneered by Saaty (1980). It stands as one of the most widely employed methodologies within MCDM worldwide, in both academia and industry, to make well-informed and rational choices (Syed & Lawryshyn, 2020). Its popularity stems from its ease of comprehension and mathematical simplicity while maintaining rigour (Munier & Hontoria, 2021). The AHP involves decomposing complex problems into better understandable hierarchical structures, facilitating the weighting of factors through straightforward pairwise comparisons at each hierarchical level. These comparisons are based on expert judgement, but the consistency of these judgements can be evaluated. The approximate AHP method is deemed suitable for an initial approach to determine the relative weights of the contributing factors due to its simplicity, efficacy, and established validity, as affirmed by Mu & Pereyra-Rojas (2016). Further elaboration on the implementation of this approach is provided in the subsequent paragraphs.

AHP for Weighting

A brief overview of the practical application of the AHP methodology is presented herein, focusing on obtaining the contributing factors' prevalence weights. For an in-depth theoretical and mathematical foundation of the method, interested readers are directed to Saaty & Vargas (2012) explanation, or alternatively, to Brunelli (2015)'s work on the subject. Mu & Pereyra-Rojas (2016) describes 5 main steps within AHP, briefly explained below.

Step 1: Modelling Hierarchical Structure

The initial stage entails breaking down the decision model into multiple hierarchical levels. At the apex resides the PoF. The second level comprises the categories of contributing factors (site conditions, design elements, and LoP). Further granularity is achieved in the third level, where sub-categories with sub-criteria are delineated, as depicted in Figure 7.1. Note that for some criteria there are also sub-sub factors, which are part of the fourth level.

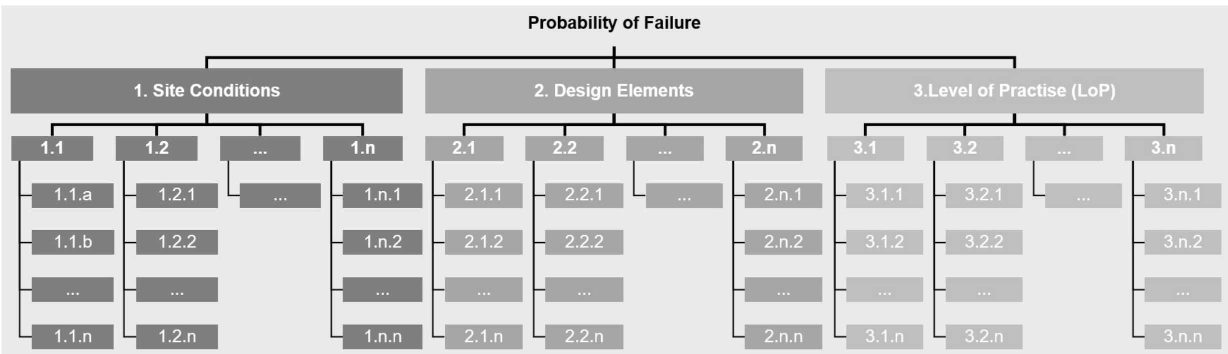


Figure 7.1: Hierarchical Structure Analytical Hierarchy Processing (AHP) Method

Step 2: Pairwise Comparision

Subsequently, deriving prioritisation of contributing factors for a specific dam and failure mode involves employing pairwise comparisons. This process entails creating an n by n matrix of the contributing factors at each level, as illustrated in Equation 7.2.

$$\boldsymbol{CF} = \begin{bmatrix} CF_{11} & CF_{12} & \cdots & CF_{1n} \\ CF_{21} & CF_{22} & \cdots & CF_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ CF_{n1} & CF_{n2} & \cdots & CF_{nn} \end{bmatrix} \tag{7.2}$$

To populate this matrix, and to capture the relationships among contribution factors, the relative importance of one factor over another is assessed based on judgement, informed by the FTA, and incident descriptions accessible in the database. Saaty (1980) numerical scale, as presented in Table 7.1, is used for these comparisons. In essence, the core question addressed in this matrix is: 'How much more influential is one factor on failure probability compared to another?' (Saaty & Vargas, 2006). Reciprocal values are assigned to the 'opposite' comparison (Equation 7.3).

Table 7.1: Numerical Grading Scale Analytical Hierarchy Processing (AHP) Method

Intensity of Importance	Explanation	Numerical Rating	Reciprocal*
Equal Importance	Equal contribution	1	1
Moderate Importance	Moderate importance of the first element over the second element in the pair	3	1/3
Strong Importance	Strong essential importance of the first element over the second element in the pair	5	1/5
Very Strong Importance	Very Strong importance of the first element over the second element in the pair	7	1/7
Extreme Importance	Extreme importance of the first element over the second element in the pair	9	1/9
	Intermediate value between two adjacent judgements (when compromise is required)	2,4,6,8	1/2, 1/4, 1/6, 1/8

** The inverse of the importance*

$$\boldsymbol{R} = \left[\frac{1}{CF_{i,j}}\right]_{nxn} \tag{7.3}$$

An example of a pairwise comparison matrix is shown in Figure 7.2a. For instance, if factor 1.1 is notably more important than factor 1.20, the cell (1.1, 1.20) holds a value of 7, with its reciprocal (1/7) representing the reverse comparison (1.20, 1.1). Self-comparisons yield an input value of 1, signifying equal importance due to the inherent equality of a factor's ratio to itself. Additionally, note that the AHP method, regardless of the number of factors involved, simplifies comparisons to pairs of elements, reflecting its inherent simplicity and practicality (Davoudi & Sheikhvand, 2012). Pairwise comparison matrices are generated for factor sets within each hierarchy for each failure category and dam construction method.

Step 3: Normalisation

Prior to calculating the weightings, the pairwise comparison matrix requires normalisation. This is achieved through the approximate eigenvector method, where each matrix element is divided by the sum of its respective column, as indicated in Equation 7.4. An example is outlined in Figure 7.2b.

$$\boldsymbol{X} = \frac{CF_{ij}}{\sum_{i=1}^{n} CF_{ij}} = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ X_{n1} & X_{n2} & \cdots & X_{nn} \end{bmatrix} \tag{7.4}$$

Step 4: Weight Calculation

The final weights are derived from the normalised matrix by calculating the average value of each row, mathematically expressed by Equation 7.5. A characteristic of a single pairwise comparison matrix is that the sum of its weights equals 1. Figure 7.2c shows the weights of the above-introduced example.

$$\boldsymbol{w} = \frac{\sum_{j=1}^{n} X_{ij}}{n} = \begin{bmatrix} w_1 \\ w_1 \\ \vdots \\ w_n \end{bmatrix} \tag{7.5}$$

	1.1	1.2	1.15	1.20
1.1	1	4	3	7
1.2	1/4	1	1/2	1/3
1.15	1/3	2	1	5
1.20	1/7	1/3	1/5	1
Sum	*1.73*	*7.33*	*4.70*	*16.00*

(a) *Pairwise Comparison*

	1.1	1.2	1.15	1.20
1.1	0.58	0.55	0.64	0.44
1.2	0.14	0.14	0.11	0.19
1.15	0.19	0.27	0.21	0.31
1.20	0.08	0.05	0.04	0.06

(1/3)/7.33 = 0.05

(b) *Matrix Normalisation*

1.1	0.55
1.2	0.14
1.15	0.25
1.20	0.06

(0.58 + 0.55 + 0.64 + 0.44)/4 = 0.55

(c) *[*Weight Determination]Weight Determination

Figure 7.2: Example Analytical Hierarchy Processing (AHP) Method

Yet, in a multi-level hierarchical structure where matrices at various levels are assigned weights, the weighted sum of 1 is not directly maintained. As previously indicated, pairwise comparisons are made at each hierarchical level, for each dam construction method and failure category (2,068 matrixes). To ensure a total weight sum of 1 in the analysis, the weights of the lowest hierarchical level are multiplied by preceding hierarchical level weights, ensuring a cumulative weight of 1. This approach facilitates a comprehensive evaluation of the relative importance of all 259 diverse factors in the decision-making process. Besides, this is essential to prevent an extreme increase or decrease in the PoF.

Step 5: Consistency Check

The judgements of a person making decisions may be subjective, but inconsistency is also inherently part of this method. Imagine the situation where you provide the judgements $A = 2B$ and $A = 3C$. The perfectly consistent value for the comparison of B versus C would be $B = 1.5C$. However, since 1.5 is not a feasible value on the scale (Table 7.1), this leads to inconsistency in the judgements provided. Furthermore, judgement will also introduce inconsistency. Therefore it is crucial to verify the consistency of the matrixes. While some degree of inconsistency is permissible in an AHP analysis, the weights may become invalid when the consistency of the matrix is excessively low.

To assess the inconsistency, a comparison is made between the Consistency Index (CI) of the matrix in question and the consistency index of a randomly generated matrix (Random Index (RI)); the Consistency Ratio (CR), as defined in Equation 7.6. A widely acknowledged threshold for acceptability is when the CR, is less than 10% (Liu et al., 2017). If the CR exceeds 10%, the pairwise comparison matrix needs to be revised.

$$CR = \frac{CI}{RI} \tag{7.6}$$

Saaty & Vargas (2012) presents different RI values for matrices with varying numbers of factors n, derived from the average CI value of 500 randomly generated matrices, shown in Table 7.2.

Table 7.2: Random Index (RI) for Different Number of Elements

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	>15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56	1.57	1.58	1.61

To calculate the CI, first, perform a matrix multiplication of the pairwise comparison matrix with the weights (Equation 7.7). Next, divide the elements of the resulting vector by their corresponding weights (Equation 7.8.

$$\boldsymbol{y} = CF_{ij} \cdot w_i = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \tag{7.7}$$

$$\boldsymbol{c} = y_i \cdot \frac{1}{w_i} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix} \tag{7.8}$$

Subsequently, calculate the principle eigenvalue λ_{max}, in other words, the maximum eigenvalue. The CI can then be computed using Equation 7.9, where n represents the number of compared elements. An example of the consistency calculation is shown in Figure 7.3.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{7.9}$$

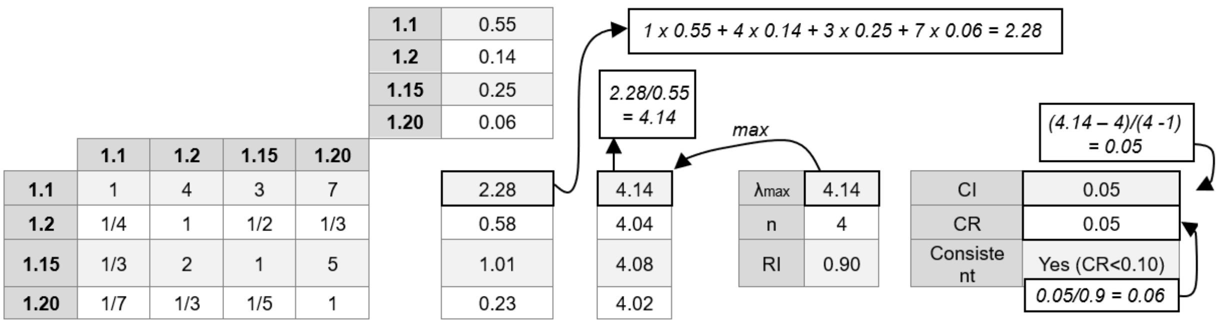


Figure 7.3: Example Calculation Consistency Check Analytical Hierarchy Processing (AHP) Method

Weights Contributing Factors

The distribution of relative weights for contributing factors concerning different failure modes and dam construction methods is detailed in Appendix B. For a summary overview of these weights, please refer to Figure 7.4 and Table 7.3. In general, the weights are distributed relatively equally across the categories of site conditions, design elements, and LoP, showing overall failure categories of equal importance. On average, site conditions tend to have higher individual weights compared to design elements, and design elements have higher individual weights compared to LoP. This distribution is influenced by the number of criteria within each category, with site conditions having the fewest criteria and LoP having the most. For similar reasons, the factors with the highest contributions are primarily found within the site conditions. In addition, the site conditions have a critical role in some of the failure categories, e.g. having a seismic area strongly influences the probability of an EQ failure to occur. On average, each contributing factor is weighted at 0.39 (100% divided by the total of 255 factors).

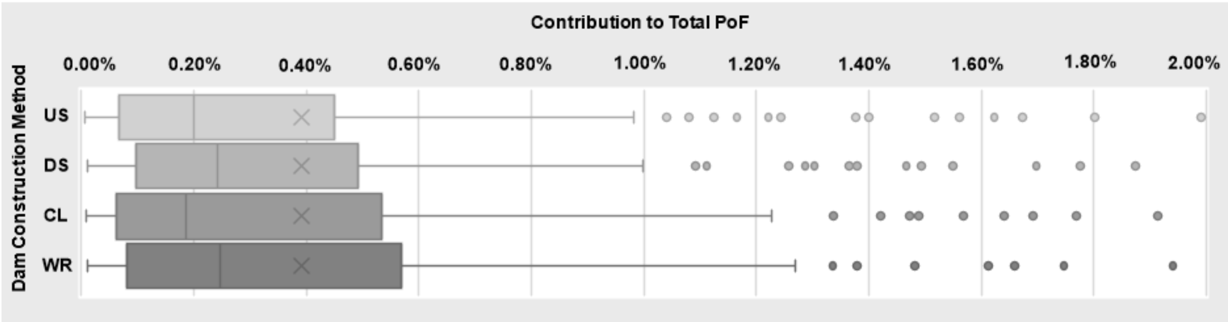


Figure 7.4: Box and Whisker Plot of Weights by Dam Construction Method, Showing Individual Contributions of Factors to the Total Probability of Failure (PoF) *(US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention)*

Table 7.3: Overview of Distribution of Weights over Site Conditions, Design Elements and Level of Practise (LoP) by Dam Construction Method

Category	US	DS	CL	WR
Site Conditions Total Min | Average | Max	33.84% *0.03% | 0.91% | 7.62%*	32.93% *0.14% | 0.89% | 5.93%*	33.47% *0.11% | 0.90% | 3.26%*	28.65% *0.10% | 0.77% | 2.52%*
Design Elements Total Min | Average | Max	33.19% *0.01% | 0.49% | 1.80%*	31.34% *0.04% | 0.46% | 1.87%*	38.10% *0.03% | 0.56% | 2.32%*	34.98% *0.02% | 0.51% | 1.94%*
Level of Practise (LoP) Total Min | Average | Max	32.96% *0.01% | 0.22% | 1.22%*	35.73% *0.01% | 0.24% | 1.47%*	28.44% *0.01% | 0.19% | 1.47%*	36.38% *0.01% | 0.24% | 1.75%*
All Factors Total Min | Average | Max	100% *0.01% | 0.39% | 7.62%*	100% *0.01% | 0.39% | 5.93%*	100% *0.01% | 0.39% | 3.26%*	100% *0.01% | 0.39% | 2.52%*

7.2.2. Fulfilment Assessment with Modifiers

For each contributing factor, an evaluation is required regarding the extent to which it is met at the investigated site. The fulfilment or non-fulfilment of a factor can either positively affect the PoF (resulting in a decrease) or negatively influence it (resulting in an increase). Alternatively, conditions may be deemed 'average' and typical for a generic tailings dam, classifying the influence as neutral. Another option is that the condition is unknown.

Users are presented with a drop-down list containing various input choices. While clear guidelines ideally exist for assessing factor fulfilment, this process is intricate and often dependent on numerous variables. Therefore, it's essential to recognise that expertise and judgement may be necessary to make the correct input selections. Each input option is associated with a favourable, neutral, adverse, or unknown outcome. These outcomes are linked to modifiers, which will subsequently adjust the PoF, as explained in the following section.

However, it is important to note that not all contributing factors offer favourable, neutral, adverse, or unknown options. For example, artesian pressures are typically absent in an average tailings dam, resulting in a neutral weighting when absent and an adverse weighting when present. In certain cases, the 'unknown' option may not be applicable, either because accurate input can be readily determined or because the factor holds significant importance. For instance, seismic activity can be easily obtained from a provided seismic hazard map. At the same time, this factor receives one of the highest weights when assessing the dam's potential for earthquake-induced failures.

Fulfilment Modifiers

Each condition (favourable, neutral, adverse, or unknown) is associated with a corresponding modifier that will proportionally adjust the PoF. These modifiers are determined through a process of rational analysis and trial and error. The selected modifiers are as follows:

- Neutral: 1
- Favourable: 0.2
- Adverse: 5
- Unknown: 2

The modifiers allow for an increase or decrease of the PoF by a factor of 5, as shown in Figure 7.5. Initially, less extreme modifiers were considered for favourable and adverse conditions, but the validation exercises in Chapter 9 indicated that these modifiers resulted in more reasonable adjustments.

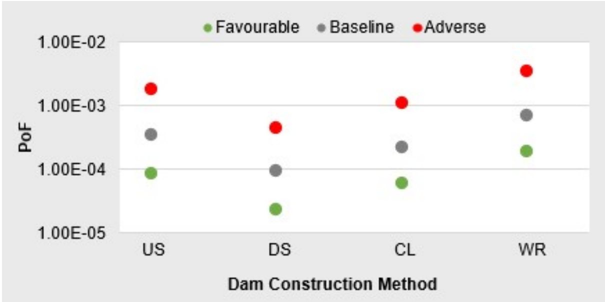


Figure 7.5: Probability of Failure (PoF) Under Favourable and Adverse Conditions Compared to the Baseline PoF for Each Dam Construction Method *(US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention)*

A neutral condition does not influence the baseline PoF and is thus assigned a modifier of 1. Given that the total sum of weights for the contributing factors adds up to 1, the baseline PoF can be increased or decreased by up to half an order of magnitude using these favourable and adverse modifiers.

An unknown condition is assigned a modifier of 2. It is important to note the distinction between 'unknown' and 'unknown-unknown' conditions. When a condition is labelled as 'unknown,' it signifies that someone is unfamiliar with the site and lacks comprehensive knowledge. In such cases, the expected value is considered average and therefore could be assigned a modifier of 1, equalling the baseline PoF. However, the fact that the condition is unknown introduces a higher level of risk compared to actually knowing that a condition is average. Additionally, there is the possibility of a condition being 'unknown-unknown', where despite having in-depth knowledge and understanding of the dam and having performed a throughout investigation, the condition remains unknown or uncertain. This may pose an even higher risk than adverse conditions because not knowing that an adverse condition exists can be riskier than being aware of it. Assuming that the distribution of inputs for 'unknown' and 'unknown-unknown' is roughly equal, a modifier of 2 is considered appropriate.

If no input is selected, the fulfilment factors are automatically populated with a modifier of 1, indicating an expected average condition. This allows for obtaining results even when not all fulfilment data is provided, although it is important to be aware of the limitations.

7.3. Comments

In this section, several important considerations come to light. It is crucial to be aware of potential ambiguities and errors associated with the prevalence examination, which will be briefly discussed in this section.

Quality of Factor Descriptions

While the ideal approach would involve statistical analysis of failure databases, such data is often unavailable and subject to biases and limitations (as elaborated in Section 5.4). Consequently, the descriptions of contributing factors and their conditions concerning favourability or adversity relative to expected averages can offer a practical alternative.

It is recognised that there is room for refining the definitions and descriptions of contributing factors. Some factors may still be inadequately defined, and there might be instances where certain effects are overlooked. It is important to stress that the current tool is not a final solution but serves as a starting point, intended to stimulate discussions among experts and encourage improvements or alternative solutions.

Enhancing the specificity of input descriptions could reduce ambiguity and user interpretation challenges, despite the inherent difficulties in achieving precision (e.g., establishing clear criteria for identifying when soil is considered gap-graded). It is acknowledged that interpreting and selecting the correct input can be a challenging task.

Time Effects

As discussed in Chapter 2 tailings dams are continuously evolving structures, in a dynamic environment with constantly changing conditions. One limitation of the tool is its inability to accommodate these changing conditions. To assess the change in PoF over time, one would need to perform a comprehensive analysis at two distinct points in time, particularly considering the influence of the LoP over time. In reality, a poorly designed and/or poorly maintained initial raise can significantly impact the overall stability of the dam. Regrettably, this tool does not account for such factors, constituting a notable limitation that requires consideration.

Weighting method

Although the AHP is one of the most commonly used methods for MCDM, it is often criticised. Dyer (1990) calls it even: 'Fundamentally Unsound and Flawed'. The main drawbacks mentioned in the literature are the high computational requirements and the subjective nature (Oguztimur, 2011; Jiménez et al., 2016). For an in-depth exploration of the shortcomings of AHP, readers are directed to Munier & Hontoria (2021), who identify 30 specific limitations. However, Harker & Vargas (1990) indicate that much of the criticism is based on the misunderstanding of the theoretical foundations of the AHP. While the weighting method relies on subjective judgement, the ability to assess consistency provides at least a form of validation.

Ideally, weightings would be derived from empirical analysis, but the lack of readily available data poses challenges in this regard. An alternative approach to enhance weighting accuracy would involve obtaining input from multiple experts or decision-makers. However, it is recognised that this could be a labour-intensive task, with experts potentially facing the challenge of completing over 2,000 pairwise comparison matrices or evaluating more than 200 criteria.

Another option would be to advance the assessment process by exploring extensions of the AHP method. For example, Fuzzy AHP addresses the vagueness and uncertainties arising from human subjectivity (Ocampo, 2019), and the Analytical Network Process (ANP) allows for consideration of dependencies and feedback loops between elements (Kadoić et al., 2017), but it lacks a consistency check. These methods, among others reviewed by Taherdoost, H. and Madanchian, M. (2023), may offer the potential for improvement as the tool continues to develop.

Given that the relative weightings are fundamental to the outcomes, ensuring their accuracy is paramount. Further validation and input from experts in the field are recommended, as elaborated in Chapter 12.

Fulfilment Method

An additional crucial consideration is that the impact of a contributing factor on the PoF may vary significantly compared to another when meeting or not meeting the criteria. Therefore, offering more nuanced options between the extremes could accommodate this variability.

Furthermore, it is important to recognise that dependencies, akin to those observed in the weighting factors, may exist in the fulfilment method. Given that both the weighting and fulfilment methods directly influence the outcomes, conducting further validation exercises on the modifiers is strongly recommended.

Dependencies

The AHP does not directly account for dependencies between criteria, despite their existence. Specifically, the significance of contributing factors may vary based on the selected inputs. For instance, the meticulous evaluation of a detailed water balance may be more critical in regions with high rainfall rates compared to arid climates. Additionally, certain inputs may become irrelevant when specific conditions are met. For example, considering faults in the design may not be necessary when there are no faults present in the region under investigation. To address the latter type of dependencies, several adjustments have been incorporated, and irrelevant inputs will not be required to be filled out by the user, as will be highlighted in Appendix B. However, one should be aware that more dependencies are likely to exist and it would be advised to have a deeper look into these dependencies, as recommended in Chapter 12.

Number of Inputs

The tool currently necessitates 255 inputs, which is a substantial number. There is a potential reduction of 32 inputs of site conditions and design elements when certain input criteria are selected, as dependencies between criteria are considered, see Appendix B.3. Further reduction in the number of inputs can be achieved by implementing dependencies within the LoP as well. Combining various GISTM criteria into a more comprehensive set with substantial individual impact is another option. An example of such a set is provided in Appendix B.1 in Table B.4, reducing the LoP inputs from 150 to 64. However, this approach may have the drawback that results from the GISTM cannot be directly copied and pasted as input. It may still be a faster option to copy and paste the results from a GISTM assessment, if performed. Additionally, keeping the GISTM criteria intact could incentivise dam owners to assess these criteria for their dams. On the other hand, keeping the GISTM criteria may not provide quick results, especially when having a large portfolio of dams, one of the main objectives of the tool. Another possibility is to eliminate GISTM LoP criteria that have consistently shown a very small impact on the PoF across various case studies. It has been observed that some criteria make such a minimal contribution to the PoF.

The baseline PoF should be adjusted according to the site conditions, design elements, and LoP of the dam under investigation. Various contributing factors affecting one or more failure categories are identified and weighted using the AHP method, based on their expected impact on PoF. Users provide input based on the fulfilment of the different factors. This will adjust the baseline PoF accordingly. The development of the database, the calculation of the baseline PoF, and the prevalence examination of various contributing factors form a solid foundation for the tool for a preliminary PoF assessment. The developed tool is presented in the subsequent chapter, Chapter 8*.*

IV. Product

Objective 4: Demonstrating Validity and Addressing Challenges and Limitations

The developed tool is presented. A pseudocode of the calculation procedures is presented and a description of inputs and outputs is provided. It also explains how the tool can be downloaded. Furthermore, a practical demonstration through two case studies is offered, demonstrating the validity of the tool and addressing the remaining challenges and limitations. One failure case is analysed and a case where several mitigation measures have been implemented. The latter is evaluated before and after the mitigation measures have been implemented.

8
The Tool

This chapter outlines the pseudocode for the calculations made within the tool and addresses the essential inputs and the outcomes of the developed tool, along with usage considerations and points to note. Furthermore, it is explained how the tool could be utilised for ALARP evaluation.

8.1. Pseudocode Calculation Procedures

Upon completing all required inputs, the tool conducts background calculations to estimate the dam's PoF. A pseudocode outlining the calculation process is presented in Figure 8.1 on the following page, with colour-coded indicators depicting in which sheet the calculations occur.

8.2. Description of Inputs

In utilising the tool, users are prompted to provide input. First of all, the required inputs are explained. Afterwards, the different elements within the input sheet are explained.

8.2.1. Input Requirements

The tool necessitates certain general information about the dam in question to offer a brief overview. While this information is not mandatory for performing the calculations, it can prove valuable for anyone reviewing the investigation. However, there is one vital piece of information that is indispensable: the primary method used in constructing the dam. In cases where the dam incorporates an US component, please select 'Upstream (US)' from the provided drop-down menu. The other required inputs are rooted in the contributing factors identified from the prevalence examination detailed in Chapter 7. The input can also be selected from various drop-down lists. To ensure simplicity, the descriptions of inputs are formulated as straightforward as possible. While certain criteria leave no room for ambiguity, like the climate at the site, others may require user interpretation. For instance, users may be asked to assess how well the tailings dam under consideration aligns with its objective. Therefore, it is crucial that competent and independent individuals with expertise in both geo-engineering and the tailings industry employ the tool to yield an unbiased outcome. For certain inputs, relevant information is provided by maps or descriptions, aiding users in making appropriate selections from the drop-down lists. When uncertainty or a lack of information persists, users have the option to choose 'uncertain' or 'unknown' as their input.

The tool requires 255 inputs from the user, comprising 37 inputs related to site conditions, 68 inputs concerning design elements, and 150 inputs focusing on the LoP. Although this number initially seems sub-

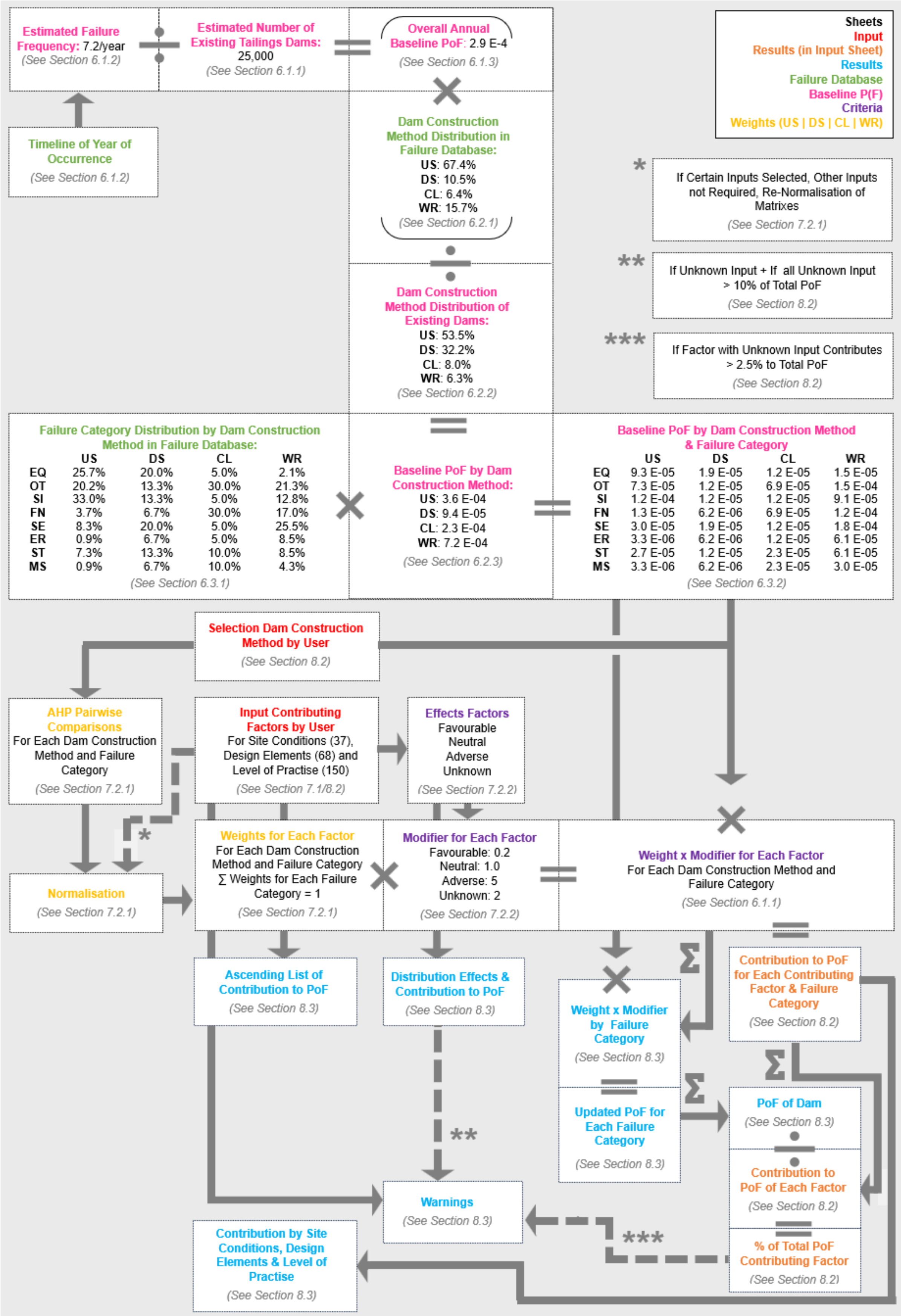


Figure 8.1: Pseudocode of Calculation Procedures within the Tool *(PoF: Probability of Failure, US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention, AHP: Analytical Hierarchy Processing)*

stantial, efforts have been made to ensure that the options are straightforward, facilitating rapid progress. Moreover, it is anticipated that many owners would have already addressed the inputs pertaining to the LoP, as they largely align with the requirements outlined in the GISTM (GISTM, 2020). Considering the straightforward nature of the inputs and the level of familiarity with the LoP requirements, completing the input for the tool within a single day by a single person should be achievable. However, keep in mind that discussions among multiple individuals are likely to yield more valuable insights.

The inputs provided by the user are linked with the modifiers and weights, consequently influencing the PoF across various failure categories for the selected dam construction method. It is advised to have a designated maximum limit for unknown inputs (10% of the total PoF). Should the unknowns surpass this threshold, the tool's reliability may be compromised, necessitating a more in-depth investigation to obtain relevant inputs for the tool. If any single unknown input accounts for over 2.5% of the total PoF, it necessitates additional evaluation; when there is uncertainty regarding a high-risk factor, it introduces an additional risk by unknowing a potential hazard. At a 2.5% threshold, an individual factor begins to exert a notable influence on the estimated probability of failure. A slightly higher or lower threshold could be applied; the selection of 2.5% serves to illustrate the tool's principles and capabilities.

If no input is selected by the user, the inputs will be auto-populated and a modifier of 1 is assigned to that factor. This allows interim evaluation of the results; however, it is imperative to ensure that all relevant information is provided to maintain the trustworthiness and accuracy of the tool's output. It is advised to perform the analysis for every dam section. Site-wide factors are indicated and can be copied for every dam section in the TSF to enhance a quick evaluation of multiple dam sections.

8.2.2. Input Elements

The main components of the input file comprise the sections for general dam information and contributing factors, both of which are explained with accompanying screenshots. Additionally, the tool's safeguarding is underscored. The inputs are randomly generated, to illustrate the concepts.

General Dam Information

The tool features a user input sheet where input is required for the blue-shaded cells. It includes space for general dam information (Figure 8.2), offering a quick overview of the dam under investigation. This general dam information also contains a field where the responsible persons can be indicated. Furthermore, the dominant dam construction method must be chosen from the drop-down menu.

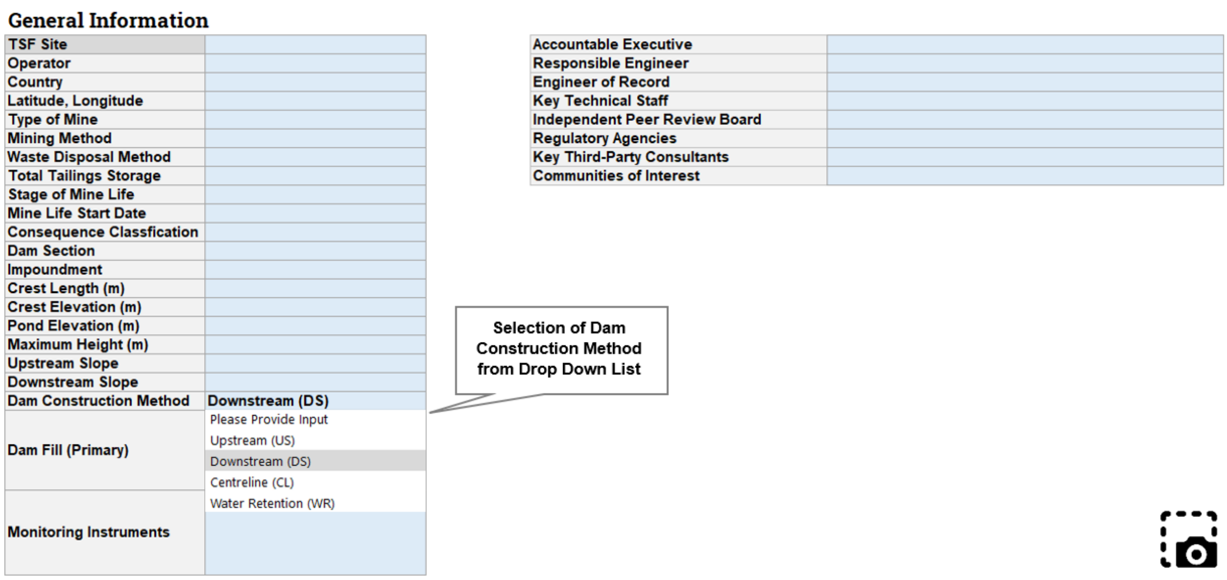


Figure 8.2: Input for General Dam Information

Contributing Factors

The input assessing the contributing factors can be selected from a drop-down list, as shown in Figure 8.3. Appendix B provides an overview of all all input options. There is also room for an explanation of the chosen input, which can be essential for further investigation or as information for other analysers. Note/detailed explanation of different cells and columns is available within the tool. You can access relevant information by selecting the cell of interest. Information will show up when available, as shown in Figure 8.3 as well.

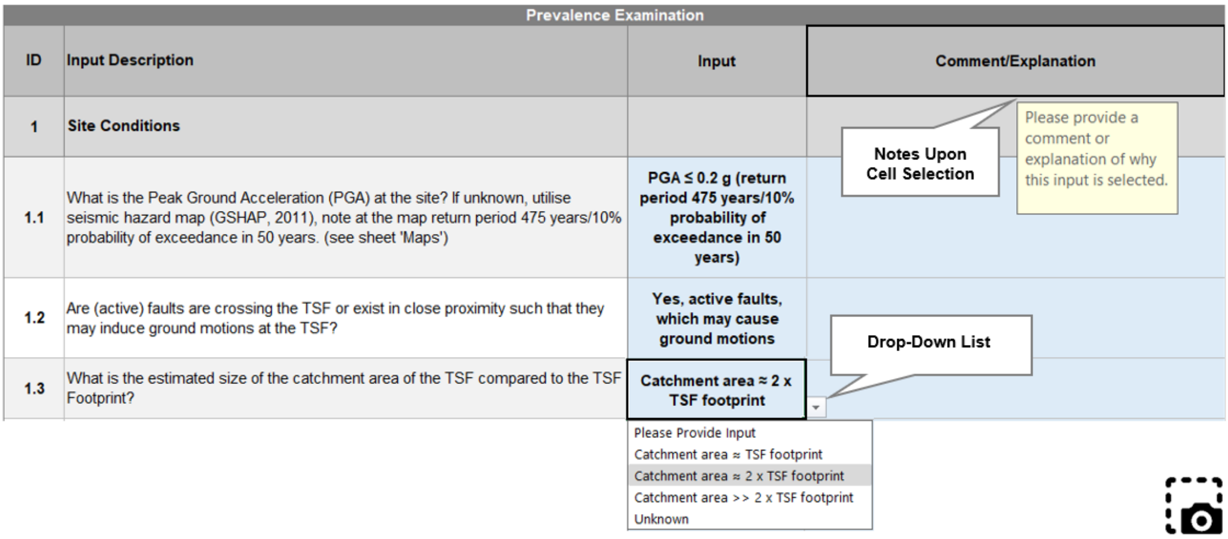


Figure 8.3: Input for Prevalence Examination: Contributing Factors

Within the input sheet, the effect of the selected input is displayed, as well as the resulting contribution to PoF, which is also broken down per failure category (Figure 8.4). This allows for a quick evaluation of the input provided. If 'Unknown' input surpasses 2.5% of the total PoF, an exclamation mark warns for uncertainty and suggests further investigation to determine the correct input for this criterion, shown in Figure 8.4 too.

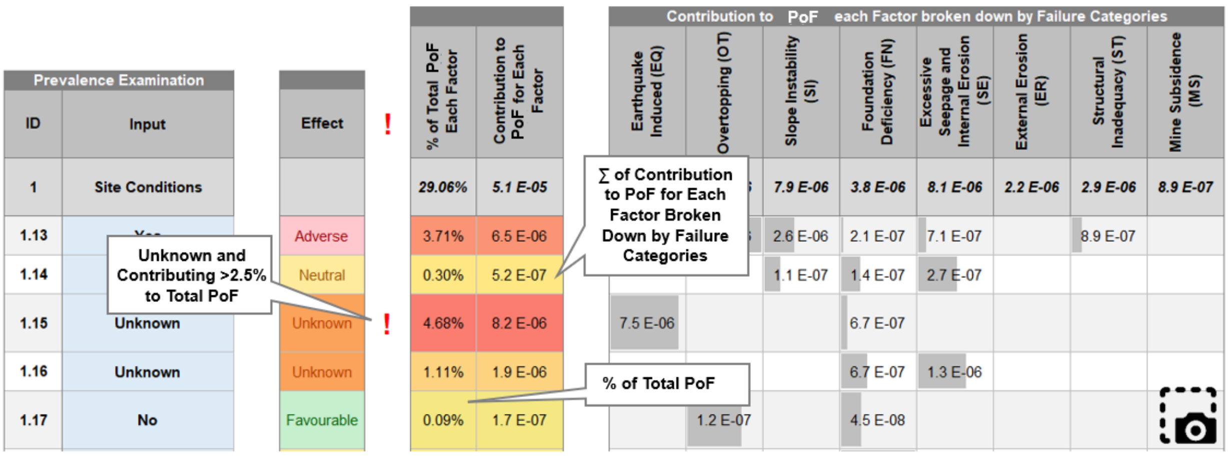
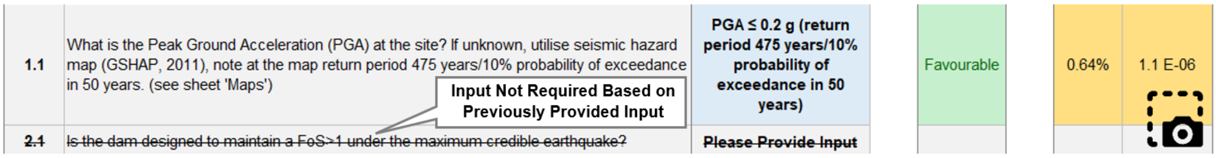
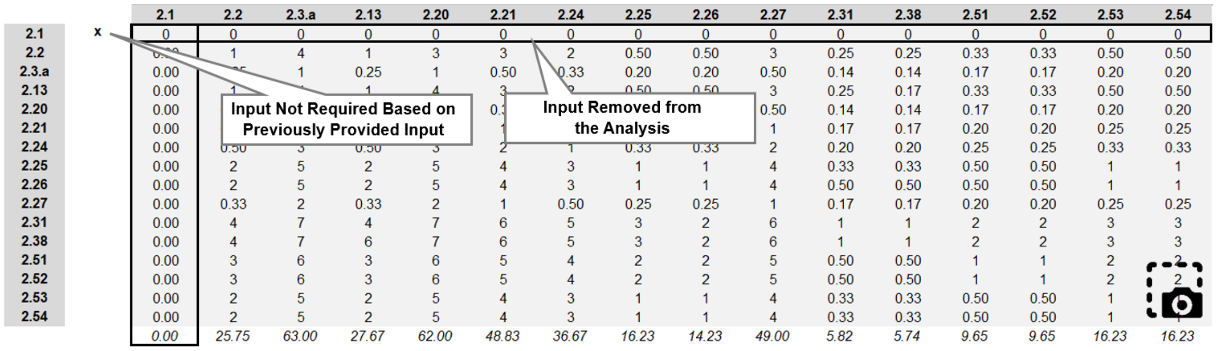


Figure 8.4: Quick Overview of Impact of Selected Input – *Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange), Highest Contribution (Red) - Lowest Contribution (Green)*

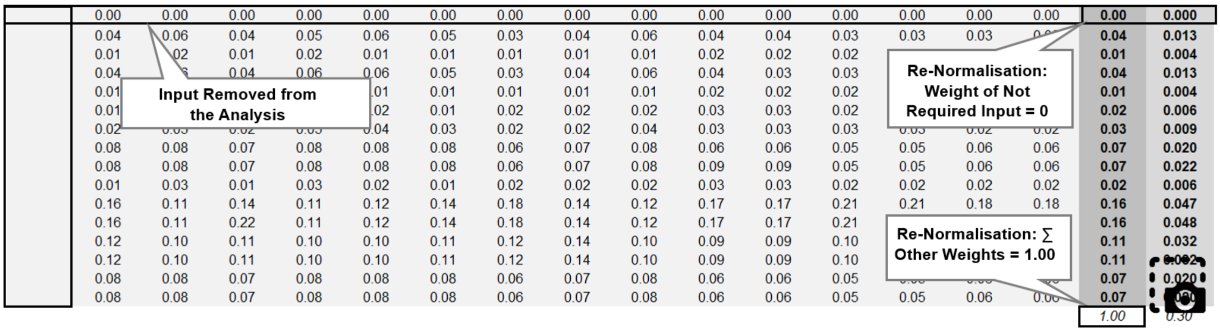
32 inputs may become unnecessary after selecting a specific input. The unneeded cells will be crossed out and excluded from the analysis. The weightings will be automatically adjusted, and matrices will be re-normalised, see Figure 8.5.



(a) Non-Required Input Based on Previously Selected Input



(b) Removal of the Non-Required from the Analysis



(c) Re-Normalisation of Matrix After Removal of Non-Required Input

Figure 8.5: Illustration of Non-Required Inputs

Safeguarding

To safeguard the tool's calculation system, only the blue-shaded cells are editable. Altering other cells triggers a warning, as depicted in Figure 8.6. The protection cannot be removed; however, there is also a non-protected version of the tool available.

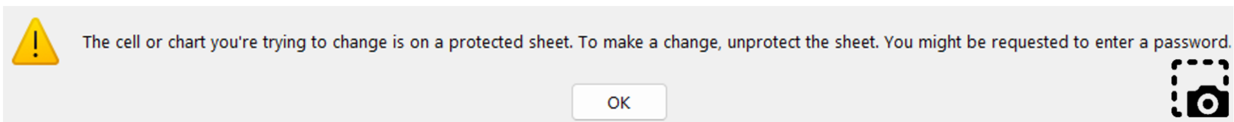


Figure 8.6: Protection of the Tool to Prevent Undesirable Alteration to the Underlying Calculation System

8.3. Description of Outputs

This section highlights the outputs and the insights that may be obtained from the results of the analysis. Furthermore, the different elements of the outputs are described.

8.3.1. Output Insights

The analysis offers valuable insights into various aspects of dam safety. It provides information about the overall PoF, categorises the contributions of failure categories, and assesses the relative impact of site conditions, design elements, and LoP. These insights pinpoint high-risk areas and areas requiring potential improvement. It also provides a distribution of input parameter effects, identifying areas of high uncertainty that require special attention.

While aiming for an overall PoF within the thresholds defined in Figure 3.3 (refer to Section 3.2.1) is advisable, the inherent inaccuracies in probability estimation, as discussed in Chapter 10, suggest that adopting the ALARP thinking approach is essential. Users can adjust input parameters to assess relative PoF reductions, identify improvement opportunities, and evaluate the mitigation measures' cost-effectiveness for different scenarios (e.g. by using a disproportionality factor (Section 3.2.3)).

The ALARP thinking process is currently a manual task performed by the user, but the tool offers a solid foundation for rational decision-making. It is essential to acknowledge the potential presence of uncertainties and discrepancies within the tool. Moreover, the tool does not account for the consequences of various factors, which are integral to the overall risk assessment. Future tool development should address these inaccuracies and explore automating this process, as discussed in Chapter 12. Note that extensive validation of the tool is essential, as elaborated in Chapter 9.

Nevertheless, these insights benefit both individual dam owners and those with a large portfolio of dams. Individual owners can identify key risk factors and focus on reducing PoF, thereby enhancing dam safety. For owners with multiple dams, the tool also helps prioritise resource allocation between different dams, ensuring a rational and efficient use of resources.

8.3.2. Output Elements

The different elements within the output sheet of the tool are shown in this section. Screenshots of the output results support explanations. The output contains warnings, the PoF by failure category, the PoF by effect and a list of contributing factors.

Warnings

The results tab contains a summary of the results, starting with eventual warnings. The potential warnings that could occur are shown in Figure 8.7. The warnings consider the number of inputs that are not provided by the tool and the proportion of unknown inputs, both of which can impact the reliability of the results. Kindly give due consideration to the warnings.

! Warnings !

Please fill out the remaining 2 Inputs

Be aware there are 27 factor(s) for which the input is defined as 'Unknown', which contributes to 15.15 % of the total PoF

As the 'Unknown' factors collectively contribute to more than 10% of the total PoF, it is highly advisable to prioritise and conduct thorough investigations into these factors

There are 1 factor(s) with 'Unkown' input that individually influence the total PoF for more than 2.5%

It is strongly recommended to conduct further investigations on these factors to obtain a known input value that can be confidently selected for analysis

Figure 8.7: Warnings Based on Provided Input

Probability of Failure (PoF) by Failure Category

Following the warnings, the tab displays the PoF by failure category, both the baseline PoF and the modified PoF after applying the modifier. The relative change and the share of the total PoF are highlighted (Figure 8.8). A figure shows both baseline and updated PoF for a quick overview (Figure 8.9).

Failure Category	Baseline PoF	Modifier	Updated PoF	Change	% of Total Updated PoF
Earthquake Induced (EQ)	9.3 E-05	1.91	1.8 E-04	8.5 E-05	25.27%
Overtopping (OT)	7.3 E-05	2.14	1.6 E-04	8.4 E-05	22.21%
Slope Instability (SI)	1.2 E-04	1.88	2.3 E-04	1.1 E-04	31.87%
Foundation Deficiency (FN)	1.3 E-05	2.01	2.7 E-05	1.4 E-05	3.80%
Excessive Seepage and Internal Erosion (SE)	3.0 E-05	1.92	5.7 E-05	2.7 E-05	8.13%
External Erosion (ER)	3.3 E-06	1.93	6.4 E-06	3.1 E-06	0.91%
Structural Inadequacy (ST)	2.7 E-05	2.01	5.4 E-05	2.7 E-05	7.59%
Mine Subsidence (MS)	3.3 E-06	0.45	1.5 E-06	-1.8 E-06	0.21%
Total	*3.6 E-04*		*7.1 E-04*	*3.4 E-04*	

Figure 8.8: Probability of Failure (PoF) by Failure Category – *Colour Scale: Highest Modifier (Red) - Lowest Modifier (Green), Increase in PoF (Red), Decrease in PoF (Green), Highest Contribution (Grey) - Lowest Contribution (White)*

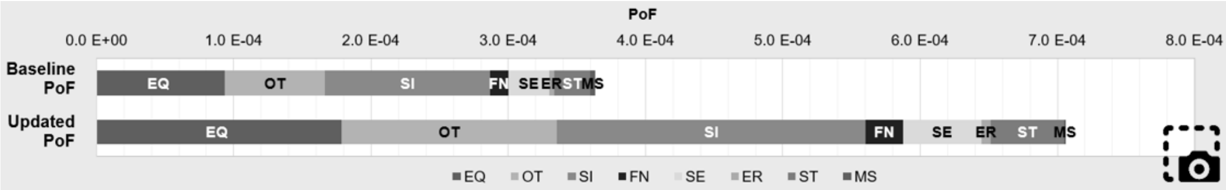


Figure 8.9: Overview Probability of Failure (PoF) by Failure Category

Probability of Failure (PoF) by Site Conditions, Design Elements and Level of Practise

Additionally, the contribution to PoF is provided for site conditions, design elements, and the LoP (Figure 8.10, highlighting the primary risk factors. The tool also includes the visualisation of results through pie charts, which are not displayed here.

	Site Conditions			Design Elements			Level of Practise			*Total*	
Failure Category	Contribution to PoF	% of Total PoF within Failure Category	% of Total PoF within Site Conditions	Contribution to PoF	% of Total PoF within Failure Category	% of Total PoF within Design Elements	Contribution to PoF	% of Total PoF within Failure Category	% of Total PoF within Level of Practise	Contribution to PoF	% of Total PoF of all Failure Categories
EQ	8.0 E-05	44.63%	33.55%	7.0 E-05	39.02%	29.33%	2.9 E-05	16.36%	12.61%	*1.8 E-04*	*25.27%*
OT	5.3 E-05	33.57%	22.19%	5.8 E-05	37.23%	24.61%	4.6 E-05	29.19%	19.78%	*1.6 E-04*	*22.21%*
SI	7.6 E-05	33.79%	32.05%	6.2 E-05	27.67%	26.24%	8.7 E-05	38.54%	37.46%	*2.3 E-04*	*31.87%*
FN	8.2 E-06	30.53%	3.45%	1.6 E-05	58.11%	6.57%	3.0 E-06	11.36%	1.32%	*2.7 E-05*	*3.80%*
SE	1.3 E-05	22.53%	5.45%	1.6 E-05	27.05%	6.55%	2.9 E-05	50.42%	12.51%	*5.7 E-05*	*8.13%*
ER	1.2 E-06	18.40%	0.50%	2.9 E-06	45.58%	1.23%	2.3 E-06	36.02%	1.00%	*6.4 E-06*	*0.91%*
ST	6.2 E-06	11.54%	2.61%	1.3 E-05	24.01%	5.42%	3.5 E-05	64.45%	14.93%	*5.4 E-05*	*7.59%*
MS	4.8 E-07	31.47%	0.20%	9.5 E-08	6.29%	0.04%	9.4 E-07	62.24%	0.41%	*1.5 E-06*	*0.21%*
Total	*2.4 E-04* *33.61%*			*2.4 E-04* *33.61%*			*2.3 E-04* *32.78%*			*7.063 E-04* *100.00%*	

Figure 8.10: Probability of Failure (PoF) by Site Conditions, Design Elements and Level of Practise (LoP) – *Colour Scale: Highest Contribution (Red) - Lowest Contribution (Green)*

Probability of Failure (PoF) by Effect (Favourable, Neutral, Adverse, Unknown)

Moreover, the effects of the inputs are summarised, indicating the number of favourable, neutral, adverse, and unknown factors, see Figure 8.11. It also highlights factors requiring input. The contribution of the different effects to PoF is in the tool also presented in pie charts, offering insights into sub-optimal conditions. These are not displayed here.

Effect	Number of Contributing Factors	% of Total Contributing Factors	Contribution PoF	% of Contribution to Total PoF	Contribution to PoF Earthquake Induced (EQ)	Contribution to PoF Overtopping (OT)	Contribution to PoF Slope Instability (SI)	Contribution to PoF Foundation Deficiency (FN)	Contribution to PoF Excessive Seepage and Internal Erosion (SE)	Contribution to PoF External Erosion (ER)	Contribution to PoF Structural Inadequacy (ST)	Contribution to PoF Mine Subsidence (MS)	Contribution to Total PoF
Favourable	83	35.78%	3.5 E-05	4.99%	9.5 E-06	6.0 E-06	1.4 E-05	8.9 E-07	2.3 E-06	2.8 E-07	1.9 E-06	6.1 E-07	3.5 E-05
Neutral	65	28.02%	7.7 E-05	10.93%	6.6 E-06	1.7 E-05	3.4 E-05	3.0 E-06	8.4 E-06	7.7 E-07	8.0 E-06	1.3 E-07	7.7 E-05
Adverse	55	23.71%	4.9 E-04	68.73%	1.1 E-04	1.3 E-04	1.5 E-04	1.8 E-05	3.7 E-05	4.3 E-06	3.7 E-05	5.9 E-07	[illegible]
Unknown	27	11.64%	1.1 E-04	15.15%	5.3 E-05	8.1 E-06	2.5 E-05	3.8 E-06	9.7 E-06	1.0 E-06	6.8 E-06	1.9 E-07	1.1 E-04
Input Required	2	0.86%	1.4 E-06	0.20%	0.0 E+00	0.0 E+00	0.0 E+00	1.4 E-06	0.0 E+00	0.0 E+00	0.0 E+00	0.0 E+00	1.4 [illegible]
Total	*232*	*100.00%*	*7.1 E-04*	*100.00%*	*1.8 E-04*	*1.6 E-04*	*2.3 E-04*	*2.7 E-05*	*5.7 E-05*	*6.4 E-06*	*5.4 E-05*	*1.5 E-06*	*7.1 E-04*

Figure 8.11: Probability of Failure (PoF) by Effect (Favourable, Neutral, Adverse, Unknown, Input Required) – *Colour Scale: Highest Contribution (Red) - Lowest Contribution (Green)*

List of Contributing Factors

Finally, the contributing factors are listed and sortable in ascending or descending order for quick assessment of critical factors in the analysis, shown in Figure 8.12 on the next page.

ID	Selected Input	Effect	!	% Total PoF	Contribution	EQ	OT	SI	FN	SE	ER	ST	MS	*Total*
2.53	No/Limited measures in place	Adverse		5.49%	9.6 E-06	1.9 E-06			1.6 E-06	1.5 E-06	9.7 E-07	3.6 E-06		9.6 E-06
2.3.a	No	Adverse		5.07%	8.9 E-06	4.0 E-07	4.6 E-06	1.4 E-07		3.5 E-07	2.4 E-06	9.3 E-07		8.9 E-06
1.4	Cs (temperate; dry summer)	Adverse		4.99%	8.7 E-06		5.6 E-06	1.0 E-06		3.6 E-07	1.4 E-06	3.3 E-07		8.7 E-06
1.15	Unknown	Unknown	!	4.68%	8.2 E-06	7.5 E-06			6.7 E-07					8.2 E-06
2.31	Moderately, 25-100 m	Adverse		4.36%	7.6 E-06	4.4 E-06		1.4 E-06	1.6 E-06	2.4 E-07				7.6 E-06
1.2	Yes, active faults, which may cause ground motions	Adverse		4.15%	7.2 E-06	7.2 E-06								7.2 E-06
1.13	Yes	Adverse		3.71%	6.5 E-06			2.6 E-06	2.1 E-07	7.1 E-07		8.9 E-07		4.4 E-06
2.25	No	Adverse		3.27%	5.7 E-06	1.9 E-0	[illegible]	[illegible]	[illegible]	1.5 E-06				5.7 E-06
2.26	Yes	Adverse		3.26%	5.7 E-06	2	[illegible]	[illegible]	[illegible]	1.5 E-06				5.7 E-06
3.1.2.b	Does Not Meet	Adverse		2.66%	4.6 E-06	1.0	[illegible]	[illegible]	[illegible]	9.9 E-07	2.8 E-07	8.6 E-07	9.4 E-08	4.6 E-06
1.23	Yes	Adverse		2.34%	4.1 E-06		[illegible]	[illegible]	[illegible]	2.1 E-06		1.3 E-06		4.1 E-06
1.11	Yes, embankments must be greater than 100 m	Adverse		2.31%	4.0 E-06		[illegible]	[illegible]	[illegible]	4.0 E-07	2.3 E-07	1.0 E-07		4.0 E-06
2.52	Unknown	Unknown		1.79%	3.1 E-06	1.8 E-0	[illegible]	[illegible]	[illegible]	5.1 E-07				3.1 E-06
3.10.2	Does Not Meet	Adverse		1.72%	3.0 E-06	2.5 E-0	[illegible]	[illegible]	[illegible]	9.2 E-07	2.0 E-07	8.1 E-07	8.8 E-08	3.0 E-06
...	...	...		...	...					...	...	...	...	...
3.3.6.a	Unknown	Unknown		0.45%	7.8 E-07	5.4 E-08	7.3 E-08	1.8 E-07	2.4 E-08	2.0 E-07	4.4 E-08	1.8 E-07	1.9 E-08	7.8 E-07
3.6.4.b	Partially Meets	Neutral		0.44%	7.7 E-07	6.6 E-08	8.9 E-08	8.7 E-08	1.2 E-08	2.4 E-07	5.3 E-08	2.1 E-07	2.3 E-08	7.7 E-07
3.7.6.b	Does Not Meet	Adverse		0.44%	7.7 E-07	6.5 E-08	8.8 E-08	9.8 E-08	1.4 E-08	2.3 E-07	5.3 E-08	2.0 E-07	2.2 E-08	7.7 E-07
3.2.1	Partially Meets	Neutral		0.44%	7.7 E-07	6.2 E-08	2.5 E-07	7.9 E-08	1.1 E-08	1.6 E-07	1.5 E-07	4.7 E-08	5.1 E-09	7.7 E-07
1.3	Catchment area ≈ 2 x TSF footprint	Neutral		0.44%	7.6 E-07		4.1 E-07	2.0 E-07			1.1 E-07	4.0 E-08		7.6 E-07
3.9.2.c	Does Not Meet	Adverse		0.40%	7.0 E-07	5.7 E-08	7.8 E-08	8.4 E-08	1.1 E-08	2.1 E-07	4.7 E-08	1.9 E-07	2.0 E-08	7.0 E-07
1.8	tential vulnerability falls within the 0-5th decile of hazar	Neutral		0.40%	7.0 E-07		2.9 E-07	1.1 E-07		5.7 E-08	1.2 E-07	1.2 E-07		7.0 E-07
3.8.1.a	Unknown	Unknown		0.39%	6.8 E-07	5.7 E-08	7.7 E-08	8.6 E-08	1.2 E-08	2.0 E-07	4.6 E-08	1.8 E-07	1.9 E-08	6.8 E-07
3.8.1.b	Unknown	Unknown		0.39%	6.8 E-07	5.7 E-08	7.7 E-08	8.6 E-08	1.2 E-08	2.0 E-07	4.6 E-08	1.8 E-07	1.9 E-08	6.8 E-07
3.4.6.a	Does Not Meet	Adverse		0.38%	6.6 E-07	5.4 E-08	7.2 E-08	7.9 E-08	1.1 E-08	2.0 E-07	4.3 E-08	1.8 E-07	1.9 E-08	6.6 E-07
3.6.3.a	Partially Meets	Neutral		0.37%	6.5 E-07	5.6 E-08	7.5 E-08	7.3 E-08	9.8 E-09	2.0 E-07	4.5 E-08	1.8 E-07	1.9 E-08	6.5 E-07
3.6.3.b	Partially Meets	Neutral		0.37%	6.5 E-07	5.6 E-08	7.5 E-08	7.3 E-08	9.8 E-09	2.0 E-07	4.5 E-08	1.8 E-07	1.9 E-08	6.5 E-07
...	...	...		...	...	...	...	...	...	...	...	...	...	...
3.9.2.d	Meets	Favourable		0.01%	1.4 E-08	1.1 E-09	1.6 E-09	1.7 E-09	2.3 E-10	4.3 E-09	9.3 E-10	3.8 E-09	4.1 E-10	1.4 E-08
3.7.4.a	Meets	Favourable		0.01%	1.1 E-08	8.9 E-10	1.2 E-09	1.4 E-09	1.9 E-10	3.2 E-09	7.2 E-10	2.8 E-09	3.0 E-10	1.1 E-08
3.8.4.a	Meets	Favourable		0.01%	1.0 E-08	8.7 E-10	1.2 E-09	1.3 E-09	1.8 E-10	3.1 E-09	7.1 E-10	2.7 E-09	2.9 E-10	1.0 E-08
3.5.5.d	Meets	Favourable		0.01%	9.7 E-09	6.9 E-10	9.4 E-10	2.1 E-09	3.0 E-10	2.6 E-09	5.7 E-10	2.3 E-09	2.5 E-10	9.7 E-09
3.7.5.a	Meets	Favourable		0.01%	9.6 E-09	8.1 E-10	1.1 E-09	1.2 E-09	1.7 E-10	2.9 E-09	6.6 E-10	2.5 E-09	2.7 E-10	9.6 E-09
3.7.5.c	Meets	Favourable		0.01%	9.6 E-09	8.1 E-10	1.1 E-09	1.2 E-09	1.7 E-10	2.9 E-09	6.6 E-10	2.5 E-09	2.7 E-10	9.6 E-09
3.7.7.b	Meets	Favourable		0.00%	7.0 E-09	5.9 E-10	8.0 E-10	9.0 E-10	1.3 E-10	2.1 E-09	4.8 E-10	1.8 E-09	2.0 E-10	[illegible]
3.7.2.c	Meets	Favourable		0.00%	4.8 E-09	4.0 E-10	5.5 E-10	6.1 E-10	8.6 E-11	1.4 E-09	3.3 E-10	1.3 E-09	1.4 E-10	[illegible]

List of Contributing Factors Sorted From Largest Contribution to Smallest Contribution

Figure 8.12: List of Contributing Factors in Descending order of Contribution to Probability of Failure (PoF) – *Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange), Highest Contribution (Red) - Lowest Contribution (Green)*

8.4. Supplementary Sections in Tool

In addition to the input and output sheets, the tool includes additional sheets, briefly described below.

- **Maps**: Contains maps that assist users in selecting inputs for contributing factors.
- **Criteria**: Central location for performing calculations, provides detailed descriptions of contributing factors and emphasises their relative significance to failure categories. The weights and contributions of each factor to the PoF are also shown, along with a list of possible input options and their potential effects.
- **Failure Database**: This tab presents the database with historical dam failures used to calculate the baseline PoF. It is crucial to keep this database updated yearly.
- **Baseline PoF**: Users can find the calculation of the overall baseline PoF, the baseline PoF by dam construction method and the baseline PoF by dam construction method and failure category.
- **Weights (US | DS | CL | WR)**: These sheets contain weightings assigned to contributing factors using the AHP method. The process is carried out separately for each dam construction method and failure category, taking into account sub-criteria and sub-sub-criteria from the prevalence examination.

8.5. Download

It is recognised that there is room for improvement in enhancing the tool's performance. Nonetheless, this product serves as a foundation for sparking further discussions within the industry. Key topics for additional discussion are emphasised in Chapter 10. The tool can be accessed through the Delft University of Technology research data repository (4TU.Research Data) and is downloadable from this link.

The developed tool offers a potential solution for evaluating PoF and demonstrating the reduction in PoF through the implementation of mitigation measures, assisting in preliminary ALARP evaluation. The validity of the tool and its functionality is demonstrated in the subsequent chapter, Chapter 9.

9

Demonstration Tool Based Analysis

In this section, the functionality of the tool, as presented in Chapter 8 is showcased. First of all, a validation exercise is carried out by analysing a failure case. Secondly, the tool's capabilities are demonstrated by the analysis of a project that has recently undergone several improvements.

9.1. Case 1: Failure Analysis

On April 25, 1998, the foundation of the tailings dam at the Aznalcóllar mine failed. The failure is attributed to several factors including design flaws, heavy rainfall, erosion and seepage, lack of maintenance and regulatory oversight. Refer to Appendix C.1.1 for background information. The dam section is analysed using the developed tool. The results are presented below, validating if this section indeed had a high PoF and whether the critical factors appear within the tool's findings. Please note that this particular case has been employed as an example, any well-documented failure scenario could have been utilised.

9.1.1. Provided Input

Table 9.1 summarises the selected inputs, highlighting some difficulty in obtaining answers to all input questions, particularly for the LoP, where 99 inputs were declared 'Unknown'. To obtain accurate inputs for the LoP inside information and specific dam documents will be needed. For both site conditions and design elements, most inputs selected are favourable, although also a significant number of adverse conditions are selected. All selected inputs are listed in Appendix C.1.2.

Table 9.1: Summary Selected Inputs Failure Case

Factors	Effect				*Total*
	Favourable	Neutral	Adverse	Unknown	
Site Conditions	16	4	8	4	*32*
Design Elements	16	7	14	16	*53*
LoP	13	21	14	99	*147*
Total	*45*	*32*	*36*	*119*	*232*

9.1.2. Summary of Results and Reflection

The anticipated PoF stands at 2.1 E-04, which is tolerable if ALARP according to the thresholds defined by FERC (2016) shown in Figure 3.3 in Section 3.2.1, knowing that the failure did not result in any fatalities. Nevertheless, the PoF is double the baseline PoF, as illustrated in Figure 9.1. Notably, it reveals a substantially increased probability of EQ failure. A more than two-fold increase in FN is also evident when examining the estimated PoF values presented in Table 9.2.

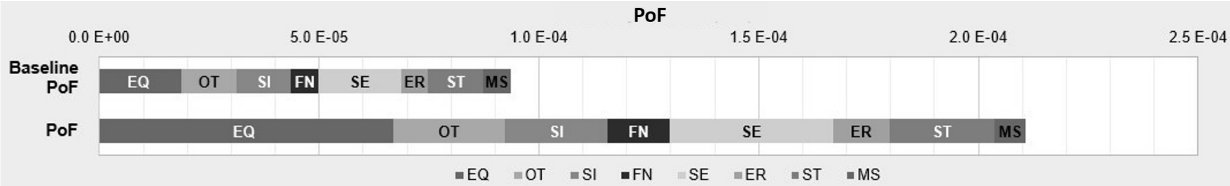


Figure 9.1: Probability of Failure (PoF) Failure Case Compared to the Baseline Probability of Failure (PoF) *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*

Table 9.2: Probability of Failure (PoF) by Failure Category Failure Case *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy) – Colour Scale: High Modifier (Red) - Low Modifier (Green), Increase in PoF (Red), Decrease in PoF (Green), High Contribution (Red/Grey) - Low Contribution (Green/White)*

X	Baseline PoF	Modifier	Updated PoF	Change	% of Total PoF
EQ	1.9 E-05	3.57	6.7 E-05	4.8 E-05	31.68%
OT	1.2 E-05	2.05	2.6 E-05	1.3 E-05	12.15%
SI	1.2 E-05	1.86	2.3 E-05	1.1 E-05	11.04%
FN	6.2 E-06	2.27	1.4 E-05	7.9 E-06	6.73%
SE	1.9 E-05	1.98	3.7 E-05	1.8 E-05	17.61%
ER	6.2 E-06	2.06	1.3 E-05	6.6 E-06	6.10%
ST	1.2 E-05	1.92	2.4 E-05	1.2 E-05	11.38%
MS	6.2 E-06	1.12	7.0 E-06	7.5 E-07	3.32%
Total	*9.4 E-05*		*2.1 E-04*	*1.2 E-04*	

Table 9.3: Probability of Failure (PoF) and Share in Site Conditions, Design Elements and Level of Practise (LoP) Failure Case *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy) – Colour Scale: High Contribution (Red/Grey) - Low Contribution (Green/White)*

X	Site Conditions		Design Elements		LoP	
	Contribution to PoF	% of Total PoF in Site Conditions	Contribution to PoF	% of Total PoF in Design Elements	Contribution to PoF	% of Total PoF in LoP
EQ	4.6 E-05	64.03%	1.5 E-05	20.93%	5.3 E-06	8.13%
OT	6.4 E-06	8.96%	1.0 E-05	13.79%	9.0 E-06	13.81%
SI	3.0 E-06	4.19%	1.1 E-05	15.34%	9.0 E-06	13.75%
FN	3.9 E-06	5.46%	9.0 E-06	12.24%	1.3 E-06	1.93%
SE	9.2 E-06	12.85%	9.5 E-06	12.95%	1.8 E-05	28.08%
ER	1.4 E-06	2.00%	5.7 E-06	7.82%	5.7 E-06	8.67%
ST	9.2 E-07	1.27%	8.0 E-06	10.86%	1.5 E-05	23.11%
MS	8.9 E-07	1.24%	4.5 E-06	6.06%	1.6 E-06	2.52%
Total	*7.2 E-05*		*7.3 E-05*		*6.5 E-05*	
	34.15%		*34.86%*		*30.99%*	

The high modifier applied to earthquake risks substantially contributes to a PoF of over 30%. Factor 1.1 exerts significant influence, accounting for 13.16% of the PoF (see Table 9.5 on Page 91). Site conditions are responsible for 60.4% of the probability of an EQ failure, while the LoP represents just 8.3%, see Table 9.3. This emphasis on EQ and site condition failures, though expected due to the moderate earthquake potential, as can be derived from the seismic and geological map in Figure 9.2, appears to be higher than usual, especially since one is dealing with an DS dam here.

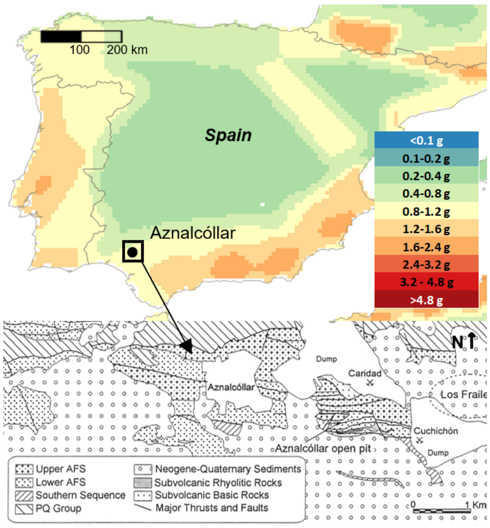


Figure 9.2: Seismic and Geological Map of Aznalcóllar *(GSHAP,2011;Almodóvar et al.,1998)*

Referring back to Table 9.2, despite the more than twofold increase (2.84) in PoF, FN contribute with 6.73% relatively modest to the PoF. It is crucial to refrain from placing excessive reliance on the percentage of the total PoF, particularly for dams constructed other than US, like the DS construction in this instance. The distribution may exhibit biases, given the scarcity of reported failures. When the PoF exceeds the baseline PoF, there is a heightened potential for failure occurrence. It is advised to evaluate the relative change of the PoF, rather than the magnitude.

Another striking observation is the modifier for MS failure, exceeding 1, despite this being a highly improbable event due to the absence of underground mines. This failure type could only occur if there are unidentified underground mining workings. Thus, some factors receive disproportionate penalties for MS.

As shown in Table 9.4 36 adverse factors collectively contribute to 67.26% of the total PoF. Addressing these factors would have offered a substantial opportunity to reduce the PoF, particularly in the realms of EQ, OT,SI, FN and SE failure categories. Furthermore, 119 factors remain unknown, collectively contributing 22.35% to the total PoF. There are no unidentified factors with individual contributions exceeding 2.5% to the total PoF. The substantial uncertainty in these unknown factors primarily results from data accessibility limitations, particularly within the LoP. These 'unknowns' arise from the 'unknown-unknown' principle (as described in Section 7.2.2), whereby the situation is unknown because of a lack of information, rather than a lack of understanding or investigation.

Therefore, it is more objective to treat these unknown factors with a modifier of 1, implying that the dam statistically performs at an average level for these factors. This adjustment changes the PoF from 2.1 E-04 to 1.8 E-04, still surpassing the baseline PoF. The distribution among the site conditions, design elements and LoP stays the same. Finally, it should be noted that three inputs are inapplicable, indicating the need for additional dependencies, underscoring the existence of areas that require further improvement.

Table 9.4: Probability of Failure (PoF) and Share in Effects (Favourable, Neutral, Adverse, Unknown) Failure Case *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy) – Colour Scale: High Contribution (Grey) - Low Contribution (White)*

		Favourable	Neutral	Adverse	Unknown
	Number of Contributing Factors	45	32	36	119
	% of Total Contributing Factors	19.15%	13.62%	15.32%	50.64%
	Contribution to PoF	4.8 E-06	1.6 E-05	1.4 E-04	4.7 E-05
	% of Contribution to Total PoF	2.29%	7.60%	67.26%	22.35%
Failure Category	**EQ**	1.8 E-07	3.0 E-06	5.7 E-05	6.4 E-06
	OT	8.4 E-07	1.9 E-06	1.7 E-05	5.5 E-06
	SI	6.4 E-07	2.8 E-06	1.3 E-05	6.8 E-06
	FN	3.9 E-07	8.8 E-07	1.1 E-05	2.1 E-06
	SE	9.0 E-07	3.9 E-06	2.0 E-05	1.2 E-05
	ER	4.2 E-07	6.4 E-07	8.1 E-06	3.7 E-06
	ST	5.4 E-07	2.7 E-06	1.1 E-05	9.7 E-06
	MS	9.2 E-07	2.4 E-07	5.1 E-06	7.5 E-07
Effect	**Site Conditions**	2.5 E-06	2.7 E-06	6.1 E-05	5.6 E-06
	Design Elements	1.3 E-06	4.3 E-06	5.2 E-05	1.5 E-05
	LoP	1.0 E-06	9.0 E-06	2.8 E-05	2.7 E-05

The factors which are found to be the root causes of the failure could have been identified with the tool. Noteworthy examples, that show a high PoF in the tool, include the existence of brittle foundation materials (factor 1.15), excessive rainfall (factor 1.4), the monitoring of pore water pressures (factor 2.51) and deformations (factor 2.54), the low permeability of the foundation (factor 1.20.b), and the presence of discontinuities in the foundation (factor 1.24), see Table 9.5. The tool also sheds light on other factors that did not contribute to this specific failure. However, note that the absence of their contribution in this instance does not necessarily imply that they were not high-risk factors.

The tool highlights several factors that have contributed to the eventual failure. It also shows a relatively high, almost three-fold increase of the baseline PoF for FN, the eventual failure type. However, there are still discrepancies and it is challenging to definitively assert its expected performance on this single case. As such, the tool should be further calibrated using several dams with known and accepted risk profiles. It is recognised that calibration is an ongoing process, which is essential to improve the accuracy of the tool.

Table 9.5: Factors with the Highest Individual Contribution to the Probability of Failure (PoF) Failure Case – *Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange), Highest Contribution (Red) - Lowest Contribution (Green))*

ID	Input Question	GISTM	Selected Input	Effect	% of PoF	Contribution
1.1	What is the Peak Ground Acceleration (PGA) at the site? If unknown, utilise seismic hazard map (GSHAP, 2011), note at the map return period 475 years/10% probability of exceedance in 50 years. (see sheet 'Maps')	-	riod 475 years/10% probability of e	Adverse	13.16%	2.8 E-05
1.15	Is the foundation underlying the TSF characterised by strain-softening or contractive material?	-	Yes	Adverse	6.46%	1.4 E-05
2.51	Are measures in place for monitoring pore water pressures within the foundation and do the results confirm the design assumptions and are within the design standards.	-	No/Limited measures in place	Adverse	4.75%	1.0 E-05
1.4	What is the climate at site (according to Köppen Climate Classification)? If unknown, utilise climate map (Beck, 2018). (see sheet 'Maps')	-	Cs (temperate; dry summer)	Adverse	3.94%	8.3 E-06
2.54	Are measures in place for monitoring deformations within the embankment and do the results confirm the design assumptions and are within the design standards?	-	No/Limited measures in place	Adverse	3.94%	8.3 E-06
2.21.a	Is there a tailings beach present?	-	No	Adverse	3.30%	6.9 E-06
3.1.1.a	Evaluate uncertainties associated with climate change that may impact upon the safety of the tailings facility (see also GISTM requirement 3.1).	2.1.b	Does Not Meet	Adverse	3.26%	6.9 E-06
2.31	Are the embankments of significant height?	-	Moderately, 25-100 m	Adverse	3.16%	6.7 E-06
2.27	Do the filter materials meet the requirements for filter compatibility?	-	No filter materials used	Adverse	2.03%	4.3 E-06
2.38	Are the tailings lacking adequate liquefaction resistance (e.g. low-density, loose, contractive material that is uniformly graded, with high silt content, and low permeability)?	-	Yes ('regular tailings")	Adverse	1.98%	4.2 E-06
3.2.1	To enhance resilience, climate change knowledge is regularly updated and used to evaluate risks and opportunities to the tailings facility lifecycle, in accordance with the principles of adaptive management, with the aim of enhancing resiliency to climate change.	3.1.a	Does Not Meet	Adverse	1.82%	3.8 E-06
2.4.a	Has an permanent spillway with stable walls been constructed?	-	No	Adverse	1.64%	3.5 E-06
1.16	Is there collapsible or dispersive material present within the foundation (e.g. karst or salt domes)?	-	Yes	Adverse	1.54%	3.2 E-06
1.20.b	Is the permeability of the foundation underlying the TSF relatively low, to the extent that it may significantly contribute to the generation of excessive pore pressures?	-	Yes	Adverse	1.42%	3.0 E-06
1.2	Are (active) faults are crossing the TSF or exist in close proximity such that they may induce ground motions at the TSF?	-	Unknown	Unknown	1.38%	2.9 E-06
2.23	Are the structural elements designed to accommodate tailings and embankment consolidation, deformation, and ice loads?	-	Unknown	Unknown	1.33%	2.8 E-06
3.5.6.a	Reviews of new and emerging technologies and approaches for tailings management are carried out considering the tailings facility lifecycle.	6.6.a	Does Not Meet	Adverse	1.23%	2.6 E-06
3.5.6.a	Material results of the reviews have been incorporated into refinements of the facility design, construction and operations.	6.6.b	Does Not Meet	Adverse	1.23%	2.6 E-06
1.24	Are there significant discontinuities or cracks expected to be present in the foundation?	-	Yes	Adverse	1.21%	2.5 E-06
3.6.4.d	The EOR promptly reviews the tailings facility performance monitoring analysis results and if required, directs that the risk assessment and design be updated.	7.4.d	Does Not Meet	Adverse	1.09%	2.3 E-06
2.30	Are the upstream and downstream embankment slopes steeply inclined?	-	ose to or exceeding natural angle o	Adverse	1.08%	2.3 E-06
2.26	Are instances of blockage in the drainage systems (caused by factors such as sediment, vegetation, or ice, geochemical precipitation) observed or expected?	-	Unknown	Unknown	1.02%	2.2 E-06
1.25	Is there a boundary in the foundation between two units with a significant difference in grain size, where the presence of water flow along the boundary is possible?	-	Yes	Adverse	1.00%	2.1 E-06

9.2. Case 2: Project Improvement Example

The second case of investigation is a TSF, which has recently undergone various improvements. The dam is a legacy structure with a history that spans over 80 years. Its history is complex and was not well documented during the early periods of operations. The foundation was found to consist of glaciolacustrine clay, peat, as well as loose, contractive hydraulically deposited tailings. These units govern the stability of the dam, which was found to not meet the project FoS criteria based on the conditions and geometry in 2017. Since 2017, efforts have been made to reduce the risk of the dam. The dam is an US dam and is analysed with the tool for the 2017 situation and compared to the 2022 situation. It is verified whether the changes are reflected in the results. A background on the case is presented in Appendix C.2. For confidentiality reasons, the specific name and precise location of the TSF are not disclosed. The main improvements are summarised in the subsequent section.

9.2.1. Summary of Improvements

Between 2017 and 2022, a number of improvements were undertaken at the site to improve safety; these improvements were related to both design elements and LoP. The improvements included the following.

- The number of site investigation locations has increased. In 2017, 19 Drill Holes (DHs) were available. In 2022, 36 DHs were available. There has also been additional Cone Penetration Test (CPT) testing. While in 2017 just 2 CPT profiles were made, 28 were available in 2022.
- The material characterisation of the foundation units has been improved; a significant number of thin-walled (Shelby) tube samples were collected for laboratory analysis. The analysis included characterisation units within the critical state soil mechanics framework. 3 Shelby tubes were collected in 2017, while in 2022 there were 33 collected.
- There has been an improvement in the monitoring of piezometric conditions and subsurface deformations. The number of Vibrating Wire (VW) piezometers has increased from 12 to 68. In 2017, there was 1 Shape Accel Arrays (SAA), while in 2022 there were installed 2. Furthermore, 3 additional slope inclinometers were added to the existing one in 2017, totalling 4 slope inclinometers in 2022.
- The VW Piezometers and SAAs transmit data automatically to an online database platform for near-real-time viewing of instrumentation readings. This system has Trigger Level and Response Plans (TARPs) established for each instrument. The system was upgraded in 2019 to permit more frequent transmission of instrument readings (less than hourly frequency).
- The governance was enhanced in 2017, with the establishment of regular monthly meetings that involved tailings operations staff, key management personnel, and the Engineer of Record (EoR).
- In 2017, also an Independent Tailings Review Board (ITRB) has been established. The board has bi-annual meetings, with an annual site visit to review the facility performance observations, design process and construction summaries.
- Several improvements were made to upgrade water management throughout the site in 2018, including upgrades of spillways and water management structures.
- A Design Basis Report (DBR) was established for the site in 2019. It contains clear and consistent criteria for geotechnical, hydrogeological, hydrological and hydro technical considerations in design.
- An upgrade of the Emergency Preparedness and Response Plan (EPRP) was undertaking in 2019. The upgrade includes engagement with external stakeholders and first responder groups.
- A major revision of the Operations, Maintenance and Surveillance (OMS) manual was undertaken in 2021.
- In 2021, the construction of a toe berm was completed to buttress the structure and improve stability, particularly to provide sufficient resistance in consideration of post-liquefied strengths of loose

contractive tailings in the foundation. Toe berm construction consisted of approximately 350,000 m^3 of fill; initial fill placement consisted of placement into the downstream pond in a manner to achieve displacement of soft sediment. Subsequent lifts occurred above pond level and resulted in an overall dam slope of approximately 12H:1V. The toe berm included erosion protection along the downstream slope in direct contact with pond water.

9.2.2. Provided Inputs

An overview of the inputs is presented in Table 9.6 for both 2017 and 2022, indicating a notable reduction in the number of unknown factors when compared to the case study described in the previous section (Section 9.1). This can be attributed to the accessibility of internal documents and dam design information for this particular case.

It is essential to emphasise that the inputs are provided by the author of this study, an external party, who possesses an external perspective and lacks in-depth knowledge of the dam itself but has access to the aforementioned documents. The inputs for the conditions in 2017 and 2022 are filled with values that reflect hindsight, encompassing what is currently known, as opposed to what was known at those specific points in time.

To assess the tool's suitability for external use, a comparison is made between the inputs and outcomes provided by the author and those supplied by the EoR, responsible for the tailings dam under investigation. The inputs provided by the EoR are presented in Table 9.7. The complete list of inputs is listed in Appendix C.2.2.

Upon comparing the inputs, several differences emerge. In the 2017 scenario, there are 5 inputs selected differently for site conditions, 20 for design elements, and 24 for the LoP. In the 2022 situation, 5 different inputs were chosen for site conditions, 14 for design elements, and 12 for LoP. These differences are deemed reasonable. The subsequent section will explore their potential impact on the outcomes.

Table 9.6: Summary Selected Inputs Improvement Case (Author)

Factors	Effect (2017 | 2022)				*Total*
	Favourable	Neutral	Adverse	Unknown	
Site Conditions	10 | 11	12 | 11	11 | 11	4 | 4	*37 | 37*
Design Elements	20 | 22	11 | 15	21 | 17	6 | 6	*58 | 60*
LoP	34 | 56	35 | 31	41 | 23	40 | 40	*150 | 159*
Total	*64 | 89*	*58 | 57*	*73 | 51*	*50 | 50*	*245 | 247*

Table 9.7: Summary Selected Inputs Improvement Case (Engineer of Record (EoR))

Factors	Effect (2017 | 2022)				*Total*
	Favourable	Neutral	Adverse	Unknown	
Site Conditions	12 | 12	12 | 11	12 | 13	1 | 1	*37 | 37*
Design Elements	19 | 27	11 | 14	24 | 20	2 | 0	*56 | 61*
LoP	26 | 62	44 | 28	40 | 20	40 | 40	*150 | 150*
Total	*57 | 10*	*67 | 53*	*76 | 53*	*40 | 41*	*243 | 248*

9.2.3. Summary of Results and Reflection

The striking results are evaluated in this section. The results based on the input of the author are described and are compared to the results obtained based on inputs of the EoR.

Results (Input Provided by Author)

In 2017, the estimated PoF is 8.1 E-04, which reduces to 6.4 E-04 in 2022, see Figure 9.3. This reduction of approximately 20% signifies a relatively modest improvement, given the substantial investment and effort expended on enhancements. The dam owner may have anticipated a more significant decrease in PoF as a result of these investments and efforts.

The corresponding PoF by failure category expressed in numbers are shown in Table 9.8. Both before and after the improvements, the PoF remains relatively high, approximately 40% higher than the baseline PoF and, therefore, higher than the PoF of the 'average' existing dam. Nonetheless, it is apparent that the 2022 conditions yield lower PoF values for each failure category compared to the 2017 situation.

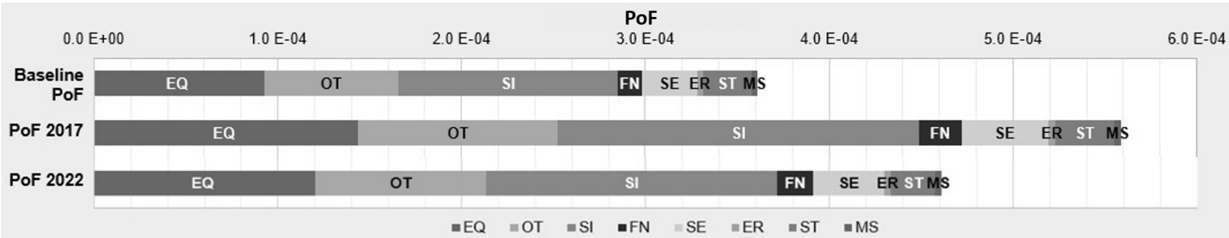


Figure 9.3: Probability of Failure (PoF) Improvement Case 2017 and 2022 Compared to the Baseline Probability of Failure (PoF) (Author) *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*

Similar patterns of relatively high and low categories persist, as can be observed from Table 9.8. Among these categories, the most challenging conditions are observed in the context of FN, which features a modifier greater than 2.5. However, it is worth noting that despite this high modifier, FN contributes minimally to the PoF, similarly to the previously discussed case. In contrast to the previous case, this is an US dam, for which a relatively large number of records are present, providing a relatively trustworthy distribution, and corresponding baseline PoF.

The SI failure category emerges as the primary contributor to the PoF, constituting 34.84% in 2017 and 33.78% in 2022. In 2017, it carried a modifier of 2.35, which reduced to 1.80 in 2022. Similarly, EQ and OT failure categories exhibit relatively high PoF values, accompanied by modifiers of respectively 2.35 and 2.11 in 2017 and 1.88 and 1.75 in 2022. The SE category features a notable modifier of 2.23 in 2017, decreasing to 1.76 in 2022. Like FN, it contributes less significantly to the overall PoF. These relatively low contributions, despite their modifiers, result from the relatively low baseline PoF for that specific failure category. Be aware that this baseline PoF, derived from a database that is, still statistically small.

Table 9.8: Probability of Failure (PoF) by Failure Category Improvement Case (Author) *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy) – Colour Scale: High Modifier (Red) - Low Modifier (Green), Increase in PoF (Red), Decrease in PoF (Green), High Contribution (Red/Grey) - Low Contribution (Green/White)*

X	Baseline PoF	Modifier		PoF		% of Total PoF		Change Compared to Baseline PoF	
		2017	2022	2017	2022	2017	2022	2017	2022
EQ	9.3 E-05	1.55	1.30	1.4 E-04	1.2 E-04	25.75%	26.11%	5.1 E-05	2.7 E-05
OT	7.3 E-05	1.49	1.27	1.1 E-04	9.3 E-05	19.42%	20.15%	3.6 E-05	2.0 E-05
SI	1.2 E-04	1.65	1.33	2.0 E-04	1.6 E-04	35.15%	34.35%	7.7 E-05	3.9 E-05
FN	1.3 E-05	1.73	1.49	2.3 E-05	2.0 E-05	4.11%	4.30%	9.7 E-06	6.5 E-06
SE	3.0 E-05	1.58	1.30	4.7 E-05	3.9 E-05	8.45%	8.40%	1.7 E-05	8.9 E-06
ER	3.3 E-06	1.25	1.05	4.1 E-06	3.5 E-06	0.74%	0.75%	8.1 E-07	1.6 E-07
ST	2.7 E-05	1.19	0.91	3.2 E-05	2.4 E-05	5.66%	5.26%	5.2 E-06	-2.3 E-06
MS	3.3 E-06	1.21	0.94	4.0 E-06	3.1 E-06	0.72%	0.68%	6.9 E-07	-2.0 E-07
Total	*3.6 E-04*			*5.6 E-04*	*4.6 E-04*			*2.0 E-04*	*1.0 E-04*

As can be observed from Table 9.9, the site conditions have about the same contribution to the PoF. In contrast, the contributions of design elements and LoP to the PoF have diminished, highlighting the improvements achieved over the course of five years. However, please note some of the improvements appear to be very small compared to the mitigation efforts.

A clarification on how improvements in the LoP contribute to a reduction in the PoF: by enhancing diligence and oversight, one effectively minimises the PoF. For example, one is more likely to operate within the intended pond water level and handle correctly to unforeseen circumstances. Furthermore, e.g. employing good monitoring allows timely intervention of failure mechanisms before they fully progress.

Table 9.9: Probability of Failure (PoF) and Share in Site Conditions, Design Elements and Level of Practise (LoP) Improvement Case (Author) *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy) – Colour Scale: High Contribution (Grey) - Low Contribution (White), Increase in PoF (Red), Decrease in PoF (Green), No Change in PoF (Yellow)*

X	PoF								
	Site Conditions			Design Elements			LoP		
	2017	2022	Change	2017	2022	Change	2017	2022	Change
EQ	5.3 E-05	5.3 E-05	0.0 E+00	6.7 E-05	5.2 E-05	-1.6 E-05	2.4 E-05	1.6 E-05	-7.9 E-06
OT	3.4 E-05	3.4 E-05	0.0 E+00	3.5 E-05	3.1 E-05	-4.0 E-06	4.0 E-05	2.8 E-05	-1.2 E-05
SI	5.6 E-05	5.6 E-05	0.0 E+00	7.5 E-05	5.9 E-05	-1.7 E-05	6.5 E-05	4.3 E-05	-2.1 E-05
FN	8.7 E-06	8.7 E-06	0.0 E+00	1.2 E-05	9.7 E-06	-2.3 E-06	2.3 E-06	1.4 E-06	-9.1 E-07
SE	1.3 E-05	1.3 E-05	0.0 E+00	1.2 E-05	9.7 E-06	-2.3 E-06	2.2 E-05	1.6 E-05	-6.2 E-06
ER	7.9 E-07	7.9 E-07	0.0 E+00	1.0 E-06	8.8 E-07	-1.6 E-07	2.3 E-06	1.8 E-06	-4.9 E-07
ST	2.5 E-06	2.5 E-06	0.0 E+00	3.3 E-06	3.3 E-06	0.0 E+00	2.6 E-05	1.8 E-05	-7.4 E-06
MS	2.7 E-06	2.1 E-06	-5.3 E-07	6.3 E-07	4.7 E-07	-1.6 E-07	7.0 E-07	5.0 E-07	-2.0 E-07
Total	*1.7 E-04*	*1.7 E-04*	-5.3 E-07	*2.1 E-04*	*1.6 E-04*	*-4.2 E-05*	*1.8 E-04*	*1.3 E-04*	-5.6 E-05
	30.54%	*36.95%*		*36.94%*	*35.79%*		*32.52%*	*27.26%*	

As shown in Table 9.10, the favourable factors rose from 64 to 89 between 2017 and 2022. The overall impact of these favourable factors has grown, as favourable conditions still carry a risk of failure (being favourable does not rule out a certain PoF), even though their contribution remains relatively minor.

58 and 57 factors received a neutral score in 2017 and 2022, respectively. Notably, within the neutral factors, the PoF for EQ has notably increased, while SI and ST failures show a decrease in PoF. In 2017, a total of 73 factors were identified as adverse, whereas in 2022, this number has been reduced to 51, see Table 9.10. This reduction has resulted in a decrease in share of approximately 7% (corresponding to a drop of 0.6 E-04).

In both 2017 and 2022, there are 50 unknown factors. In 2017, these unknown factors contributed to 12.07% of the PoF, while in 2022, they contributed to 14.52%, while the PoF contribution to the PoF stayed the same at 6.7 E-05. This is attributable to the lower contributions of other factors in 2022.

Examining the data in Table 9.8 improvements are particularly evident in the FN failure category, but these seem to have a minimal decrease to the PoF looking at Table 9.10. Conversely, in Table 9.8 there is a minimal decrease within the SI failure category, while Table 9.8 shows a significant decrease compared to the other failure categories. The latter is expected, due to the extensive measures taken to prevent this type of failure.

Lastly, there is an increase in favourable factors especially within the LoP, which is favourable for the PoF. There has been observed a significant decrease in adverse conditions to the PoF, mainly in design elements and LoP. It can be concluded that most of the design elements were marked neutral instead of adverse in 2022, while the LoP turned into neutral and favourable conditions.

Table 9.10: Probability of Failure (PoF) and Share Effects (Favourable, Neutral, Adverse, Unknown) Improvement Case (Author) *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy) – Colour Scale: High Contribution (Grey) - Low Contribution (White)*

		Favourable			Neutral		
		2017	2022	Change	2017	2022	Change
	Number of Contributing Factors	64	89	25	58	57	-1
	% of Total Contributing Factors	25.81%	35.89%	10.08%	23.39%	22.98%	-0.40%
	Contribution to PoF	2.2 E-05	2.8 E-05	6.7 E-06	1.0 E-04	9.2 E-05	-7.3 E-06
	% of Contribution to Total PoF	3.86%	6.15%	2.29%	17.81%	20.03%	2.22%
Failure Category	EQ	7.0 E-06	7.8 E-06	7.8 E-07	1.6 E-05	2.2 E-05	6.3 E-06
	OT	4.3 E-06	5.5 E-06	1.3 E-06	2.1 E-05	2.0 E-05	-1.0 E-06
	SI	5.6 E-06	8.3 E-06	2.6 E-06	4.2 E-05	3.3 E-05	-8.5 E-06
	FN	7.0 E-07	9.3 E-07	2.3 E-07	3.2 E-06	3.1 E-06	-8.0 E-08
	SE	1.5 E-06	2.3 E-06	7.8 E-07	8.1 E-06	6.9 E-06	-1.2 E-06
	ER	2.1 E-07	2.7 E-07	5.8 E-08	1.0 E-06	9.4 E-07	-7.8 E-08
	ST	2.1 E-06	3.0 E-06	9.2 E-07	7.2 E-06	4.4 E-06	-2.8 E-06
	MS	1.5 E-07	2.1 E-07	6.3 E-08	1.2 E-06	1.2 E-06	3.5 E-09
Effect	Site Conditions	8.1 E-06	8.1 E-06	3.8 E-08	4.7 E-05	3.7 E-05	-1.0 E-05
	Design Elements	8.3 E-06	8.7 E-06	3.5 E-07	1.3 E-05	3.2 E-05	1.9 E-05
	LoP	5.2 E-06	1.2 E-05	6.3 E-06	3.9 E-05	2.3 E-05	-1.7 E-05

		Adverse			Unknown		
		2017	2022	Change	2017	2022	Change
	Number of Contributing Factors	73	51	-22	50	50	0
	% of Total Contributing Factors	29.44%	20.56%	-8.87%	20.16%	20.16%	0.00%
	Contribution to PoF	3.7 E-04	2.7 E-04	-9.6 E-05	6.7 E-05	6.7 E-05	-5.4 E-07
	% of Contribution to Total PoF	66.02%	59.25%	-6.77%	12.07%	14.52%	2.46%
Failure Category	EQ	1.1 E-04	8.1 E-05	-3.1 E-05	9.8 E-06	9.8 E-06	-4.3 E-08
	OT	6.8 E-05	5.2 E-05	-1.6 E-05	1.5 E-05	1.5 E-05	-1.4 E-07
	SI	1.3 E-04	9.5 E-05	-3.1 E-05	2.2 E-05	2.2 E-05	-2.3 E-07
	FN	1.8 E-05	1.4 E-05	-3.2 E-06	1.3 E-06	1.3 E-06	-8.1 E-09
	SE	2.9 E-05	2.1 E-05	-8.0 E-06	8.8 E-06	8.7 E-06	-5.6 E-08
	ER	1.9 E-06	1.2 E-06	-6.3 E-07	8.2 E-07	8.1 E-07	-3.8 E-09
	ST	1.4 E-05	8.6 E-06	-5.5 E-06	8.3 E-06	8.2 E-06	-6.0 E-08
	MS	1.4 E-06	4.1 E-07	-9.5 E-07	1.1 E-06	1.1 E-06	-1.6 E-09
Effect	Site Conditions	1.1 E-04	1.2 E-04	9.6 E-06	6.4 E-06	6.4 E-06	0.0 E+00
	Design Elements	1.7 E-04	1.1 E-04	-6.0 E-05	1.4 E-05	1.4 E-05	0.0 E+00
	LoP	9.1 E-05	4.5 E-05	-4.5 E-05	4.7 E-05	4.6 E-05	-5.4 E-07

Factor 1.15, which pertains to the dam foundation material, consistently remains the factor with the highest individual contribution in both 2017 and 2022, which in both years is 6.4 E-05 (see Table 9.11). Furthermore, factors 1.13, 2.31, 2.38, 2.52, 2.26, 2.25, 2.51, 3.1.1.a, 1.26, and 1.17 each contribute more than 2E-05 to the PoF. Notably, factors 2.52, 2.25, and 2.51 do not appear in this list for 2022. This suggests improvements in monitoring pore water pressures in the embankment and foundations, as well as enhancements in the drainage capacity. The other improvements do not address the highest PoF's and are therefore not in this list, although related factors show a reduction in PoF. Despite the big efforts, the total reduction in PoF is also not significant. This can be ascribed to the significant penalising impact of adverse conditions, although present to a lesser extent. It will be advised to check if there are mitigation measures for the highest risks which could reduce the PoF significantly.

Table 9.11: Factors with the Highest Individual Contribution to the Probability of Failure (PoF) Improvement Case (Author) – *Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange), Highest Contribution (Red) - Lowest Contribution (Green))*

			2017				2022			
ID	Input Question	GISTM	Selected Input	Effect	% of PoF	Contribution	Selected Input	Effect	% of PoF	Contribution
1.15	Is the foundation underlying the TSF characterised by strain-softening or contractive material?	-	Yes	Adverse	6.90%	3.9 E-05	Yes	Adverse	8.38%	3.9 E-05
1.13	Is the site prone to generation of material/debris accumulation or ice damming?	-	Yes	Adverse	4.33%	2.4 E-05	Yes	Adverse	5.25%	2.4 E-05
2.31	Are the embankments of significant height?	-	Moderately, 25-100 m	Adverse	4.11%	2.3 E-05	Moderately, 25-100 m	Adverse	4.98%	2.3 E-05
2.38	Are the tailings lacking adequate liquefaction resistance (e.g. low-density, loose, contractive material that is uniformly graded, with high silt content, and low permeability)?	-	Yes ('regular tailings")	Adverse	3.26%	1.8 E-05	Yes ('regular tailings")	Adverse	3.96%	1.8 E-05
2.52	Are measures in place for monitoring pore water pressures within the embankment and do the results confirm the design assumptions and are within the design standards.	-	No/Limited measures in place	Adverse	3.12%	1.7 E-05	Measures in place, but do not meet design	Neutral	1.26%	5.8 E-06
2.26	Are instances of blockage in the drainage systems (caused by factors such as sediment, vegetation, or ice, geochemical precipitation) observed or expected?	-	Yes	Adverse	2.72%	1.5 E-05	Yes	Adverse	3.29%	1.5 E-05
2.25	Is the drainage capacity (demonstrated to be) sufficient over the lifespan of the dam?	-	No	Adverse	2.69%	1.5 E-05	Considered to be	Neutral	1.09%	5.0 E-06
2.51	Are measures in place for monitoring pore water pressures within the foundation and do the results confirm the design assumptions and are within the design standards.	-	No/Limited measures in place	Adverse	2.25%	1.3 E-05	Measures in place, but do not meet design	Neutral	0.91%	4.2 E-06
3.1.1.a	Evaluate uncertainties associated with climate change that may impact upon the safety of the tailings facility (see also GISTM requirement 3.1).	2.1.b	Does Not Meet	Adverse	2.18%	1.2 E-05	Does Not Meet	Adverse	2.65%	1.2 E-05
1.26	Do the available materials for the dam core, filters, and shell possess the potential for internal instability?	-	Yes	Adverse	2.11%	1.2 E-05	Yes	Adverse	2.56%	1.2 E-05
1.17	Is there compressible material present within the foundation (e.g. peat)?	-	Yes	Adverse	2.09%	1.2 E-05	Yes	Adverse	2.54%	1.2 E-05
2.13	In the presence, is soil or fill material origionally present in the foundaiton excavated?	-	No	Adverse	1.85%	1.0 E-05	No	Adverse	2.24%	1.0 E-05
1.31	Do activities such as working on the embankment crest, nearby construction work, open-pit mining operations, or the operation of machinery and vehicles in close proximity to the TSF result in substantial loads or vibrations at the site?	-	Potentially	Neutral	1.82%	1.0 E-05	Yes	Adverse	2.20%	1.0 E-05
3.1.2.b	Site characterisation is supported by data including site-specific climate, geomorphology, geology, geochemistry, hydrology, and hydrogeology (surface and groundwater flow and quality), geotechnical, and seismicity.	2.2.b	Does Not Meet	Adverse	1.63%	9.1 E-06	Partially Meets	Neutral	0.66%	3.0 E-06
2.4.a	Has an permanent spillway with stable walls been constructed?	-	No	Adverse	1.60%	9.0 E-06	No	Adverse	1.95%	9.0 E-06
1.4	What is the climate at site (according to Köppen Climate Classification)? If unknown, utilise climate map (Beck, 2018). (see sheet 'Maps')	-	Dfc (continental; no dry season; cold summer)	Neutral	1.54%	8.6 E-06	Dfc (continental; no dry season; cold summer)	Neutral	1.87%	8.6 E-06
3.1.2.a	A detailed site characterisation of the tailings facility site(s) exists and it is updated as warranted throughout the lifecycle to reflect material changes in conditions and new knowledge.	2.2.a	Does Not Meet	Adverse	1.46%	8.2 E-06	Partially Meets	Neutral	0.59%	2.7 E-06
2.24	Is there an underdrainage system installed at the basal level of the dam?	-	Unknown	Unknown	1.44%	8.1 E-06	Unknown	Unknown	1.75%	8.1 E-06
2.30	Are the upstream and downstream embankment slopes steeply inclined?	-	Yes, close to or exceeding natural angle of repose	Adverse	1.42%	7.9 E-06	Slightly, but < natural angle of repose	Neutral	0.57%	2.6 E-06
3.2.1	To enhance resilience, climate change knowledge is regularly updated and used to evaluate risks and opportunities to the tailings facility lifecycle, in accordance with the principles of adaptive management, with the aim of enhancing resiliency to climate change.	3.1.a	Does Not Meet	Adverse	1.41%	7.9 E-06	Does Not Meet	Adverse	1.71%	7.9 E-06
1.27	Do the available materials for the dam core, filters, and shell possess the potential for geochemical incompatibility?	-	Yes	Adverse	1.39%	7.8 E-06	Yes	Adverse	1.69%	7.8 E-06
2.14	Do the drained and undrained factors of safety, under both static and dynamic loads, for potential failure surfaces through the embankment, meet industry standards of practice?	-	No	Adverse	1.37%	7.7 E-06	No	Adverse	1.67%	7.7 E-06
2.16	Does the embankment design consider time-dependent, deformation-dependent, and stress-path dependent processes that may affect material properties?	-	No	Adverse	1.37%	7.7 E-06	Partially	Neutral	0.56%	2.6 E-06
1.2	Are (active) faults are crossing the TSF or exist in close proximity such that they may induce ground motions at the TSF?	-	Yes, inactive faults which may potentially cause ground motions	Neutral	1.29%	7.2 E-06	Yes, inactive faults which may potentially cause ground motions	Neutral	1.56%	7.2 E-06
2.21.b	Are wide zones of beaches compacted to a dilative state, free from contractive tailings?	-	No	Adverse	1.26%	7.1 E-06	No	Adverse	1.53%	7.1 E-06
1.5	What is the climate at site (according to Köppen Climate Classification)? If unknown, utilise climate map (Beck, 2018). (see sheet 'Maps')	-	Dfc (continental; no dry season; cold summer)	Neutral	1.01%	5.6 E-06	Dfc (continental; no dry season; cold summer)	Neutral	1.22%	5.6 E-06

Results (Input Provided by EoR)

The results from the EoR exhibit some differences compared to the author's results. The results are illustrated in Figure 9.4 and Table 9.12 to Table 9.15. The estimated PoF is 7.7 E-04 in 2017 and 6.3 E-04 in 2022, falling within similar ranges as estimated by the author. In the 2017 EoR's estimate, there are higher modifiers for the OT and ER failure categories. In 2022, a slightly higher modifier is observed for EQ and OT, but no significant differences in their relative contribution to the PoF are apparent.

The PoF is similarly high to the results obtained by the author. 2022 shows a PoF that is approximately 20% lower then the PoF in 2017. A more significant decrease in PoF is expected based on the mitigation efforts taken. The EoR remarks: 'Even in the 2022 condition, this dam still has its shortcomings, but compared to the population of tailings dams in existence, I would not expect this to have a PoF twice that of the 'average' dam. Furthermore, considering the efforts and costs that went into improving conditions, the hope would be to see a higher reduction in PoF.'

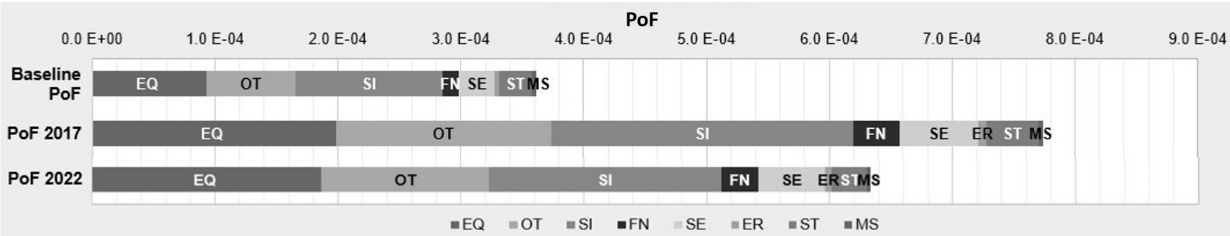


Figure 9.4: Probability of Failure (PoF) Improvement Case 2017 and 2022 Compared to the Baseline Probability of Failure (PoF) (Engineer of Record (EoR)) *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*

Table 9.12: Probability of Failure (PoF) by Failure Category Improvement Case (Engineer of Record (EoR)) *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy) – Colour Scale: High Modifier (Red) - Low Modifier (Green), Increase in PoF (Red), Decrease in PoF (Green), High Contribution (Red/Grey) - Low Contribution (Green/White)*

X	PoF	Modifier		PoF		% of Total PoF		Change Compared to Baseline PoF	
		2017	2022	2017	2022	2017	2022	2017	2022
EQ	9.3 E-05	2.14	2.01	2.0 E-04	1.9 E-04	25.62%	29.47%	1.1 E-04	9.4 E-05
OT	7.3 E-05	2.40	1.87	1.8 E-04	1.4 E-04	22.63%	21.52%	1.0 E-04	6.3 E-05
SI	1.2 E-04	2.06	1.58	2.5 E-04	1.9 E-04	31.73%	29.83%	1.3 E-04	7.0 E-05
FN	1.3 E-05	2.84	2.28	3.8 E-05	3.0 E-05	4.86%	4.77%	2.4 E-05	1.7 E-05
SE	3.0 E-05	2.16	1.82	6.5 E-05	5.4 E-05	8.33%	8.58%	3.5 E-05	2.5 E-05
ER	3.3 E-06	2.04	1.71	6.7 E-06	5.7 E-06	0.87%	0.89%	3.4 E-06	2.3 E-06
ST	2.7 E-05	1.58	1.08	4.2 E-05	2.9 E-05	5.42%	4.53%	1.5 E-05	2.2 E-06
MS	3.3 E-06	1.25	0.77	4.1 E-06	2.5 E-06	0.53%	0.40%	8.2 E-07	-7.8 E-07
Total	*3.6 E-04*			*7.7 E-04*	*6.3 E-04*			*4.1 E-04*	*2.7 E-04*

According to Table 9.12 and Table 9.13. The distributions by failure category and factors related to site conditions, design elements, and the LoP are consistent with those obtained by the author. A notable distinction is a larger share of OT PoF within the design elements for both the 2017 and 2022 conditions. Another striking result is the increase in PoF for the site conditions in 2022 for most of the failure categories. This is mainly due to to increased size of the footprint of the TSF compared to the 2017 situation. Moreover, the available rock material for the dam shell has been marked adversely as having low erosional resistance in 2022, while in input selected in 2017 leads to a favourable condition.

As can be observed by comparing Table 9.10 and Table 9.14 fewer factors are unknown by the EoR, with only 43 factors in 2017 and 41 in 2022 (compared to the author's 50 unknown factors). In 2017, the EoR selected less favourable conditions compared to the author, while in 2022, more favourable conditions were chosen. Simultaneously, a similar number of adverse conditions were selected in both 2017 and 2022, ultimately contributing to more than 70% of the total PoF. This explains the limited differences in the final results.

Table 9.13: Probability of Failure (PoF) and Share in Site Conditions, Design Elements and Level of Practise Improvement Case (Engineer of Record (EoR)) *(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy) – Colour Scale: High Contribution (Grey) - Low Contribution (White), Increase in PoF (Red), Decrease in PoF (Green), No Change in PoF (Yellow)*

X	PoF								
	Site Conditions			Design Elements			LoP		
	2017	2022	Change	2017	2022	Change	2017	2022	Change
EQ	7.8 E-05	8.9 E-05	1.2 E-05	9.4 E-05	7.9 E-05	-1.5 E-05	2.7 E-05	1.8 E-05	-8.8 E-06
OT	4.4 E-05	4.8 E-05	3.6 E-06	7.8 E-05	5.3 E-05	-2.5 E-05	5.3 E-05	3.6 E-05	-1.8 E-05
SI	6.8 E-05	7.3 E-05	5.2 E-06	9.2 E-05	6.5 E-05	-2.7 E-05	8.6 E-05	5.0 E-05	-3.5 E-05
FN	1.3 E-05	1.3 E-05	9.7 E-08	2.2 E-05	1.5 E-05	-6.4 E-06	2.7 E-06	1.6 E-06	-1.1 E-06
SE	2.0 E-05	2.0 E-05	3.0 E-20	1.6 E-05	1.6 E-05	-1.7 E-07	2.9 E-05	1.9 E-05	-1.0 E-05
ER	6.8 E-07	1.3 E-06	6.3 E-07	3.0 E-06	2.0 E-06	-1.0 E-06	3.1 E-06	2.4 E-06	-7.2 E-07
ST	3.0 E-06	3.0 E-06	-4.2 E-21	6.4 E-06	4.5 E-06	-1.9 E-06	3.3 E-05	2.1 E-05	-1.1 E-05
MS	2.5 E-06	1.6 E-06	-9.0 E-07	7.9 E-07	4.1 E-07	-3.8 E-07	8.9 E-07	5.8 E-07	-3.1 E-07
Total	*2.3 E-04*	*2.5 E-04*	2.0 E-05	*3.1 E-04*	*2.4 E-04*	*-7.6 E-05*	*2.3 E-04*	*1.5 E-04*	-8.5 E-05
	29.53%	*39.31%*		*40.18%*	*37.13%*		*30.29%*	*23.56%*	

Table 9.14: Probability of Failure (PoF) and Share Effects (Favourable, Neutral, Adverse, Unknown) Improvement Case (Engineer of Record (EoR))*(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy) – Colour Scale: High Contribution (Grey) - Low Contribution (White)*

		Favourable			Neutral		
		2017	2022	Change	2017	2022	Change
	Number of Contributing Factors	57	101	44	67	53	-14
	% of Total Contributing Factors	23.46%	40.73%	17.27%	27.57%	21.37%	-6.20%
	Contribution to PoF	2.1 E-05	3.0 E-05	8.9 E-06	1.1 E-04	8.8 E-05	-1.8 E-05
	% of Contribution to Total PoF	2.74%	4.76%	2.02%	13.62%	13.83%	0.21%
Failure Category	EQ	7.6 E-06	8.9 E-06	1.3 E-06	1.8 E-05	1.4 E-05	-4.6 E-06
	OT	3.1 E-06	5.0 E-06	1.9 E-06	2.5 E-05	2.4 E-05	-1.6 E-06
	SI	6.2 E-06	9.2 E-06	3.1 E-06	3.8 E-05	3.4 E-05	-4.3 E-06
	FN	6.8 E-07	1.0 E-06	3.3 E-07	2.8 E-06	2.6 E-06	-1.6 E-07
	SE	1.5 E-06	2.4 E-06	9.1 E-07	9.7 E-06	6.9 E-06	-2.8 E-06
	ER	1.5 E-07	2.5 E-07	1.0 E-07	1.2 E-06	9.9 E-07	-2.0 E-07
	ST	1.8 E-06	3.1 E-06	1.2 E-06	8.7 E-06	4.6 E-06	-4.1 E-06
	MS	2.1 E-07	3.0 E-07	8.5 E-08	1.3 E-06	1.2 E-06	-1.1 E-07
Effect	Site Conditions	8.7 E-06	8.3 E-06	-3.5 E-07	3.8 E-05	3.5 E-05	-2.9 E-06
	Design Elements	8.8 E-06	1.0 E-05	1.5 E-06	1.8 E-05	2.9 E-05	1.0 E-05
	LoP	3.7 E-06	1.2 E-05	7.8 E-06	5.0 E-05	2.4 E-05	-2.5 E-05

		Adverse			Unknown		
		2017	2022	Change	2017	2022	Change
	Number of Contributing Factors	76	53	-23	43	41	-2
	% of Total Contributing Factors	31.28%	21.37%	-9.90%	17.70%	16.53%	-1.16%
	Contribution to PoF	6.0 E-04	4.7 E-04	-1.3 E-04	4.7 E-05	4.6 E-05	-7.5 E-07
	% of Contribution to Total PoF	77.56%	74.10%	-3.46%	6.07%	7.31%	1.24%
Failure Category	EQ	1.7 E-04	1.6 E-04	-8.5 E-06	5.8 E-06	5.8 E-06	-1.1 E-08
	OT	1.4 E-04	9.9 E-05	-3.9 E-05	8.7 E-06	8.7 E-06	-1.5 E-08
	SI	1.8 E-04	1.3 E-04	-5.6 E-05	1.7 E-05	1.7 E-05	-3.1 E-08
	FN	3.4 E-05	2.6 E-05	-7.6 E-06	5.1 E-07	5.1 E-07	-9.8 E-10
	SE	4.7 E-05	3.9 E-05	-8.0 E-06	6.1 E-06	5.8 E-06	-3.3 E-07
	ER	4.5 E-06	3.9 E-06	-6.4 E-07	9.0 E-07	5.5 E-07	-3.5 E-07
	ST	2.4 E-05	1.3 E-05	-1.0 E-05	7.9 E-06	7.9 E-06	-1.4 E-08
	MS	2.0 E-06	4.3 E-07	-1.6 E-06	4.5 E-07	4.5 E-07	-3.9 E-10
Effect	Site Conditions	1.8 E-04	2.1 E-04	2.4 E-05	2.4 E-07	2.4 E-07	0.0 E+00
	Design Elements	2.8 E-04	2.0 E-04	-8.7 E-05	6.6 E-07	0.0 E+00	-6.6 E-07
	LoP	1.4 E-04	6.7 E-05	-6.8 E-05	4.6 E-05	4.6 E-05	-8.2 E-08

Both the author and the EoR identify similar 'high-risk' factors. However, in 2017, factors 2.3.a, 2.51, 2.16, and 2.30 received significantly higher weights, while factors 1.31, 2.14, 2.37 received lower weights. In 2022, 1.28 has a higher weight, while factors 1.31, 2.14, 2.37, and 3.6.2.b receive lower weights.

However, it is apparent that several high-risk factors have remained unidentified by the author, which could pose a risk. The author missed high-risk factors, like water balance quality (2.3.a) and the absence of a basal drainage system (2.24). These could have been identified with careful attention and do not necessarily require in-depth technical knowledge, just sufficient information.

While improvements are evident, they do not seem to accurately reflect the expected changes in PoF magnitude. The current inputs in the tool appear to disproportionately penalise adverse conditions. When the modifier for adverse conditions is adjusted to 3, the PoF experiences a significant decrease to 5.6 E-04 and 4.6 E-04 in 2017 and 2022, respectively. Nonetheless, it remains higher than the baseline PoF and the changes due to the improvements are even less apparent in the results.

Table 9.15: Factors with the Highest Individual Contribution to the Probability of Failure (PoF) Improvement Case (Engineer of Record (EoR)) – *Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange), Highest Contribution (Red) - Lowest Contribution (Green))*

			2017				2022			
ID	**Input Question**	**GISTM**	**Selected Input**		**% of PoF**	**Contribution**	**Selected Input**		**% of PoF**	**Contribution**
1.15	Is the foundation underlying the TSF characterised by strain-softening or contractive material?	-	Yes	Adverse	8.31%	6.4 E-05	Yes	Adverse	10.12%	6.4 E-05
1.13	Is the site prone to generation of material/debris accumulation or ice damming?	-	Yes	Adverse	5.21%	4.0 E-05	Yes	Adverse	6.34%	4.0 E-05
2.31	Are the embankments of significant height?	-	Moderately, 25-100 m	Adverse	4.93%	3.8 E-05	Moderately, 25-100 m	Adverse	6.00%	3.8 E-05
2.3.a	Does the design consider a detailed water balance?	-	No	Adverse	4.59%	3.6 E-05	Yes	Favourable	0.10%	6.1 E-07
2.38	Are the tailings lacking adequate liquefaction resistance (e.g. low-density, loose, contractive material that is uniformly graded, with high silt content, and low permeability)?	-	Yes ('regular tailings")	Adverse	3.92%	3.0 E-05	Yes ('regular tailings")	Adverse	4.78%	3.0 E-05
2.26	Are instances of blockage in the drainage systems (caused by factors such as sediment, vegetation, or ice, geochemical precipitation) observed or expected?	-	Yes	Adverse	3.26%	2.5 E-05	Yes	Adverse	3.97%	2.5 E-05
2.51	Are measures in place for monitoring pore water pressures within the foundation and do the results confirm the design assumptions and are within the design standards.	-	No/Limited measures in place	Adverse	2.69%	2.1 E-05	Measures in place meet design	Favourable	0.13%	8.3 E-07
3.1.1.a	Evaluate uncertainties associated with climate change that may impact upon the safety of the tailings facility (see also GISTM requirement 3.1).	2.1.b	Does Not Meet	Adverse	2.62%	2.0 E-05	Does Not Meet	Adverse	3.20%	2.0 E-05
2.24	Is there an underdrainage system installed at the basal level of the dam?	-	No	Adverse	2.59%	2.0 E-05	No	Adverse	3.15%	2.0 E-05
1.26	Do the available materials for the dam core, filters, and shell possess the potential for internal instability?	-	Yes	Adverse	2.54%	2.0 E-05	Yes	Adverse	3.09%	2.0 E-05
1.17	Is there compressible material present within the foundation (e.g. peat)?	-	Yes	Adverse	2.52%	2.0 E-05	Yes	Adverse	3.07%	2.0 E-05
2.13	In the presence, is soil or fill material origionally present in the foundaiton excavated?	-	No	Adverse	2.22%	1.7 E-05	No	Adverse	2.70%	1.7 E-05
2.4.a	Has an permanent spillway with stable walls been constructed?	-	No	Adverse	1.93%	1.5 E-05	No	Adverse	2.35%	1.5 E-05
2.30	Are the upstream and downstream embankment slopes steeply inclined?	-	Yes, close to or exceeding natural angle of repose	Adverse	1.72%	1.3 E-05	Slightly, but < natural angle of repose	Neutral	0.42%	2.6 E-06
3.2.1	To enhance resilience, climate change knowledge is regularly updated and used to evaluate risks and opportunities to the tailings facility lifecycle, in accordance with the principles of adaptive management, with the aim of enhancing resiliency to climate change.	3.1.a	Does Not Meet	Adverse	1.70%	1.3 E-05	Does Not Meet	Adverse	2.07%	1.3 E-05
1.27	Do the available materials for the dam core, filters, and shell possess the potential for geochemical incompatibility?	-	Yes	Adverse	1.67%	1.3 E-05	Yes	Adverse	2.04%	1.3 E-05
2.16	Does the embankment design consider time-dependent, deformation-dependent, and stress-path dependent processes that may affect material properties?	-	No	Adverse	1.65%	1.3 E-05	Yes	Favourable	0.08%	5.1 E-07
2.21.b	Are wide zones of beaches compacted to a dilative state, free from contractive tailings?	-	No	Adverse	1.53%	1.2 E-05	No	Adverse	1.85%	1.2 E-05
1.14	Are artesian pressures identified which may affect the embankment?	-	Yes	Adverse	1.16%	9.0 E-06	Yes	Adverse	1.41%	9.0 E-06
1.4	What is the climate at site (according to Köppen Climate Classification)? If unknown, utilise climate map (Beck, 2018). (see sheet 'Maps')	-	Dfc (continental; no dry season; cold summer)	Neutral	1.11%	8.6 E-06	Dfc (continental; no dry season; cold summer)	Neutral	1.35%	8.6 E-06
2.34	Is the embankment characterised by strain-softening or contractive material?	-	Yes	Adverse	1.06%	8.2 E-06	Yes	Adverse	1.29%	8.2 E-06
3.3.2.b	Document the rationale for the design criteria selected to minimise risk.	4.4.b	Does Not Meet	Adverse	0.95%	7.4 E-06	Meets	Favourable	0.05%	2.9 E-07
1.2	Are (active) faults are crossing the TSF or exist in close proximity such that they may induce ground motions at the TSF?	-	Yes, inactive faults which may potentially cause ground motions	Neutral	0.93%	7.2 E-06	Yes, inactive faults which may potentially cause ground motions	Neutral	1.13%	7.2 E-06
3.3.3.a	Develop and apply design criteria such as factors of safety for slope stability and seepage management, for each lifecycle phase that considers: the estimated operational properties of materials and expected performance of the design elements, and; the quality of the implementation of the risk management systems.	4.5.a	Does Not Meet	Adverse	0.84%	6.5 E-06	Partially Meets	Neutral	0.21%	1.3 E-06
3.3.3.b	Account for these design and implementation issues in assessments that are based on deformation analyses.	4.5.b	Does Not Meet	Adverse	0.84%	6.5 E-06	Meets	Favourable	0.04%	2.6 E-07
3.6.2.b	Monitoring procedures for non-brittle failure modes are developed and implemented to support the Observational Method.	7.2.b	Does Not Meet	Adverse	0.81%	6.3 E-06	Meets	Favourable	0.04%	2.5 E-07
3.6.2.c	Brittle failure modes are addressed by conservative design criteria.	7.2.c	Does Not Meet	Adverse	0.81%	6.3 E-06	Meets	Favourable	0.04%	2.5 E-07

9.3. Key Findings

In the pursuit of enhancing the safety and risk assessment of tailings dams, the development of a comprehensive evaluation tool shows promise. However, a nuanced examination reveals several challenges, inaccuracies, and uncertainties that persist in the analysis.

One notable challenge is the difficulty in obtaining crucial information when access to in-depth knowledge and internal documents is lacking, especially concerning the LoP. In the case where there is no internal knowledge, a significant number of inputs are unknown. This significant occurrence of 'unknown-unknown' scenarios (as explained in Section 7.2.2) requires lower modifiers for 'Unknown' inputs (ideally, aligning more closely with the statistical median), compared to 'unknown' scenarios where in-depth knowledge and internal documents are available.

The final results of the tool reveal minimal differences between the EoR's input and the author's input, suggesting that it would be possible to analyse the dam section without having experience or in-depth knowledge of the specific dam. Nevertheless, it is advised to perform the analysis in collaboration with an individual possessing in-depth knowledge of the TSF, which is essential to prevent the oversight of 'high-risk' factors.

Moreover, there are instances of missing dependencies within the tool, where certain input factors become irrelevant under specific conditions. The clarity of input descriptions remains an area for improvement as well, especially when inputs fall between two options, making a selection is challenging.

Notably, the tool tends to estimate a higher PoF than expected, consistently exceeding the baseline PoF in all evaluated cases. Despite the implementation of risk mitigation measures, the reduction in PoF is less significant than anticipated. Alterations in modifiers demonstrate just minor impacts on the PoF. The current effects appear to disproportionately penalise adverse conditions. Further evaluation of the fulfilment factors and weights is necessary.

Remarkably, the EQ failure category exerts a higher contribution to the PoF than initially projected, with site condition factors related to EQ bearing notably high individual weights. The MS category exhibits an incorrect high modifier in the absence of an underground mine.

In summary, while the tool offers a valuable potential solution, there is room for improvement. The validation process through additional case studies is recommended to identify critical areas requiring further investigation and adjustment.

*The tool demonstrates potential as a solution, but necessitates further validation through a more extensive array of case studies, particularly to determine correct weights and modifiers that accurately represent the expected magnitude of the PoF and its relative changes. The next chapter (*Chapter 10 *will stress key discussion points and in* Chapter 12 *recommendations for further investigation and development are presented.*

V. Evaluation

Objective 4: Demonstrating Validity and Addressing Challenges and Limitations

An in-depth evaluation of the research is provided, featuring a comprehensive discussion covering an interpretation of the results, an identification of discrepancies and limitations, and the study's broader implications. The main research questions and associated sub-questions are answered in the conclusion. A series of recommendations are made, covering the tool's utilisation, potential improvements, validation and verification processes, prospects for further expansion, and considerations for future growth.

10 Discussion

While the developed tool demonstrates the potential to systematically and effectively assess the PoF and provide rational guidance for the prioritisation of mitigation efforts, the results also reveal weaknesses and limitations. This section critically discusses these shortcomings in the context of the methods employed, shedding light on the applicability and the need for cautious interpretation.

10.1. Potential

The developed tool offers a systematic and scientifically rigorous approach for assessing the PoF of existing tailings dams and facilitates the prioritisation of risk mitigation measures within the framework of the ALARP principle. The tool provides a rapid estimation of PoF without the need for significant time, expertise, financial resources, or specific parameters.

The semi-quantitative approach of combining the frequency of observations from historical data with expert judgement, as initiated by Silva et al. (2009) and Chovan et al. (2021), simplifies the assessment of PoF for complex risk scenarios. It avoids the complexities associated with demanding mathematical models and their required parameters and shows a solution at the extreme end of the risk framework. In contrast to these existing methods, the tool considers all failure categories and all factors that may affect the PoF, encompassing site conditions, design elements, and the LoP of the specific dam section under examination. The tool is designed to be able to be used within a single day, but even when not all factors are available as inputs, the tool still allows for a preliminary estimation of the PoF. Furthermore, the tool supports the demonstration of ALARP and avoids ethical questions. The tool provides a transparent result and offers rational decision-making. It gives insight into high-risk factors and the relative PoF reduction upon the implementation of mitigation measures for this factor, serving as a good starting point for further discussion of what is the best strategy to improve tailings dam safety.

10.2. Challenges and Shortcomings

Not all outcomes align with expectations, and several challenges and inaccuracies persist within the analysis, particularly regarding input requirements and the magnitude of the PoF.

Inconvenience Input Requirements

The acquisition of certain input information is sometimes challenging, particularly for the LoP. The inputs for the LoP stem from the detailed GISTM (GISTM, 2020) requirements, and the majority of these inputs necessitate a deep and inside knowledge of the subject matter. While it is feasible to adapt these inputs, there is a concurrent need to encourage companies to align with the GISTM requirements. Once an evaluation of the TSF has been conducted based on the GISTM, fulfilling the LoP requirements becomes a relatively straightforward task.

However, the existing count of 255 inputs over the site conditions, design elements and LoP also surpasses industry preferences for conciseness. The 150 LoP inputs could be refined by consolidating the highly detailed GISTM criteria to a level where each individual criterion significantly contributes to the assessment of PoF. Some LoP factors carry low weights in the analysis and may be excluded. Similarly, factors with minimal contributions to PoF for site conditions and design elements may be considered for exclusion, further reducing the input count. The reduction of highly specific inputs may also decrease the number of unknown factors, mainly due to reduced information requirements and increased available time for comprehensive determination of the remaining inputs.

Some inputs lack clarity, and their descriptions may require revision. Choosing from the available input options can be challenging, especially when an input falls on the border of two options within the dropdown menu. Enhancing flexibility and introducing additional input options, including options in between, could be beneficial and enhance accuracy. This may also facilitate more nuanced steps for fulfilment modifiers. However, psychologist Barry Schwartz's theory suggests that when someone has three options, they confidently choose from the extremes. In contrast, when faced with ten options, the decision-making process may become more challenging, leading to a higher likelihood of avoiding extreme options (1, 2, 9, and 10) and potentially choosing a middle option. Hence, the rise in alternatives may result in decision fatigue, leading individuals to make suboptimal choices or avoid decisions altogether.

Not collaborating with a knowledgeable individual and lacking access to internal documents during the analysis may result in numerous 'unknown-unknown' inputs. The presence of such 'unknown-unknown' inputs necessitates the assignment of lower modifiers for unknown effects, aligning more closely with the statistical median. This differs from 'unknown' scenarios, where the modifier should be worse than average due to the risk of not identifying potential hazards posing a risk itself. Conducting independent analysis without the input of a knowledgeable, familiar individual also increases the risk of overlooking high-risk factors. While it is possible for a single individual to complete the tool and conduct the analysis, collaboration with at least one other person is recommended. In-depth discussions about inputs and outputs are paramount, given the tool's subjectivity and uncertainties.

Inaccurate Magnitude of the PoF (over Time)

The PoF estimates for the analysed cases are notably high, as expected for a dam that has experienced failure. However, it also shows a similarly elevated PoF (above the baseline) for another dam that has not failed to date. While this doesn't rule out the possibility of such a high PoF, it contradicts expert expectations. In 2017, it was anticipated that this dam would have a PoF comparable to an 'average' dam, with figures close to the baseline PoF, but a significantly higher PoF was estimated. Despite significant improvements from 2017 to 2022, the PoF remains high. The discrepancy is acknowledged by the external author, who recognises substantial improvements not reflected in the PoFs magnitude. The tool seems to disproportionately penalise adverse conditions.

The tool lacks adequate consideration of changes over time within its factors. It does not account for earlier site conditions, design elements, and the level of practice, which may be significant from a stability point of view. For instance, if the initial raise experiences less favourable conditions, it would significantly impact the structural integrity of the dams, resulting in worse stability than if only the last raise had issues. Consequently, completing the tool presently may result in an overestimation of the design and level of practice.

Other

Noteworthy discrepancies include the disproportionately high influence of EQ failures on the PoF, where individual factors carry excessively high weights. These weightings are imbalanced and potentially inaccurate when compared to other factors. Additionally, the weightings for MS failure may also be excessive, exemplified by a modifier exceeding 1 in a case lacking an underground mine, which is incorrect. The possibility of missing dependencies in this context should be considered.

10.3. Sources of Discrepancies

For instance, caution is warranted when considering the baseline PoF for dams constructed outside the US. Additionally, there may be other underlying discrepancies affecting the results that are not directly evident from the analysed cases.

Discrepancies Regarding the Baseline PoF

The baseline PoF in the tool faces inaccuracies due to the incompleteness and biases within the failure database, leading to uncertainties in specific numerical values associated with the PoF. These inaccuracies not only raise concerns but also have the potential to compromise the reliability of specific numerical values associated with the PoF assessment.

The overall baseline probability of failure introduces a significant degree of uncertainty due to the lack of precise information regarding the total number of existing tailings dams. Various estimates by different authors place the number of dams within a wide range, from 3,500 to over 30,000. The estimated frequency of failures is also subject to high uncertainty, potentially underestimating the actual magnitude of failure due to unreported incidents.

When examining the distributions of dam construction methods and failure categories within the database, it becomes apparent that the distribution is relatively stable for US dams. However, for other dam construction methods, questions arise due to the scarcity of failure data. The addition of a single failure can have a substantial impact on these distributions.

Several factors contribute to the limitations in data: the lower number of existing DS, CL and WR dams, limited records predating the 1970s, reporting gaps in remote regions with limited regulatory oversight, and companies' reluctance to externally report failures, resulting in undetected incidents.

The differential detectability of various failure types may lead to over- or underrepresentation within the database. Failures like slope instability, with visible surface indicators, are more easily detected, while issues like excessive seepage can go unnoticed for extended periods. The database may contain distortions from misreported failures, such as the uncertain classification of some dams as WR dams, some of which are suspected to be starter dams.

Failures are also susceptible to being inaccurately categorised, potentially introducing errors. The absence of interdependencies between failure categories assumes that the failure categories are mutually independent. Although this enables the straightforward addition of their respective baseline PoFs, this assumption is incorrect, as demonstrated by the FTA (Figure 2.8, Page 20). The complex failure mechanisms are interrelated, sharing common root causes. Ambiguities and the absence of clear descriptions lead to varying interpretations by different classifiers. A limited understanding of the often complex failures contributes to this challenge.

Besides, there is also a notable overlap between site conditions, design elements, and the level of practice. These interdependencies are not consistently integrated into the tool, introducing potential inaccuracies in the analysis as well. Furthermore, the database contains records of very old failures, which may not reflect current industry practices. Nevertheless, this argument can be countered by acknowledging the continued existence of dams constructed using traditional methods, despite the unknown ages of these existing dams and the fact that the majority of failures occur in operational dams.

The limited frequency of observations of rare events makes it challenging to make robust statistical derivations. A more complete database, reflecting accurate distributions would be beneficial. The developed database is the best currently available, but the increasing use of satellite imagery in recent times has decreased the likelihood of failures going unnoticed, and it is anticipated that a more complete database can be developed over the coming decades.

Inaccuracies in Weights and Modifiers

The established weights and modifiers also introduce inaccuracies. One source of potential inaccuracy lies in the use of the AHP method for assigning weights to various contributing factors. While the method allows for consistency checks, the weights assigned are inherently subjective, leading to potential errors that do not reflect all situations, especially given the complexity of the scenarios.

Furthermore, discrepancies arise from the fact that the value of the modifiers is not based on empirical analysis but rather on educated guesses. These modifiers are chosen in a way that makes the baseline PoF increase or decrease by a factor of approximately 5. With lower modifiers, changes in the PoF become not apparent. However, the adverse effect appears to penalise conditions excessively. This is the logical consequence of an adverse modifier of 5 causing a more significant increase in PoF than the favourable modifier of 0.2 causing a decrease in PoF (e.g., baseline: 1x8 = 8, adverse: 5x8= 40 (+32), and 0.2x8 = 1.6 (-8.4)).

The magnitude of the unknown modifier also warrants discussion. The modifiers should perhaps differ for unknown-unknown factors (around the statistical median), while in cases of true unknowns, the modifier might even exceed that of adverse modifiers. This is because the risk of not identifying a potential hazard itself poses a significant risk. The tool currently does not distinguish between these scenarios and relies on an average expectation.

Another issue to consider is the granularity of modifiers. Currently, there are significant steps between the modifiers, and there are no intermediate options. While simplicity avoids extensive investigations like mathematical modelling, it can compromise accuracy. Introducing more options between modifiers would provide a more precise reflection of the actual situation and allow for nuanced adjustments. However, complexity brings multiple error opportunities, and as discussed earlier, additional input options may lead to decision fatigue. In addition, avoiding overly specific input options facilitates universal application across tailings dams worldwide. Balancing simplicity and precision is therefore essential.

The requirement that the sum of all weights must equal one, along with these imposed bounds, will result in underestimations and overestimations of the PoF for the worst and best-case scenarios, respectively. However, this requirement is essential for facilitating relative comparisons; otherwise, the PoF can frequently be too low or too high, making it challenging to assign accurate weights.

It is important to emphasise that the validation of the modifiers and weights is limited, and discussions are primarily grounded in just two cases. Nevertheless, these modifiers, when combined with the baseline PoF, form the fundamental working mechanism of the tool, which, inappropriately handled, could carry inherent risks.

Factors Not Considered by the Tool

Several factors are not considered in the tool, despite their potential to have a substantial impact on the PoF. First of all, the operational status is not considered, while around 75% of failures within the database occurred during the active stage. It is not integrated into the tool due to challenges associated with creating a 3D matrix of weightings and uncertainty about the distribution of existing active and inactive dams.

Furthermore, the tool focuses on the total number of TSFs, overlooking that TSFs often contain multiple individual sections, where failure typically occurs within one section. This omission contributes to a relatively high baseline PoF. The tool also disregards dam length, also impacting the PoF. Longer dams may inherently face more instability, with pronounced variability and potential weak paths in sections. Factors like corner configurations or dam intersections are also not accounted for. The tool does not fully acknowledge that failure occurs through the weakest part, it rather considers an average of favourable and adverse conditions.

As described previously, changing conditions can also significantly impact the PoF. While the site conditions are expected to remain relatively constant, the tool overlooks the potential shifts in design elements and LoP. The tool does not account for potential future changes in the expected failure frequency and the number of dams. The anticipated increase in the demand for minerals and metals suggests that the number of dams will likely rise. The failure rate may either rise, drop or remain constant. Consequently, it is imperative to periodically update these overall base rates to maintain accuracy.

For a complete ALARP evaluation, it is essential to define the consequence part of risk as well and align it with various factors and failure modes. Furthermore, it is crucial to identify all potential mitigation measures and assess how they will reduce both the PoF and the consequences. Additionally, it is necessary to identify the costs associated with these mitigation measures and establish risk thresholds and guidelines for disproportionality, although often specific to the company and the period.

10.4. Limitations and Opportunities

High uncertainties regarding the results exist. The use of numerical estimates of PoF should be approached with caution, as they can be potentially misleading and lead to decisions that do not meet the required safety standards. Quantitative data should be used in conjunction with qualitative or engineering arguments, and the tool is intended to complement sound engineering practices, not replace them. It is not meant for simple checkbox exercises but can provide valuable guidance on identifying high-risk factors and those that can significantly reduce the PoF, information that is pertinent for the ALARP assessment. This tool serves as a starting point for discussions on risk factors specific to dams and the corresponding mitigation measures. It also paves the way for industry-wide dialogues on the tool's further development.

The tool is not applicable for designing new dams, as additional considerations come into play in the design phase. However, it can highlight potential risk areas and criteria that designers should consider. A design standard may be more suitable for this purpose, with the tool serving as a support.

The tool is crucial for decision-making because constraints in available funding, time, and resources, both in terms of expertise and execution, prevent the simultaneous implementation of all mitigation measures. Selecting the right mitigation measures is crucial, as failing to address the highest risks can increase the PoF significantly. Given the catastrophic consequences, preventing such failures is a paramount goal. The biggest risk is doing nothing.

*The developed tool offers a systematic approach for PoF assessment, which could enhance the prioritisation of mitigation measures within the ALARP principle. Nevertheless, it is subject to inherent inaccuracies and uncertainties, such as a relatively high PoF, limited consideration of temporal changes, and a substantial number of inputs, some of which are challenging to obtain. These inaccuracies and uncertainties stem from discrepancies in the baseline probability of failure, weightings, modifiers, and unaccounted factors. Acknowledging these limitations is essential when interpreting results and drawing conclusions. The subsequent conclusion chapter (*Chapter 11*) will provide final insights, while* Chapter 12 *(Recommendations) will outline suggestions for tool utilisation and further development.*

11 Conclusion

In light of the occurrence of numerous catastrophic tailings dam failures, it is crucial to take steps toward enhancing the safety of tailings dam practices. The main goal of this study is to address the need for and the development of a systematic and scientifically grounded method or tool for the evaluation of the Probability of Failure (PoF) of existing tailings dams, to support the prioritisation of risk mitigation measures within the As Low As Reasonably Practicable (ALARP) principle. This chapter will conclude the study by summarising the key research findings in relation to the research aims and questions.

The stability of tailings dams is a source of significant concern due to their frequent failures, which encompass various mechanisms such as dynamic and static liquefaction, overflow, sliding, shearing, erosion, excessive seepage, and internal erosion. These failures can be triggered by numerous factors. This study identifies the main contributors: 31 related to site conditions, 54 linked to design elements, and 150 associated with the Level of Practise (LoP). The Fault Tree Analysis (FTA) identifies common root causes and underscores the complexity of failures. The failures usually result from a combination of factors rather.

Water plays a central role in numerous failure mechanisms, and assessing the water balance, considering factors like rainfall and the presence of atmospheric rivers and snowfall is vital. Other key contributors to the PoF include seismic activity in the region, artesian pressures, weak foundation and construction materials (such as strain softening, compressible, or dispersive materials) and the presence of discontinuities. The spatial and lateral variability in foundation and embankment, adjacent construction or mining activities, the condition of structures like drainage systems and spillways, and the impact of climate change are also significant. The PoF is further influenced by the level of site investigation, the extent and quality of stability and risk analysis, dam height, construction material, slope steepness and construction method. Additionally, inadequate regulation, documentation and poor monitoring contribute to the PoF. The challenges are compounded by ever-changing stress states from ongoing development over a lengthy lifespan, as well as resource constraints in terms of finances, time, and resources, including expertise. The absence of clear standards and efficient assessment methods further adds to the vulnerability of tailings dams.

Elevated concerns arise from the hazardous constituents and post-failure behaviour of tailings, in combination with significant stored volumes and projected production growth driven by mining at lower grades to meet the increasing mineral and metal demand. Meanwhile, alternative handling of tailings remains underdeveloped and costly. The rising trend of tailings dam failures underscores the imperative for enhanced risk evaluation and mitigation practices.

Within the risk management process, risks are assessed (identified, analysed and evaluated) using various methods within established frameworks. The tailings industry, for example, employs the Global Industry Standard on Tailings Management (GISTM) (GISTM, 2020) for the first time introduced in 2020 as a risk-based approach. While these frameworks offer valuable guidance, they often do not provide a clear answer to the question 'How safe is safe enough?'. To address this, principles such as ALARP are applied, also utilised by the GISTM for decision-making.

The GISTM defines risk as ALARP when all reasonable measures are taken with respect to tolerable or acceptable risks to reduce them even further until the cost and other impacts of additional risk reduction are grossly disproportionate to the benefit. ALARP offers a systematic and rational approach to prioritise risk mitigation efforts. While it is applied across various industries, there is no standardised method to demonstrate ALARP, and disproportionality is often determined through codes, standards, best practices, engineering judgement, cost-benefit analysis, peer review, benchmarking, and stakeholder consultation. Ethical considerations may play a role in the determination. Demonstrating ALARP can be resource-intensive, and the complexity of risk scenarios adds to the challenge, particularly in quantifying the components of risk; the consequences and PoF. The latter was the focus of this study.

Common methods for quantitatively determining PoF include frequency of observations, mathematical modelling, and expert judgement. However, these approaches often involve complexities, highlighting the demand for cost-effective, user-friendly, and time-efficient risk assessments for TSFs. Several authors have established relationships between e.g. the FoS and LoP, for earthen and tailings dams based on historical failure data and expert judgement. Yet, these methods are not universally applicable. They address only slope (SI) and foundation (FN) failures, neglecting the other six failure categories defined in the literature (e.g., Earthquake Induced (EQ), Overtopping (OT), Excessive Seepage and Internal Erosion (SE), External Erosion (ER), Structural Inadequacies (ST), Mine Subsidence (MS)). The site conditions and design elements are also not captured within these methods, while they are expected to impact the PoF too. Therefore, a comprehensive tool is needed to scientifically evaluate PoF across all failure categories and contributing factors, aiding in the systematic and effective ALARP demonstration and a rational risk prioritisation process.

Despite the challenges and shortcomings, the semi-quantitative approach that combines engineering judgement with observation frequency holds promise. Recognising these challenges and shortcomings leads to a set of requirements for a PoF evaluation tool. These requirements, as depicted in Figure 11.1, address comprehensiveness, prioritisation, rational decision-making, efficiency, accessibility, user-friendliness, transparency and documentation, aiming to support the scientifically grounded prioritisation of ALARP mitigation measures. These requirements form the basis of the development of a novel tool.

A total of 255 contributing factors are identified from the FTA and the GISTM requirements and linked to the failure categories for which they affect the baseline PoF. These factors are weighted relative to each dam construction method and failure category using the AHP method. To ensure the total sum of all contributing factors equals one, the weights are normalised and multiplied with the corresponding weight in the higher hierarchical level. The factor weights are adjusted by modifiers that reflect the site-specific conditions, as determined by user inputs from drop-down menus. Each input is associated with a modifier of 0.2 (favourable), 1 (neutral), 5 (adverse), or 2 (unknown). These adjusted weights are then multiplied by the baseline PoF of the relevant failure category, enabling the modification of the baseline PoF. The total PoF for the dam section under investigation is obtained by summing all the PoF for each factor and failure category.

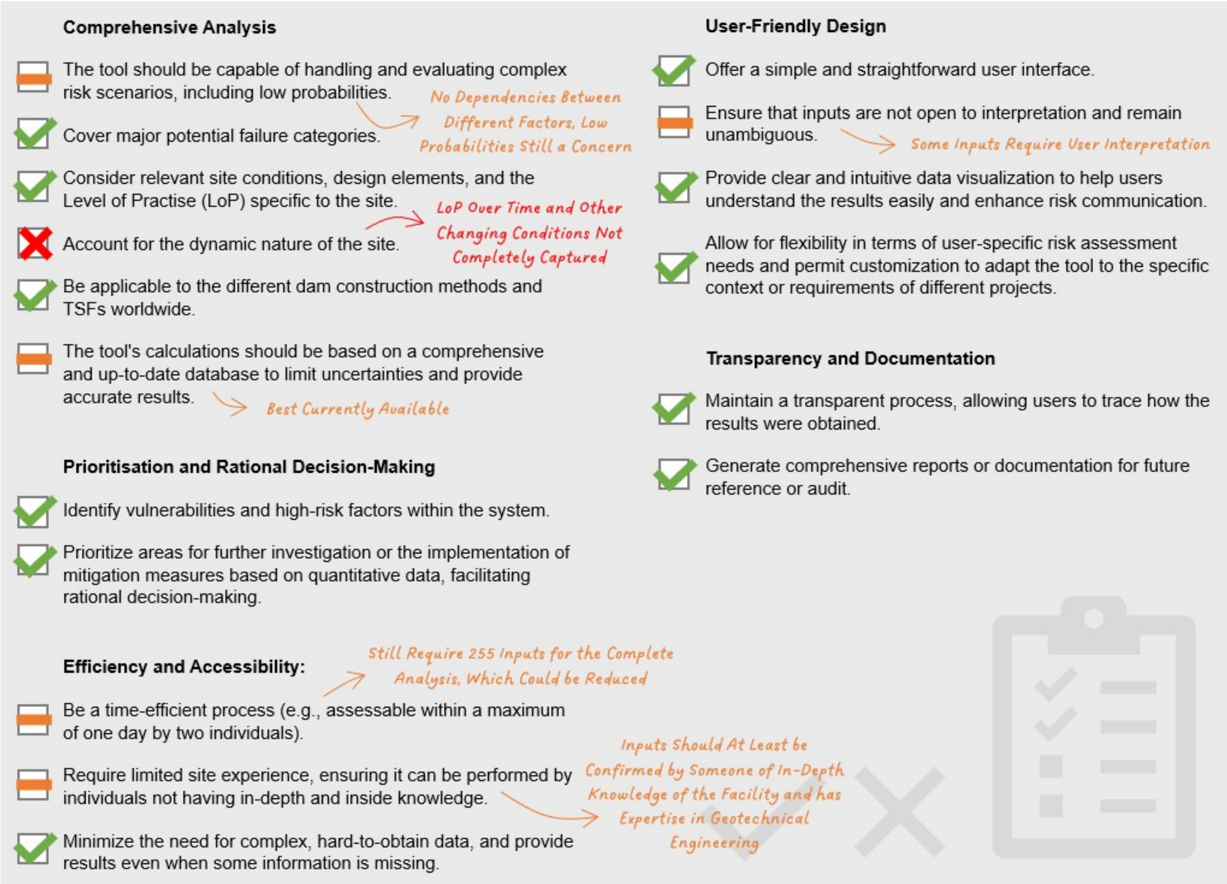


Figure 11.1: Assessment of Requirements of Tool

To validate and showcase the tool's capabilities, two cases were examined: one involving a failure scenario and another illustrating substantial enhancements. The latter case was assessed at two different points in time, before and after the improvements. While the tool exhibits promise, the analysis also uncovers weaknesses and limitations.

As depicted in Figure 11.1, the tool falls short of meeting all the established requirements. Challenges persist in managing dependencies between contributing factors and failure categories. The tool also encounters difficulties in adapting to site changes. Although improvements are noted in the contributing factors within the improvement case, their magnitude does not align with expectations given the mitigation efforts. Incorporating LoP over time presents challenges as well, which can significantly impact dam structural integrity especially when LoP was poor during initial raises. Notably, the PoF for the analysed cases exceeds the baseline PoF, which is contrary to expectations in the improvement case. There are also disparities in the weights, with some appearing too high and others too low. Further validation is required for the weights and modifiers. Moreover, while the database is the best available, uncertainties persist, introducing discrepancies in the baseline PoF. Besides, it is believed the number can be reduced further to enhance time efficiency. Distinguishing between unknown and unknown-unknown inputs could enhance the accuracy of results. Involving someone with in-depth knowledge of TSF and geotechnical engineering to confirm selected inputs is advisable, although this ideally should not be necessary. Furthermore, enhancing the input descriptions and options in the drop-down menu can reduce the need for user interpretation. The existing uncertainties and limitations underscore the challenges associated with obtaining the best estimates of the PoF.

Regardless of the remaining uncertainties and limitations, this tool demonstrates the potential to systematically and effectively assess the PoF in existing tailings dams. This supports the scientific prioritisation of mitigation measures, aligning with the ALARP principle, confirming the hypothesis. It relies on the integration of observation frequency and engineering judgement, addressing all failure mechanisms and contributing factors, rendering it an advanced solution that was not available a year ago.

The tool is not meant to replace sound expert-based engineering practices. Instead, the tool should be used to facilitate quick, preliminary insights into what factors could significantly reduce the PoF. These insights can then be linked to existing consequences and mitigation options. The reduction in risk can be weighed against mitigation costs in terms of time, effort, resources, and finances, based on which it can be confirmed whether all risks are reduced to a level of ALARP. The analytical results serve as a valuable starting point for further discussions and promote proactive risk management aiding in taking action before dam(n) big problems arise.

*While acknowledging the limitations of the developed model, this study contributes to the ongoing efforts aimed at improving the safety of tailings dams and minimising the associated risks. The tool offers a systematic and effective approach for evaluating the PoF in existing tailings dams, serving as a valuable starting point to scientifically facilitate the prioritisation of mitigation measures in line with the ALARP principle. The subsequent chapter (*Chapter 12*) provides recommendations for tool usage, as well as opportunities for potential improvement, further validation and expansion.*

12 Recommendations

This study marks progress in risk mitigation for tailings dams, a crucial factor in minimising the risk and preventing prospective future failures. Caution should be exercised in interpreting the results since improvements in the tool are needed. Further validation and verification are advised and value can be added by incorporating additional components into the tool. This chapter provides recommendations relevant to these considerations.

12.1. Utalisation of the Tool

The result obtained by the tool should be interpreted with caution, as discrepancies exist in the baseline PoF, weights, and modifiers. Besides, the tool lacks considerations for the LoP over time and the operational status of the dam, both of which can significantly impact results. It should not be treated as a simple checkbox exercise or a substitute for sound engineering practices. Instead, it is intended to highlight high-risk factors and areas necessitating further discussion and in-depth analysis using established engineering practices. It is essential to view the tool as an initial step, with ongoing development needed. An industry debate on enhancing the tool's capabilities is recommended.

It is also recommended to provide inputs in collaboration with industry experts to obtain a reliable outcome and not miss high-risk factors. The results should always be interpreted with the limitations in mind. Consider having the analysis conducted by an independent party for a more objective assessment. Honesty in the process is crucial.

While acknowledging the tool's significant potential, it is advisable not to exclusively prioritise its further development. Diversify focus to explore alternative solutions for early recognition of hazardous situations. Satellite identification, for example, presents notable opportunities, particularly for abandoned mine sites, where the tool may face challenges due to limited available information.

12.2. Improvement of the Tool

The tool is not yet in the stage of a finalised product for flawless use. Initial recommendations for improvement include streamlining the contributing factors, particularly for the LoP, by removing consistently low-impact factors. This will enhance the comprehensiveness of the model, an important requirement. It is recommended to improve the clarity of input descriptions to reduce ambiguity. Increasing the available options for each factor allows for greater precision, particularly when selections fall between two choices. This adjustment also enables finer adjustments in applying modifiers, compared to the current broad steps of favourable, neutral, and adverse. An option would be to implement a scale rather than a rigid drop-down list with fixed choices. For instance, Figure 12.1 illustrates a potential scale where users can select specific points or slide a button between markers. However, be aware of decision fatigue that may occur upon providing such a scale. Additionally, it is recommended to differentiate between 'unknown' and 'unknown-unknown,' assigning them distinct and less ambiguous labels. Possible alternatives include terms such as unidentified, unspecified, not applicable, unfamiliar, uncertain, and unexplored. It would also be worth considering providing an option for users to express their confidence in the input, as depicted in Figure 12.1.

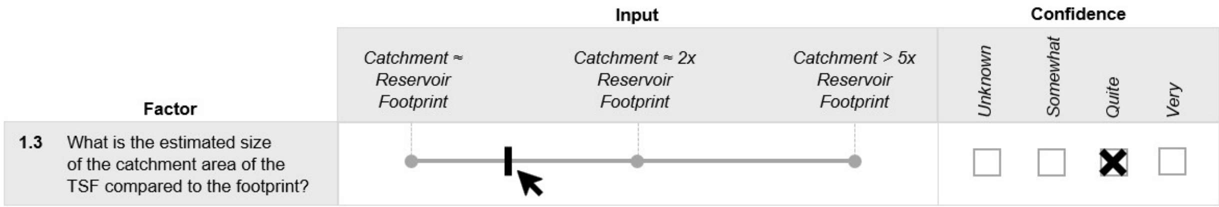


Figure 12.1: Example of Input Scale and Confidence Selection

Next, refinement of dependencies is necessary, especially within the LoP category where dependencies are currently missing. Introducing connections between inputs and weights is also suggested. For instance, in regions with high rainfall rates, the water balance level/depth may gain relatively more significance, especially in relation to overtopping, compared to arid areas. Additionally, one should explore the possibility of creating distinct failure categories according to methodologies such as FTA to allow for the inclusion of conditional probabilities. This approach mitigates the incorrect assumption of mutual independence. However, be aware that reclassifying failures within the database may pose challenges, given the limited data available for most reported cases.

Crucial for further improvement is refining the weightings and modifiers, as they form the foundation of the system. Weighting in AHP is straightforward but subjective. To mitigate subjectivity, consider involving multiple industry experts in determining weightings, possibly through methods like the Delphi technique, although this technique can be time-consuming, time which the industry may not have. Alternatively, an average of expert opinions could be considered. It is worth noting that efficiency may be enhanced by reducing the number of criteria before seeking industry input on weightings, as assessing over 2,000 matrices could be time-prohibitive. Regarding modifiers, offering more steps in input options, including less granular choices and options in between, can improve their flexibility. Additionally, exploring the use of varying magnitudes of modifiers for different factors could provide a more realistic assessment. A thorough validation of weights and modifiers is advised, as elaborated on in the following section.

Factors that are expected to have a substantial impact on the PoF, which are not currently incorporated in the tool, are advised to be implemented. First, the operational status should somehow be integrated into baseline PoF or weightings, as 75% of the failures within the database failed while they were active. This may be caused by the bathtub model, a curve illustrates the reliability of a system over time, depicting three phases—infant mortality with a higher initial failure rate, a normal life phase with a constant low failure rate, and a wear-out phase marked by an increasing failure rate due to ageing or deterioration. Therefore, it may also be interesting to investigate what the dam age does with the PoF, although Rana et al. (2022) did not find a clear correlation between dam age and failure. Secondly, addressing how the LoP changes over time is essential since it affects the PoF. For instance, even if current practices are perfect, poor construction during the initial raise can still result in instability. Thirdly, the estimation of the number of dam sections, rather than TSF, should be considered, as many TSFs consist of multiple dam sections. The current estimation of TSF numbers may lead to a higher baseline PoF than expected. Further investigation into the influence of dam section length is also warranted. Lastly, introducing a fourth category encompassing observations, in addition to site conditions, design elements, and LoP, could enhance the tool's capabilities. This would require evaluating these observations in the failure records.

The accuracy of the estimated PoF could be increased by increasing the comprehensiveness of the failure database. The high percentage of unknown failures emphasises the challenges associated with identifying and understanding the failures. Creating a more diverse dataset, although challenging, is desirable and may necessitate access to mine failure reports or leveraging efforts by organisations like ICOLD, which is currently working on a more comprehensive database of reported failures. Another option would be to include more 'mundane' incidents or accidents, as still valuable lessons can be learnt from these. A robust database would enable linking additional statistics, like dam age and country specifics, to the baseline PoF. Furthermore, coupling failure events with publicly available data, such as global rainfall or seismicity, may have a valuable contribution to the tool. Clear relationships could potentially be integrated into the tool.

Another recommendation is to make sure there are standardised reporting protocols in place, which increase transparency. This fosters improved regulatory oversight and facilitates collaboration among industry stakeholders, researchers, and government agencies for information sharing, which could lead to a more comprehensive understanding of failures, and knowledge that can be used to prevent future failures.

Maintaining detailed records of dam site conditions, design elements, and operational practices is crucial. After a failure, a thorough investigation by diverse groups should identify contributing factors and root causes for failure, considering these factors. Besides the root causes, it is recommended to standard document critical elements impacting the PoF significantly under adverse conditions to improve and extend the database, so that maybe in the future, also statistical correlations can be drawn from these elements. These critical elements include dam construction method, dam height, slope steepness, recent rainfall, available freeboard, foundation material, dam age, presence of vibrations, and monitoring instrumentation and measurements, among others. Completing the tool for each failure case allows for empirical evaluation of the weights and modifiers. If this process is applied to a sufficient number of failure cases, it becomes possible to back-calculate the weights and modifiers, further enhancing the tool's accuracy. Notably, recent and current failure case studies are generally expected to provide more available information, thus instilling higher confidence in the inputs to the tool.

Additionally, exploring lessons from dikes, which share similarities with tailings dams, could provide valuable insights for improving the tool. The Netherlands, in particular, has advanced tools and methods for evaluating dikes.

12.3. Verification and Validation

To enhance the tool's robustness, it is recommended to verify it against expectations and validate its performance across a broader range of case studies, encompassing all failure categories and construction methods. Particular attention should be given to validating the weightings and modifiers. Caution is advised when validating the overall PoF against quantitative methods like LEM, as discrepancies may arise. Incorporating a mechanism for quantifying uncertaintieswould add further value to the tool.

Conducting sensitivity analyses for different weightings, modifiers, baseline PoF, and associated distributions is advised to understand their impact on results. Such analyses can provide valuable insights into critical combinations of factors, which should be avoided in the design of new dams. For existing dams, it highlights key monitoring areas. Additionally, a sensitivity analysis sheds light on factors with negligible contributions to PoF, enabling their removal for improved comprehensiveness.

In addition to validating weights, modifiers, and uncertainties, it is advisable to examine the classification of dams as WR in the failure database. A relatively high proportion within the failure database contributes to an unexpectedly elevated baseline PoF when compared to other construction methods. This anomaly may stem from misclassifications, where starter dams or single-stage dams are erroneously labelled as WR dams. Verification of such classifications is recommended for accuracy in PoF assessments.

12.4. Further Expansion

Expanding the tool to facilitate a comprehensive ALARP evaluation could enhance its value in the industry. This would require a consequence assessment, which should of course be related to the dam construction method and failure category as well. Furthermore, mitigation options and costs should be identified. Establishing links between mitigation measures and factors influencing PoF as well as the consequences is a complex task, potentially prone to uncertainty and inaccuracy, though not deemed impossible.

Augmenting the tool's capability to be able to evaluate the design of new tailings dams would further enhance its utility. The design specifications would guide the selection of inputs, allowing testing of whether the PoF falls within an acceptable range and identifying high-risk factors. Addressing these factors before construction or implementing enhanced monitoring measures can be of great value in preventing future failures. Adapting the tool for new tailings storage facilities necessitates modifying certain inputs and identifying additional factors for consideration.

Growth Considerations

In the ongoing refinement of the tool, attention must be directed toward practical considerations as well. In the event of global deployment, it is essential to offer the tool in diverse languages and provide comprehensive training to ensure its proper utilisation while cultivating awareness of its limitations. Additionally, as the tool gains wider usage, it is recommended to transition away from the spreadsheet-based model. Instead, the development of a web-based frontend, coupled with the integration of a Structured Query Language (SQL) database, is advised, mitigating the occasional operational challenges associated with the existing spreadsheet paradigm.

An additional practical consideration involves automating outcomes to enhance risk assessment. The current tool just sorts based on high-risk factors without specifying optimal PoF reduction strategies. The rest of the process is manual, while it is desirable to establish criteria for enhancement, suggest potential mitigation measures, and assess the proportionality of such measures automatically for less resource-intensive processes. Ideally, this is further refined by the automation to the extent where users input coordinates, prompting automatic determination of climate, seismicity, rainfall, and related statistical data, thereby streamlining the risk assessment process.

Additional research potential lies in exploring the failure database and its cross-correlations, specifically in relation to existing tailings dams which did not fail. Previous attempts by various authors using earlier databases have yielded limited analyses and there is interest in the potential new insights with the more complete database presented in this study. While enhancing the model with relationships between these factors is theoretically beneficial, statistical limitations arising from relatively sparse data may render this impractical. Nevertheless, a detailed examination of cross-collaborations within the database and their relation to failure mechanisms and consequences could contribute significantly to understanding essential factors in this context.

The tool represents a positive step forward, but the current results should be approached with caution. Numerous areas for improvement exist, promising relatively feasible implementation. Additionally, rigorous verification and validation are crucial. Furthermore, there are prospects for extending the tool's capabilities, with practical considerations necessitating attention during further development.

References

Abrahamsen, E., Abrahamsen, H., Milazzo, M., & Selvik, J. (2018). Using the ALARP Principle for Safety Management in the Energy Production Sector of Chemical Industry. *Reliability Engineering & System Safety*, *169*, 160–165. https://doi.org/10.1016/j.ress.2017.08.014

Adamo, N., Al-Ansari, N., Sissakian, V., Laue, J., & Knutsson, S. (2020). Dam Safety: The Question of Tailings Dams. *Journal of Earth Sciences and Geotechnical Engineering*, *11*(1), 1–26. https://doi.org/10.47260/jesge/1111

Adams, A., & Gerritsen, T. (2021). *Can 'Alternative Tailings Disposal' Become the Norm in Mining?*

Agwe, J., Arnold, M., Buys, P., Chen, R., Deichmann, U., Dilley, M., … Yetman, G. (2005). *Natural disaster hotspots: A global risk analysis.* Retrieved from http://documents.worldbank.org/curated/en/621711468175150317/Natural-disaster-hotspots-A-global-risk-analysis

Almodóvar, G., Saéz, R., Pons, J., Maestre, A., Toscano, M., & Pascual, E. (1998). Geology and Genesis of the Aznalcóllar Massive Sulphide Deposits, Iberian Pyrite Belt, Spain. *Mineralium Deposita*, *33*(33), 111–136.

Alonso, E. (2012). *Deformation Analysis of Landslides: Progressive Failure, Rate Effects and Thermal Interactions*. CRC Press.

Alonso, E., & Gens, A. (2006a). Aznalcóllar Dam Failure. Part 1: Field Observations and Material Properties. *Géotechnique*, *56*(3), 165–183.

Alonso, E., & Gens, A. (2006b). Aznalcóllar Dam Failure. Part 2: Dynamics of the Motion. *Géotechnique*, *56*(3), 203–210.

Alonso, E., & Gens, A. (2006c). Aznalcóllar Dam Failure. Part 2: Stability Conditions and Failure Mechanism. *Géotechnique*, *56*(3), 185–201.

Araujo, F., Taborda-Llano, I., Nunes, E., & Santos, R. (2022). Recycling and Reuse of Mine Tailings: A Review of Advancements and Their Implications. *Geosciences*, *12*(9), 319. https://doi.org/10.3390/geosciences12090319

Armstrong, M., Petter, R., & Petter, C. (2019). Why Have So Many Tailings Dams Failed in Recent Years? *Resources Policy*, *63*. https://doi.org/10.1016/j.resourpol.2019.101412

Association for Project Management (APM). (n.d.). *APM Glossary of Project Management Terms.* Retrieved February 8, 2023, from https://www.apm.org.uk/resources/glossary/

Autralian National Committee on Large Dams (ANCOLD). (2012). *Guidelines on Tailings Dams: Planning, Design, Construction, Operation and Closure.*

Azam, S., & Li, Q. (2010). Tailings Dam Failures: A Review of the Last One Hundred Years. *Geotechnical News*, *28*(4), 50–54.

Badger, J., Bauwens, I., Casso, P., Davis, N., Hahmann, A., Krohn Hansen, S., … Volker, P. (2023, June). *Global Wind Atlas.* Retrieved August 4, 2023, from https://globalwindatlas.info/en/

Baecher, G., & Christian, J. (2003). *Reliability and Statistics in Geotechnical Engineering*. John Wiley & Sons Ltd.

Beck, H., Zimmermann, N., McVicar, N., T.R. Vergopolan, Berg, A., & Wood, E. (2018). Present and Future Köppen-Geiger Climate Classification Maps at 1-km Resolution. *Scientific Data*, *5*(1). https://doi.org/10.1038/sdata.2018.214

Beedle, S. (2021, November). *Demonstration of ALARP.* ABB.

Bjelkevik, A., & Knutsson, S. (2005). Swedish tailings: Comparison of mechanical properties between tailings and natural geological materials. In *International Conference on Mining and the Environment, Metals and Energy Recovery* (pp. 117–129).

Blight, G. (2009). *Geotechnical Engineering for Mine Waste Storage Facilities*. CRC Press.

Blight, G., & Bentel, G. (1983). The Behaviour of Mine Tailings During Hydraulic Deposition. *Journal of the South African Institute of Mining and Metallurgy*, *83*(4), 73–86.

Bonelli, S. (2013). *Erosion in Geomechanics Applied to Dams and Levees.* Wiley Online Library. https://doi.org/10.1002/9781118577165

Bourguignon, D. (2015, December). *The Precautionary Principl: Definitions, Applications and Governance.* European Parliamentary Research Service. https://doi.org/10.2861/821468

Bowker, L., & Chambers, D. (2015). The Risk, Public Liability, & Economics of Tailings Storage Facility Failures. *Earthwork Act*, *24*, 1–56.

Bowles, D. S. (2004). ALARP Evaluation: Using Cost Effectiveness and Disproportionality to Justify Risk Reduction. In *ANCOLD 2003 Conference on Dams* (pp. 89–104).

Brown, J., Ferrians, O., Heginbottom, J., & Melnikov, E. (2001). *Circum-Arctic Map of Permafrost and Ground-Ice Conditions.* National Snow and Ice Data Center/World Data Center for Glaciology.

Brunelli, M. (2015). Introduction and Fundamentals. *Introduction to the Analytic Hierarchy Process*.

Cacciuttolo, C., & Valenzuela, F. (2022). Efficient Use of Water in Tailings Management: New Technologies and Environmental Strategies for the Future of Mining. *Water*, *14*(11), 1741. https://doi.org/10.3390/w14111741

Caldwell, J., Oboni, F., & Oboni, C. (2015). Tailings Facility Failures in 2014 and an Update on Failure Statistics. In *Tailings and Mine Waste Conference.* https://doi.org/10.14288/1.0320843

Cambridge University Press. (n.d.). Risk. In *Cambridge Dictionary* (Online ed.). Retrieved February 8, 2023, from https://dictionary.cambridge.org/dictionary/english/risk

Casey, J. (2021, March 15). *In Numbers: How Mining Came to be Australia's Most Profitable Sector.* Retrieved 2023-10-15, from https://www.mining-technology.com/features/in-numbers-how-mining-came-to-be-australias-most-profitable-sector/

Center for Hazards and Risk Research (CHRR), Columbia University, & Center for International Earth Science Information Network (CIESIN). (2005). *Global Flood Hazard Frequency and Distribution.* NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4668B3D

Center for Hazards and Risk Research (CHRR), Columbia University, Center for International Earth Science Information Network (CIESIN), International Bank for Reconstruction and Development (The World Bank), & United Nations Environment Programme Global Resource Information Database Geneva (UNEP/GRID-Geneva). (2005). *Global Cyclone Hazard Frequency and Distribution.* NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4CZ353K

Center for Science in Public Participation (CSP2). (2023, January 31). *CSP2 Tailings Dam Failues 1915-2022.* Retrieved May 10, 2023, from http://www.csp2.org/technical-reports

Cho, G., Dodds, J., & Santamarina, J. (2006). Particle Shape Effects on Packing Density, Stiffness, and Strength: Natural and Crushed Sands. *Journal of Geotechnical and Environmental Engineering*, *132*(5), 591–602.

Chovan, K., Julien, M., Ingabire, É.-P., Masengo, E., Lépine, T., James, M., & Lavoie, P. (2021). Risk Assessment for Tailings Management. *Canadian Geotechnical Journal*, *58*(1), 1898–1914. https://doi.org/10.1139/cgj-2020-0329

Christian, J., Ladd, C., & Baecher, G. (1994). Reliability Applied to Slope Stability Analysis. *Journal of Geotechnical Engineering*, *120*(12), 2180–2207.

Costa, C. (n.d.). *Crisis Management: Vale's Brumadinho dam bursts in Brazil.* Retrieved August 08, 2023, from https://outsideinsight.com/insights/crisis-management-vales-brumadinho-dam-bursts-in-brazil/

D'Andrea, R., & Sangrey, D. (1982). Safety Factors for Probabilistic Slope Design. *Journal of the Geotechnical Engineering Division*, *108*(9), 1101–1118.

Davies, M. (2002). Tailings Impoundment Failures: Are Geotechnical Engineers Listening? *Geotechnical News Vancouver*, *20*(3), 31–36.

Davies, M., Martin, T., & Lighthall, P. (2000). Mine Tailings Dams: When Things Go Wrong. *Tailings Dams*, 261–273.

Davoudi, M. R., & Sheikhvand, K. (2012). An Approach Towards Enterprise Architecture Analysis Using AHP and Fuzzy AHP. *International Journal of Machine Learning and Computing*, *2*(1), 46.

DeCoff, S. (2022, February 8). *Australia - Mining by the Numbers 2021.* Retrieved October 15, 2023, from https://www.spglobal.com/marketintelligence/en/news-insights/research/australia-mining-by-the-numbers-2021

Dilley, M., Chen, U., Deichmann, A., Lerner-Lam, M., Arnold, J., Buys, P., … Yetman, G. (2005). *Natural Disaster Hotspots: A Global Risk Analysis.* Retrieved from http://documents.worldbank.org/curated/en/621711468175150317/Natural-disaster-hotspots-A-global-risk-analysis.

Dimitrova, R., & Yanful, E. (2012). Effect of Drainage Conditions, Bed Thickness, and Age on the Shear Strength of Mine Tailings in a Very Low Stress Range. *Canadian Geotechnical Journal*, *49*(3), 285–297.

Dobry, R., & Alvarez, L. (1967). Seismic failures of Chilean Tailings Dams. *Journal of the Soil Mechanics and Foundations Division*, *93*(6), 237–260. https://doi.org/10.1061/JSFEAQ.0001054

Donnelly, R., Jamieson, K., Stephen, C., Perkins, S., & Orton, M. (2016). A Description of Application of a New Quantitative Dam Safety Risk Screen Tool. In *47th Annual H.G. Acres Seminar 2016.* Climate Change & Waterpower-Myths, Science and Impacts.

dos Santos Vergilio, C., Lacerda, D., de Oliveira, B., Sartori, E., Munis Campos, G., de Souza Pereira, A., … de Rezende, D. (2020). Metal Concentrations and Biological Effects from One of the Largest Mining Disasters in the World (Brumadinho, Minas Gerais, Brazil). *Scientific Reports*, *10*. https://doi.org/10.1038/s41598-020-62700-w

Elements Visual Capitalist. (2021, May 15). *Visualizing the Size of The World's Mine Tailings.* Retrieved July 29, 2023, from https://elements.visualcapitalist.com/visualizing-the-size-of-mine-tailings/

Elms, D. (Ed.). (1998). *Owning the Future: Integrated Risk Management in Practsie*. Centre for Advanced Engieneering.

European Council. (2003). *Council Directive 2003/105/CE of the European Parliament and of the Council of 16 December 2003 amending Council Directive 96/82/EC on the Control of Major Accident Hazards Involving Dangerous Substances.* (Document 32003L0105)

Faber, M., & Stewart, M. (2003). Risk Assessment for Civil Engineering Facilities: Critical Overview and Discussion. *Reliability Engineering & System Safety*, *80*(2), 173–184. https://doi.org/10.1016/S0951-8320(03)00027-9

Federal Energy Regulatory Commission (FERC). (2016). *Risk-Informed Decision Making Guidelines: Risk Assessment.*

Fourie, A., Blight, G., & Papageorgiou, G. (2001). Static Liquefaction as a Possible Explanation for the Merriespruit Tailings Dam Failure. *Canadian Geotechnical Journal*, *38*(4), 707–719.

Fourie, A., Verdugo, R., Bjelkevik, A., Torres-Cruz, L., & Znidarcic, D. (2022). Geotechnics of Mine Tailings: A 2022 State of the Art. In *20th International Conference on Soil Mechanics and Geotechnical Engineering* (pp. 121–183).

Franks, D., Boger, D., Côte, C., & Mulligan, D. (2011). Sustainable Development Principles for the Disposal of Mining and Mineral Processing Wastes. *Resources Policy*, *36*(2), 114–122. https://doi.org/10.1016/j.resourpol.2010.12.001

Franks, D., Stringer, M., Torres-Cruz, L., Yuan, Q., Baker, E., Valenta, R., … Barrie, S. (2021). Tailings Facility Disclosures Reveal Stability Risks. *Scientific Reports*, *11*(1), 5353. https://doi.org/10.1038/s41598-021-84897-0

Global Seismic Hazard Assessment Program (GSHAP). (2011, November). *Global Seismic Hazard Assessment Program (GSHAP).* Retrieved August 5, 2023, from http://gmo.gfz-potsdam.de/

Global Tailings Review (GTR): International Council on Mining and Metals (ICMM, United Nations Environment Programme (UNEP), Principles for Responsible Investment (PRI). (2020). *Global Industry Standard On Tailings Management (GISTM).*

GRID-Arendal, Church of England Pensions Board, Swedish National Pension Funds'Council on Ethics, & UN Environment Programme. (2020, January 24). *Dashboard Tailings Storage Facility.* Retrieved June 20, 2023, from https://tailing.grida.no/map/analysis/

Haeri, S., Motlagh, A., Gholami, R., & Soleimani, S. (2021). Tailings Dam Failure Modes; Recognition, Prevention and Case Studies. In *International Symposium on Water and Dams* (pp. 24–27).

Halabi, A., Iacara, A., Sakano, V., Pileggi, R., & Futai, M. (n.d.). Tailings Dam Failures: A Historical Analysis of the Risk. *Journal of Failure Analysis and Prevention*, *22*(2), 464–477. https://doi.org/10.1007/s11668-022-01355-3

Hansen, M., McAndrews, C., & Berkeley, E. (2008). *History of Aviation Safety Oversight in the United States*. Office of Aviation Research and Development, Federal Aviation Administration.

Harker, P., & Vargas, L. (1990). Reply to "Remarks on the Analytic Hierarchy Process" by JS Dyer. *Management Science*, *36*(3), 269–273.

Hatch. (2022, March). *Hatch Analysis on the Effectiveness of Technologies to Reduce Mine Waste.*

Health, & (HSE), S. E. (2001). *Reducing risks, Protecting People: HSE's Decision-Making Process*.

Health and Safety Executive (HSE). (2004). *Investigating Accidents and Incidents: A Workbook for Employers, Unions, Safety Representatives and Safety Professionals.*

Hurst, J., McIntyre, J., Tamauchi, Y., Kinuhata, H., & Kodama, T. (2019). A Summary of the'ALARP' Principle and Associated Thinking. *Journal of Nuclear Science and Technology*, *56*(2), 241–253. https://doi.org/10.1080/00223131.2018.1551814

Institute of Risk Management (IRM). (2002). *A Risk Management Standard.*

International Commission on Large Dams (ICOLD). (2001). *Tailings Dams, Risk of Dangerous Occurrences: Lessons Learnt from Practical Experiences.* ((Bulletin 121))

International Commission on Large Dams (ICOLD). (2005). *Risk Assessment in Dam Safety Management: A Reconnaissance of Benefits, Methods and Current Applications.*

International Commission on Large Dams (ICOLD). (2019). *Tailings dam design: Technology update.*

International Commission on Large Dams (ICOLD). (2020). *Tailings dam safety.*

International Council on Mining and Metals (ICMM). (2021). *Tailings management: Good practise.*

International Council on Mining and Metals (ICMM). (2022). *Tailings reduction roadmap.*

International Organization for Standardization (ISO). (2018). *Risk Management Guidelines.* (ISO Standard No. 31000:2018 (2))

Islam, K., & Murakami, S. (2021). Global-Scale Impact Analysis of Mine Tailings Dam Failures: 1915–2020. *Global Environmental Change*, *70*. https://doi.org/10.1016/j.gloenvcha.2021.102361

James, M., Aubertin, M., Wijewickreme, D., & Wilson, G. W. (2011). A Laboratory Investigation of the Dynamic Properties of Tailings. *Canadian Geotechnical Journal*, *48*(11), 1587–1600. https://doi.org/10.1139/t11-060

Jarvie-Eggart, M. (2015). *Responsible Mining: Case Studies in Managing Social & Environmental Risks in the Developed World*. Society for Mining, Metallurgy & Exploration.

Jiménez, M., Salvador, M., Gargallo, P., & Altuzarra, A. (2016). Systemic Decision Making in AHP: a Bayesian Approach. *Annals of Operations Research*, *245*, 261–284.

Jones-Lee, M., & Aven, T. (2011). ALARP—What Does it Really Mean? *Reliability Engineering & System Safety*, *96*(8), 877–882. https://doi.org/10.1016/j.ress.2011.02.006

Julien, M., Masengo, E., Lavoie, P., & Lepine, T. (2019). A Risk-Based Approach to Support the Implementation of the New Guidelines Related to Tailings Management. In *Proceedings of the 6th International Seminar on Tailings Management, Santiago, Chile* (pp. 10–12).

Kadoić, N., Begičević Ređep, N., & Divjak, B. (2017). Decision Making with the Analytic Network Process. In *Proceedings of the 14th International Symposium on Operational Research* (pp. 180–186).

Kaplan, S., & Garrick, B. (1981). On the Quantitative Definition of Risk. *Risk Analysis*, *1*(1), 11–27. https://doi.org/10.1111/j.1539-6924.1981.tb01350.x

Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikytö-Reponen, P., & Mäkinen, J. (2022). A Review of Circular Economy Strategies for Mine Tailings. *Cleaner Engineering and Technology*, *8*, 100499. https://doi.org/10.1016/j.clet.2022.100499

Kulhawy, F., & Phoon, K. (1996). Engineering Judgment in the Evolution from Deterministic to Reliability-Based Foundation Design. In *Proceedings of Uncertainty* (pp. 29–48).

Lambe, T. (1985). Amuay landslides. In *11th International Conference on Soil Mechanics and Foundation Engineering, Golden Jubilee Volume, San Francisco, Balkema, Boston* (pp. 137–158).

Leonards, G. (1982). Investigation of Failures. Sixteenth Terzaghi Lecture. *ASCE Journal of Geotechnical Engineering*, *108*(GT2), 224–283.

Liang, T., Werner, T., Heping, X., Jingsong, Y., & Zeming, S. (2021). A Global-Scale Spatial Assessment and Geodatabase of Mine Areas. *Global and Planetary Change*, *204*, 103578. https://doi.org/10.1016/j.gloplacha.2021.103578

Lin, S., Wang, G., Liu, W., Zhao, B., Shen, Y., Wang, M., & Li, X. (2022). Regional Distribution and Causes of Global Mine Tailings Dam Failures. *Metals*, *12*(6), 905. https://doi.org/10.3390/met12060905

Liu, F., Peng, Y., Zhang, W., & Pedrycz, W. (2017). On Consistency in AHP and Fuzzy AHP. *Journal of Systems Science and Information*, *5*(2), 128–147. https://doi.org/10.21078/JSSI-2017-128-20

Lottermoser, B. (2011). Recycling, Reuse and Rehabilitation of Mine Wastes. *Elements*, *7*(6), 405–410. https://doi.org/10.2113/gselements.7.6.405

Luko, S. (2014). Risk Assessment Techniques. *Quality Engineering*, *26*(3), 379–382. https://doi.org/10.1080/08982112.2014.875769

Lyu, Z., Chai, J., Xu, Z., Qin, Y., & Cao, J. (2019). A Comprehensive Review on Reasons for Tailings Dam Failures Based on Case History. *Advances in Civil Engineering*, *2019*. https://doi.org/10.1155/2019/4159306

Maciotta, R., & Lefsrud, L. (2018). Framework for Dedeveloping Risk to Life Evaluation Criteria Associated with Landslides in Canada. *Geoenvironmental Disasters*, *5*(10). https://doi.org/10.1186/s40677-018-0103-7

Martin, T., & Davies, M. (2022). Trends in the Stewardship of Tailings Dams. In *Tailings and Mine Waste 2000* (pp. 393–407). CRC Press.

Martin, T., & McRobers, E. (1999). Some Considerations in the Stability Analysis of Upstream Tailings Dams. In *Proceeding Tailings and Mine Waste* (p. 287).

Martí, J., Riera, F., & Martínez, F. (2021). Interpretation of the Failure of the Aznalcóllar Tailings Dam. *Mine Water and the Environment*, *40*(1), 189–208. https://doi.org/10.1007/s10230-020-00712-8

Maus, V., Giljum, S., Gutschlhofer, J., da Silva, D., Probst, M., Gass, S., … McCallum, I. (2020). A Global-Scale Data Set of Mining Areas. *Scientific Data*, *7*(1). https://doi.org/10.1038/s41597-020-00624-w

Meilli, F. (2016, February 19). *5 Reasons Why the World Needs Mining and Always Will.* Retrieved May 30, 2022, from https://blog.se.com/mining-metals-minerals/2016/02/19/5-reasons-why-the-world-needs-mining-and-always-will/

Melchers, R. (2001). On the ALARP Approach to Risk Management. *Reliability Engineering & System Safety*, *71*(2), 201–208. https://doi.org/10.1016/S0951-8320(00)00096-X

Miller, K. (2018). Quantifying Risk and How It All Goes Wrong. In *Symposium Hazards 28.*

Miller, K. (2019). Constructing a Legally Sound Demonstration of ALARP. In *Symposium Hazards 29* (Vol. 166).

Mining, Minerals and Sustainable Development (MMSD). (2002). *Large Volume Waste Paper.*

Morgenstern, N. (1995). Managing Risk in Geotechnical Engineering. In *10th Pan American Conference on Soil Mechanics and Foundation Engineering* (pp. 102–126).

Morgenstern, N., Vick, S., Viotti, C., & Watts, B. (2016). Fundão Tailings Dam Review Panel Report on the Immediate Causes of the Failure of the Fundão Dam. *Cleary Gottlieb Steen & Hamilton LLP, New York*.

Mu, E., & Pereyra-Rojas, M. (2016). *Practical decision making: an introduction to the Analytic Hierarchy Process (AHP) using super decisions V2*. Springer.

Mudd, G. (2016). The McArthur River project: The Environmental Case for Complete Pit Backfill. *Mineral Policy Institute*.

Munier, N., & Hontoria, E. (2021). Shortcomings of the AHP Method. In *Uses and Limitations of the AHP Method.* Springer. https://doi.org/10.1007/978-3-030-60392-2

Oboni, F., & Oboni, C. (2013, July 1). *What You Need to Know About Risk Management Methods.*

Oboni, F., & Oboni, C. (2016). A Systemic Look at Tailings Dams Failure Process. In *Tailings and Mine Waste Conference* (pp. 2–5).

Oboni, F., & Oboni, C. (2020). *Tailings Dam Management for the Twenty-First Century: What Mining Companies Need to Know and Do to Thrive in Our Complex World*.

Ocampo, L. (2019). Decision Modeling for Manufacturing Sustainability with Fuzzy Analytic Hierarchy Process. *Global Business Review*, *20*(1), 25–41. https://doi.org/10.1177/0972150917736990

Oguztimur, S. (2011, September). *Why Fuzzy Analytic Hierarchy Process Approach For Transport Problems?* (ERSA conference papers No. ersa11p438). Retrieved from https://ideas.repec.org/p/wiw/wiwrsa/ersa11p438.html

Oldenburg, C., & Budnitz, R. (2016). Low-Probability High-Consequence (LPHC) Failure Events in Geologic Carbon Sequestration Pipelines and Wells: Framework for LPHC Risk Assessment Incorporating Spatial Variability of Risk. Energy Geosciences Division Lawrence Berkely National Laboratory. https://doi.org/10.2172/1332329

Ostrom, L., & Wilhelmsen, C. (2019). (2nd ed.). John Wiley & Sons. Retrieved from https://app.knovel.com/hotlink/khtml/id:kt0125ND81/risk-assessment-tools/monte-carlo-analysis

Owen, J., Kemp, D., Lèbre, E., Svobodova, K., & Pérez Murillo, G. (2020). Catastrophic Tailings Dam Failures and Disaster Risk Disclosure. *International Journal of Disaster Risk Reduction*, *42*, 101361. https://doi.org/10.1016/j.ijdrr.2019.101361

Oxford Languages. (2003). Risk. In C. Soanes & A. Stevenson (Eds.), *Oxford English Dictionary* (2nd ed.). Oxford University Press.

Pan, H., Zhou, G., Cheng, Z., Yang, R., He, L., Zeng, D., & Sun, B. (2014). Advances in Geochemical Survey of Mine Tailings Project in China. *Journal of Geochemical Exploration*, *139*, 193–200. https://doi.org/10.1016/j.gexplo.2013.07.012

Peter, H., Bowles, D., Jordan, P., & Nathan, R. (2003). Estimating Overall Risk of Dam Failure: Practical Considerations in Combining Failure Probabilities. In *ANCOLD 2003 Risk Workshop.*

Piciullo, L., Storrøsten, E., Liu, Z., Nadim, F., & Lacasse, S. (2022). A New Look at the Statistics of Tailings Dam Failures. *Engineering Geology*, *303*, 106657. https://doi.org/10.1016/j.enggeo.2022.106657

Porter, M., Russell, B., & Watts, B. (2023). Using Statistics and Judgment to Generate Screening-Level Estimates of Tailings Dam Risk. In *Proceedings of Tailings and Mine Waste 2023.*

Project Management Institute (PMI). (2013). *A Guide to the Project Management Body of Knowledge (PMBOK Guide).*

Quddus, N., Su-Feher, D., Gordon, C., & SHarma J. O'Brien, T. (2020, Januray). *Risk Acceptance Criteria: Overview of ALARP and Similar Methodologies as Practised Worldwide.* Mary Kay O'Connor Process Safety Center, Texas A&M Engineering Experiment Station.

Rana, N., Ghahramani, N., Evans, S., McDougall, S., Small, A., & Take, W. (2021). Catastrophic Mass Flows Resulting from Tailings Impoundment Failures. *Engineering Geology*, *292*, 106262. https://doi.org/10.1016/j.enggeo.2021.106262

Rana, N., Ghahramani, N., Evans, S., Small, A., Skermer, N., McDougall, S., & Take, W. (2022). Global Magnitude-Frequency Statistics of the Failures and Impacts of Large Water-Retention Dams and Mine Tailings Impoundments. *Earth-Science Reviews*, *232*, 104144. https://doi.org/10.1016/j.earscirev.2022.104144

Redmill, F. (2010, March). *ALARP Explored.* Computing Science University of Newcastle.

Rico, M., Benito, G., Salgueiro, A., Díez-Herrero, A., & Pereira, H. (2007). Reported Tailings Dam Failures. A Review of the European Incidents in the Worldwide Context. *Journal of Hazardous Materials*, *152*(2), 846–852. https://doi.org/10.1016/j.jhazmat.2007.07.050

Ridlen, P., & Coffin, J. (2020). Tailings and Water Management. In H. N. Dougherty & A. P. Schissler (Eds.), *SME Mining Reference Handbook* (2nd ed.). Society for Mining, Metallurgy & Exploration (SME), Incorporated.

Risktec Essentials. (2018). *Risk-Based Decision Making and ALARP: An Introduction to Making Risk-Based Decisions and Reducing Risks As Low As Reasonably Practicable.* Risktec TUV Rheinland.

Roca, M., Murphy, A., Walker, L., & Vallesi, S. (2019, January). *A Review of the Risks Posed by the Failure of Tailings Dams.*

Roche, C., Thygesen, K., & Baker, E. (Eds.). (2017). *Mine Tailings Storage: Safety is No Accident*. United Nations Environment Programme (UNEP) and GRID-Arendal.

Rodrigues, J., & Edeskär, T. (2013). Case of Study on Particle Shape and Friction Angle on Tailings. *Journal of Advanced Science and Engineering*, *3*(4), 373–387.

Saaty, T. (1980). The Analytic Hierarchy Process. In *McGraw-Hill, New York.*

Saaty, T., & Vargas, L. (2006). *Decision Making with the Analytic Network Process*. Springer.

Saaty, T., & Vargas, L. (2012). *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*. Springer Science & Business Media.

Sanz-Ramos, M., Bladé, E., Dolz, J., & Sánchez-Juny, M. (2022). Revisiting the Hydraulics of the Aznalcóllar Mine Disaster. *Mine Water and the Environment*, *41*(2), 335–356. https://doi.org/10.1007/s10230-022-00863-w

Schafer, H., Beier, N., & Macciotta, R. (2021). A Failure Modes and Effects Analysis Framework for Assessing Geotechnical Risks of Tailings Dam Closure. *Minerals*, *11*(11). https://doi.org/10.3390/min11111234

Sharma, R. (2013). Case Histories of Earthen Dam Failures. In *International Conference on Case Histories in Geotechnical Engineering.*

Silva, F., Lambe, T., & Marr, W. (2009). Probability and Risk of Slope Failure. *Journal of Geotechnical and Geoenvironmental Engineering*, *134*(12), 1691–1699. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:12(1691)

Singh, R., & Herza, J. (2019). Development of a Preliminary Risk Assessment Tool for a Portfolio of TSFs with Limited and Uncollated Data. In *Conference Proceeding of ICOLD 2019 Annual Symposium.*

Sonter, L., Dade, M., Watson, J., & Valenta, R. (2020). Renewable Energy Production Will Exacerbate Mining Threats to Biodiversity. *Nature Communications*, *11*, 4174. https://doi.org/10.1038/s41467-020-17928-5

Spencer, D., Hatton, C., Bareither, C., Ward, K., & Scalia IV, J. (2021). Deck Hands Needed! Experience Necessary – Addressing the Impeding Qualified Tailings Professional Resource Shortage. In *International Symposium on Water and Dams.*

Stark, T., Moya, L., & Lin, J. (2022). Rates and Causes of Tailings Dam Failures. *Advances in Civil Engineering*, *2022*. https://doi.org/10.1155/2022/7895880

Statista Research Department. (2013, March 19). *Duration of the Extraction Period of a Mine by Selected Commodities.* Retrieved November 20, 2023, from https://www.statista.com/statistics/255479/mine-life-per-commodity/

Strachan, C., & Goodwin, S. (2015). The Role of Water Management in Tailings Dam Incidents. In *Proceedings Tailings and Mine Waste 2015.*

Syed, Z., & Lawryshyn, Y. (2020). Multi-Criteria Decision-Making Considering Risk and Uncertainty in Physical Asset Management. *Journal of Loss Prevention in the Process Industries*, *65*, 104064.

Taherdoost, H. and Madanchian, M. (2023). Multi-Criteria Decision Making (MCDM) Methods and Concepts. *Encyclopedia*, *3*(1), 77–87. https://doi.org/10.3390/encyclopedia3010006

Tang, W., Duncan, J., Cornell, C., Gardner, W., Rosenblueth, E., Schuster, R., … Mitchell, J. (1995). *Probabilistic Methods in Geotechnical Engineering*. The National Academies Press. https://doi.org/10.17226/9476

Tavares, L., & Serafim, J. (1983). Probabilistic Study on Failure of Large Dams. *Journal of Geotechnical Engineering*, *109*(11), 1483–1486.

The Canadian Standards Association (CSA). (2022). *Occupational Health and Safety: Hazard Identification and Elimination and Risk Assessment and Control.*

The National Institute for Occupational Safety and Health (NIOSH). (2023). *Hierarchy of Controls.* Retrieved May 20, 2023, from https://www.cdc.gov/niosh/topics/hierarchy/

The National Institute for Occupational Safety and Health (NIOSH) Mining. (2021). *Number of Active Mines By Sector and Year.* Retrieved June 20, 2023, from https://wwwn.cdc.gov/NIOSH-Mining/MMWC/Mine

United Nations Environment Programme (UNEP). (1996). *Environmental and Safety Incidents Concerning Tailings Dams at Mines: Results of a Survey for the Years 1980-1996 by the Mining Journal Research Services.*

United States Committee on Large Dams (USCOLD). (1994). *Tailings dams incidents.*

U.S. Bureau of Economic Analysis. (2023, September 28). *Value added by Industry as a Percentage of Gross Domestic Product.* Retrieved October 15, 2023, from https://apps.bea.gov/iTable/?reqid=150&step=2&isuri=1&categories=gdpxind

US Environmental Protection Agency (US EPA). (1994). *Design and Evaluation of Tailings Dams.*

Vanden Berghe, J., Ballard, J., Jewell, R., Pirson, M., & Uwe, R. (2009). Importance of Shear Stress Anisotropy and Bottom Drainage on Tailings Dam Stability: A Case History. In *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering (ISSMGE)* (pp. 1626–1629). https://doi.org/10.3233/978-1-60750-031-5-1626

Vanden Berghe, J., Ballard, J., Wintgens, J., & List, B. (2011). Geotechnical Risks Related to Tailings Dam Operations. In *Proceedings Tailings and Mine Waste.*

Van Zyl, D., Sassoon, M., Digby, C., Fleury, A., & Kyeyune, S. (2002). Mining for the Future. *International Institute for Environment and Development, World Business Council for Sustainable Development*, *68*, 31.

Vermeulen, N. (n.d.). *The Composition and State of Tailings.* [Doctoral Dissertation, Pretoria University].

Vick, S. (1990). *Planning, Design, and Analysis of Tailings Dams* (2nd ed.). BiTech Publishers Ltd.

Vick, S. (1994). Geotechnical Risk and Reliability: From Theory to Practice in Dam Safety. In *Proceedings Earth, Engineers, and Education* (pp. 45–58).

Villavicencio, G., Espinace, R., Palma, J., Fourie, A., & Valenzuela, P. (2014). Failures of Sand Tailings Dams in a Highly Seismic Country. *Canadian Geotechnical Journal*, *51*(4), 449–464. https://doi.org/10.1139/cgj-2013-0142

Vlek, C., & Stallen, P. (1980). Rational and Personal Aspects of Risk. *Acta Psychologica*, *45*(1-3), 273–300.

Waldek, S. (2000, February 26). *Upstream Tailings Dam Raises – Safe or Unsafe.* Retrieved December 20, 2022, from https://www.linkedin.com/pulse/upstream-tailings-dam-raises-safe-unsafe-stefan-waldek/

Wang, L., Ji, B., Hu, Y., Liu, R., & Sun, W. (2017). A Review on in Situ Phytoremediation of Mine Tailings. *Chemosphere*, *184*, 594–600. https://doi.org/10.1016/j.chemosphere.2017.06.025

Warburton, M., Hart, S., Ledur, J., Scheyder, E., & Levine, A. (2020). *The Looming Risks of Tailings Dams.* Retrieved May 30, 2022, from https://graphics.reuters.com/MINING-TAILINGS1/0100B4S72K1/index.html

Watari, T., Nansai, K., & Nakajima, K. (2021). Major Metals Demand, Supply, and Environmental Impacts to 2100: A Critical Review. *Resources, Conservation and Recycling*, *164*, 105107. https://doi.org/10.1016/j.resconrec.2020.105107

Watson, A., Corser, P., Garces Pardo, E., Lopez Christian, T., & Vandekeybus, J. (2010). A Comparison of Alternative Tailings Disposal Methods: The Promises and Realities. In *Mine Waste 2010: Proceedings of the First International Seminar on the Reduction of Risk in the Management of Tailings and Mine Waste* (pp. 499–514).

Wei, Z., Yin, G., Wang, J., Wan, L., & Li, G. (2013). Design, Construction and Management of Tailings Storage Facilities for Surface Disposal in China: Case Studies of Failures. *Waste management & Research: the Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *31*(1), 106–112. https://doi.org/10.1177/0734242X12462281

Williams, D. (2021). Lessons from Tailings Dam Failures—Where to Go from Here? *Minerals*, *11*(8). https://doi.org/10.3390/min11080853

World Information Service on Energy (WISE). (2023, April 18). *Chronology of Major Tailings Dam Failures.* Retrieved May 15, 2023, from http://www.wise-uranium.org/mdaf.html

World Mine Tailings Failures (WMTF). (2019, May 20). *World Mine Tailings Failures from 1915: Supporting Global Research in Tailings Failure Root Cause, Loss Prevention and Trend Analysis.* Retrieved May 16, 2023, from https://www.resolutionmineeis.us/sites/default/files/references/bowker-2019.pdf

Yin, G., Li, G., Wei, Z., Wan, L., Shui, G., & Jing, X. (2011). Stability Analysis of a Copper Tailings Dam via Laboratory Model Tests: A Chinese Case Study. *Minerals Engineering*, *24*(2), 122–130. https://doi.org/number10.1016/j.mineng.2010.10.014

Zardari, M. (n.d.). *Stability of Tailings Dams: Focus on Numerical Modelling.* Licentiate Thesis, Lulea University of Technology, Sweden.

A

Database

The created database is presented in Appendix A.1 **(**Page 128**). Subsequently, incident descriptions are provided in** Appendix A.2 **(**Page 141**) and its references in** Appendix A.2.2 **(**Page 170**). Additionally, geographical statistics of the database are displayed on a map in** Appendix A.3 **(**Page 176**), and cross-correlations between different attributes are illustrated in** Appendix A.3 **(**Page 181**).**

A.1. Database

The database is a compilation of existing databases on tailings dam failures. It combines the ICOLD (2001) database (1915-2001), which includes USCOLD (1994) (1915-1989) and UNEP (1996) (1980-1996), with the databases of WISE (2023) (1960-2023), WMTF (2019) (1915-2019), and (1915-2023). This results in a comprehensive database that records 450 incidents and accidents. For each record, it is indicated in which of the existing databases the failure is recorded.

The attributes within the database can be categorised into:

- **General Dam Information**: ID, Name(/Owner), Location, Year of Occurrence, Deposit Type, Ore Type, Dam Construction Method, Dam Height and Storage Volume
- **Failure Type:** Event Classification, Operational Status and Failure Category
- **Impacts:** Release Volume, Runout, Fatalities and Severity

In cases where a failure is reported in two databases, and the information does not align, corrections are implemented using one of the following methods: correction from sources, assumption of human error, averaging, relying on the most reliable information, majority consensus, or making an educated guess based on the worst-case scenario, as explained in Section 5.2.

Within the database, the following abbreviations are utilised.

Deposit Type

HT Manto	High-Temperature Manto
PC	Porphyry Copper
VMS	Volcanic Massive Sulphide
SSC	Sediment Hosted Copper

Dam Fill Material

T	Tailings
E	Earthfill
R	Rockfill
MW	Mine Waste
CST	Cycloned Sand Tailings

Dam Construction Method

US	Upstream
DS	Downstream
CL	Centreline
WR	Water Retention

Event Classification

1	Accident
2	Incident
3	Groundwater Issue
U	Unknown

Operational Status

A	Active
B	Inactive
U	Unknown

Failure Category

EQ	Earthquake Induced
OT	Overtopping
SI	Slope Instability
FN	Foundation Deficiency
SE	Excessive Seepage and Internal Erosion
ER	External Erosion
ST	Structural Inadequacies
MS	Mine Subsidence

severity

1	Very Serious
2	Serious
3	Minor
4	Potential

Table A.1: Database

I. General Dam Information																	II. Failure Type			III. Impacts			
ID	CSP22	WISE	WMT	ICOLD	ICOLD ID	UNEP	USCOLD	Name/Location (Owner)	Location	Year of Occurrence	Deposit Type	Ore Type	Dam Fill Material	Dam Construction Method	Dam Height	Storage Volume (m^3)	Event Classification	Operational Status	Failure Category	Release Volume (m^3)	Runout (m)	Fatalities	Severity
1	Y	N	Y	N	-	N	N	Agua Dulce, Sewell, VI Region, Rancagua	Chile	1915	PC	Cu			61		1	A	OT	180,000			2
2	Y	N	Y	Y	136	Y	N	Unidentified	South Africa	1917		Au					1	A	U	180,000			3
3	Y	N	Y	Y	9	Y	N	Barahona	Chile	1928	PC	Cu	CST	US	61	20,000,000	1	A	EQ	3,250,000		54	1
4	Y	N	Y	Y	110	Y	N	Simmer and Jack	South Africa	1937	Wits	Au	T	US			1	A	SI	2,800,000		2	2
5	Y	N	Y	N	-	N	N	Los Cedros, Tlalpujahua, Michoacán	Mexico	1937	Wits	Au/Ag	T	US	35	10,000,000	1	B	ST	2,500,000	1,100	300	1
6	Y	N	N	Y	21	Y	N	Captains Flat Dump 6A	Australia	1939		Cu	T	US			1	A	SI				3
7	Y	N	N	N	-	N	N	Abercyon	UK	1939		Coal			37		1	A	SI	164,000	600		2
8	Y	N	Y	Y	115	Y	N	St. Joe Lead, Flat Missouri	USA	1940		Pb	T	US	15		1	A	OT	10,000,000			2
9	Y	N	Y	Y	62	Y	N	Kennecott, Garfield, Utah	USA	1941	PC	Cu	T	US			1	A	SI				3
10	Y	N	Y	Y	20	Y	N	Captains Flat Dump 3	Australia	1942	PC	Cu	T				1	A	U	40,000			3
11	Y	N	Y	Y	63	Y	N	Kennecott, Utah	USA	1942	PC	Cu	T	US			1	A	FN				3
12	Y	N	Y	Y	58	Y	N	Hollinger	Canada	1944	Vein	Au	T	US	15		1	A	FN	40,000			3
13	Y	N	N	N	-	N	N	Tip No. 4	UK	1944		Coal			46	1,550,000	1	A	SI		700		4
14	Y	N	Y	Y	25	Y	N	Castle Dome, Arizona	USA	1947	PC	Cu	T	US			1	A	SE	150,000	100		3
15	Y	N	Y	Y	66	Y	N	Sullivan Mine, Kimberley, Britisch Columbia	Canada	1948	VMS	Fe	T	US			1	A	SI	1,100,000			2
16	Y	N	Y	Y	166	Y	N	Unidentified, Peace River, Florida	USA	1951	Stratified	P	MW	WR	30		1	A	SE				3
17	Y	N	Y	Y	167	Y	N	Unidentified, Peace River, Florida	USA	1951	Stratified	P	MW	WR	6		1	A	SE				3
18	Y	N	Y	Y	168	Y	N	Unidentified, Peace River, Florida	USA	1951	Stratified	P	E	DS			1	A	SE	1,100,000			2
19	Y	N	Y	N	-	N	N	Casapulca, Minera Del Centro Peru, Huarochiri Province	Peru	1952		Cu/Ag/Pb/Zn	T	US	60		1	B	EQ			Y	2
20	Y	N	Y	Y	165	Y	N	Unidentified, Peace River, Florida	USA	1952	Stratified	P	E	WR	8		1	A	SI				3
21	Y	N	Y	Y	156	Y	N	Unidentified, Alfaria River, Florida	USA	1952	Stratified	P	E	WR	8		1	A	SI				3
22	Y	N	Y	Y	54	Y	N	Grootvlei	South Africa	1956	Wits	Au	T	US			1	A	SI				3
23	Y	N	Y	N	-	N	N	Milpo	Peru	1956	Wits	Au		US	60		1	B	EQ			Y	2
24	Y	N	Y	N	-	N	N	Mailuu-Suu	Kyrgyzstan	1958		U				1,200,000	1	A	EQ	600,000	40,000	3	2
25	Y	N	Y	Y	170	Y	N	Union Carbide, Green River, Utah	USA	1959		U					1	A	OT	8,400			3
26	Y	N	Y	Y	72	Y	N	Lower Indian Creek, Montana	USA	1960		Pb	E	US			2	A	SI	8,400			3
27	Y	N	Y	N	-	N	N	La Luciana, Reocín, Cantabria	Spain	1960		Pb	T	US	24	1,250,000	1	A	SI	2,000,000	500	18	2
28	Y	N	Y	N	-	N	N	Jupille	Belgium	1961		Coal			46	550,000	1	A	SE	136,000	600	11	2
29	Y	Y	Y	Y	124	Y	N	Tymawr 1	UK	1961	Stratified	Coal					1	A	OT		800		3
30	Y	N	Y	Y	171	Y	N	Union Carbide, Maybell, Colorado	USA	1961	Stratified	U					1	A	U	280			3

31	Y	N	Y	Y	3	Y	N	American Cyanamid, Florida	USA	1962	Stratified	Gypsum					1	A	U	37,854			1
32	Y	Y	Y	Y	135	Y	N	Quiruvilca mine, Almivirca Tailings Dam	Peru	1962		Cu/Ag/Pb/Zn			40		1	A	EQ	11,356,230			3
33	Y	N	Y	Y	80	Y	N	Mines Development, Edgemont, South Dakota	USA	1962		U					1	A	U	100	40,000		2
34	Y	Y	Y	N	-	N	N	Huogudu, Yunnan Tin Group Co. Yunnan	China	1962	Stratified	Sn		US	19	5,420,000	1	A	U	3,300,000	4,750	171	1
35	Y	N	N	N	-	N	N	Louisville	USA	1963		Carbide			31	910,000	1	A	SE	667,000	100		2
36	Y	N	Y	Y	174	Y	N	Utah Construction, Riverton, Wyoming	USA	1963		U					2	A	OT	100			3
37	N	Y	N	N	-	N	N	El Descargador, Cartagena-La Unión, Murcia Province, Bell	Spain	1963		Fe/Zn/Pb/Ag					1	U	SI	66,000			U
38	Y	N	Y	N	-	N	N	Castano Viejo Mine, San Juan	Argentina	1964		Pb/Zn/Cu/Ag	T	Wood	9	26,500	1	A	SE	17,250	2,100	3	2
39	Y	N	Y	Y	2	Y	N	Alcoa, Texas	USA	1964		Al			19	4,500,000	1	A	U				3
40	Y	N	Y	Y	4	Y	N	American Cyanamid, Florida 2	USA	1965	Stratified	P					1	A	U				3
41	Y	N	Y	Y	89	Y	N	N'yukka Creek	USSR	1965	Stratified		E	WR	12		2	A	FN				3
42	Y	N	Y	Y	150	Y	N	Unidentified, Idaho	USA	1965		P	E	DS	18		2	A	SI				3
43	Y	Y	Y	Y	12	Y	N	Bellavista	Chile	1965	HT Manto	Cu	T	US	20	450,000	1	A	EQ	70,000	900		3
44	Y	N	Y	Y	26	Y	N	Cerro Blanco de Polpaico	Chile	1965	Stratified	Limestone	R	WR	9		2	A	EQ				3
45	Y	N	Y	Y	27	Y	N	Cerro Negro No. 1	Chile	1965		Cu	T	US	46		2	B	EQ				3
46	Y	N	Y	Y	28	Y	N	Cerro Negro No. 2	Chile	1965		Cu	T	US	46		2	B	EQ				3
47	Y	Y	Y	Y	29	Y	N	Cerro Negro No. 3	Chile	1965	Stratified	Cu	T	US	20	500,000	1	A	EQ	85,000	5,000		3
48	Y	N	Y	Y	42	Y	N	El Cerrado	Chile	1965		Cu	T	US	25		2	B	EQ				3
49	Y	N	Y	Y	43	Y	N	El Cobre New Dam	Chile	1965	HT Manto	Cu	CST	DS	19	350,000	1	A	EQ	350,000	12,000		2
50	Y	Y	Y	Y	45	Y	N	El Cobre Old Dam	Chile	1965	HT Manto	Cu	T	US	35	4,250,000	1	A	EQ	1,900,000	12,000	200	1
51	Y	N	Y	Y	46	Y	N	El Colbre Small Dam-El Soldado (Pnarroya)	Chile	1965	HT Manto	Cu	T	US	26	985,000	2	B	EQ				3
52	Y	N	Y	Y	55	Y	N	Hierro Viejo	Chile	1965		Cu	T	US	5		1	A	EQ	800	1,000		3
53	Y	Y	Y	Y	69	Y	N	La Patague New Dam	Chile	1965		Cu	T	US	15	100,000	1	A	EQ	35,000	5,000		3
54	Y	N	Y	Y	70	Y	N	Los Maquis No. 1	Chile	1965		Cu	T	US	15	30,000	2	B	EQ	20,000			3
55	Y	Y	Y	Y	71	Y	N	Los Maquis No. 3	Chile	1965	HT Manto	Cu		US	15	43,000	1	A	EQ	21,000	5,000		3
56	Y	N	Y	Y	99	Y	N	Ramayana No. 1	Chile	1965	Stratified	Cu	T	US	5		1	A	EQ	150			3
57	Y	N	Y	Y	104	Y	N	Sauce No. 1	Chile	1965		Cu	T	US	6		2	A	EQ				3
58	Y	N	Y	Y	105	Y	N	Sauce No. 2	Chile	1965		Cu	T	US	5		2	B	EQ				3
59	Y	N	Y	Y	106	Y	N	Sauce No. 3	Chile	1965		Cu		US	5		2	B	EQ				3
60	Y	N	Y	Y	107	Y	N	Sauce No. 4	Chile	1965		Cu	T	US	5		2	B	EQ	10			3
61	Y	Y	Y	Y	125	Y	N	Tymawr 2	UK	1965	Stratified	Coal			12		1	A	OT		800		3
62	Y	Y	Y	Y	38	Y	N	Derbyshire	UK	1966	Stratified	Coal		DS	8		1	B	FN	30,000	100		3
63	N	N	Y	Y	154	Y	N	Unidentified, Texas	USA	1966	Stratified	Gypsum	T	US	16		1	A	SE	130,000	300		2
64	Y	N	Y	Y	216	N	Y	Williamthorpe 1	UK	1966	Stratified	Coal	MW				1	A	OT				3
65	Y	Y	Y	N	-	N	N	Gypsum Tailings Dam, Texas	USA	1966	Stratified	Gypsum	T	US	16	6,500,000	1	A	SE	130,000	300	0	3
66	Y	N	Y	Y	183	Y	N	Williamthorpe 2	UK	1966	Stratified	Coal	MW				1	A	FN				3
67	Y	Y	Y	Y	81	Y	N	Mire Mine, sgurigrad	Bulgaria	1966	Stratified	Pb/Zn	T	US	45	1,520,000	1	A	OT	450,000	8,000	488	1
68	Y	Y	Y	N	-	N	N	Geising/Erzgebirge	Germany	1966		Sn					1	U	ST	70,000			3
69	Y	Y	Y	N	-	N	N	Aberfan, Tip No. 7, South Wales Colliery	UK	1966	Stratified	Coal		None	37	230,000	1	U	U	162,000	600	144	1

70	Y	N	Y	Y	73	Y	N	Iwiny Tailings Dam, lower Silesia	Poland	1967		Cu/Mo	E	US	25	16,000,000	1	A	MS	4,600,000	15,000	18	1
71	Y	Y	Y	Y	144	Y	N	Unidentified	UK	1967	Stratified	Coal		DS	20		1	A	SI				3
72	Y	N	Y	Y	145	Y	N	Unidentified 2	UK	1967	Stratified	Coal	MW	DS	14		2	A	SI				3
73	Y	N	Y	Y	146	Y	N	Unidentified 3	UK	1967	Stratified	Sand	E	DS	30		2	A	SE				3
74	Y	Y	Y	Y	83	Y	N	Mobil Chemical, Fort Meade, Florida, Phosphate	USA	1967	Stratified	P					1	A	U	225,000			1
75	Y	N	Y	Y	33	Y	N	Climax, Grand Junction, Colorado	USA	1967	Stratified	U					1	A	U	12,000			3
76	Y	N	Y	Y	1	Y	N	Agrico Chemical, Florida	USA	1968		P					1	A	U				3
77	Y	Y	Y	Y	57	Y	N	Hokkaido	Japan	1968	Stratified	Pb/Zn	T	US	12	300,000	1	A	EQ	90,000	150		3
78	Y	N	Y	Y	60	Y	N	IMC K-2 Saskatchewan	Canada	1968	Stratified	K	T	US	30		3	U	U				4
79	Y	N	Y	N	-	N	N	Yauli-Yacu	Peru	1968				US	80		1	B	EQ				3
80	Y	N	Y	Y	217	N	Y	Stoney, Middleton	UK	1968		Pb/Zn					1	A	SI				3
81	Y	Y	Y	Y	15	Y	N	Bilbao	Spain	1969	Stratified	Fe	R				1	A	SI	115,000	35	1	2
82	Y	N	Y	Y	86	Y	N	Monsanto Dike 15, TN	Columbia	1969	Stratified	P	E	DS	43	1,230,000	2	A	SE				3
83	Y	N	Y	N	-	N	N	Buenaventura	Peru	1969							1	B	EQ				3
84	Y	N	Y	N	-	N	N	Phoenix Copper, Britisch Columbia	Canada	1969		Cu		US			2	A	SE	11,356			3
85	Y	N	Y	Y	93	Y	N	Park	UK	1970	Stratified	Clay	T	WR	3		1	A	OT				3
86	Y	N	Y	Y	97	Y	N	Portworthy	UK	1970	Stratified	Clay	R	DS	15		1	A	ST				3
87	Y	N	Y	Y	152	Y	N	Unidentified, Missisippi	USA	1970	Stratified	Gypsum	T	US	15		1	A	OT				3
88	Y	N	Y	Y	182	Y	N	Williamsport Washer, Maury Country, Tennessee	USA	1970	Stratified	P			21		1	A	U				3
89	N	N	N	Y	186	N	Y	Health Steele Main dam, New Brunswick	Canada	1970		Cu/Zn	R & E	WR	30		2	A	FN				U
90	Y	Y	Y	Y	75	Y	N	Maggie Pye, Clay	UK	1970	Stratified	Clay	T	US	18		1	A	SI	15,000	35		3
91	Y	Y	Y	Y	88	Y	N	Mulfulira, Roan Consolidated Mines	Zambia	1970	SSC	Cu			50	1,000,000	1	A	MS	1,000,000		89	1
92	Y	N	Y	Y	95	Y	N	Pinchi Lake, Britisch Columbia	Canada	1971	Vein/Stratified	Hg	E	WR	13		2	A	ER				3
93	Y	N	Y	Y	181	Y	N	Wester Nuclear, Jeffrey City, Wyoming	USA	1971	Stratified	U/Cu					1	A	ST				3
94	Y	N	Y	N	-	N	N	Ticapampa	Peru	1971					20		1	B	EQ			3	2
95	Y	N	Y	N	-	N	N	Atochocha	Peru	1971	Stratified	Cu/Pb/Zn					1	B	ST				3
96	Y	N	Y	N	-	N	N	Quiruvilca mine, Almivirca Tailings Dam 2	Peru	1971	Stratified	Cu/Ag/Pb/Zn			40		1	A	EQ				3
97	Y	N	Y	N	-	N	N	Chungar	Peru	1971	Stratified						1	A	EQ			Y	2
98	Y	Y	Y	N	-	N	N	Certej Gold Mine	Romania	1971	Vein/Stratified	Au/Ag		US	25		1	A	SI	300,000	5,000	89	1
99	Y	Y	Y	Y	31	Y	N	Cities Service, Fort Meade, Florida, Phosphate	USA	1971	Stratified	P	E	CL	15	12,340,000	1	A	U	9,000,000	120,000		1
100	Y	N	Y	Y	48	Y	N	Galena Mine, Idaho 1 (ASARCO)	USA	1972	Vein	Ag/Pb	E	US	14		2	A	ER				3
101	Y	Y	Y	N	-	N	N	Buffalo Creek, West Virginia (Pittson Coal Co.)	USA	1972	Stratified	Coal	R	US	16	500,000	1	A	OT	500,000	64,000	125	1
102	Y	Y	Y	N	-	N	N	Brunita Mine, Caragena (SMM Penaroya)	Spain	1972	Stratified	Zn/Pb/Cu	MW	US	25	1,080,000	1	A	OT	70,000		1	2
103	Y	N	Y	Y	100	Y	N	Ray Mine, Arizona	USA	1972	PC	Cu	T	US	52		1	A	SI				3
104	Y	N	Y	Y	41	Y	N	Earth Resources, N.M.		1973	PC	Cu	T	US	21	13,000,000	1	A	OT				3
105	Y	Y	Y	Y	169	Y	N	Unidentified, Southwestern	USA	1973		Cu	E	US	43	500,000	1	A	SI	170,000	25,000		2
106	Y	N	Y	Y	101	Y	N	Ray Mine, Arizona 2	USA	1973	PC	Cu	T	US	52		2	A	SI				3
107	Y	N	Y	Y	10	Y	N	Berrien	France	1974	Stratified	Ag/Pb	R	US	9		1	A	SE				3
108	Y	N	Y	Y	47	Y	N	GCOS, Alberta	Canada	1974		Oil Sands	T	US	61		2	A	SI				3

109	Y	N	Y	Y	153	Y	N	Unidentified, Missisippi 2	USA	1974		Gypsum	T	US	20		2	A	FN				3
110	Y	N	Y	Y	159	Y	N	Unidentified, Canaca	Mexico	1974	PC	Cu	T	US	46		1	A	OT				3
111	Y	N	Y	Y	49	Y	N	Galena Mine, Idaho 2 (ASARCO)	USA	1974	Stratified	Ag/Pb	MW	US	9		1	A	OT	3,800	750		3
112	Y	N	Y	Y	109	Y	N	Silver King, Idaho	USA	1974		Ag/Cu	E	DS	9		1	A	OT	6,000			3
113	Y	Y	Y	Y	37	Y	N	Deneen Mica Yancey Country, North Carolina	USA	1974		Mica	CST	US	18	300,000	1	A	SI	38,000	30		3
114	Y	Y	Y	Y	7	Y	N	Bafokeng	South Africa	1974	Magmatic	Pt	T	US	20	13,000,000	1	A	SE	3,000,000	45,000	12	2
115	Y	N	Y	Y	50	Y	N	Golden Gilpin Mine, Colorado	USA	1974		Au			12	300,000	1	B	U				3
116	N	N	Y	N	-	N	N	Bokafeng, Morensky Tailings Dam, 2nd Occurance	South Africa	1974		Pt	T	US	20	17,000,000	1	A	SE	13,000,000	45,000	13	1
117	Y	N	Y	Y	40	Y	N	Dresser No. 4, Montana	USA	1975		Barite	E	CL	15		1	A	FN				3
118	Y	N	Y	Y	65	Y	N	Keystone Mine, Crested Butte, Colorado	USA	1975	VMS	Mo					1	B	U				3
119	Y	Y	Y	Y	79	Y	N	Mike Horse, Montana	USA	1975	Vein	Pb/Zn	T	US	18	750,000	1	B	OT	150,000	24,000		2
120	Y	N	Y	Y	92	Y	N	PCS Rocanville, Saskatchewan	Canada	1975	Stratified	K	T	US	12		3	U	U				4
121	Y	N	Y	Y	161	Y	N	Unidentified, Green River, Wyoming	USA	1975	Stratified	Trona	E	WR	18		3	U	U				4
122	Y	N	Y	N	-	N	N	Heath Steele Main Dam, Brusnwick (American Metals)	Canada	1975	VMS	Pb/Zn	R & E	WR	30		2	A	FN				4
123	Y	N	Y	Y	22	Y	N	Carr Fork, Utah	USA	1975	Skarn	Cu/Au			10		1	A	ST				3
124	Y	Y	Y	Y	219	N	Y	Madjarevo	Bulgaria	1975	Skarn	Pb Zn/Au	T	US	40	3,000,000	1	A	ST	250,000	20,000		2
125	Y	Y	Y	N	-	N	N	Silverton, Colorado	USA	1975		Au/Ag					1	A	U	72,500	160,000	0	3
126	Y	N	Y	Y	18	Y	N	Cadet No. 2, Montana	USA	1975		Barite	E	CL	21		2	A	SI				3
127	Y	N	Y	Y	36	Y	N	Dashihe	China	1976	Stratified	Fe		US	37		2	A	EQ				3
128	Y	N	N	Y	149	Y	N	Unidentified, Idaho	USA	1976	Stratified	P	E	DS	34		2	A	SI				3
129	Y	Y	Y	Y	184	Y	N	Zlevoto No. 4	Yugoslavia	1976		Pb/Zn	T	US	25	1,000,000	1	A	SI	300,000			2
130	Y	N	Y	Y	64	Y	N	Kerr-McGee, Churchrock, New Mexico	USA	1976		U	E	WR	9		1	A	FN				3
131	Y	N	Y	Y	96	Y	N	Pit No. 2, Western		1977		REE	T	US	9		1	A	SI				3
132	Y	N	Y	Y	162	Y	N	Unidentified, Hernando, County, Florida	USA	1977	Stratified	Limestone	E	CL	6		2	A	FN				3
133	Y	N	Y	Y	180	Y	N	Western Nuclear, Jeffrey City, Wyoming	USA	1977	Stratified	U					1	A	SI	8,700			3
134	Y	Y	Y	Y	59	Y	N	Grans, Milan, New Mexico, (Homestake Mining)	USA	1977	Stratified	U	T	US	21		1	A	ST	30,000			3
135	Y	N	Y	Y	74	Y	N	Madison, Missouri	USA	1977		Pb	E	WR	11		1	A	OT				3
136	Y	N	Y	Y	56	Y	N	Hirayama	Japan	1978	Stratified	Au		DS	9	87,000	2	B	EQ			0	3
137	Y	N	Y	Y	120	Y	N	Syncrude,Alberta	Canada	1978		Oil Sands	T	CL			2	A	FN				3
138	Y	Y	Y	Y	84	Y	N	Mochikoshi No. 1	Japan	1978		Au	T	US	28	480,000	1	A	EQ	80,000	7,500	1	2
139	N	N	Y	N	-	N	N	Mochikoshi No. 3	Japan	1978		AU	T	US			1	A	EQ		0		3
140	Y	N	Y	Y	85	Y	N	Mochikoshi No. 2	Japan	1978		Au	T	US	19	480,000	1	A	EQ	3,000	200		3
141	Y	N	Y	Y	90	Y	N	Norosawa	Japan	1978		Au		DS	24	225,000	2	B	EQ				3
142	Y	Y	Y	Y	185	Y	N	Arcurus (Corsyn Consolidated Mines)	Zimbabwe	1978		Au	T	US	25	1,700,000	1	A	OT	35,000	300	1	2
143	Y	N	Y	Y	35	Y	N	Incident No. 1, Elliot, Ontario	Canada	1979		U	E	WR	9		3	U	U				4
144	Y	N	Y	Y	118	Y	N	Suncor EW Dike, Alberta	Canada	1979	Stratified	Oil Sands	MW	WR	30		2	A	SI				3
145	Y	Y	Y	N	-	N	N	Unidentified, Britisch Columbia	Canada	1979							1	A	FN	40,000			3
146	Y	N	Y	Y	172	Y	N	Union Carbide, uravan, Colorado	USA	1979		U	T	US	43		2	A	SI				3
147	Y	Y	Y	Y	173	Y	N	Churchork, New Mexico, United Nuclear	USA	1979		U	E	CL	11	370,000	1	A	FN	370,000	110,000		2

148	Y	N	Y	N	-	N	N	Churchill Copper, Britisch Columbia	Canada	1979		Cu					1	A	SE	37,854			3
149	Y	N	Y	Y	67	Y	N	Kyanite Mining, Virgina	USA	1980		Kyanite			11	430,000	2	A	OT				3
150	Y	N	Y	N	-	N	N	San Niculas	Peru	1980	PC						1	B	ST				3
151	Y	N	Y	Y	119	Y	N	Sweeney Tailings Dam, Longmont, Colorado	USA	1980	Stratified	Sand			7		1	A	SE				3
152	Y	N	Y	Y	76	Y	N	Marga, Sewell, VI Region, Rancagua	Chile	1980	PC	Cu					1	B	OT				3
153	Y	N	Y	N	-	N	N	Arena, Sewell, VI Region, Rancagua	Chile	1980	PC	Cu					1	B	OT				3
154	Y	Y	Y	Y	94	Y	N	Tyrone, New Mexico (Phelps Dodge)	USA	1980	PC	Cu	CST	US	66	2,500,000	1	A	SI	2,000,000	8,000		1
155	Y	N	Y	Y	123	Y	N	Texasgulf No. 1 Pond, Beaufort Co., North Carolina	USA	1981	Stratified	P	E	WR		24,700,000	2	A	SI				3
156	Y	Y	Y	Y	176	Y	N	Veta de Agua A	Chile	1981		Cu					1	A	EQ	280,000	5,000		3
157	Y	N	Y	Y	177	Y	N	Veta de Agua B	Chile	1981		Cu		US			1	A	EQ				3
158	Y	Y	Y	Y	211	N	Y	Balka Chuficheva, Ledeinksy	Russia	1981	Stratified	Fe	CST	US	25	27,000,000	1	A	SI	3,500,000	1,200		1
159	Y	N	Y	Y	39	Y	N	Dixie Mine, Colorado	USA	1981	Vein	Au					1	B	U				3
160	Y	Y	Y	N	-	N	N	Ages, Harlan County, Kentucky	USA	1981		Coal					1	A	U	96,000	163,000	1	2
161	Y	N	Y	Y	102	Y	N	Royster, Florida	USA	1982	Stratified	Gypsum	T	CL	21		1	A	FN				3
162	Y	Y	Y	Y	187	N	Y	Sipalay, No. 3 Tailings Pond (Maricalum Mining Corp)	Philippines	1982	PC	Cu	MW	WR		37,000,000	1	A	FN	20,000,000	1,500		1
163	Y	N	Y	Y	53	Y	N	Grey Eagle, California	USA	1983	Vein	Au	E	DS			3	U	U	100			4
164	Y	N	Y	Y	175	Y	N	Vallenar 1 and 2		1983		Cu		WR			1	B	OT				3
165	Y	N	Y	Y	51	Y	N	Golden Sunlight Mine, Idaho	USA	1983	Vein	Au	CST	CL			3	U	U	664			4
166	Y	N	Y	Y	32	Y	N	Clayton Mine, Idaho	USA	1983	Vein	Pb	T	CL	24	215,000	2	A	ST				3
167	Y	N	Y	Y	11	Y	N	Battle Mt. Gold, Nevada	USA	1984		Au	E	DS	8	1,540,000	2	A	SI				3
168	Y	N	Y	Y	179	Y	N	Virginia Vermiculite, Louisa Country, Virginia	USA	1984		Vermiculite	E	WR	9		1	A	ST				3
169	Y	N	Y	Y	122	Y	N	Texasgulf 4B Pond, Beaufort, Co., North Carolina	USA	1984	Stratified	P	T	WR	8	12,300,000	2	A	SI				3
170	Y	N	Y	Y	210	N	Y	Mirolubovka	Ukraine	1984		Fe	E & T	WR	32	80,000,000	2	A	SI	0			4
171	Y	N	Y	Y	44	Y	N	El Cobre No. 4 El Soldado (Exxon)	Chile	1985	HT Manto	Cu	CST	DS	50		2	A	EQ				3
172	Y	Y	Y	Y	91	Y	N	Olinghouse, Nevada	USA	1985		Au	E	WR	5	120,000	1	A	SE	25,000	1,750		3
173	Y	Y	Y	N	-	N	N	Niujiaolong, Hunan (Shizhuyuan Non-ferrous Metals Co.)	China	1985	Stratified	P		DS	40	1,100,000	1	A	U	731,000	4,100	49	1
174	Y	N	Y	N	-	N	N	Marga, Chile, El Teniente (Codelco)	Chile	1985	PC	Cu					1	B	OT				3
175	Y	N	Y	N	-	N	N	Quintette, Maëmot, Britisch Columbia	Canada	1985	Stratified	Coal					2	U	U	2,500,000	2,750		4
176	Y	Y	Y	Y	30	Y	N	Cerro Negro No. 4	Chile	1985		Cu	CST	US	40	2,000,000	1	A	EQ	500,000	8,000		2
177	Y	N	Y	Y	178	Y	N	Veta de Agua No. 1	Chile	1985		Cu	T	US	24	700,000	1	A	EQ	280,000	5,000		2
178	Y	Y	Y	Y	117	Y	N	Pretstavel Mine-Stave, 2, 3 (Prealpi Minerals)	Italy	1985	Stratified	F	CST	US	29	350,000	1	A	SI	190,000	4,100	269	1
179	Y	N	Y	Y	68	Y	N	La Bella, Pennsylvania	USA	1985	Stratified	Coal	MW	DS	79	1,230,000	2	A	FN				3
180	Y	N	Y	Y	17	Y	N	Bonsal, North Carolina	USA	1985	Stratified	Sand	E	WR	6	38,000	1	A	OT	11,000	900		3
181	Y	N	N	N	-	N	N	Niujiaolong Tailings Pond	China	1985		Cu	T	US	40	1,100,000	1	A	OT	730,000	4,200		2
182	Y	N	Y	Y	114	Y	N	Spring Creek Plant, Borger, Texas	USA	1986	Stratified	Sand			5	30,000	1	A	OT				3
183	Y	Y	Y	N	-	N	N	Huangmeishan	China	1986	Stratified	Fe					1	A	SE			19	2
184	Y	N	Y	Y	188	N	Y	Mineral King, Britisch Columbia	Canada	1986		Pb/Zn	CST	CL	6	0	1	B	OT	100,000	12,000		3
185	Y	Y	Y	Y	189	N	Y	Itabirito, Minas Gerais	Brazil	1986	Stratified	Fe	Masonry	Gravity	30		1	A	ST	100,000	12,000	7	2
186	Y	N	Y	Y	190	N	Y	Rossarden, Tasmania	Australia	1986	Stratified	Sn/Fe	E	WR	7.5	200,000	1	B	OT	10			3

187	Y	N	Y	Y	191	N	Y	Story's Creek, Tasmania	Australia	1986		Sn		Valley side	17	30,000	1	B	OT	100			3
188	Y	N	Y	Y	192	N	Y	Pico de Sao Luis, Gerais	Brazil	1986	Stratified	Fe	T		20		1	A	ER				3
189	Y	N	Y	Y	193	N	Y	Mankayan District, Luzon, Philippines, No.3 Tailings Pond (	USA	1986	Stratified	Cu/Au	E				1	A	ST	100,000			2
190	Y	N	Y	Y	77	Y	N	Marianna Mine 58, Pensylvennia	USA	1986	Stratified	Coal	E	US	37	300,000	2	A	SI				3
191	N	N	N	Y	13	Y	N	Big Four, Florida	USA	1986		P	E	CL	18		2	A	ST				U
192	Y	N	Y	Y	87	Y	N	Montana Tunnels, Montana (Pegasus Gold)	USA	1987		Au	MW	DS	33	250,000	3	U	U				4
193	Y	N	Y	Y	194	N	Y	Xishimen	China	1987		Fe	T	US	31		1	A	SI	2,230			3
194	Y	N	Y	Y	212	N	Y	Bekovsky, Western Siberia	Russia	1987	Stratified	Coal	Argillite & Aleurolite	US	53	52,000,000	1	A	SI	0			3
195	Y	Y	Y	N	-	N	N	Montcoal No. 7, Raleigh County, West Virginia	USA	1987	Stratified	Coal					1	A	U	87,000	80,000		2
196	Y	N	Y	N	-	N	N	Surgao Del Norte Placer	Philippines	1987	Placer	Au					1	A	U				3
197	Y	N	Y	Y	98	Y	N	Rain Starter Dam, Elko, Nevada	USA	1988		Au	E & R	WR	27	1,500,000	3	U	U				4
198	Y	N	Y	Y	164	Y	N	Unidentified, Hernando, County, Florida 1	USA	1988	Stratified	Limestone	E	DS	12		2	A	FN				3
199	Y	Y	Y	N	-	N	N	Riverview, Hillsborough County, Florida (Gardiner/Cargill)	USA	1988	Stratified	P					1	A	ER	246			3
200	Y	Y	Y	Y	121	Y	N	Consolidated Coal No. 1, Tennessee	USA	1988	Stratified	Coal	MW	DS	85	1,000,000	2	A	ST	250,000			2
201	Y	Y	Y	Y	195	N	Y	Jinduicheng, Shaanxi Province	China	1988		Mo		US	40		1	A	OT	700,000		20	1
202	Y	N	Y	Y	163	Y	N	Unidentified, Hernando, County, Florida 2	USA	1988	Stratified	Limestone	E	US	12	3,300,000	1	A	OT	4,600			3
203	Y	N	Y	Y	14	Y	N	Big Four, Florida	USA	1989	Stratified	P	E	CL			2	A	FN				3
204	Y	N	Y	Y	34	Y	N	Thompson Creeck, Idaho (Cyprus)	USA	1989	Stratified	Mo	CST	CL	146	27,000,000	2	A	SE				3
205	Y	N	Y	N	-	N	N	Little Bay Mine (Atlantic Coast Copper Co), Little Bay, Newfo	Canada	1989	Stratified	Cu				1,250,000	1	A	U	500,000			2
206	Y	N	Y	Y	108	Y	N	Silver King, Idaho	USA	1989		Ag/Pb	E	DS	9	37,000	2	A	OT	100			3
207	Y	Y	Y	Y	116	Y	N	Stancil, Perryville, Maryland	USA	1989	Stratified	Sand	E	US	9	74,000	1	A	SI	38,000	100		3
208	Y	N	Y	Y	111	Y	N	Soda Lake, California	USA	1989	Stratified	Sand & Gravel	E	US	3		2	A	EQ	300			3
209	Y	N	Y	N	-	N	N	Matchewon Mines, Kirtland Lake, Ontario	Canada	1990		U					1	A	U	190,000	168,000		2
210	Y	N	Y	N	-	N	N	Brewer Gold Mine, Jefferson, South Carolina	USA	1990		Au					1	A	U	41,640	80,000		2
211	Y	N	Y	N	-	N	N	Magma Mine Tailings Dam 3		1991		Cu		US			1	A	SI	8,000			3
212	Y	Y	Y	Y	196	N	Y	Iron Dyke, Sullivan Mine, Kimberley, Britisch Columbia (Con	Canada	1991	VMS	Pb/Zn		US	21		1	A	SI	75,000			3
213	Y	N	Y	N	-	N	N	Ajka Alumina Plant, Kolontár	Hungary	1991		Al	Compacted Fly Ash	DS	25	4,500,000	1	A	ST	43,200			3
214	Y	Y	Y	Y	197	N	Y	Tubu, Benguet, No. 2 Tailings Pond, Luzon	Philippines	1992	PC	Cu				90,000,000	1	A	FN	50,000,000			1
215	Y	Y	Y	Y	218	N	Y	Maritsa Istok 1	Bulgaria	1992	Stratified	Coal	Ash		15	52,000,000	1	A	ER	500,000			2
216	Y	N	Y	Y	198	N	Y	Kojkovac	Montenegro	1992		Pb/Zn	E	WR		3,500,000	2	B	ER	0			4
217	Y	Y	Y	N	-	N	N	Marsa (Marsa Mining Corp)	Peru	1993	Vein	Au					1	A	OT			6	2
218	Y	N	Y	N	-	N	N	Ray Complex, Pinal County, Arizona AB-BA Impoundment	USA	1993		Cu		US	46		1	A	OT	216,000	18,000		2
219	Y	N	Y	N	-	N	N	Saaiplaas, Failure on West Ring Dyke	South Africa	1993	Wits	Au	CST	US	28		1	A	SI	100			3
220	Y	N	Y	N	-	N	N	Saaiplaas, Failure on South Ring Dyke	South Africa	1993	Wits	Au	CST	US	28		1	A	SI	100			3
221	Y	N	Y	Y	199	N	Y	Itogon-Suyoc, Baguio Gold District, Luzon	Philippines	1993	Vein	Au/Ag					1	A	OT				3
222	Y	N	Y	Y	200	N	Y	TD 7, Chingola	Zambia	1993		Cu	T & E	US	5		1	A	OT	75,000			3
223	Y	Y	Y	N	-	N	N	Gibsonton, Florida (Cargill)	USA	1993	Stratified	P					2	A	U				3
224	Y	N	Y	N	-	N	N	Marcopper, Marinduque Island, Mogpog 1 (Placer Dome-Pre	Philippines	1993		Cu					1	A	U			2	2
225	Y	N	N	N	-	N	N	Magma Copper Company Pinto Valley Operations, Arizona	USA	1993		Cu					1	A	OT	90,000			3

226	N	N	Y	N	-	N	N	Helmsdrf Uranium, Zwckau, Saxny (Wismut Uranium)	Germany	1994		U		US	59		2	B	SE	0	0	0	4
227	Y	Y	Y	N	-	N	N	Longjiaoshan, Daye Iron Ore Mine, Jubei	China	1994		Fe		US			1	A	U			31	1
228	Y	N	Y	N	-	N	N	Fort Meade, Florida, Cargill Phospate 3	USA	1994		P					1	A	U	76,000			3
229	Y	N	Y	N	-	N	N	Tapo Canyon, Northbridge, California	USA	1994		Aggregate	T	US	24		2	A	EQ	135,000	180		2
230	Y	N	Y	Y	214	N	Y	Minera Sera Grande, Crixas, Goias	Brazil	1994		Au	CST	US	41	2,250,000	2	A	SI	0			3
231	N	N	Y	N	-	N	N	Mineracao Serra Grande Tailings Dam, State of Goias (Ang	Brazil	1994		Au		CL	27		1	U	U	1,000	0	0	3
232	Y	Y	Y	N	-	N	N	Olympic Dam, Roxby Downs	Australia	1994		Cu/U					3	U	U	5,000,000			3
233	Y	Y	Y	Y	202	N	Y	Merriespruit, near Virginia (Harmonay, No. 4A. Tailings Com	South Africa	1994	Wits	Au	T	US	31	8,000,000	1	B	OT	2,500,000	3,000	17	1
234	Y	Y	Y	N	-	N	N	IMC-Agrigo Phosphate, Florida	USA	1994	Stratified	P					2	A	MS				4
235	Y	Y	Y	N	-	N	N	Fort Meade Phosphate, Florida (cargill)	USA	1994	Stratified	P					2	A	SE	76,000			3
236	Y	Y	Y	N	-	N	N	Payne Creek Mine, Polk County, Florida (IMC-Agrico)	USA	1994	Stratified	P					1	A	U	6,800,000			1
237	Y	Y	Y	N	-	N	N	Hopewell Mine, Hillsborough County Florida (IMC-Agrigo)	USA	1994	Stratified	P					1	A	U	1,900,000			1
238	N	N	Y	Y	206	N	Y	Surigao del Norter Placer (Manila Mining Corp)	Philippines	1995			E	WR	17		1	A	ER	50,000			4
239	Y	N	Y	Y	203	N	Y	Riltec, Mathinna, Tasmania	Australia	1995		Au	E	CL	7	120,000	2	A	SE	40,000			3
240	Y	N	Y	Y	204	N	Y	Middle Arm, Launceson, Tasmania	Australia	1995		Au	E	CL	4	25,000	1	A	OT	5,000			3
241	Y	Y	Y	Y	205	N	Y	Omai Mine, Tailings Dam No 1, 2 (Cambior)	Guyana	1995	Vein	Au	R	WR	44	5,250,000	1	A	ER	4,200,000	80,000		1
242	Y	Y	Y	N	-	N	N	Surigao del Norte Placer 2 (Manila Mining Corp)	Philippines	1995	Placer	Au	E	WR	17		1	B	FN	50,000		12	2
243	Y	Y	Y	Y	207	N	Y	Golden Cross, Waitekauri Valley (Coeur d'Alene Mine)	New Zealand	1995		Au	R		27	3,000,000	1	A	FN	50	0		3
244	Y	N	Y	N	-	N	N	Negros Occidental, Bulawan Mine Sipalay River (Philex Min	Philippines	1995		Au					1	A	U	0			3
245	Y	N	Y	N	-	N	N	Laisvall (Boliden)	Sweden	1996		Pb/Zn/Ag	T & Moraine	US	40	20,000,000	1	A	ER	0			3
246	Y	Y	Y	Y	208	N	Y	Marcopper, Marinduque Island, Mogpog 2 (Placer Dome-Pre	Philippines	1996	PC	Cu		Open Pit		15,000,000	1	B	ST	2,000,000	25,500		1
247	Y	N	Y	Y	220	N	Y	Sgurigrad	Bulgaria	1996		Pb/Zn	T	US	45	1,520,000	1	A	SI	220,000	6,000		2
248	Y	Y	Y	N	-	N	N	El Porco	Bolivia	1996	Vein	Pb/Zn					1	A	U	166,000	300,000		2
249	Y	Y	Y	N	-	N	N	Amatista	Peru	1996				US			1	B	EQ	450,000	600		2
250	Y	N	Y	N	-	N	N	Caraveli	Peru	1996							1	B	EQ				3
251	Y	N	Y	N	-	N	N	Tranque Antique Planta La Cocinera, IV Region, Vallenar	Chile	1997				US	30		1	A	EQ	60,000	150		3
252	Y	N	Y	N	-	N	N	Algarrobo, IV region, Vallenar	Chile	1997	Magmatic	Fe		US	18		1	A	EQ				3
253	Y	N	Y	N	-	N	N	Algarrobo, IV region, Vallenar	Chile	1997	Magmatic	Fe		US	20		1	A	EQ				3
254	Y	N	Y	N	-	N	N	Maitén, IV Region, Vallenar	Chile	1997				US	15		1	A	EQ				3
255	Y	Y	Y	N	-	N	N	Pinto Valley, Arizona (BHP Copper)	USA	1997	PC	Cu		US			1	B	SI	230,000		1	2
256	Y	N	Y	N	-	N	N	Zamboanga Del Norte, Sibutad Gold Project (Philex Mining	Philippines	1997		Au					1	A	OT				3
257	Y	Y	Y	N	-	N	N	Mulberry Phosphate, Polk County, Florida (Mulberry Phosph	USA	1997	Stratified	P					1	A	SE	200,000			2
258	Y	Y	Y	Y	209	N	Y	Los Frailes, Aznancollar, near Seville (Boliden Ltd.)	Spain	1998	VMS	Pb/Zn/Cu	R	WR	27	15,000,000	1	A	FN	6,800,000	40,500		1
259	Y	N	Y	N	-	N	N	Zamboanga Del Norte, Sibutad Gold Project (Philex Mining	Philippines	1998		Au					1	A	OT				3
260	Y	Y	Y	N	-	N	N	Huelva (Fertiberia, Foret)	Spain	1998	Stratified	P					1	A	OT	50,000			3
261	Y	Y	Y	N	-	N	N	Surigao del Norte Placer 3 (Manila Mining Corp)	Philippines	1999	Placer	Au					3	U	U	500,000	12,000	4	2
262	Y	N	Y	N	-	N	N	Red Mountain, Britisch Columbia	Canada	1999		Au/Ag		Jumbo			1	A	SE	10,000			3
263	Y	N	Y	N	-	N	N	Toledo City (Atlas Con Mining Corp)	Philippines	1999	PC	Cu					1	B	ST	5,700,000			1
264	Y	Y	Y	Y	221	N	Y	Baia Mare (Aurul S.A., Esmeralda Exploration)	Romania	2000		Au	T	US	5	800,000	1	A	ST	100,000	100,000		1

265	Y	Y	Y	N	-	N	N	Borsa (Remin, S.A.-govt)	Romania	2000		Pb/Zn					1	A	U	20,000			3
266	Y	Y	Y	N	-	N	N	Aitik Mine, near Fällivare (Boliden Ltd.)	Sweden	2000	PC	Cu	MW & E	DS	15	15,000,000	1	A	ER	2,000,000	5,200		1
267	Y	Y	Y	N	-	N	N	Inez, Martin Country, Kentucky (Massey Energy Subsidiary I	USA	2000		Coal				7,500,000	1	A	MS	1,000,000	120,000		1
268	Y	Y	Y	N	-	N	N	Nandan Tim Mine, Dachang, Guangxi Province	China	2000		Sn		US			1	A	U			28	1
269	Y	Y	Y	N	-	N	N	Sebastião das Águas Claras, Nova Lima district, Minas Gera	Brazil	2001	Stratified	Fe	MW				1	A	U		7,000	2	2
270	Y	N	Y	N	-	N	N	Cuajone Mine, Torata water supply dam	Peru	2001		Cu	R	DS	130	16,000,000	3	A	EQ	0			4
271	Y	N	Y	N	-	N	N	Tarkwa (Goldfields)	Ghana	2001		Au					1	A	SI				4
272	Y	N	Y	N	-	N	N	Thalanga Mine, Queensland	Australia	2002	VMS	Cu/Pb/Zn		US		290,000	2	B	MS			0	4
273	Y	Y	Y	N	-	N	N	San Marcelino Zambales, Camalca dam (Benguet Corp-Diz	Philippines	2002	PC	Cu/Au					1	B	OT			0	3
274	Y	Y	Y	N	-	N	N	San Marcelino Zambales, Bayarong dam (Benguet Corp-Diz	Philippines	2002	PC	Cu/Au				47,000,000	1	B	OT	1,000,000		0	1
275	Y	N	Y	N	-	N	N	El Cobre, 2, 3, 4, 5 (Exxon)	Chile	2002	HT Manto	Cu	T	US			1	B	OT	8,000			3
276	Y	N	Y	N	-	N	N	El Cobre, El Soldado (Exxon)	Chile	2002	HT Manto	Cu	T	US			1	B	OT	4,500			3
277	Y	N	Y	N	-	N	N	Mineracao Rio Pomba Cataguases, Mirai, Minas Gerais, Mi	Brazil	2003	Laterite	Al					1	A	U	1,200,000			1
278	Y	Y	Y	N	-	N	N	Sasa Mine (State Owned)	Macedonia	2003		Pb/Zn		US		2,000,000	1	A	ST	90,000	12,000		2
279	Y	Y	Y	N	-	N	N	Cerro Negro, Petorca Province, Quinta region 5, (Cia Minera	Chile	2003		Cu	T	US			1	A	EQ	70,000	20,000		2
280	Y	Y	Y	N	-	N	N	Malvési, Aude (Comurhex, Cogéma/Areva)	France	2004		U					1	A	U	30,000	700		3
281	Y	Y	Y	N	-	N	N	Partizansk, Primorski Krai (Dalenergo)	Russia	2004	Stratified	Coal		Ring		20,000,000	1	A	U	160,000			2
282	Y	Y	Y	N	-	N	N	Riverview, Florida (Cargill)	USA	2004	Stratified	P					1	U	OT	227,000			2
283	N	N	Y	N	-	N	N	Prestea Gold Mine Bogoso Gold. Ltd.	Ghana	2004		Au					U	U	SI				U
284	Y	Y	Y	N	-	N	N	Pinchi Lake, BC (Teck Cominco Ltd.)	Canada	2004	Vein/Stratified	Hg	E	WR	12		2	A	ER	7,000			3
285	Y	Y	Y	N	-	N	N	Bangs Lake, Jackson County, Mississippi (Mississippi Phos	USA	2005	Stratified	P					1	A	OT	64,350			3
286	Y	N	N	N	-	N	N	Captains Flat Dump No. 3	Australia	2005		Cu					U	U	U	40,000	12,000		3
287	Y	N	N	N	-	N	N	Tailings Dam	USA	2005		Cu	E	US	43	500,000	1	A	SE	170,000	25,000		2
288	N	N	Y	N	-	N	N	Prestea Gold Mine Bogoso Gold. Ltd. 2	Ghana	2005		Au					U	U	U				U
289	Y	N	N	N	-	N	N	Lafayette Mining Polymetallic, Rapu Rapu Island, Albay	Philippines	2005		Au					1	A	OT				2
290	Y	N	Y	N	-	N	N	Mineracao Rio Pomba Cataguases, Mirai, Minas Gerais, Mi	Brazil	2006	Laterite	Al					1	A	U	400,000			2
291	Y	Y	Y	N	-	N	N	Miliang, Zhen'an County, Shangluo, Shaanxi Province	China	2006		Au					1	A	ST		5,000	17	1
292	N	N	Y	N	-	N	N	Dayton Power & Light		2006		Coal					1	U	SI	0	0	1	2
293	Y	Y	Y	N	-	N	N	Nchanga, Chingola (Konkola Copper Mines - Vedanta)	Zambia	2006	SSC	Cu					1	A	SI				4
294	Y	N	Y	N	-	N	N	Fonte Santa ,Freixia De Espado a Cinta	Potugal	2006			E	DS	25		1	B	OT	1,600	2,750		2
295	Y	Y	Y	N	-	N	N	Mineracao Rio Pomba Cataguases, Mirai, Minas Gerais, Mi	Brazil	2007	Laterite	Al			32.5	3,800,000	1	A	OT	2,000,000			1
296	Y	N	Y	N	-	N	N	Glebe Mines, Cavendish Mill	UK	2007		F	E	US			1	B	OT	20,000			3
297	Y	N	N	N	-	N	N	Bernburg (Solvay)	Germany	2007		Limestone		US	22		1	A	SI	150,000			2
298	N	Y	N	N	-	N	N	Shiqiaozi, Haichenc, Liaoning	China	2007		Fe				150,000	2	U	U				4
299	Y	N	Y	N	-	N	N	Ekati Mine, Northwest Territories (BHP Billiton)	Canada	2008		Diamonds					1	A	SI	4,500			3
300	Y	Y	Y	N	-	N	N	Taoshi, Linfen City, Xiangfen county, Shanxi province (Tahs	China	2008		Fe	R	US	50.7	290,000	1	A	SI	200,000	2,750	277	1
301	Y	Y	Y	N	-	N	N	Kingston fossil plant, Harriman, Tennessee (TVA)	USA	2008	Stratified	Coal		US			1	A	OT	5,000,000	4,100		1
302	Y	Y	Y	N	-	N	N	Huayuan County, Xiangxi Autonomous Prefecture, Hunan P	China	2009		Mn				50,000	1	A	U	50,000		4	2
303	Y	Y	Y	N	-	N	N	Karamken, Magadan Region (cyanide-leach processing faci	Russia	2009	Vein	Au			25	4,600,000	1	B	ST	130,000		2	1

304	Y	N	Y	N	-	N	N	Las Palmas, Pencahue, VII Region, Maule (COMINOR)	Chile	2010			CST	DS	15	220,000	1	B	EQ	170,000	750,000	4	2
305	Y	N	Y	N	-	N	N	Veta del Agua Tranque No. 5, Nogales, V Region, Valparaís	Chile	2010		Cu	CST	US	16	80,000	1	B	EQ	30,000	100		3
306	Y	N	Y	N	-	N	N	Tranque Adosado Planta Alhué, Alhué, Region Metropolitan	Chile	2010				DS	15		1	A	EQ				3
307	Y	N	Y	N	-	N	N	Tranque Planta Chacón, Cachapoal, VI Region, Rancagua	Chile	2010							1	B	EQ				3
308	Y	N	Y	N	-	N	N	Tranque Adosado Planta Alhué, Alhué, Region Metropolitan	Chile	2010				US			1	B	EQ				3
309	Y	Y	Y	N	-	N	N	Huancavelica, Unidad Minera Caudalosa Chica	Peru	2010		Ag/Cu/Pb/Zn			10		1	A	SE	21,420	110,000		2
310	Y	N	N	N	-	N	N	Zijin Mining, Zijinshan Gold & Copper Mine (Ting River)	China	2010		Au/Cu					2	A	U	9,100			3
311	Y	N	N	N	-	N	N	Zijin Mining, Zijinshan Gold & Copper Mine (Ting River)	China	2010		Au/Cu					3	A	U	500			4
312	Y	N	Y	N	-	N	N	Zijin Mining, Xinyi Yinyan Tin Mine, Guangdong Province	China	2010		Sn					1	A	OT			22	1
313	Y	Y	Y	N	-	N	N	Ajka Alumina Plant, Kolontár (MAL Magyar Aluminum)	Hungary	2010		Al	Compacted Fly Ash	DS	22	30,000,000	1	A	SE	800,000		10	1
314	Y	N	N	N	-	N	N	Kayakari	Japan	2011		Au/Ag		US	36	400,000	1	U	EQ	41,000		2	3
315	Y	Y	Y	N	-	N	N	Bloom Lake, Newfoundland (Cleveland Cliffs)	Canada	2011		Fe					1	A	U	200,000			2
316	Y	N	Y	N	-	N	N	Ray Mine, Hayden, AZ (Asarco)	USA	2011		Cu					1	A	ST	3,600			3
317	Y	Y	Y	N	-	N	N	Mianyang City, Songpan County, Sichuan Province	China	2011		Mn					1	A	OT	10,000			3
318	N	N	Y	N	-	N	N	Vales Point Ash Dam, Wyong, New South Wales	Australia	2011		Coal					1	A	U				3
319	Y	N	Y	N	-	N	N	Mineracao Serra Grande Tailings Dam, State of Goias (Ang	Brazil	2012		Au		CL			1	A	OT	900			3
320	Y	N	Y	N	-	N	N	Johson Gold Mining Corporation at Baranggay Bangong-Ba	Philippines	2012		Au					1	A	ER				3
321	Y	N	Y	N	-	N	N	Hudson Bay (HB) Mine, Salmo, British Columbia (Regional I	Canada	2012		Pb/Zn			25	1,800,000	1	B	SE				3
322	Y	Y	Y	N	-	N	N	Padcal No 3, Benquet (Philex)	Philippines	2012	PC	Au/Cu		US		102,000,000	1	A	OT	17,000,000			1
323	Y	Y	Y	N	-	N	N	Sotkamo, Kainuu Province (Talvivaara)	Finland	2012		Ni/U			25	5,400,000	1	A	SE	240,000			2
324	Y	Y	Y	N	-	N	N	Gullbridge Mine, Newfoundland	Canada	2012		Cu	E	DS	7	800,000	1	B	SI	100,000	500		2
325	Y	Y	Y	N	-	N	N	El Herrero mine, Otáez, Barrancas province, Durango state,	Mexico	2013		Au/Ag					1	U	OT	300,000	130,000	4	2
326	Y	N	Y	N	-	N	N	Casa Berardi Mine, La Sarre, Abitibi region, Quebec (Hecla	Canada	2013		Au					1	B	OT	57,000			3
327	Y	N	Y	N	-	N	N	Coalmont Energy Corporation, Basin Coal Mine	Canada	2013		Coal					1	A	OT	30	30,000		3
328	Y	Y	Y	N	-	N	N	Obed Mountain Coal Mine Alberta	Canada	2013		Coal					1	B	U	760,000	180,000		2
329	Y	Y	Y	N	-	N	N	Kajaran, Syunik Province (Zangezur Copper Molybdenum C	Armenia	2013		Cu/Mo			53.6	31,000,000	2	A	U				3
330	N	N	Y	N	-	N	N	Arcelor Mittal, Minorca Mine, Minnesota	USA	2013							2	A	ST				4
331	N	N	Y	N	-	N	N	Arcelor Mittal, Minorca Mine, Minnesota	USA	2013							2	A	ST				4
332	N	N	Y	N	-	N	N	Minas De Bacis Mine Co	Mexico	2013							U	U	U		130,000		2
333	Y	Y	Y	N	-	N	N	Dan River Steam Station, North Carolina (Duke Energy)	USA	2014		Coal			12	155,000,000	1	A	ST	334,000			2
334	Y	N	Y	N	-	N	N	Queensland Nickel, Yabulu Refnery, Townsville	Australia	2014		Ni					1	A	OT	80,000			2
335	Y	Y	N	N	-	N	N	Stolice mine (Farmakom MB)	Serbia	2014		Sb				1,200,000	1	B	OT	100,000			2
336	Y	y	Y	N	-	N	N	Imperial Metals, Mt Polley, British Columbia	Canada	2014	PC	Cu/Au	MW	Modified CL	40	74,000,000	1	A	FN	23,600,000	7,000		1
337	Y	Y	Y	N	-	N	N	Buenavista del Cobre mine, Cananea, Sonora (Grupo Mexic	Mexico	2014	PC	Cu					1	A	SI	40,000			3
338	Y	Y	Y	N	-	N	N	Herculano Iron Mine, Itabirite, Minas Gerais	Brazil	2014		Fe			61.5	4,500,000	1	A	U			3	2
339	N	N	Y	N	-	N	N	Arcelor Mittal, Minorca Mine, Minnesota	USA	2014							1	A	ST				4
340	N	Y	N	N	-	N	N	Dos Senores Mines, La Concordia, Sinaloa	Mexico	2014		Au/Ag					1	U	U	10,800	900		3
341	N	Y	N	N	-	N	N	Santiago Apóstol Mining Operations, Tacobamba, Potosí	Bolivia	2014		Zn/Ag/Pb/Sn					1	U	U	30,000			3
342	N	N	Y	N	-	N	N	Rosario Mine, San Luis Potosi, Sant Cruz Silver Mining	Mexico	2015		Ag					1	A	ST	2,000			3

343	Y	N	Y	N	-	N	N	Yellow Giant Mine, Banks Island, British Columbia	Canada	2015		Au					2	A	ST	240	1,000		4
344	Y	N	Y	N	-	N	N	Gold King Mine, near Silverton, Colorado	USA	2015		Au					1	B	ST	11,356			4
345	Y	Y	Y	N	-	N	N	Fundao-Santarem (Germano), Minas Gerais (Samarco = Va	Brazil	2015		Fe	MW	US	100	55,000,000	1	A	ST	40,000,000	665,000	19	1
346	Y	Y	Y	N	-	N	N	Hpakant Jade Mines, San Kat Kuu, Kachin states	Myanmar	2015		Jade			60		3	U	U			115	1
347	Y	Y	N	N	-	N	N	Hpakant Jade Mines, Lamaungkone, Kachin state (Tun Tau	Myanmar	2015		Jade					3	U	U			21	1
348	N	N	Y	N	-	N	N	Sepon Mine Western TSF Pipline	Loas	2015		Cu/Au	E				2	A	ST				4
349	N	Y	N	N	-	N	N	Taishihe Town, Xihe County, Longnan City, Gansu Province	China	2015		Sb					1	U	ST	25,000			3
350	Y	Y	N	N	-	N	N	Kazzinc Mining & Metallurgical Company (Glencore) - Conce	Kazakhstan	2016		Pb/Zn					1	A	ST		750		1
351	Y	Y	Y	N	-	N	N	Dahegou Village, Luoyang, Henan Province (Luoyang Xiang	China	2016		Al	MW	US	45	2,000,000	1	A	SI	2,000,000	2,000		1
352	Y	Y	Y	N	-	N	N	New Wales plant, Polk County, Mulberry, Florida (Mosaic Co)		2016		P					1	U	U	820,000			3
353	Y	N	Y	N	-	N	N	Duke Energy Coal Ash, Goldsboro, North Carolina	USA	2016		Coal				415,000	1	B	OT				3
354	Y	Y	Y	N	-	N	N	Antamok, Baguio (Philex)	Philippines	2016		Au					2	B	ST	50,000			3
355	Y	Y	N	N	-	N	N	Hpakant Jade Mines (Jade Palace Company)	Myanmar	2016		Jade					3	U	U			50	1
356	N	Y	N	N	-	N	N	Baracarena, Pará	Brazil	2016		Bauxite					1	U	OT				4
357	N	Y	N	N	-	N	N	Ujina, Pica, Tamarugal Province, Tarapacá Region	Chile	2016		Cu/Mo					1	U	EQ	4,500			3
358	Y	Y	Y	N	-	N	N	Tonglvshan Mine, Hubei Province (China Daye Ltd.)	China	2017		Cu/Au/Ag/Fe					1	A	U	200,000	500	2	2
359	Y	N	Y	N	-	N	N	Highland Valley Copper, British Columbia (Teck Resources)	Canada	2017		Cu	Sand		140		1	A	ER	850	0	0	3
360	Y	N	Y	N	-	N	N	Husab (Swakop Uranium (Taurus Minerals))	Namibia	2017		U					1	A	OT				3
361	Y	Y	Y	N	-	N	N	Mishor Rotem (Rotem Amfert Negev Ltd.,Israel Chemicals (	Israel	2017		P		US	60		1	A	SI	100,000	20,000		2
362	N	N	Y	N	-	N	N	Husab (Swakop Uranium (Taurus Minerals))	Namibia	2017		U					1	A	OT			0	3
363	Y	N	Y	N	-	N	N	Vedanta Aluminium Limited Smelter Ash Pond, Jharsuguda	India	2017		Al					1	A	U	2,625,000			1
364	Y	Y	Y	N	-	N	N	Kokoya mine (MNG Gold-Liberia)	Liberia	2017		Au	R	CL		300,000	1	A	ST	11,400			3
365	N	N	Y	N	-	N	N	Kentucky Power and Light	USA	2017		Coal					1	U	U	0	0	0	2
366	Y	N	Y	N	-	N	N	Hernic PGM Project (Jubilee Metals Group)	South Africa	2017		Cr/Pl	MW		39	4,875,000	1	A	SI	0			3
367	N	N	Y	N	-	N	N	Duke Energy, L.V. Sutton Power Station, Wilmington, North	USA	2018		Coal					1	U	OT			0	4
368	Y	N	N	N	-	N	N	Hpakant Jade Mines	Myanmar	2018		Jade					3	U	U			6	4
369	Y	Y	Y	N	-	N	N	Barcarena, Pará , Alunorte (Hydro Alu Norte/Norsk Hydro AS	Brazil	2018		Al					1	A	OT				3
370	Y	Y	Y	N	-	N	N	Huancapatí, Recuay province, Áncash region (Compañía Mi	Peru	2018		Au/Cu					1	A	U	80,000			3
371	Y	Y	Y	N	-	N	N	Cadia, New South Wales (Newcrest Mining)	Australia	2018		Cu/Au	MW	US	94		1	A	FN	1,330,000	500		2
372	Y	N	N	N	-	N	N	Hector Mine Pit Pond, MN	USA	2018		Fe			17	185,000	1	B	OT	123,000			4
373	Y	N	N	N	-	N	N	Hpakant Jade Mines	Myanmar	2018		Jade					3	U	U			20	4
374	Y	Y	Y	N	-	N	N	Cieneguita mine, Urique municipality, Chihuahua (Minera Ri	Mexico	2018		Au/Ag		US			1	A	SI	490,000	27,500	5	2
375	N	N	Y	N	-	N	N	Caserones Copper Mine, Lumina Copper	Chile	2018		Cu					1	A	ST	15			3
376	N	N	Y	N	-	N	N	Antamok Mine, Itogon Benguet Mining Corp	Philippines	2018		Au					1	B	ST			0	3
377	Y	N	Y	N	-	N	N	Duke Energy, L.V. Sutton Power Station, Wilmington, North	USA	2018		Ash				2,100,000	2	B	OT			0	3
378	Y	N	Y	N	-	N	N	Duke Energy, HF Lee Power Plant, Goldsboro, North Caroli	USA	2018		Ash				875,000	2	B	OT	2,000		0	3
379	N	N	Y	N	-	N	N	Rosebery Mine 2 5 TSF, MMG, Tasmania	Australia	2018		Zn/Cu/Au					1	A	U			0	3
380	N	N	Y	N	-	N	N	Cerro Crona Mine, Goldfields, Cajamarca	Peru	2018		Cu/Au	R	CL			2	A	U			0	4
381	Y	Y	Y	N	-	N	N	Brumadinho, Mina Córrego do Feijão, Minas Gerais (Vale)	Brazil	2019		Fe	T	US	100	12,000,000	1	B	SI	12,000	7,500	270	1

382	Y	Y	N	N	-	N	N	Machadinho d'Oeste, Oriente Novo, Rondônia (Metalmig Mi	Brazil	2019		Sn					1	B	U			0	2
383	Y	Y	N	N	-	N	N	Muri, Jharkhand (Hindalco Industries Limited)	India	2019		Al					1	B	ST		200	1	3
384	Y	Y	N	N	-	N	N	Hpakant, Kachin state (Shwe Nagar Koe Kaung Gems Co. L	Myanmar	2019		Jade					1	U	U			3	4
385	Y	Y	N	N	-	N	N	Cobriza mine, San Pedro de Coris district, Churcampa provi	Peru	2019		Cu		US			1	A	U	67,488	375,000		3
386	Y	Y	N	N	-	N	N	Nossa Senhora do Livramento, Mato Grosso (VM Mineraçã	Brazil	2019		Au			15	580,000	1	A	U		2,000		3
387	N	Y	N	N	-	N	N	La Rinconada, Ananea, San Antonio de Putina Province, Pu	Peru	2019		Au					1	U	U			1	2
388	Y	Y	N	N	-	N	N	Yichun Luming Mining, Heilongjiang Province (China Railwa	China	2020		Mo		US			1	A	ST	2,530,000	208,000		1
389	Y	N	N	N	-	N	N	Sasan Ultra Mega Power Project, Harrahva in Singrauli distr	India	2020		Ash					1	A	U		7,700	6	1
390	Y	Y	N	N	-	N	N	San José de Los Manzanos, Canelas, Durango (Exportacion	Mexico	2020		Pb/Zn					1	A	OT	6,000	5,000		3
391	Y	Y	N	N	-	N	N	Hpakant, Kachin state	Myanmar	2020		Jade					1	U	U			174	4
392	Y	N	N	N	-	N	N	Ponce Enríquez, Azuay Province (Austro Gold)	Equador	2020		Au					1	A	ST	50			3
393	Y	N	N	N	-	N	N	Levikhinsky mine, Sverdlovsk Oblast	Russia	2020		Cu					2	B	U				4
394	Y	N	N	N	-	N	N	Sasa Tailings Storage Facility 4 (Central Asia Metals)	Macedonia	2020		Pb/Zn/Ag					1	A	SE				3
395	Y	N	N	N	-	N	N	Aurizona mine, Maranhão (Equinox Gold)	Brazil	2021		Au					1	A	OT				4
396	Y	Y	N	N	-	N	N	Catoca Mine (Angolan state diamond company Endiama-41	Angola	2021		Diamonds					1	A	ST		100,000	12	1
397	Y	N	N	N	-	N	N	Rio Panusco SA de CV, municipality of Concordia, Sinaloa S	Mexico	2021		Ag/Cu/Pb/Zn					1	B	OT				3
398	Y	Y	N	N	-	N	N	Nesko Madencilik AŞ (Yıldızlar Holdings) Şebinkarahisar dis	Turkey	2021		Cu/Pb/Zn					1	A	SI	4,500	5,000		3
399	Y	Y	N	N	-	N	N	San Antonio de María mine, Ananea Puno Mineria, La Rinco	Peru	2021		Au					1	A	OT				2
400	Y	Y	N	N	-	N	N	Zululand Anthracite Colliery (ZAC) coal mine, KwaZulu-Nata	South Africa	2021		Coal					1	A	ST	1,500			3
401	Y	Y	N	N	-	N	N	Pau Branco mine, Quadrilátero Ferrífero region (Vallourec)	Brazil	2022		Fe					1	A	OT				2
402	Y	N	N	N	-	N	N	MMK Chrome smetler, (MMK - Metallurgy Industry Trade an	Turkey	2022		Cr					1	A	SE				3
403	Y	Y	N	N	-	N	N	Thelkoloi, in Odisha (JSW Bhushan Power and Steel Limite	India	2022		Fe					1	A	U				3
404	Y	N	N	N	-	N	N	QMM Mandena Mine (QIT Madagascar Minerals / Rio Tinto)	Madagascar	2022		Ti					1	A	OT				3
405	Y	Y	N	N	-	N	N	Shanxi Daoer Aluminum Co, Wenquan Township Jiaokou C	China	2022		Al					1	A	ST				3
406	Y	Y	N	N	-	N	N	Agua Dulce, Potosí (Federación Departamental de Coopera	Bolivia	2022		Ag/Zn					1	A	U				3
407	Y	Y	N	N	-	N	N	Jagersfontein (De Beers, a unit of Anglo American)	South Africa	2022		Diamonds				22,000,000	1	A	ST	5,040,000	63,000	3	1
408	Y	Y	N	N	-	N	N	Williamson Mine, Mwadui Lohumbo, Kishapu District, Shiny	Tanzania	2022		Diamonds	Sand	Modified CL	26	25,760,000	1	A	SI	12,800,000	7,500		1
409	N	Y	N	N	-	N	N	Kearl oil sands mine, Fort Chipewyan, Alberta	Canada	2022		Bitumen					1	U	SE				4
410	N	Y	N	N	-	N	N	Kearl oil sands mine, Fort Chipewyan, Alberta	Canada	2023		Bitumen					1	U	SE	5,300			3
411	Y	N	Y	Y	112	Y	N	Southern Clay, Tennessee	USA	1989	Stratified	Clay	E	WR	5		1	A	SE	300			3
412	N	N	N	Y	5	Y	N	Atlas Consolidated	Philippines								1	A	MS				U
413	N	N	N	Y	6	Y	N	Avoca Mines	Ireland			Cu	T	WR			1	A	SI				U
414	N	N	N	Y	8	Y	N	Bancroft, Ontario	Canada			U					3	U	SE				U
415	N	N	N	Y	16	Y	N	Blackbird, Idaho	USA			Co	MW	CL	15	1,230,000	2	B	ST				U
416	N	N	N	Y	19	Y	N	Captains Flat Dam 2	Australia			Cu	E	CL	22		2	A	SI				U
417	N	N	N	Y	23	Y	N	Casapalca	Peru			Pb/Zn	T	US	107		1	A	ST				U
418	N	N	N	Y	24	Y	N	Casapalca	Peru			Pb/Zn	T	US	107		1	A	EQ				U
419	N	N	N	Y	52	Y	N	Gransisle, Britisch Columbia	Canada			Cu	MW	DS	24		2	A	SE				U
420	N	N	N	Y	61	Y	N	Irelyakh	USSR				E	WR	10		2	A	ST				U

421	N	N	N	Y	78	Y	N	Miami Copper, Arizona	USA			Cu	T	US			2	A	SE				U
422	N	N	N	Y	82	Y	N	Missouri Lead, Missouri	USA			Pb	CST	DS	17		2	A	ST				U
423	N	N	N	Y	103	Y	N	Santander	Spain								1	A	FN				U
424	N	N	N	Y	113	Y	N	Southwest USA	USA				T	US			2	A	SI				U
425	N	N	N	Y	126	Y	N	Undefined						US			1	A	SI				U
426	N	N	N	Y	127	Y	N	Undefined					E	WR			1	A	ST				U
427	N	N	N	Y	128	Y	N	Undefined					T	US			2	A	ST				U
428	N	N	N	Y	129	Y	N	Undefined					MW	US			1	A	SI				U
429	N	N	N	Y	130	Y	N	Undefined					T	US			2	A	SE				U
430	N	N	N	Y	131	Y	N	Undefined						US			2	A	SI				U
431	N	N	N	Y	132	Y	N	Undefined				Au	E	WR	8		3	U	U				U
432	N	N	N	Y	133	Y	N	Undefined				Au	E	DS			3	U	SE				U
433	N	N	N	Y	134	Y	N	Undefined					R	WR	24		2	A	FN				U
434	N	N	N	Y	137	Y	N	Undefined	South Africa			Au	T	US			2	A	FN				U
435	N	N	N	Y	138	Y	N	Undefined	South Africa			Au	T	US			2	A	SE				U
436	N	N	N	Y	139	Y	N	Undefined	South Africa			Au	T	US			1	A	SI				U
437	N	N	N	Y	140	Y	N	Undefined	USA			Cu	CST	US	60		2	A	SI				U
438	N	N	N	Y	141	Y	N	Undefined	USA			Mg	E	WR	6		2	A	FN				U
439	N	N	N	Y	142	Y	N	Undefined	UK				R		12		1	A	U				U
440	N	N	N	Y	143	Y	N	Undefined	UK			Coal		DS			2	B	SI				U
441	N	N	N	Y	147	Y	N	Undefined, Arizona	USA			Cu	CST	US	18		2	A	SE				U
442	N	N	N	Y	148	Y	N	Undefined, Colorado	USA				E	WR			3	U	SE				U
443	N	N	N	Y	151	Y	N	Undefined, Indiana	USA			Coal					1	B	OT				U
444	N	N	N	Y	155	Y	N	Undefined, Wyoming	USA			Trona	E	WR	24		3	U	SE				U
445	N	N	N	Y	157	Y	N	Undefined, Britisch Columbia	Canada				CST	DS			2	A	SE				U
446	N	N	N	Y	158	Y	N	Undefined, Britisch Columbia	Canada				MW	DS	30		2	A	SE				U
447	N	N	N	Y	160	Y	N	Undefined, Eastern USA	USA			Coal	MW		150		2	A	SI				U
448	N	N	N	Y	201	N	Y										U	U	U				U
449	N	N	N	Y	213	N	Y	Fernandinho, Belo Horizonte	Brazil			Fe	T	US	40		1	A	SI				U
450	N	N	N	Y	215	N	Y	Forquilha	Brazil			Fe					1	A	OT				U

A.2. Incident Descriptions

In this section, the incident descriptions of the recorded failures in the database are presented, along with their respective references.

A.2.1. Incident Descriptions

For each failure record, the incident descriptions available in the existing databases are presented, and they can be linked with the database using their ID. The sources are also marked. The sources that could not be traced back are indicated with an asterisk (*), and therefore. These cannot be found in the reference list.

1 | Heavy rains led to the overflow of the tailings dam (Villavicencio et al., 2014).

2 | There is no available description of the incident (White, 2017)* .

3 | The failed tailings dam was constructed using cycloned sand tailings to create its outer shell, with embankment slopes as steep as 1:1. At the time of failure, the last perimeter dike on the embankment crest reached a height of 55 feet. The dam succumbed to liquefaction during the 8.3 Talca earthquake on October 1, 1928. Consequently, a tailings flow slide emerged, resulting in a breach section about 1500 feet wide, which cascaded down a valley and tragically caused the loss of 54 lives (Macías et al., 2015; Smith, 1969; Dobry & Alvarez, 1967; Brawner, 1979; Jigins, 1957).

4 | Following a period of rainfall, the embankment breach was exacerbated in an area that had been weakened by excavation. Subsequently, the tailings flow slide travelled a considerable distance and tragically engulfed a mine train, resulting in multiple fatalities (Donaldson et al., 1976).

5 | On May 27, 1937, a catastrophic flow failure occurred, involving gold tailings, in Tlalpujahua, Michoacán, Mexico (Infomine*; Macías et al., 2015).

6 | No details about the failure are available, except that the gold tailings liquefied, leading to a tailings flow slide that extended to a nearby river. The resulting flow caused extensive damage to river flats, affecting an area up to 10 miles downstream (Ash, 1976).

7 | There is no available description of the incident (CDA,2017)*.

8 | During the process of embankment raising, a portion of the tailings was inadvertently discharged from the rear of the impoundment, creating a narrow sand tailings beach and causing water to accumulate near the embankment crest. This accumulated water was typically decanted using a vertical riser decant system, but due to inattention to flashboard placement, ponded water rose and ultimately overtopped the embankment. As a result, a narrow breach occurred, leading to the loss of some tailings. To address the breach, mine waste rock was used to fill the affected area. After resolving the issue, the impoundment was put back into operation, and further embankment raising was conducted, ultimately reaching a height of 110 feet without encountering any subsequent incidents (Anecdotal)*.

9 | The breach of the embankment served as the trigger for a subsequent tailings flow slide. According to accounts, there was rainfall preceding the failure, which likely contributed to increased dike saturation. Additionally, it is suggested that the failure may have been initiated by "minor shearing" in the embankment structure (Maclever, 1961).

10 | The available information about the failure is limited, and it only indicates that the tailings liquefied, resulting in a tailings flow slide that reached a nearby river. Further details are not provided (Ash, 1976).

11 | The dam breach was attributed to a shear failure in weak foundation materials. (Maclever, 1961).

12 | The dam was built on a foundation consisting of 5 to 17 feet of muskeg overlying alluvial sands, clays, and clayey silts. Over the period between 1936 and 1944, the dam experienced 17 distinct episodes of foundation sliding, resulting in subsidence of the embankment crest and lateral spreading. These failures occurred rapidly, within a few minutes, and without any prior warning. The extent of crest subsidence ranged from 4-8 feet when the embankment height was approximately 15 feet and increased to 20-25 feet after raising the embankment to a height of 50 feet (Hollinger Mill Staff, 1951).

13 | There is no available description of the incident (CDA,2017)*.

14 | The failure of a sand dike occurred due to excessive seepage and high phreatic conditions (Lenhart, 1950).

15 | The embankment was constructed through direct spigotting of tailings, utilising upstream raising procedures. The foundation is believed to have been comprised of low-permeability glacial till. The failure has been attributed to the freezing of the dam face during a period of elevated snowmelt and spring runoff, which resulted in an increase in the phreatic surface and subsequent slope instability. As a consequence of the instability, a significant tailings flow slide occurred, moving towards the St. Mary River several miles away. However, it seems that the tailings flow slide did not reach the river. Notably, frozen blocks of material were observed within the flow failure mass Robinson and Toland (1979).

16 | The dam had been constructed to a height of 100 feet, utilising draggling-cast mine waste, likely composed of sands and clays. At the time of failure, the dam held phosphate slimes and clear water, with the impounded depth reaching 25 feet. The failure is believed to have been caused by seepage and piping, potentially worsened by significant rainfall shortly before the incident. Following the failure, the released phosphate slimes resulted in suspended solids concentrations as high as 800 ppm in the Peace River. (Anecdotal)*.

17 | The dam was constructed using mine waste, likely consisting of sand and clay. At the time of failure, the impoundment contained approximately 12 feet of phosphatic clay slimes and 1.5 feet of water, which were in direct contact with the upstream embankment face. The failure occurred as a result of seepage and piping on the downstream face of the embankment, and it is possible that 1.6 inches of rainfall prior to the failure contributed to the incident. Following the failure, the released phosphatic clay slimes led to suspended solids concentrations of 15,000 ppm in a nearby creek immediately adjacent to the impoundment and 800 ppm in the Peace River located farther downstream (Anecdotal)*.

18 | Several months prior to the failure, the dam's height had been increased using sand fill. At the time of failure, the upstream face of the dam was in direct contact with water at least 5 feet deep, including the interface between the new and old fill. The failure is believed to be linked to either the presence of logs and brush in the original portion of the structure or an old decant pipe discovered at the bottom of the breach. In either scenario, the eventual cause of failure was seepage and piping. As a result of the failure, the released phosphate clay slimes caused suspended solids concentrations as high as 8000 ppm in the Peace River (Anecdotal)*.

19 | The incident resulted in contamination of the Rimac River, and there were several reported deaths as a consequence (Olecop & Pacheco, 2007; Pacheco, 2019).

20 | The dam failure was a result of sliding along both the downstream and possibly the upstream slopes. Contributing causes included the retention of clearwater above the level of the impounded phosphate clay slimes, directly against the upstream face of the dam. Additionally, active mining and blasting at adjacent locations downstream from the dam, along with inadequate stripping and grubbing of the dam/foundation contact, were identified as potential factors that contributed to the failure (Anecdotal)*.

21 | The dam included a return-water canal at its downstream toe, which impounded water against the downstream face of the dam. The failure ensued when the water in the canal was suddenly released due to a break in its confining dike. The rapid reduction in canal tailwater level likely triggered rapid-drawdown instability of the downstream slope of the impoundment dam. As a result, the breach measured approximately 100 feet wide, allowing the release of phosphatic clay slimes impounded behind the dam. The released phosphatic clay slimes led to suspended solids concentrations as high as 20,000 ppm in the Alafia River (Anecdotal)*.

22 | Following an extended period of rainfall, an embankment slope failure took place, leading to water covering the tailings beach and encroaching upon the embankment crest. As a result of the failure, approximately one-third of the impoundment contents were lost during the subsequent tailings flow slide (Donaldson et al., 1976).

23 | The incident resulted in several fatalities, the interruption of the mountain road Pasco-Huánuco, and significant environmental damage (Olecop & Pacheco, 2007.

24 | Approximately 50% of the total volume of the dam flowed into the swift Mailuu-Suu River, located only 30 m (98 ft) downhill from the breach point. The waste subsequently spread about 40 km (25 mi) downstream, crossing the national border into Uzbekistan, and extending into the densely populated Fergana Valley. The incident resulted in multiple deaths, meeting the minimum criteria of three fatalities. The exact number of deaths was not provided.

25 | The tailings dam failure occurred during a flash flood event, leading to the discharge of tailings and mill effluent into a nearby creek and river (US AEC, 1974)*.

26 | The original earth fill dam was initially constructed in 1953 at a height of 45 feet and was subsequently raised multiple times using additional earth fill. In 1959, a flood caused the spillway to wash out, resulting in some tailings release, but the dam embankment itself remained intact with no breaches or damage. In 1960, signs of slumping were observed on the dam's downstream face with a 2:1 slope, prompting the construction of a rockfill toe berm at a 3:1 slope as a buttress. Despite these challenges, the dam remained operational and was further raised between 1971 and 1976 using cycloned sand tailings, reaching an ultimate height of 83 feet (Missisouri Department of Natural Resources, Dam and Reservoir Safety Program)*.

27 | The first failure resulted in several victims who tragically lost their lives when they became trapped during a second landslide, which buried them. The material from the landslide travelled distances of over 500 m until it was eventually channelled to the Besaya River. Through forensic study, static liquefaction was identified and confirmed in 2017 as the contributing factor to the incident (Férnandez-Narajano et al., 2017).

28 | The failure of the fly ash dump was caused by the removal of its support, resulting in 11 fatalities and the destruction of houses (Blight & Fourie, 2003; CDA, 2017*).

29 | A lagoon had formed at the base of a colliery waste pile on a valley side, situated at an elevation of approximately 183 m. Washery tailings were pumped to this lagoon through a pipeline. However, the downslope bund of the lagoon overtopped and breached, leading to the release of tailings. The flowing tailings reached an elevation of 65 m, near the Rhondda River (Aberfan Report: Her Majesty's Stationery Office, 1967)*.

30 | The dam failed due to unspecified causes, which were not reported. Fortunately, no damage was reported, and the released effluent did not reach any flowing stream (US AEC, 1974)*.

31 | A gypsum stack dike break occurred at the American Cyanamid Phosphate Complex in Brewster, Florida. This incident resulted in the release of approximately 3 billion gallons of process water into Hooker's Prairie. The water was contained and treated with lime on-site before being discharged into the South Prong of the Alafia River. As a consequence of the dam breach, 10 million gallons of acid water were released, causing pollution of the Alafia River. Unfortunately, no further details about the incident are available (Anecdotal*; Beavers, 2013).

32 | An earthquake with a magnitude of M6-3/4 struck northern Peru after 3 weeks of heavy rainfall. This seismic event led to the liquefaction failure of the embankment of a nearby tailing facility. The impact of the failure resulted in damage to agriculture and infrastructure in the affected area (Smith, 1969; Oldecop & Pacheco, 2007).

33 | The dam failure occurred due to unspecified causes, which were not reported. The released tailings reached a nearby creek, and a portion of them were carried as far as 25 miles downstream to a reservoir (US AEC, 1974)*.

34 | The upstream dam failed after three days of moderate rainfall, resulting in the release of 380 m^3 of water. The incident led to the destruction of 11 villages, causing injuries to 92 people, and leaving 13,970 people homeless (Wei et al., 2013; Quelopana, 2019).

35 | The dam failure was attributed to excessive seepage, which led to subsequent erosion of the embankment (CDA, 2017)*.

36 | The dam was intentionally breached to release a 2-foot depth of effluent. This measure was taken to prevent an uncontrolled release of the impoundment contents during heavy rain (US AEC, 1974)*.

37 | The failure of the tailings dam due to static liquefaction resulted in the release of highly acidic water, impacting an area of 5 km^2, various infrastructures, the water course of Beal wadis stream, and the El Mar Menor Lagoon. The El Mar Menor Lagoon is of significant ecological and patrimonial value in the Mediterranean Sea region.

38 | The mine operated with several primitive dams, and one of them collapsed during its operation. The exact reason for the failure remains unknown, but there is evidence suggesting it might have been caused by water injection due to the rupture of a decant pipe, leading to erosion of the external slope and subsequent tailings liquefaction. The liquefied tailings flowed downstream, resulting in three casualties. However, it is not clear whether these deaths directly resulted from the dam failure. Unfortunately, no contemporaneous documentation or images are available, but forensic analysis indicates that the rupture of the decant pipe led to tailings saturation and liquefaction, triggering the failure (Garino et al., 2016; Pacheco, 2019; Zabala et al., 2018).

39 | The cause of the failure is not specified in the available information. However, it is mentioned that the released material was contained in a downstream impoundment. Further details regarding the incident are not provided (MHSA*).

40 | The release of impounded phosphatic clay slimes resulted in the pollution of an adjacent creek and the Alafia River (Anecdotal*).

41 | The dam was initially constructed as a starter dike for future upstream raising and operated to retain water. During the first filling, sinkholes emerged in both abutments, and initial attempts to address them involved covering them with tailings. However, this proved ineffective. Subsequently, a concrete cutoff wall was constructed through the embankment and into the foundation to address the sinkhole issue. The development of sinkholes was attributed to the thawing of foundation permafrost, which enabled ice-filled joints in the foundation rock to transmit seepage, leading to piping and sinkhole formation (Biyanov, 1967).

42 | The dam was initially constructed and raised using clay and gravel soils, with downstream slopes of 1.5:1. The instability of the slope occurred as a result of inadequate internal drainage and the steep embankment slopes. To address this issue, an internal drainage zone was incorporated during subsequent raises of the dam to improve stability and prevent further slope instability (Anecdotal)*.

43 | The tailings failures that occurred on March 28, 1965, were a result of the La Ligua earthquake in Chile. The embankment of the dam was of the upstream type with steep slopes as steep as 1.4:1, and there was only an 8 m separation between the edge of the ponded water and the crest of the embankment. Eyewitness accounts described the failure sequence, with the face of the embankment sliding first, followed by flow sliding of the tailings behind the breach. This led to the release of the tailings and subsequent damage during the earthquake event (Dobry & Alvarez, 1967).

44 | The tailings failures that occurred on March 28, 1965, were a result of the La Ligua earthquake in Chile. The dam involved was a rockfill dam with slide slopes of approximately 1.5:1. The damage caused by the earthquake was limited to shallow longitudinal cracking on the crest of the dam (Dobry & Alvarez, 1967).

45 | The Cerro Negro No. 1 dam was not operational during the time of the M7-7 1/4 La Ligua earthquake. It was located adjacent to the No. 3 dam, which experienced failure. The slopes of the No. 1 dam were as steep as 1:1. As a result of the earthquake, the No. 1 dam experienced cracking, particularly along the crest, and some small slides occurred (Dobry & Alvarez, 1967).

46 | The Cerro Negro No. 2 dam was also inactive during the M7-7 1/4 La Ligua earthquake and situated adjacent to the failed No. 3 dam. The slopes of the No. 2 dam were as steep as 1:1. Similar to the neighbouring inactive No. 1 dam, the No. 2 dam also experienced cracking along the crest and small slides as a result of the earthquake (Dobry & Alvarez, 1967).

47 | The upstream-type dam was subjected to intense shaking during the M7-7 1/4 La Ligua earthquake. According to eyewitness accounts, surface waves were observed on the liquefied slimes for a duration of up to 1 minute after the shaking had ceased. These waves of liquefied slimes caused erosion of the small perimeter dike on the embankment crest, resulting in a breach of the embankment. Consequently, a tailings flow slide was generated due to the breach (Dobry & Alvarez, 1967; Rico et al., 2007).

48 | The tailings failures that occurred on March 28, 1965, were a result of the La Ligua earthquake in Chile. The impoundment, which consisted of 3 levels, had been abandoned for a period of 10 years. The embankments of the impoundment were constructed with slopes of 1.4:1. During the earthquake, the embankments experienced significant damage. Cracks up to 6 feet deep appeared along the entire crest, and several circular slides occurred, particularly at the corners of the embankment. Additionally, crest deformation of up to 1 foot was observed as a result of the seismic activity (Dobry & Alvarez, 1967).

49 | The tailings failures that occurred on March 28, 1965, were a result of the La Ligua earthquake in Chile. The dam was constructed using the cycloning method and is inferred to have been raised according to the downstream method with a downstream slope of 3.7:1. The impoundment had undergone rapid filling immediately prior to the M7-7 1/4 La Ligua earthquake of March 28, 1965. Eyewitness accounts indicated that the impounded slimes were completely liquefied, and waves were generated on the surface. The combination of inertial forces from the earthquake and increased pressure from the liquefied slimes resulted in the opening of a breach near the abutment. This breach was rapidly enlarged by the flow slide. The failure of the dam, along with that of the adjacent Old Dam, caused destruction to the town of El Cobre and tragically resulted in the loss of more than 200 lives (Dobry & Alvarez, 1967).

50 | The tailings failures that occurred on March 28, 1965, were a result of the La Ligua earthquake in Chile, which accounted for a significant part of the high number of earthquakes in the period from 1960 to 1970. Among the failed dams, about half were abandoned, and the other half were located at operating mines. The dam that failed had been constructed using the upstream method by spigotting from flumes on the crest. At the time of the earthquake, it was in use as an emergency impoundment. The presence of embankment slopes as steep as 1.2:1 and slime layers near the face indicated that the static stability of the dam may have been marginal even before the earthquake occurred. The tailings flow slide resulting from the dam failure caused devastation to the town of El Cobre and tragically claimed the lives of more than 200 people (Dobry & Alvarez, 1967; Rico et al., 2007).

51 | The El Cobre Small Dam was located adjacent to the New Dam and Old Dam, both of which failed during the M7-7 1/4 La Ligua earthquake. The Small Dam had similar construction to the Old Dam, with steep slopes of 1.2:1. However, it was abandoned at the time of the earthquake and had a desiccated surface crust approximately 5 m deep. While the Small Dam did experience some damage in the form of local slides, it remained essentially intact despite the earthquake (Dobry & Alvarez, 1967).

52 | The tailings failures that occurred on March 28, 1965, were a result of the La Ligua earthquake in Chile. The upstream dam experienced a liquefaction flow failure, where the tailings liquefied and flowed. However, the liquefied tailings travelled a distance of 1 km on the gently sloping valley floor without causing any damage (Dobry & Alvarez, 1967).

53 | The tailings failures of March 28, 1965, were from the La Ligua, Chile, earthquake. The New Dam was being used to retain mill process water at the time of the M7-7 1/4 1965 La Ligua earthquake, and pond water levels retained by the upstream-type embankment were relatively high. Embankment slopes were a maximum of 1.4:1. The dam failed by liquefaction during the earthquake, but no damage was reported (Dobry & Alvarez, 1967; Rico et al., 2007; Rana et al., 2021).

54 | The tailings failures of March 28, 1965, were from the La Ligua, Chile, earthquake. The dam experienced strong shaking during the earthquake and was adjacent to the active Los Maguis No. 3 dam, which failed. The No. 1 dam had been out of service for many years and had undergone only slight cracking along the crest, along with small slides in dry tailings on the side slopes. The earthquake had a significant impact on the dams in the area, but the No. 1 dam, despite being adjacent to the failed No. 3 dam, experienced minimal damage as it had been inactive for an extended period (Dobry & Alvarez, 1967; Quelopana, 2019).

55 | The tailings failures that occurred on March 28, 1965, were a result of the La Ligua, Chile, earthquake. The dam failed due to liquefaction. It had been constructed using the upstream method, with slopes as steep as 1.4:1. Despite the failure and resulting flow slide, no additional damage was reported. The tailings flowed downstream to an elevation of 65 m near the Rhondda river (Dobry & Alvarez, 1967; Rico et al., 2007).

56 | The tailings failures that occurred on March 28, 1965, were a result of the La Ligua, Chile, earthquake. There were two nearly identical upstream-type dams located on a 30-degree mountainside slope, and they were used alternately. During the M7-7 1/4 La Ligua earthquake, Dam No. 1 was breached, resulting in the release of a small flow slide from the upper portion of the impounded tailings (Dobry & Alvarez, 1967).

57 | The tailings failures that occurred on March 28, 1965, were due to the La Ligua, Chile, earthquake. The No. 1 dam had been constructed with slopes of 1.7:1 and was in active operation at the time of the earthquake. The dam experienced serious cracking at one corner, but the embankment itself did not fail despite the seismic activity (Dobry & Alvarez, 1967).

58 | The tailings failures that occurred on March 28, 1965, were due to the La Ligua, Chile, earthquake. The No. 2 dam was inactive at the time of the earthquake and experienced minor cracking as a result of the seismic activity (Dobry & Alvarez, 1967).

59 | The tailings failures that occurred on March 28, 1965, were due to the La Ligua, Chile, earthquake. The No. 3 dam was inactive at the time of the earthquake and experienced minor cracking as a result of the seismic activity (Dobry & Alvarez, 1967).

60 | The tailings failures that occurred on March 28, 1965, were due to the La Ligua, Chile, earthquake. The No. 4 dam was inactive at the time of the earthquake and experienced minor cracking as a result of the seismic activity (Dobry & Alvarez, 1967).

61 | A lagoon was formed in heaps of colliery waste on the mountainside. As the tailings level reached 175 m, the downslope bund breached, leading to the release of tailings that flowed downhill towards the river. The tailings entered the colliery car park at an elevation of 65 m, where they caused damage to two or three cars, narrowly avoiding entering the colliery shaft. Downstream, considerable damage was caused by the flowing tailings (Aberfan Report: Her Majesty's Stationery Office, 1967)*.

62 | The failure of the dam was attributed to foundation sliding, which was caused by artesian foundation pore pressures resulting from seepage from nearby active impoundments and natural recharge. Subsidence from underground workings was also considered a possible contributing cause to the failure (Thompson & Rodin, 1972).

63 | The impoundment operation commenced in 1962, involving the construction of a clay starter dike and a sand under-drainage system. The failure of the dam is attributed to seepage-related slumping and piping, which initiated at the toe of the embankment and gradually progressed until the breach occurred, resulting in tailings flow sliding. The drainage system's ineffectiveness is believed to be due to insufficient permeability of the sand, which led to the failure of the dam (Kleiner, 1976; Lucia, 1981*).

64 | The failure is thought to have been triggered by excess foundation pore pressures. A slurry pond that had been built into the Old Dirt Tip collapsed, sending a flow of tailings over an adjacent road which was covered to a depth of 3 m and remained closed for 10 days (Penman & Charles, 1990).

65 | The failure is believed to have been triggered by excess foundation pore pressures. A slurry pond that had been built into the Old Dirt Tip collapsed, resulting in a flow of tailings over an adjacent road. The road was covered to a depth of 3 m and remained closed for 10 days due to the tailings flow caused by the collapse of the slurry pond (CDA, 2017)*.

66 | The failure is thought to have been triggered by excess foundation pore pressures. A slurry pond that had been built into the Old Dirt Tip collapsed, resulting in a flow of tailings over an adjacent road. The road was covered to a depth of 3 m and remained closed for 10 days due to the tailings flow caused by the collapse of the slurry pond (Bishop, 1973).

67 | The tailings wave, resulting from the dam failure, travelled a distance of 8 km to the city of Vratza, causing significant destruction. Additionally, half of Sgorigrad village, located 1 km downstream, was devastated, resulting in the tragic loss of 488 lives. The failure of the dam was attributed to rising pond levels following heavy rains and/or failure of the diversion channel. Unfortunately, no further details are available regarding the incident (Abadjiev, 1990; Quelopana, 2019).

68 | The incident involved the collapse of the stream deviation tunnel located beneath the Tiefenbachtal tailings dam. As a result, the iron oxide slurry was released and reached the Müglitz River and subsequently the Elbe River, coloring it red. The red coloring extended along the Elbe River until Hamburg, causing a significant visual impact along the waterway.

69 | The failure occurred at a coal tip (waste rock pile) that was constructed on the hillside above the village. Waste was dumped over the spring, and over time, multiple tips experienced failures. In 1939, one of the tips failed, burying a road. In 1944, Tip 4 failed, and in 1966, Tip 7 failed, causing it to slide into the village. Additionally, there was a dam failure due to liquefaction caused by heavy rain. The combined incidents resulted in significant damage and potential hazards to the surrounding area (Blight & Fourie, 2003).

70 | The failure of the dam was caused by underground mining activities, specifically upward stopping, which created a cavity and eventually a sinkhole beneath the upstream slope. As the underground mining approached the fault and dewatering activities lowered the water table, vibrations from rock bursts likely contributed to the loosening of the fault gouge, further exacerbating the situation. The breach occurred near the south end of the dam, leading to the liquefaction of tailings that swept down the valley with a width ranging from 50 m to 220 m. The flow covered 7 small villages, destroyed the railway, and tragically resulted in the loss of 18 lives. The dam had been constructed on alluvium underlain by a 20 m wide fault zone, situated in an area of active underground mining. At the time of the failure, the third stage of the dam was almost completed, and no signs of defects such as cracking, seepage, or wet areas were detected, indicating the failure was not evident beforehand (Wolski et al., 1976; ICOLD Tailings Committee*).

71 | The failure occurred while regarding the operation to stabilise the bulging and deformation of the downstream dam slope, which had occurred two months prior to the incident.

A potential contributing factor to the failure was a rise in impoundment fluid levels, likely caused by displacement due to regrading of mine waste from an adjacent pile. The resulting tailings flow failure covered an area of approximately 4 hectares, leading to significant damage and loss of containment. The circumstances surrounding the failure indicate that the dam's stability was compromised, possibly exacerbated by the ongoing regard operation and fluid level changes in the impoundment (Thompson & Rodin, 1972).

72 | The slide in the downstream slope occurred after a period of heavy rain and approximately one week following the widening of the dam crest by dumping uncompacted mine wastefill. Both the original and newly constructed slopes were at the angle of repose, which could have contributed to the instability. Additionally, a high phreatic surface, indicating a high water table, existed within the embankment, further weakening its stability. These factors combined may have led to the failure of the downstream slope, resulting in a slide and potential damage to the dam structure (Thompson & Rodin, 1972).

73 | Shortly after the first stage of the dam was filled, several issues arose, including small slips on the downstream slope, high piezometer pressures, and a break in the decant pipe passing through the dam. To address these problems, repairs were made by implementing a filter and buttress on the downstream slope. Subsequently, during the downstream raising of the dam, seepage occurred at the interface between the new and original fill on the downstream dam slope while impounding runoff. To resolve this issue, a synthetic membrane was placed on the exposed upstream face of the dam. The repairs and measures taken were intended to ensure the stability and integrity of the dam following the initial construction and to mitigate any potential risks associated with seepage and other concerns (Little & Beavan, 1976).

74 | A significant dam breach led to the release of 250,000 m^3 of phosphatic clay slimes along with 1.8 million m^3 of water. The spilled material ultimately reached the Peace River, causing pollution and environmental damage. Reports indicate a fish kill in the affected area due to the release of the slimes into the river. Unfortunately, no further details are available about the specific cause of the breach or the extent of the environmental impact caused by the incident (Anecdotal)*.

75 | A dam breach occurred, leading to the discharge of 250,000 m^3 of phosphatic clay slimes and 1.8 million m^3 of water into the Peace River, causing pollution. Subsequently, a fish kill was documented as a result of the incident. Additional information regarding the breach's cause and the magnitude of its environmental consequences is currently unavailable (US AEC, 1974)*.

76 | The dam breach resulted in the pollution of a nearby creek and the Peace River (Anecdotal)*.

77 | During the M7.8 Tokachi-Oki earthquake, the embankment failed due to liquefaction, and the resulting flow slide extended to and traversed a river located at the lower end of the embankment. The embankment was designed with 3:1 slopes and featured a low rockfill starter-dike at its base (Ishihara et al., 1990; Rico et al., 2007).

78 | The collector ditch, as it turned out, was insufficiently deep to effectively manage seepage. The starter dike for the impoundment was built using compacted till, with an oxidized till foundation characterized by joints and sand seams. A cutoff trench of compacted clay was installed beneath the dike, extending to a depth of 4 feet, and a shallow collector ditch was constructed at the base. The plan included extending the ditch through the oxidized till as a remedial action (Kent et al., 1983).

79 | Interruption of the central road and pollution of the Rimac River (Gil, 2012; Oldecop & Pacheco, 2007).

80 | The retaining dam of a settling pond burst and there was damage to property and roads (Penman & Charles, 1991).

81 | The rockfill dam experienced sloughing as a result of heavy rains, leading to significant stress in the saturated tailings deposit. This stress-induced liquefaction, resulting in tailings flow sliding and a mudslide. This, in turn, caused extensive damage downstream and resulted in loss of life (Smith, 1969).

82 | In the initial years of operation, the dam experienced an issue of excessive seepage, but there were no incidents of tailings loss or damage to the dam. The tailings dam was designed as a conventional water-retention structure, featuring an internal core, layers of clayey gravel shells, and a blanket drain. The operation of the dam involved the accumulation of ponded water directly against the upstream face of the dam, which led to the excessive seepage issue. To address this, the reservoir water level was lowered, an asphalt emulsion was applied to the upstream face of the dam, significantly reducing seepage. Additionally, during the construction of subsequent downstream dam raises, a primary measure for controlling seepage involved spigotting tailings from the crest of the embankment (Smith et al., 1977).

83 | Damage to and pollution of the agriculture of Huachocolpa (Gil, 2012; Oldecop & Pacheco, 2007).

84 | The piping failure occurred 25 years after closure with a release of 9 million gallons of tailings and supernatant (Mount Polley Expert Panel, 2015)*.

85 | The overtopping failure occurred due to ice blockage of a decant structure. (Ripley, 1972).

86 | A dam breach occurred due to the structural failure of a decant conduit (Ripley, 1972).

87 | Overtopping occurred due to the accumulation of water in the impoundment from hurricane rainfall. The embankment breached and water was released, but flow failure of the tailings did not develop. The breach was repaired and the embankment was placed back into service (Anecdotal)*.

88 | No details provided (MHSA)*.

89 | Leakage of water containing copper and zinc. The dam was built on fractured bedrock, with no liner or grouting (DoE Canada)*.

90 | Slope failure occurred immediately after the completion of a perimeter dike to raise the embankment and following a period of heavy rainfall. High pore pressures and the addition of the perimeter dike fill, possibly also supplemented by vibrations of construction equipment, are thought to have been contributing factors (Ripley, 1972).

91 | Saturated slime tailings deposited in a TSF 3 over subsidence feature flowed into an underground mine killing 89 miners. Liquefaction of tailings, flowing into underground workings. Some 1,000,000 tons of tailings liquefied and flowed within 15 minutes into underground mine workings where mining was in progress beneath the impoundment, resulting in the death of 89 miners. It is believed that voids in the rock above the workings propagated upward to the tailings due to unequal extraction of ore or differential settlement of the caving rock. The tailings deposit was stabilised by dewatering and the mining method was changed (Brawner, 1979; Sandy et al., 1976; Lucia, 1981; Blight & Fourie, 2004).

92 | Water decanted from the impoundment flowed in an unlined channel parallel to the downstream toe of the dam. Erosion of the unlined channel produced a downcutting of as much as 12 feet. This triggered cracking and deformation of the downstream embankment slope, with movements seated within lacustrine foundation sediments at a depth coincident with the eroded channel bottom (Brawner, 1979).

93 | A rupture in the tailings discharge line resulted in the dike breaching, allowing tailings to flow for a duration of 2 hours. Fortunately, there was no contamination of the surrounding areas beyond the site (US AEC, 1974)*.

94 | The event resulted in 3 dead, 1 destroyed house and the interruption of the little Lima highway-Huaraz (Oldecop & Pacheco, 2007).

95 | The event resulted in the pollution of the Huallaga River and damage to road infrastructure (Oldecop & Pacheco, 2007).

96 | The event led to pollution of the San Felipe River (Oldecop & Pacheco, 2007).

97 | An earthquake with a magnitude of 4.8 triggered a landslide that ruptured the tailings dam. The mud from the tailings inundated and demolished the surface infrastructure of the mine and entered the mine shafts. Tragically, only 25 miners managed to survive the disaster (Rudolph & Coldeway, 1971).

98 | It has been 43 years since the Certej gold mine dam failure. A somber anniversary marked by Mining Watch Romania on October 30, 2014. The Certej disaster of 1971 remains a forgotten tragedy, with 89 lives lost and buried under 300,000 m^3 of mud (Mining Watch Romania*; Rana et al., 2021; Swedish Mining Association, 2001).

99 | The dam breach allowed phosphatic clay slimes to enter the Peace River, where they were carried in suspension for a distance of 120 km. Strikingly, the cause of the dam failure remains unknown, even though the dam appeared intact and without any signs of distress just 15 minutes before the catastrophic event occurred. Although these slimes are not toxic to humans, they have a devastating impact on the aquatic ecosystem. They coated the gills of fish, leading to a widespread fish kill as the fish suffocated. The tailings dam was primarily composed of a uniform section of compacted glacial till. Water that was decanted from the impoundment flowed through an unlined channel running parallel to the downstream base of the dam. Erosion within this unlined channel caused it to cut down as much as 12 feet into the ground. This erosion, in turn, resulted in cracking and deformation of the downstream embankment slope. These movements were concentrated within the lacustrine foundation sediments at a depth corresponding to the eroded channel bottom. The situation was eventually stabilized through the placement of a berm and relocation of the channel (Lucia, 1981*; Environmental Science and Technology, 1974*; Rico et al., 2007; CDA, 2017*).

100 | Erosion damage to the embankments of 4 sidehill-type impoundments was caused by flooding in the stream located near their bases. Subsequently, the damaged areas were repaired and the embankments were reinforced with riprap (MHSA)*.

101 | The tailings travelled 27 km downstream, resulting in the loss of 125 lives and the destruction of 500 homes. The damage to property and highways surpassed $65 million. The collapse of the tailings dam occurred following heavy rainfall (Rico et al., 2007; CDA, 2017*).

102 | In October 1972, an unusually intense rainfall event caused the destabilization of the Brunita mine pond. Subsequently, a flash flood of tailings occurred, resulting in the tragic loss of one life and considerable material damage. The flow of tailings impacted a highway and a railway line, disrupted electricity and telephone networks, and ultimately led to the destruction of the La Union cemetery. This catastrophic event was a direct result of the dam failure following heavy rain (Marín-Crespo et al., 2018; Rodriguez et al., 2011).

103 | The failure along a 500-foot section of the embankment was triggered by slope instability. This instability is thought to be connected to saturation and perched seepage conditions along a layer of slimes deposited within the embankment two decades earlier. The released tailings covered a small portion of an adjacent railroad. A wetted zone had been present on the embankment face at the precise location of the failure. The released tailings also affected a small section of the nearby railroad (Anecdotal)*.

104 | The overtopping failure occurred due to improper operation and insufficient deposition of tailings on the beach, which led to ponded water encroaching on the embankment crest (New Mexico State Engineers Office)*.

105 | The dam included a 60-foot-high zoned earth fill starter dike. Prior to failure, two 15-foot high upstream raises had been added using perimeter dikes of uncompacted clayey soils derived from weathered shales. A third raise of cyclone sand tailings was under construction when the uncompacted shale dikes slumped from increased load and pore pressure. The resulting embankment breach took the form of a narrow gulley down to the level of the starter dike crest and released about one-third of the impoundment contents in the form of a tailings flow slide. Tailings reached streams and rivers as far as 15 miles away. Dam failure from increased pore pressure during construction of incremental raise. The dam included a 60-foot-high zoned earth fill starter dike. Prior to failure, two 15-foot high upstream raises had been added using perimeter dikes of uncompacted clayey soils derived from weathered shales. A third raise of cycloned sand tailings was under construction when the uncompacted shale dikes slumped from increased load and pore pressure. The resulting embankment breach took the form of a narrow gulley down to the level of the starter dike crest and released about one-third of the impoundment contents in the form of a tailings flow slide. Tailings reached streams and rivers as far as 15 miles away (Schlick & Wahler, 1976; Lucia, 1981; Rico et al., 2007).

106 | Instability manifested along a small section of the embankment, precisely where a previous embankment failure had occurred on December 2, 1972. Fortunately, no tailings were released during this recent incident. The earlier failure was attributed to perched seepage conditions along a slimes layer (Anecdotal)*.

107 | The starter dike for an upstream embankment partially breached due to seepage and piping after heavy rains. The starter dike for an upstream embankment partially breached due to seepage and piping after heavy rains. Damage was repaired and plans were made for raising the dam an additional 20 m upstream methods (Londe et al., 1976).

108 | Several episodes of instability occurred within compacted fill that was being placed over spigotted beach sand tailings during the construction of upstream raises. Several episodes of instability occurred within compacted fill that was being placed over spigotted beach sand tailings during the construction of upstream raises. All showed evidence of local liquefaction of the spigotted beach tailings and took the form of subsidence of the compacted fill accompanied by shearing scarps. These failures were attributed to excess pore pressures that developed in the loose beach sand tailings in response to rapidly applied loading during fill placement. No lateral translation occurred during failure and overall embankment stability was not jeopardised (Mittal & Hardy, 1977).

109 | When the embankment reached a height of 65 feet, slope instability occurred due to undrained shearing in soft foundation clays that had reached normally consolidated conditions under the applied embankment loading. The further raising was discontinued, and the impoundment was subsequently abandoned. The embankment was constructed and raised with overall slopes of about 3.5:1. When the embankment reached a height of 65 feet, slope instability occurred due to undrained shearing in soft foundation clays that had reached normally-consolidated conditions under the applied embankment loading. The further raising was discontinued, and the impoundment was subsequently abandoned (Anecdotal)*.

110 | Overtopping resulted in the breach of the embankment, loss of impounded water, and erosional-type gullying of tailings within the impoundment. Flow sliding of the tailings mass, however, did not occur. Embankment perimeter dikes were constructed and upon fine tailings discharged from the rear of the impoundment. Overall embankment slopes were 1.5:1 (Anecdotal)*.

111 | Three tailings impoundments in a sidehill configuration adjoined each other within a narrow valley with a creek at their toe. During a rain-on-snow event, flooding on the creek reached an estimated 100-year recurrence interval. A culvert in the creek upstream from the impoundments became blocked by debris, diverting a large portion of the streamflow into the uppermost impoundment by overtopping, resulting in a cascade failure of all three impoundments. Lacking sufficient decant spillway capacity for these flows the uppermost embankment. Tailings released in the failure covered about 5 acres, including a short section of highway and railroad track. This incremental damage was insignificant in relation to general flood damages to public and private property (Montana Division State Lands*; Rico et al., 2007).

112 | Rain on a heavy snowpack caused the impoundment to fill to capacity, and emergency pumping was insufficient to prevent overtopping with the loss of 2 million gallons of water and about 20% of the impounded tailings. Downstream damage consisted of silting of streambeds. The embankment was subsequently repaired and placed back into service (Idaho Department Water Resources, Dam Safety Section)*.

113 | During heavy rain, the dam overtopped and deep gullies were eroded into the embankment face. This loss of support caused the sliding of the downstream slope over its full height and over a width of 200 ft. Slimes were released to an adjacent river. The dam was constructed of cycloned sands which were hauled by trucks and received variable compaction. Slimes were spotted from the rear of the impoundment, resulting in very soft materials beneath the upstream and raise. These conditions, combined with the steep 1.5:1 embankment face, resulted in marginal stability. (Brawner, 1979; North Carolina Department of Environment Health and Natural Resources, Land Quatily Section*).

114 | No details provided (Jennings, 1979; Rudd, 1979; Lucia, 1981*; Rico et al., 2007; Quelopana, 2019; Blight, 2000).

115 | No details provided (MHSA)*.

116 | No details provided (Rico et al., 2007; Blight & Fourie, 2003).

117 | The apparent cause of failure was embankment sliding along residual and alluvial foundation soils. The tailings flow slide reached a nearby drainage and from there entered a creek (Missouri Department of Natural Resources, Dam and Reservoir Safety Program)*.

118 | Now known as the Mt Emmons mine (MHSA)*.

119 | During extreme runoff from a rain-on-snow event, the slopes of a sidehill diversion ditch became saturated and failed, directing the diverted streamflow into the abandoned impoundment. The decant capacity was insufficient to discharge the inflow, and the embankment was breached by overtopping. Dam failure after heavy rain. Tailings were spilled down Beartrap Creek and into the Blackfoot River. In the next 5 months, alternate solutions for the continuing tailings pollution problem were evaluated, an Environmental Impact Declaration was prepared, and the replacement section of the dam was designed and constructed. The reconstructed section is a compacted, zoned earth fill keyed into the bedrock on the right abutment and the remaining tailings on the left. Exposed rock surfaces were treated with gunite to seal cracks and a 54-inch pipe spillway was installed to handle future floodwater (Toland, 1977).

120 | During operation, leakage of brine into the shallow aquifer was detected (Tallin & Pufahl, 1983)*.

121 | Foundation conditions consisted of highly fractured rock with open joints, and the dam initially incorporated a nominal cutoff. Seepage containing high salt concentrations emerged on the surface downstream from the dam. The dam was constructed to retain tailings and provide evaporation of effluent from trona mined for soda ash processing. Foundation conditions consisted of highly fractured rock with open joints, and the dam initially incorporated a nominal cutoff. When seepage containing high salt concentrations emerged on the surface downstream from the dam, foundation grouting was performed but failed to stop the seepage. Subsequently, an interceptor trench was excavated at the downstream toe to depths up to 60 feet and backfilled with drainage material. Pumping from wells installed in the interceptor trench was effective in preventing further downstream seepage migration (Anecdotal)*.

122 | Leakage of water containing copper and zinc. Dam was built on fractured bedrock, with no liner or grouting (ICOLD Tailings Committee)*.

123 | Adjacent to Bingham Canyon open pit; an underground mine operated form 1979-1982 and re-opened in 1984. The embankment was breached due to overtopping when a slide blocked the spillway structure (MHSA)*).

124 | The rising of tailings above the design level caused overloading of the decant tower and collectors, resulting in structural failure. Tailings flowed through the tower and collector into the river and backwater of water retention downstream (ICOLD Tailings Committee)*.

125 | Tailings flow slide polluted nearly 100 miles (160 km) of the Animas river and its tributaries; severe property damage; no injuries.

126 | During the initial raising of the starter dike, sand and gravel mill reject with excessive fines content was used as fill in the downstream portion of the raise. This did not provide sufficient drainage, and a slide resulted due to the high phreatic surface. During the initial raising of the starter dike, sand and gravel mill reject with excessive fines content was used as fill in the downstream portion of the raise. This did not provide sufficient drainage, and a slide resulted due to the high phreatic surface. A 10-foot wide berm of gravel and rockfill was placed to a height of about 40 feet to stabilise the area (Missouri Department of Natural Resources, Dam and Reservoir Safety Program).

127 | The area experienced an M7.8 main shock, an M7.1 shock 15 days later, and numerous aftershocks of magnitude greater than 5. Damage consisted of cracks on the downstream embankment face and tailings beach, accompanied by boils and fissures near the ponded water. The dam did not fail and remained in service. The upstream type embankment was constructed to a height of 37 m on 1.6:1 slopes at the time of the 1976 Tangshang earthquake (Morgenstern & Kupper, 1988).

128 | During the spring thaw, severe sloughing on the downstream face of the dam occurred, accompanied by extensive downslope creep of heavily saturated fill containing blocks of frozen soil. (Anexdotal)*

129 | Dam failure due to high phreatic surface and seepage breakout on the embankment face. The tailings flow reached and polluted nearby river. Dam failure due to high phreatic surface and seepage breakout on the embankment face. Tailings flow reached and polluted nearby river. 4 tailings impoundments had been constructed in a sidehill configuration by the upstream method using direct tailings spigotting. Embankment slopes ranged from 2:1 to 2.5:1. Failure was attributed to a high phreatic surface and seepage breakout on the embankment face produced by high fines content of the spigotted tailings and insufficient permeability of starter-dike materials. The tailings flow slide reached and polluted a nearby river (Scandic, 1979).

130 | Differential settlement of foundation soils caused embankment cracking and piping failure. A minor quantity of effluent was released (New Mexico State Engineers Office)*.

131 | An initial localised dike failure in 1976 was attributed to a high phreatic surface in the dike resulting from rainfall and high pond operating levels. A larger failure one year later showed evidence of upthrusting at the toe of the pit, block-type downslope movement of tailings and sand boils within the failed mass. Tailings produced by the mining of ocean beach sands for ilmenite, rutile, and zircon were deposited in a mined-out pit. The pit bottom sloped upward at a 3-4 degree angle, and deposition of tailings by direct spigotting proceeded from the lowest end of the pit and progressed upward in increments behind low tailings dikes. This procedure resulted in the deposition of slimes beneath the dikes. An initial localised dike failure in 1976 was attributed to a high phreatic surface in the dike resulting from rainfall and high pond operating levels. A larger failure one year later showed evidence of thrusting at the toe of the pit, block-type downslope movement of tailings and sand boils within the failed mass. This larger failure had no obvious trigger mechanism, and it was concluded that excess pore pressures in permeable layers within the tailings or the pit floor initiate liquefaction (Williams, 1979).

132 | Concentrated seepage and piping in karstic foundation limestone occurred at the embankment toe. A small ring dike was constructed around the area, and water within it was allowed to rise until pressure head balanced seepage exit pressures. No further piping occurred. The impoundment was used to retain tailings from limestone washing operations of a similar nature to phosphatic clay slimes. When the embankment reached a height of about 20 feet, concentrated seepage and piping karstic foundation limestone occurred at the embankment toe (Anecdotal)*.

133 | Melting of snow incorporated into the dam fill caused sufficient slumping to allow overtopping to occur. About 2.3 million gallons of effluent was released along with a small quantity of tailings, but no offsite contamination occurred. The dam slopes were steeper than 3:1 (Teknekron Inclusive, 1978)*.

134 | Dam failure, due to rupture of plugged slurry pipeline; mill decommissioned in 1993, Dam failure due to rupture of plugged slurry pipeline. A tailings slurry pipeline on the dam was restructured due to a blockage by freezing and pressure buildup. The slurry released eroded a"v"-shaped breach in the embankment, which in turn released tailings and an estimated 2 to 8 million gallons of impounded effluent. All released materials were contained on the mine site (Teknekron Inclusive, 1978*; New Mexico State Engineers Office*).

135 | The dam overtopped during an intense 6-inch rainfall due to inadequate spillway capacity. Tailings were eroded by the impounded water flowing through the breach. These tailings were subsequently deposited throughout the city of Fredericktown (Missouri Department of Natural Resources, Dam and Reservoir Safety Program)*.

136 | The dam experienced ground accelerations estimated to be 0.2-0.35 g from the M7. 0Izu-Oshima-Kinkai earthquake. The impoundment had been inactive for about 20 years. The dam experienced cracking and impounded tailings exhibited sand boils, but no failure occurred (Okusa et al., 1980).

137 | The embankment is founded on pre-sheared clay shales of low residual strength. Measured foundation movements indicated the potential for foundation instability, and portions of the embankment were re-designed with slopes as flat as 9:1 (Morgenstern, 1988).

138 | Dam failure due to earthquake, liquefaction, Magnitude 7 earthquake 1st three dams, the valley looked as though it had been painted white, with splashes as high as 30 m on the leaves of forest trees. The embankment was constructed with a rockfill starter dike and had slopes of about 3:1. Failure occurred by liquefaction during the M7.0Izu-Oshima-Kinkai earthquake. The flow slide reached and flowed down a river for 7-8 km, causing one fatality (Marcuson, 1979*; Okusa et al., 1980; Ishihara, 1984).

139 | A newly constructed starter dam (Okusa & Anma, 1980).

140 | Dam failure due to aftershock. The embankment was constructed with rockfill starter dikes, and had slopes of 2.5:1 to 3:1.Liquefaction failure occurred the day after the January 14, 1978 M 7.0 Izu–Oshima– Kinkaiearthquake, and about 5 hours after the two aftershocks of M 5.4 and M 5.8 (Marcuson, 1979*; Okusa et al., 1980; Rico et al., 2007; Quelopana, 2019; CDA, 2017*).

141 | Seepage and piping with the release of 10,000,000 gallons of supernatant. The dam had been abandoned for 13 years at the time of the M7.0 Izu-Oshima-Kinkai earthquake. Boils appeared on the surface of the impounded slimes and the dam was cracked, but no failure occurred (Okusa et al., 1980; Ishihara, 1984).

142 | Following continuous rain over several days (seasonal total rainfall above average), a breach 55m wide suddenly developed, releasing a flow slide of tailings, blocking and contaminating the public waterway. Minor damage to the local village. One child was killed and another injured. Slurry overflow after continuous rain over several days. Early in the morning, following continuous rain over several days (seasonal total rainfall above average), a breach 55m wide suddenly developed, releasing a flow slide of tailings, blocking and contaminating the public waterway. Minor damage to the local village. One child was killed and another injured (Chamber of Mines, Harare, Zimbabwe*; Rico et al., 2007).

143 | Measures to reduce seepage were undertaken in conjunction with the abandonment and closure of the impoundment. These included an embankment buttress with an internal synthetic impervious membrane and cement-bentonite grouting of selected zones of the rock foundation. Post-construction monitoring indicated seepage of less than 1 gram (Reades et al., 1981).

144 | Slope instability occurred during the construction of the dam. Remedial measures included slope flattening and incorporation of horizontal internal sand zones to enhance pore pressure dissipation (Morgenstern et al., 1988).

145 | Piping in the sand beach of the tailings dam, considerable property damage (ICOLD Tailings Committee)*.

146 | Two slides occurred on the 1.5:1 embankment slope due to snowmelt and internal seepage. Both were shallow, measuring 30-80 ft in top width, 150-200 ft in base width, and 80-100 ft in length. Interim stabilisation measures included horizontal drains and a fabric-protected drainage blanket. Long-term stabilisation that followed consisted of a rockfill berm and underlying drainage zone which flattened the slopes from 2.0:1 to 3.0:1 (ICOLD Tailings Committee)*.

147 | The mine closed in 1982, and basic surface remediation efforts were initiated, involving the pumping of tailings into the underground mine. However, high radium levels persisted, particularly in proximity to and on-site, prompting the implementation of an EPA program. Unfortunately, during this process, farmland was inundated. A dam wall breach occurred due to the presence of differential foundation sediment, resulting in the contamination of Rio Puerco sediments extending up to 110 km downstream. The embankment cracking and failure by piping were exacerbated by a combination of factors, including differential foundation settlement aggravated by a high operating pond level and a narrow tailings beach. Post-failure investigations revealed that some foundation soils experienced an excess of 10% collapse upon saturation. The absence of an adequate sand beach, coupled with direct water contact with the embankment fill, allowed piping to occur through cracks in the fill that developed in response to foundation settlement. Approximately 80 million gallons of released effluent travelled to the Rio Puerco, passing through Gallup, NM, and extending into Arizona for a distance of 60-70 miles before completely infiltrating into the streambed alluvium (Nelson & Kane, 1980; Sautter, 1984; Rico et al., 2007).

148 | The embankment is founded on pre-sheared clay shales of low residual strength. Measured foundation movements indicated the potential for foundation instability, and portions of the embankment were re-designed with slopes as flat as 9:1 (Mount Polley Expert Panel, 2015)*.

149 | The dam was overtopped, but no breach occurred and tailings were not released. The dam was placed back in service with minor repairs (Virginia Department Mines, Minerals and Engery, Division Mined Land Reclamation)*.

150 | The failure resulted in pollution of the Tingo River and significant damage to agriculture (Oldecop & Pacheco, 2007).

151 | The dam was breached as a result of piping around the outlet conduit (MHSA)*.

152 | Intense rainfall led to overflow at the abandoned dam situated across the valley. Although the dam had a decant structure, the absence of an abandonment spillway resulted in overtopping failure. This failure was attributed to inadequate decant capacity for efficiently routing streamflows through the impoundment (Villavicencio et al., 2014; Troncoso, 1990).

153 | The failure occurred due to heavy rains and overflow (Villavicencio et al., 2014).

154 | The failure is attributed to a rapid increase in dam wall height, resulting in a rapid raising rate and insufficient dissipation of pore pressures in the embankment. This led to a dam wall breach, causing high internal pore pressure and the subsequent inundation of farmland. The embankment was continuously raised by constructing perimeter dikes using cycloned sand tailings, and slimes cyclone overflow was discharged into the impoundment. During the night, flow sliding occurred through a breached section that was 215 m wide and 35 m deep. The tailings flowed downslope, ascended the opposite side, and travelled 8 km down the valley. Alternative explanations propose a breach due to pipeline ruptures as a triggering mechanism for the flow slide (New Mexico State Engineers OfficeP; Phelps Doge Phoenix*; Rico et al., 2007).

155 | From 1981 to 1983, several slides occurred along a several-thousand-foot section of the downstream slope of the phosphate slimes pond dike. The instability was attributed to seepage issues related to clay layers deposited in the dredged dike fill. The slope failures were subsequently addressed through repairs that involved the installation of filtered drains (North Carolina Department of Environmental Health and Natural Resources, Land Quality Section)*.

156 | Dam wall failure, due to liquefaction during earthquake. A dam adjacent to Veta de Agua No. 1 is reported to have failed during an earthquake in 1981. No other details are available (Castro & Troncoso, 1989).

157 | The dam wall failure adjacent to Veta de Agua No. 1 occurred due to liquefaction during an earthquake in 1981. Unfortunately, no additional details regarding the incident are available (Castro & Troncoso, 1989).

158 | The dam retained hydraulically placed chalky and sandy overburden from mine stripping. A breach occurred at the right end of the dam where it joined the valley side, expanding to a width of 55 m. This breach resulted in the formation of a ravine within the impoundment, reaching depths of up to 20 m, with a maximum width of 400 m and a length of 1 km. The primary cause of the failure was a violation of technology in performing hydro dumping works, causing the pond to shift down to the dam (ICOLD Tailings Committee)*.

159 | The operations ceased in 1954. No additional details are available (MHSA)*.

160 | The dam experienced a failure following heavy rain, resulting in the destruction of three homes, damage to 30 homes, and an extensive fish kill.

161 | The gypsum embankment was constructed on soft phosphatic clay slimes, leading to a failure of a 900-ft section of the embankment slope. This failure resulted in the release of an unknown quantity of low-pH process water (Anecdotal)*.

162 | The dam failure occurred due to the slippage of foundations on clayey soils. This led to the widespread inundation of agricultural land, reaching up to 1.5 m in height. It was the first of 4 reported discharges in this area, with the 4th reported in 1995. The mine was reactivated by Philex in 1996 but decommissioned in 2002, after which the tailings dried up, causing a dust problem extending as far as 5 km from the site. Surface materials were not removed before construction, and there was inadequate anchoring of the starter dam. Additionally, the use of mixed mine waste with a highly variable particle size contributed to the failure (Piplinks, 2015).

163 | Seepage through/under the dam exceeded expectations and carried elevated levels of cyanide. Three months after the filling began, through-seepage and infiltration into the downstream shell reached 400 gallons per minute. Undiluted cyanide concentrations within the internal drainage system reached 20 ppm free and 100 ppm total. The dam featured an upstream-sloping clay core with granular shells and was constructed on a jointed rock foundation. The unanticipated seepage and attenuated cyanide had adverse effects on the system water balance, necessitating the installation of a treatment system for the seepage. To prevent contamination of surface and groundwater, several measures were proposed, including surface diversion and drainage to manage downstream-shell infiltration, the enlargement of the seepage pump back system, construction of a treatment plant for dam seepage, and efforts to reduce impoundment inflows (Hutchinson et al., 1985; Centurion Gold Limited, Vancouver*).

164 | The two abandoned dams featured cross-valley impoundments in series and were equipped only with decant structures, lacking abandonment spillways. The failure of the upper dam occurred due to overtopping, leading to the cascade failure of the lower dam (Troncoso, 1990).

165 | Discovered in 1890, production at the mine ceased in 1945, and it was reopened as an open pit in 1983 after earlier dumps and tailings were cleaned up. The seepage control system constructed for the tailings dam included a primary bentonite-slurry cutoff wall, drains beneath the impounded tailings, and the preparation of clayey soils in the impoundment area. The cutoff wall extended as deep as 60 feet to an impermeable stratum. Tailings discharge began in February 1983, and contamination was detected in downgradient monitor wells by May 1983. An estimated 160,000 gallons of cyanide-bearing effluent leaked past the slurry cutoff between April 1983 and June 1984, with average concentrations of 1.5 mg/l total and 0.3 mg/l free cyanide. The reason for the leakage was presumed to be an undetected landslide-related discontinuity in the impermeable stratum that was not penetrated by the cutoff. A pre-existing undetected interruption in the impermeable layer was discovered through monitoring and subsequent repair. Remedial measures included repairing the cutoff and installing humpback wells that returned 400 gallons per minute to the impoundment. It is believed that these measures are effective in containing further seepage, and continued migration of the original contaminant plume was not expected to result in detectable levels of contamination in adjacent surface waters (Montana Department State Lands)*.

166 | During the night, a tailings pipeline on the dam crest broke, resulting in the erosion of a gully 2-3 feet wide and 5-6 feet deep on the downstream face of the embankment. Fortunately, no impounded tailings were released (Idaho Department Water Resources, Dam Safety Section)*.

167 | The instability of the downstream slope resulted from inadequate compaction of the fill. Subsequently, measures were taken to reconstruct and flatten the slope (Nevada Department of Conservation and Natural Resources, Divison Water Resources)*.

168 | The dam failure occurred when a pipe spillway through the clay-shale embankment collapsed. The released tailings were contained in a downstream impoundment. Subsequent repairs were implemented by plugging the old spillway and installing a new one (Virginia Department of Mines, Minerals and Energy, Division Mined Land Reclamation)*.

169 | A shallow slide, approximately 200 feet long, occurred on the downstream slope of the slimes dam at the point where the slope transitioned from 3H:1V to 6H:1V. The introduction of clay soil from an adjacent ditch excavation onto the embankment slope had obstructed seepage, leading to the rise of the phreatic surface and causing slope instability. To address this issue, the slope was repaired by implementing the installation of filtered drainage trenches (North Carolina Department of Environment Healthhand Natural Resources, Land Quality Section; Texasgulf*; Raleigh*).

170 | The phreatic surface was allowed to rise and a ditch was cut in the crest of the starter dam to collect seepage. The starter dam became saturated. Rotational slips developed and are said to be caused by incompatibility between real and design values for shear characteristics of foundation soil. The dam was stabilised by toe weighting with rockfill. The slip is said to be caused by incompatibility between real and design values for shear characteristics of foundation soil cured. The starter dam of loam was 22 m high. Two sand dykes were built on top, raising to 32 m (ICOLD Tailings Committee)*.

171 | Cycloned sands received some compaction during spreading with a bulldozer. During the M7.8 earthquake of March 3, 1985, minor damage occurred in the form of sloughing of sands in the upper part of the downstream slope and shallow slides in the upper 6 ft of the unsubmerged upstream slope. The dam was constructed with upstream slopes of 1.9:1, downstream slopes of 4.6:1, and a blanket drain (Castro & Troncoso, 1989).

172 | With no engineering supervision during construction, the dam fill was essentially uncompacted (less than 80% maximum dry density). Collapse of the fill occurred as saturation developed resulting in loss of freeboard, slumping of the slope, and breach of the dam. Embankment collapse from saturation (Nevada Department of Conservation and Natural Resources, Division Water Resources*; Centurion Gold Limited, Vancouver*; Rico et al., 2007).

173 | Failure of upstream dam after debris inflow, caused by heavy rainstorms (Wei et al., 2013; Quelopana, 2019).

174 | The cross-valley abandoned dam had a decant structure but no abandonment spillway. The overtopping failure occurred due to insufficient decant capacity for routing stream flows through the impoundment (ICOLD Tailings Committee)*.

175 | The waste dump failure occurred due to pore pressure resulting from the collapse settlement. The river valley was filled with waste for a distance of 2.5 km (Blight & Fouri, 2004).

176 | The dam wall failed due to liquefaction during an earthquake. Constructed using a combination of upstream and centerline methods, the dam had downstream slopes of 1.7:1. The failure occurred during the M7.8 earthquake on March 3, 1985. Slimes flowed through a narrow breach, reached a creek, and were deposited downstream for a distance of 8 km (Castro & Troncoso, 1989; Troncoso, 1988; Rico et al.,2007).

177 | The dam, constructed using upstream and centerline methods with downstream slopes of 1.5:1, experienced failure due to liquefaction during the M7.8 earthquake on March 3, 1985 (Castro & Troncoso, 1989; Troncoso, 1988; Rico et al.,2007; Simeoni, 2018).

178 | The damage resulting from the dam failure in Stava was valued at $133 million (in euros). The disaster razed 20 buildings in Stava and caused the flow of tailings into the Avisio River. The mining history of the area dates back to the 16th century, initially focusing on argentiferous galena and later expanding to fluorite mining, which began in 1934. Over the years, the throughput increased from 30 tons per day to 200 tpd in 1961. The first TSF was in use by 1962, and a second one was added by 1970. The dam failure was attributed to insufficient and inadequate construction of the decant pipe. The resulting tailings flow slide reached a staggering speed of 90 km/h, destroying 62 buildings and causing the loss of 269 lives. Two upstream-type impoundments had been constructed, with the upper embankment partially founded on the slime deposit of the lower one. The embankment slopes ranged from 1.2:1 to 1.5:1. The failure of the upper embankment triggered the failure of the lower one. Potential mechanisms that contributed to the failure included excess pore pressures in the soft foundation tailings due to embankment raising, seepage of ponded water into embankment sands, pressurisation of a blocked decant conduit, and excess pore pressures in natural foundation soils in response to rainfall or embankment seepage (Berti et al., 1988; Chandler & Tosatti, 1995; Rico et al., 2007; Luino & De Graff, 2012).

179 | Movements on the downstream slope were initially observed on July 17, 1985, with small daily occurrences over the subsequent two weeks. Following or during rainfall on July 31, 1985, additional sliding took place, creating a scarp up to 4 feet high and 800 feet long. 13 families were temporarily evacuated during this period. The movements were attributed to translation-type sliding along a residual foundation clay layer that dipped in a downstream direction. Repairs were implemented, which included the installation of rock drains on the downstream face and the construction of a buttress made of rock and coarse refuse. No further movement was reported through 1989 following these repair efforts (Pennsylvania Department of Environment, Division of Dam Safety*; La Belle Processing Company, Uniontown*).

180 | An overtopping failure occurred due to heavy rainfall, measuring 7 to 9 inches in 12 hours. This resulted in the release of clay tailings and approximately 3 million gallons of water into an adjacent stream. The dam, reported to have had an outlet or spillway of an unknown type, experienced the breach at this location. The materials released caused some damage to the sand and gravel plant immediately downstream, but they were contained in the plant's freshwater pond located downstream from the facility. Subsequent repairs were made to the dam, and it was successfully placed back in service (North Carolina Department of Environment Health and Natural resources, Land Quality Section)*.

181 | No details provided (CEC,2017)*.

182 | The dam experienced overtopping and a breach as a result of a 7-inch rainfall, highlighting inadequate spillway capacity (MHSA)*.

183 | The dam failure occurred due to a combination of seepage and slope instability.

184 | Tailings spilled out through the dam but were largely contained by the emergency pond downstream of the dam. The dam breach was triggered by high pond levels overtopping the crest, with the diversion ditch blocked by ice during the onset of spring snowmelt (Mount Polley Expert Panel, 2015*; Energy and Minerals Division Ministry of Employment and Investment, Victory, Canada*).

185 | The masonry dam, constructed using bricks made from clay and iron ore tailings, burst, reportedly due to saturation of the brickwork. The dam wall failed, resulting in 7 fatalities (Engineering News Record, 1986*; Rico et al., 2007).

186 | In 1931, a dam was constructed on a valley side, situated 190 m above the river. The dam was built using layered earth and tea-tree matting in an uncontrolled manner. Water breached the main side of the impoundment area, swept through the impoundment, and overtopped the front dam, leading to its failure. Consequently, the river was polluted as a result of this incident (Inspector of Mines, Tasmania)*.

187 | In 1931, a dam was constructed in an uncontrolled manner, primarily using tailings, with a crest width of 1 m and a downstream slope of 1:1. The dam experienced overtopping during a 1 in 100-year flood event. As a result of this overtopping, the dam failed, and the spillway shifted. Slimes were released, and a pipeline was washed out, leading to additional pollution of the waterway. Fortunately, there was minimal release of tailings (Inspector of Mines, Tasmania)*.

188 | The dam experienced failure when water flowing over the spillway eroded the dam toe on a soft clay foundation, resulting in the failure of the downstream slope and the release of tailings (ICOLD Tailings Committee)*.

189 | The collapse of tailings pond 3 occurred due to a weakened dam embankment caused by additional loading. This event resulted in the siltation of the Abra River, affecting 9 municipalities. The dam was situated in an ancient slide area, and the slopes of the dam were excessively steep. The failure occurred after an additional 8 m in height had been added to the dam. Furthermore, the decant tower was positioned too close to the dam (Lepanto Consolidation Mining Corporated, Makati, Philippines*; Piplinks, 2015).

190 | A slide occurred in the upstream slope during the construction of a raise using clayey fill over the fine coal refuse (tailings) beach. The cause of the slide was undrained shear failure due to rapid loading. At the time of the slide, the raise was approximately 14 feet above the tailings elevation. The sliding occurred over a brief period of 1-2 minutes, resulting in a scarp about 14 feet high and 550 feet long, with lateral movement reaching up to 20 feet. Subsequently, the raise was successfully constructed to a height of 25 feet. This was achieved through careful monitoring of piezometers and controlled placement rates to mitigate the risk of further instability (Pennsylvania Department of Environmental Resources, Division of Dam Safety)*.

191 | A metal pipe outlet conduit penetrated the dam, which impounded phosphatic clay slimes. Corrosion of the pipe led to internal erosion of embankment fill soils into it. To address this issue, remedial measures were implemented, including the repair of the pipe, backfilling of embankment soils, and regrading (Anecdotal)*.

192 | Following repairs to the liner, when tailings deposition resumed, routine groundwater monitoring revealed elevated levels of process solution immediately downstream from the embankment. However, the monitoring system effectively intercepted the contaminated groundwater, containing the contaminant plume within the mine site boundaries. The impoundment bottom was lined with a compacted soil-bentonite liner underlain by a sand filter blanket. The liner experienced erosion at several locations due to (1) concentrated runoff from high-intensity rainstorms before tailings deposition, and (2) the initial spotting of tailings and the emergency release of reclaim water into the impoundment. Although damage to the liner was repaired, some damage may not have been detected, and the integrity of the liner in repaired areas may not have been completely restored (Clark et al., 1989; Montana Department State Lands*).

193 | The failure of the downstream slope and the escape of tailings occurred when a blocked decant caused the pond water to rise excessively high. This led to the formation of a breach in the dam structure (ICOLD Tailings Committee)*.

194 | The 7th dyke was being placed over a frozen beach, raised to a dam height of 53 m. A rotational slip of 15 m high and 250 m long lowered the crest 3 m and the bottom of the slip moved 3 m downstream. This was caused by the high rate of filling (260,000 cu m during 2½ months). The starter dam was 20 m high. Raised with 5m high dykes. Inspection of 7th dyke in June 1988 showed the body completely destroyed by longitudinal cracks, indicating continuing movement. Piezometers were installed and the dam was stabilised with toe weighting. When the dam reached 60 m high, no deformations were reported (ICOLD Tailings Committee)*.

195 | Following a breach in the spillway pipe, the dam experienced failure, resulting in the flow of tailings covering a distance of 80 km downstream.

196 | No details provided (Piplinks, 2015).

197 | Unanticipated seepage through the impoundment bottom occurred, leading to an effluent spring downstream from the dam discharging at a rate of 5 gallons per minute. To manage this seepage, a catchment dam was constructed, and the seepage was retained and pumped back to the impoundment (Nevada Department of Conservation and Natural Resources, Division of Water Resources)*.

198 | Tailings, similar in nature to phosphatic clay slimes, were impounded behind a dam constructed of clay fill. Downstream raises of the dam were built on a foundation that contained slimes from a previous tailings spill. Slope instability occurred during the construction of the final raise, involving shearing through the weak foundation-slimes (Anecdotal)*.

199 | A breach at a Riverview phosphogypsum stack resulted in the release of 65,000 gallons of process water into Hillsborough Bay, causing an impact on coastal ecosystems, including sea grasses and mangroves. The spill was acidic, leading to the death of thousands of fish at the mouth of the Alafia River (Beavers, 2013).

200 | The failure of the dam wall resulted from internal erosion caused by the failure of an abandoned outlet pipe. The dam contained a disused 3-ft diameter outlet conduit that had been plugged at both ends with concrete, and its interior was drained by an 8-inch bleed pipe. A leak developed at the upstream end of the conduit, leading to an inflow greater than the capacity of the 8-inch bleed line to drain it. Water began seeping out on the downstream face of the dam near the toe. This incident drained all 6.5 million gallons of water impounded by the dam and caused severe erosion of the downstream face, exposing the buried conduit. Subsequently, the conduit was completely backfilled with concrete, and the dam was placed back in service (Division of Water Pollution Control, Tennessee Department of Health and Environment)*.

201 | The breach of the dam wall occurred due to a spillway blockage that caused the pond level to rise excessively high. The blockage of the spillway raised the phreatic surface, leading to rotational slip in the central part of the dam and ultimately resulting in catastrophic failure. Tragically, this event resulted in the loss of 20 lives (ICOLD Tailings Committee)*.

202 | The embankment was raised using clay fill over tailings, similar in nature to phosphatic clay slimes derived from limestone washing operations. Local shear failures and displacement of soft tailings occurred during the construction of upstream raises, and downstream embankment slopes were as steep as 1.3:1. Overtopping of the embankment took place due to excessive water accumulation during heavy rainfall. Overtopping may have been influenced by the settlement of the portion of the embankment constructed on soft tailings or by shear failures on the steep downstream slope. The resulting narrow breach released all of the impounded water, approximately 2 million gallons, but only a limited quantity of tailings. The absence of flow sliding was attributed to abnormally high consolidation and undrained shear strength in the lower portion of the impounded clayey slimes due to under-drainage by a pervious foundation sand layer (Anecdotal)*.

203 | The accident was associated with sinkhole-induced subsidence in the karstic limestone foundation of the dam, which was holding phosphatic clay slimes. Unfortunately, no further details are available about the incident (Anecdotal)*.

204 | An auxiliary drain at the embankment, initially installed to drain a spring with a flow of 900 gallons, was observed to be discharging fines. Upon closer inspection, a sinkhole measuring 8 feet in diameter and 4 feet deep was discovered on the downstream slope of the embankment. The original drain featured a 6-inch PVC pipe wrapped in filter cloth. It is believed that some form of failure in the filter cloth may have allowed piping into the drain, leading to the formation of the sinkhole (Idaho Department Water Resources, Dam Safety Section)*.

205 | In 1989, the dam of the tailings pond at the site of a former copper mine near Little Bay, Newfoundland and Labrador, Canada, ruptured, causing the spillage of tailings into Little Bay Arm. This event led to the contamination of the marine environment around Little Bay Arm with heavy metals from the tailings (Veinott et al., 2003).

206 | The tailings impoundment, utilized for water retention, experienced a failure when a mine waste dump located on a section of the tailings within the impoundment collapsed. This displacement led to the release of approximately 1-2 acre-feet of water, resulting in the overtopping of the dam. Fortunately, the tailings dam itself did not suffer significant damage, and the reported consequences were limited to silting downstream in stream channels (Idaho Department Water Resources, Dam Safety Section*; Alta Gold Co., Salt Lake City, USA*).

207 | Dam failure occurred during the capping of the tailings after heavy rain. The slope failure breached the embankment over a width of 280 feet, leading to the release of tailings that covered an area of 5,000 m^2. The clayey silt cap, ranging from 8 to 12 feet thick, is believed to have elevated pore pressures in the clayey tailings impounded by the embankment. A contributing factor may have been the saturation of the embankment fill by above-normal precipitation prior to the failure. The resulting tailings flow slide blocked a creek near the embankment toe, diverting creek discharge, dislodging trees, and destroying tidal vegetation over an area of 1.2 acres beyond the embankment toe (Maryland Department of Natural Resources, Dam Safety Division*; Rico et al. 2007; WISE, 2023).

208 | During the Loma Prieta earthquake, a small saddle dike impounding tailings from rock-washing operations experienced strong shaking. The dike was located 29 miles from the epicentre and 1400 feet from the main trace of the San Andreas fault. At the time of the earthquake, the impoundment contained little or no ponded water. Extensive sand boils and liquefaction-related features were observed within the impounded sediments. The damage to the dam consisted of a large wedge of embankment fill that slid in an upstream direction, extending through the embankment to the downstream face near the toe. Post-earthquake investigations revealed that the dam incorporated an upstream raise that underwent sliding due to the liquefaction of underlying tailings. Adjacent dams confining the same impoundment that did not incorporate upstream raises experienced no damage (California Department Water Resources, Division of Safety of Dams)*.

209 | In 1990, the dam failure resulted in the discharge of 190,000 m^3 of tailings into Davidson Creek and the Montreal River. The contaminant plume was observed as far away as Lake Temiskaming, approximately 168 km downstream (Proceedings of Canadian Dam Safety Conference, Niagara Falls, 1996*; Ontario Environment, 1990*).

210 | The spill resulted in the death of 11,000 fish and severe damage to 50 miles of the Lynches River (NWF, 2012).

211 | On January 4, 1991, the face of Tailings Dam No. 3 failed, resulting in the release of 150 to 250 tons of tailings into Pinto Creek. This tailings discharge was accompanied by approximately two million gallons of water, which were released over a period of 16 hours (EPA, 1997).

212 | Dam failure was initiated by liquefaction in the old tailings foundation during the construction of the incremental raise. The material was contained in an adjacent pond. A length of 300 m out of a ring dyke 1,500 m long, failed by rotational slip. A foundation embankment of tailings had been built in 1951, and the new ring dyke was built in 1975. It was raised every year and heavy construction equipment was running on the dyke. Failure is thought to be due to excess pore pressures developed in the old foundation embankment due to the weight of machines and raised height of dyke. Out of action for a year, the cost of remedial works is over a million Canadian dollars (Cominco Limited, Vancouver*; Mount Polley Expert Panel, 2015*).

213 | The Kolontar Report indicates that a dam break occurred during the construction of Reservoir 10, leading to the escape of alkaline (pH = 10-11) slag water. This event resulted in the pollution of the rivers Marcal and Rába through the Torna stream to a traceable extent (Kolontar Report*; Larrauri, 2020*).

214 | The collapse of the dam wall at Philex Mining Corp., attributed to foundation failure, resulted in the release of 80,000,000 tonnes of material. The siltation caused by this event affected the government's irrigation system. It is noteworthy that this was the second of three dams controlled by Philex that failed, with the third breaching in 2001. Additionally, Benguet Corp and Lepanto mines each built 5 TSF but no longer operate their mines. The Itogon-Suyac's TSF also collapsed in 1994, and it is thought to be related to the earthquake in July 1990, 6 months prior to the collapse (Piplinks, 2015; Larrauri, 2020*, Philex Mining Corporation*).

215 | The dam failure resulted from the inundation of the beach. Specifically, the uppermost section of the dam experienced beach inundation, leading to erosion failure. The slurry discharge from this event caused the failure of the lower dam sections through a combination of piping and overtopping (Abadjiev & Dimitrov, 1997).

216 | Around 1970, an earthfill dam with a plastic liner was constructed alongside the Tara River. The dam experienced erosion at the toe due to a flooded river, leading to a slip that reduced the thickness of the crest by half. Fortunately, there was no overtopping. To address the situation, the river was diverted, and protective measures such as gabions were implemented under a UN emergency project. This intervention aimed to prevent pollution that could have affected the Danube River (UNDRO, Geneva)*.

217 | The dam failure occurred due to overtopping (Piplinks, 2015)*.

218 | Swollen out of its banks by heavy rains, the Gila River breached the AB-BC tailings impoundment containment dike on the night of January 9, 1993. Continued flooding over the next several days led to a total of 13 separate breaches of the dike, with three of them eroding through the dike and into the toe of the tailings pile (EPA, 1997; Thienenkamp, 2004)*.

219 | Three separate events occurred within a span of 4 days. No further details were provided (Blight & Fourie, 2004).

220 | Three separate events occurred within a span of 4 days. No further details were provided (Blight & Fourie, 2004).

221 | At the Itogon-Suyoc Mines, the dam experienced overtopping during a typhoon when the dam's penstock and diversion tunnel were blocked. This led to the siltation of the adjoining river. Following this event, production ceased. The diversion tunnel, designed to redirect the river around the impoundment, was blocked, causing floodwater to enter the impoundment and overtop the dam. The result was a partial failure, specifically the collapse of part of the dam. A contributory cause identified for the incident was the typhoon (Itogon-Suyoc Mines*; Piplinks, 2015).

222 | Rainstorms caused overflow at a time when the rate of tailings deposition had increased, leading to the partial collapse of part of the dam. Additionally, the spillway was found to be inadequate for handling the increased flow during the flood (ZCCM Limited, Kalulushi, Zambia)*.

223 | Fish were killed when acidic water spilled into Archie Creek.

224 | The failure of the siltation (tailings) dam resulted in the flooding of Mogpog River and Mogpog town. The dam, which had been completed in 1992, experienced a breach or failure that led to the adverse consequences mentioned (Piplinks, 2015).

225 | In January and February 1993, heavy precipitation led to the overtopping of the No. 1 Tailings Dam berm, causing erosion on the face of the dam. Approximately 54.1 million gallons of stormwater and process water, along with 90,000 yrd^3 of tailings, were released as a result of this incident (EPA, 1998).

226 | The dam near the mill is feared to be unstable and at risk of failure, posing a high risk of toxicity to nearby residents in the event of a failure. Although the dam underwent reinforcement, it is not clear two years later whether the reinforcement measures were adequate to ensure its stability.

227 | No details provided (Wei et al., 2013; Quelopana, 2019).

228 | No details provided.

229 | The failure involved a 60 m wide breach of a tailings dam with a maximum height of 24 m. Additionally, two sections of the dam experienced downstream displacements of 60 and 90 m. The failure was attributed to the liquefaction of the impounded tailings and possibly the embankment materials (Harder & Stewart, 1996).

230 | A slip occurred due to the rise in the phreatic surface, caused by poorly constructed and ineffective drains, leading to a halt in operations for three weeks and a significant loss in revenue. There was a major rotational slip in the downstream slope that did not lower the crest. Emergency repairs were carried out, and the mine was closed for three weeks. The revenue loss was equivalent to 8,500 ounces of gold. The starter dam across the valley was constructed with compacted earth fill that was fairly impervious. However, the filter drains underneath were poorly constructed and ineffective. The grout curtain was cut off under this earth dam. Abnormal behaviour of the piezometers was not diagnosed. Heavy rainstorms in late 1993 and early 1994 brought the phreatic surface above the starter dam to 'daylight,' reaching 20 m above the downstream toe (ICOLD Tailings Committee)*.

231 | No details provided (ICOLD Tailings Committee*; Robinson, 2004).

232 | The tailings impoundment was designed to allow groundwater leakage into the surrounding subsoil, resulting in the intentional release of up to 5 million m^3 of contaminated water over a period of two years or more.

233 | The dam wall breached after heavy rainfall, leading to the travel of tailings 4 km downstream. This unfortunate incident resulted in the loss of 17 lives and extensive damage to the residential township. The No. 4 TSF, initiated in 1978 and located just 320m from the nearest houses, had been closed due to signs of instability in the ring dam closest to the township. Despite closure, the mine continued to use it for storing wastewater, including tailings. This practice reduced freeboard and isolated decant. The heavy rain caused overtopping in the evening, prompting mine personnel to attempt water release and warn the population. Unfortunately, a high phreatic surface led to the failure of the dam adjacent to houses, resulting in the tragic loss of 17 lives(Official Inquery Report*; Rico et al., 2007).

234 | A sinkhole opened in the phosphogypsum stack, leading to the release of gypsum and water into the groundwater.

235 | A spill of phosphogypsum process water occurred into the Peace River near Fort Meade.

236 | A spill occurred, releasing 6.8 million m^3 of water from a clay-settling pond. The majority of the spill was contained in the adjacent mining area, but 500,000 m^3 were released into Hickey Branch, a tributary of Payne Creek.

237 | A spill occurred, releasing nearly 1.9 million m^3 of water from a clay-settling pond. The water spilled into nearby wetlands and the Alafia River, resulting in flooding in Keysville.

238 | A dam failure occurred in a waste rockfill with a compacted saprolite core supported by a sand filter. The dam was progressively raised above its original height to match the impoundment. Piping failure, initially around the construction drain pipe, led to the failure of the dam. The core and materials were carried through the rockfill. The incident resulted in cyanide contamination, causing a minor fish kill in the Omai River. Pollution of the much larger Essequibo River is negligible, and Canadian drinking water standards have not been exceeded (Pebblescinece*; Reports from Republic of the Philippines)*.

239 | A dam failure occurred due to the leakage of cyanide-contaminated water from the base of the impoundment into groundwater. The dam had a downstream slope of 1:2 and a 4 m wide crest. It was built three months before the incident, constructed in compacted layers and clay-lined. The failure led to the pollution of streams and a fish kill. Operations were ceased, and the owner declared bankruptcy (Inspector of Mines, Tasmania)*.

240 | The failure involved the erosion of the crest, formed of tailings, due to wave action. Water containing 95 mg/L was released into the Tamarriver. The cause was identified as retained tailings being allowed to rise above the crest. The estimated cost of remediation was $20,000 - $30,000 (Inspector of Mines, Tasmania)*.

241 | The tailings dam failure occurred from internal dam erosion. The dam was of waste rockfill with a compacted saprolite core supported by a sand filter. It was raised progressively above the original height to match the impoundment. The piping failure, initially around the construction drain pipe, resulted in the core and materials being carried through the rockfill. This incident caused cyanide contamination and a minor fish kill in the Omai River. While 80 km of the Essequibo River was declared an environmental disaster zone, pollution of the larger Essequibo River was deemed negligible, and Canadian drinking water standards were not exceeded (Vick, 1996; Rico et al., 2007; Veinott et al., 2003).

242 | 12 individuals lost their lives, and coastal pollution occurred (ICOLD Tailings Committee)*.

243 | The dam, holding 3 million tonnes of tailings, experienced movement. Situated on the valley side, it slid along a substantial plane of weakness approximately 50 m deep, at the interface of lava flows and underlying materials on which the dam was built. The repair cost amounted to $5,000,000 (Mine Manager, Coeur Golden Cross)*.

244 | The decant tower of tailings pond 1 at the Bulawan gold mine experienced a leak due to the pressure exerted by impounded tailings. This incident marked the 4th discharge in the area, with the first occurring in 1982. The mine was reactivated by Philex in 1996 and decommissioned in 2002, leading to the drying up of tailings and causing a dust problem up to 5 km from the site (Piplinks, 2015).

245 | Uncontrolled erosion at an internal dam, likely caused by earthworks, led to high flows into the clarification pond.

246 | The drainage tunnel plug failed, resulting in the release of tailings that filled 26 km of the Makulaquit and Boac river systems, rendering them unusable. The event caused US $80 million in damages, leading to no production after this incident. Evacuation of 1,200 residents was required, and 18 km of the river channel was filled with tailings. The tailings were stored in a worked-out pit with drainage through a 2,250 m-long tunnel to the Makulapnit River, which had been plugged with concrete, causing the failure. The flow of tailings started at 5 to 10 m^3/sec and continued for 4 days, affecting waterways downstream with heavy sedimentation for 14 km and some material reaching the river mouth 25 km from the mine (Placer Dome Inclusive, Vancouver, Canada*; Piplinks, 2015; Rico et al., 2007).

247 | During three days of heavy rains, a rise in the pond level led to a sudden loss of stability of the dam and liquefaction of the tailings, even though the dam was not overtopped. The resulting wave destroyed half of the village located 1 km downstream, resulting in 107 victims (ICOLD Tailings Committee*; Rico et al., 2007).

248 | A release of 400,000 tonnes occurred, contaminating 300 km of the Pilcomayo River (ICOLD Tailings Committee)*.

249 | The upstream-type tailings dam experienced liquefaction failure during the M 7.5 Nazca earthquake. The flow runout extended approximately 600 m, leading to a spill into the river and contamination of croplands. As a result, the Acarí River was dammed by around 600 thousand m^3 of tailings, causing further contamination (Oldecop & Pacheco, 2007).

250 | The M7.5 Nazca earthquake resulted in the failure of the dam (Oldecop & Pacheco, 2007).

251 | In 1943, an intraplate earthquake with a magnitude of Ms = 7.0 occurred at a distance of R = 80 km. The dam, which had a slope of 1.7:1, experienced failure not during the 7.0 magnitude earthquake but after a subsequent earthquake with a magnitude of 7.9, leading to casualties (Villavicencio et al., 2014).

252 | In the case of an intraplate earthquake with a magnitude of Ms = 7.0 occurring at a distance of R = 100 km, the dam, characterized by a slope of 1.5:1, is subjected to seismic forces (Villavicencio et al., 2014).

253 | In the case of an intraplate earthquake with a magnitude of Ms = 7.0 occurring at a distance of R = 80 km, the dam, characterized by a slope of 1.5:1, is subjected to seismic forces (Villavicencio et al., 2014).

254 | In the case of an intraplate earthquake with a magnitude of Ms = 7.0 occurring at a distance of R = 120 km, the dam, characterized by a slope of 1.5:1, is subjected to seismic forces (Villavicencio et al., 2014).

255 | The slope failure of the tailings dam resulted in the flow of tailings covering an area of 16 hectares (Rana et al., 2021).

256 | Heavy rain triggered a mudflow and rockslide into the silt dam at Lalab. Subsequent flash floods caused damage to nearby houses and rice fields (Piplinks, 2015).

257 | A phosphogypsum stack failure occurred when Mulberry Phosphate experienced a gypsum stack dam break, releasing around 50 million gallons of water into nearby marshes and ponds. This incident led to the elimination of biota in the Alafia River, according to the Water Institute for Sustainability and the Environment. Subsequently, acidic water traveled downstream along the Alafia River towards Tampa Bay. Estimates of the fish killed in the aftermath ranged from 50,000 to 3,000,000 (Beavers, 2013).

258 | Modern mining in the vicinity commenced in 1876 at Aznalcollar. Andaluza de Piritas initiated an open-pit operation in 1979 following the delineation of recently-discovered mineralisation, and in 1987, Boliden acquired the company. The aftermath of the mining activities resulted in thousands of hectares of farmland being covered with slurry. The dam, constructed using waste rockfill, was designed with an upstream-sloping earth core connected to a slurry trench cut-off passing through alluvial gravels into the underlying marl. A specific 600 m section experienced forward sliding, opening like a gate, while the main body of the dam remained intact. Subsequent site investigations revealed that the failure occurred along a shear plane located approximately 14 m below the base of the dam. Water leakage through an adjacent section might have contributed to the failure (Rico et al., 2007; Boliden News Release, 1998*).

259 | Heavy rain caused the silt dam at the Sibutad gold project to overflow (Piplinks, 2015).

260 | The Fertiberia phosphate mine experienced a release of wastewater estimated to be between 50,000 and 400,000 m^3 of acidic and toxic water. The dam, constructed in 1997, failed during a storm (Wood, 2012).

261 | Manila Mining Corp. experienced a tailings spill resulting from a damaged concrete pipe. The incident led to the burial of 17 homes, and approximately 51 hectares of rice land were inundated. An estimated 700,000 tons of material were released during the spill (Piplinks, 2015; ICOLD Tailings Committee*).

262 | The failure occurred in the water diversion culvert beneath the facility, leading to the discharge of tailings into the reclaim pond downstream of the impoundment (Mount Polley Expert Panel, 2015*; Karamken, 2012*).

263 | A drainage tunnel blowout occurred (Piplinks, 2015).

264 | The catastrophic event involved the release of toxic substances from a tailings dam in Hungary, causing severe environmental damage and impacting human communities. The incident occurred during extreme weather conditions, including high precipitation and snowfall. The tailings dam, containing cyanide-laden materials from over 2,000 years of mining activity, experienced a failure at the crest, leading to overflow and breach. The breach, approximately 25 m wide and 2.5 m deep, resulted from the saturation of tailings deposited on the inner embankment, known as the starter dam. This instability caused local displacement and eventually developed into a breach of approximately 23 m in length. The effluent released through the breach filled the area between the starter dam and the outer perimeter dam, both surrounding the impoundment, covering an area of 93 hectares. The overflow spilled over the outer embankment, releasing around 100,000 m^m of cyanide-rich effluent, containing 50-100 tonnes of cyanide and some heavy metals. The contaminated effluent flowed into the Somes/Szamos stream, a tributary of the Tisza River, resulting in the death of tonnes of fish and poisoning the drinking water of more than 2 million people in Hungary. The pollution eventually reached the Danube River and, ultimately, the Black Sea. The significant contamination along a stretch of 150 to 180 m caused extensive fishkill and the destruction of aquatic species in the affected river system (Rico et al., 2007; UNEP/OCHA Assessment Mission Report, 2000).

265 | A failure occurred after heavy rain, leading to the release of 22,000 tons of heavy-metal-contaminated tailings. This event resulted in the contamination of the Vaser stream, a tributary of the Tisza River.

266 | A failure at the containment wall, separating the tailings pond from the decant pond, led to a 1.3 m rise in the water level. The discharge was controlled, but suspended solids increased in the Leipojoki and Sakajoki Rivers. The tailings dam failure was attributed to the insufficient perviousness of the filter drain (ICOLD Tailings Committee)*.

267 | A tailings dam failure occurred, resulting in the release of an estimated 250 million gallons (950,000 m^3) of water and 155,000 yrd^3 (118,500 m^3) of coal waste into local streams. The spill reached depths of 80 feet over a 15-18 foot crown pillar. The cleanup costs amounted to $46 million, and the state-imposed fines of $3.5 million. Following this incident, an additional 22 impoundment spills were attributed to Massey-operated sites. The tailings dam failure was caused by the collapse of an underground mine beneath the slurry impoundment. The environmental impact was significant, with about 120 km of rivers and streams turning an iridescent black colour. This pollution led to a fish kill along the Tug Fork of the Big Sandy River and some of its tributaries. Consequently, towns along the Tug were compelled to shut down their drinking water intakes (Wood, 2012).

268 | 15 people lost their lives, with 100 individuals reported missing, and approximately 100 houses were destroyed (Wei et al., 2013).

269 | Two people lost their lives, and three are missing. The tailings, located 8 km downstream of the Córrego Taquaras stream, resulted in mud affecting an area of 30 hectares.

270 | The effects from the June 26, 2001, Peruvian earthquake at the dam site included minor cracking and joint separation in the concrete face near the left abutment. Additionally, there was densification cracking observed in the uncompacted portion of the downstream rockfill.

271 | After a heavy downpour, a joint in the main pipe, responsible for transporting cyanide wastewater to the tailings dam, became dislodged. This event resulted in the cyanide solution spewing onto the ground. In response, chlorine was introduced into the river to neutralise the toxicity of the cyanide. Unfortunately, a significant fish kill was associated with the accident (Environmental News Service)*.

272 | The bulkheads, which were designed to retain tailings in underground workings, failed under pressures generated by groundwater recharge. The groundwater pressures increased from -450 at closure in 1998 to -35 in 2002, contributing to the failure of the retaining structures.

273 | Heavy rains resulted in water impoundment on the Bayarong tailings dam and Camalca silt dam. The spillways of these dams eroded over time, eventually causing leaks. Consequently, some tailings spilled into Mapanuepe Lake and further into the Sto. Tomas River. The overflow and spillway failure occurred in two abandoned dams following the heavy rainfall (Piplinks, 2015).

274 | Dizon Copper Silver Mines Inc. experienced a significant incident when the spillway of the Bayarong tailings dam collapsed, and the Camalca tailings dam was damaged during heavy rainfall. The failure of these structures led to the flooding of low-lying villages with mine waste, resulting in the evacuation of 250 families. In response to the environmental and safety concerns, the mining operations ceased in 1997. Additionally, there was an overflow and spillway failure reported in two abandoned dams following the heavy rain (Piplinks, 2015).

275 | The dam failure occurred due to strong rains and subsequent overflow (Villavicencio et al., 2014).

276 | The dam failure occurred due to strong rains and subsequent overflow (Villavicencio et al., 2014).

277 | 1.2 billion L (1.2 million m^3) of toxic water were discharged into the Pomba and Paraíba do Sul rivers (Brazil Magazine)*.

278 | There was a culvert failure beneath the Sasa Mine Tailings Dam, leading to a subsequent tailings dam break. The waste flowed into Lake Kalimanci, situated 12 km from the mine, with an estimated release of 70,000-100,000 m^3. The incident involved a partial dam collapse, triggered by the failure of an ancillary structure responsible for diverting captured drainage water from the tailings storage (Vrhovnik et al., 2011; Vrhovnik et al., 2013; Peck, 2007; Rana et al., 2021).

279 | Tailings flowed 20 km downstream of the Río La Ligua (Villavicencio et al., 2014).

280 | The release of uranium slurries resulted in elevated nitrate levels in the river. The dam failure of the decantation and evaporation pond at the uranium conversion plant occurred after heavy rain in the preceding year. This release led to increased nitrate concentrations, reaching up to 170 mg/L in the Tauran canal for several weeks (Rana et al., 2022).

281 | A ring dike, enclosing an area of approximately 1 km^2 and containing around 20 million m^3 of coal ash, experienced a breach. The rupture resulted in a hole approximately 50 m wide in the dam. The coal ash then flowed through a drainage canal into a tributary that feeds into the Partizanskaya River, ultimately emptying into Nahodka Bay in Primorski Krai (east of Vladivostok). For further details, please refer to the September 2004 report by Paul Robinson, SRIC.

282 | A dike located at the summit of a 100-foot-high gypsum stack, which held 150 million gallons of polluted water, ruptured following the impact of waves driven by Hurricane Frances, particularly striking the southwest corner of the dike. The released liquid flowed into Archie Creek, subsequently leading to Hillsborough Bay.

283 | No details provided.

284 | Mercury-contaminated tailings were discharged into Pinchi Lake, a site that was operated by Cominco from 1940 to 1943 and again from 1968 to 1975. The release amounted to approximately 6,000-8,000 m^3. The incident occurred when the dam of the former emergency spills lagoon collapsed during reclamation work, resulting in the spillage of material into the 5,500-hectare Pinchi Lake.

285 | A failure occurred in a phosphogypsum stack as the company attempted to expedite the pond's capacity expansion at a rate faster than usual, as reported by officials from the Mississippi Department of Environmental Quality. While the company attributed the spill to unusually heavy rainfall, liquid from the failure flowed into adjacent marshlands, resulting in the death of vegetation.

286 | No details provided. (CDA, 2017).

287 | Excessive seepage and breaching of the dyke occurred due to erosion. The loss of confinement resulted in the liquefaction and flow of the tailings (CDA, 2017).

288 | No details provided.

289 | Following an independent fact-finding mission, it was revealed that the fish kill in the nearby waters of Rapu-Rapu Island in Albay, approximately 600 km from Manila, was purportedly caused by a deliberate cyanide leakage. Two mine spills on October 11 and 31 were allegedly responsible for cyanide contamination and the subsequent fish kill in the adjacent waters. Mine workers informed the fact-finding team that they were allegedly directed by Lafayette officials to excavate canals and install new pipes to redirect the mine's waste and tailings directly into the sea.

290 | In March 2006, a leak resulted in the release of 400 million L (400,000 m^3) of muddy water, which made its way to Rio de Janeiro. The mud flow displaced approximately 4,000 residents in the cities of Miraí and Muriaé in the Zona da Mata, rendering them homeless. The incident also led to the destruction of crops and pastures, compromising the water supply in cities located in the states of Minas Gerais and Rio de Janeiro. The company responsible for the incident was cited for a TSF infraction in 2006 (Brazil Magazine)*.

291 | The landslide buried approximately 40 rooms across 9 households, with 17 residents reported missing. 5 injured individuals were transported to the hospital. Over 130 local residents have been evacuated due to the incident. The Huashui River was contaminated about 5 km downstream as a result of the release of toxic potassium cyanide. The incident was attributed to a tailings dam failure during the 6th upraising of the dam.

292 | A Tetra Tech employee, working as a contractor, lost their life in a coal ash slide while involved in the removal of ash from the ash pond for the purpose of reuse.

293 | The failure of a tailings slurry pipeline from the Nchanga tailings leaching plant to the Muntimpa tailings dumps resulted in the release of highly acidic tailings into the Kafue River. This discharge led to elevated concentrations of copper, manganese, and cobalt in the river water, prompting the shutdown of the drinking water supply for downstream communities.

294 | On the 24th of November 2006, an unusual amount of rainfall was experienced in the region. The continuous inflow into the reservoir for three consecutive days, coupled with the obstruction of the spillway, resulted in the overtopping of the Fonte Santa dam crest, leading to its breach and subsequent total failure. Duque in 2011 estimated the runout distance to be 17.5 km (Fraca et al., 2007; Duque, 2011).

295 | The mud flow resulting from the tailings dam failure after heavy rain left approximately 4,000 residents of the cities of Miraí and Muriaé in the Zona da Mata homeless. Crops and pastures were extensively destroyed, and the water supply was compromised in cities in the states of Minas Gerais and Rio de Janeiro (Larrauri, 2020)*.

296 | No details provided (HSE Report; Rana et al., 2021).

297 | In February 2007, a tailings dam utilized as a sedimentation pond for lime particles experienced a failure. This resulted in an estimated volume of 150,000 m^3 of tailings flowing from the breach in the dam slope (Van den Berghe et al., 2021).

298 | An 80 m wide mudflow struck 33 homes in the village of Xiangyang and additional homes in Caijia. Tragically, 10 people lost their lives, 3 were reported missing, and 17 sustained injuries as a result of the incident.

299 | Overtopping was identified as another reported failure mechanism. Approximately 4.5 million L of processed kimberlite tailings and treated sewage overflowed from the Long Lake Containment Facility, spilling onto the tundra and reaching nearby Fay Lake, which was frozen at the time (Technical Report, 2008/2009; Independent Envirionmental Monitoring Agency, Yellowknife*).

300 | A mudslide, several m high, cascaded 2.5 km downstream, burying a market, several homes, and a three-storey building. Tragically, 277 people lost their lives, and 33 sustained injuries. The mine was not operational at the time, with the state-owned company claiming to have "sealed" the TSF. The incident was attributed to the collapse of a waste-product reservoir at an illegal mine during rainfall (Larrauri & Lall, 2018)*.

301 | A release of 5.4 million yrd^3 (1.09 billion gallons) of fly ash occurred due to a retention wall failure. The ash slide covered an area of 1.6 km^2. The wave of ash and mud toppled power lines, covered Swan Pond Road, and ruptured a gas line. The incident resulted in damage to 12 homes, and while one person had to be rescued, fortunately, no one was seriously hurt (Rana et al., 2021).

302 | The landslide triggered by the tailings dam failure destroyed a home, resulting in the tragic loss of three lives and injuries to 4 people.

303 | 11 houses were lost, and there was one reported death due to a tailings dam failure following heavy rain. The dam, which had been shut down in the 1990s, experienced failure attributed to a combination of bad design, poor construction, and a lack of maintenance. Prior to the failure, groundwater contamination had occurred. The incident resulted in the release of more than 1 million m^3 of water, 150,000 m^3 of tailings, and 55,000 m^3 of dam materials (MACE*; Glotov et al., 2018).

304 | An intraplate earthquake with a magnitude of 8.8 resulted in the loss of an estimated 80% of the total volume. The incident involved overtopping with flow failure (Villavicencio et al., 2014; Quelopana, 2019).

305 | Following an intraplate earthquake with a magnitude of 8.8, a slope with a ratio of 1.4:1 experienced instability due to seismically induced deformations (Villavicencio et al., 2014; Quelopana, 2019; Samarco, 2016).

306 | After an intraplate earthquake with a magnitude of 8.8, where the epicentral distance was 252 km, a slope with a ratio of 4.5:1 exhibited instability due to seismically induced deformations (Villavicencio et al., 2014).

307 | Following an intraplate earthquake with a magnitude of 8.8, a slope with a ratio of 1.8:1 experienced instability due to seismically induced deformations (Villavicencio et al., 2014).

308 | After an intraplate earthquake with a magnitude of 8.8, where approximately 80% of the total volume was estimated to be lost, a slope with a ratio of 1.2:1 experienced instability due to seismically induced deformations (Villavicencio et al., 2014).

309 | Contamination of río Escalera and río Opamayo occurred, extending 110 km downstream (Wood, 2012; SME, 2014).

310 | The break of a Heap Leach pond refers to the failure or breach of a containment structure designed for the heap leaching process. This incident can result in the uncontrolled release of leachate or process solutions, potentially leading to environmental contamination if not properly managed (Zijin Mining Group)*.

311 | A transfer tank, utilized for the disposal of waste water in the context of heap leaching, experienced a leak during an emergency situation. There have been updates regarding the environmental incident involving the sudden leakage of the waste water pond at the Zijinshan Copper Mine hydrometallurgical plant (Zijin Mining Group*; Reid & Fourie, 2017).

312 | The Gaoqiling tailing pool dam at Qianpai Town, Xinyi City, Guangdong, is associated with the Yinyan Tin Mine Dam Failure (Zijing Mining Group*; Fry et al., 2012*).

313 | 10 people lost their lives, and nearly 150 individuals were injured in an incident that led to about 1,000 acres of polluted land. Approximately 8 km^2 were flooded, affecting several towns (Kolontár Report*; Zanbak, 2010; Quelopana, 2019).

314 | No details provided (Rana et al., 2021).

315 | Cliffs' Bloom Lake mine received a record environmental fine of $7.5 million (Bertrand, 2014).

316 | 6,000-8,000 tons of copper ore tailings were released from one of the tailing ponds due to a breach in the dike (National Response Center)*.

317 | Heavy rain on July 20 prompted the managers of the electrolytic manganese metal plant to release water from its tailing dams into the Fujiang River, which serves as the drinking water source for Sichuan's second-largest city. Landslides caused by the heavy rains damaged the tailings dam. The ensuing damage extended to residential roads and houses, forcing 272 people to evacuate. Additionally, the tailings were washed into the Fujiang River, leaving approximately 200,000 people without a drinking water supply (Future Directions)*.

318 | An old, unlined facility covering 362 hectares experienced an unauthorized release, leading to the EPA issuing orders for necessary repairs (Coast County News)*.

319 | Due to torrential rain, the lake's level in the tailings dam rose, resulting in an overflow of up to 900 m^3 of rainwater mixed with effluent. This overflow entered the Vermelho River through a channel in the drainage system (Operational Profile, Serra Grande, Brazil, 2012)*.

320 | Cyanide-laden mine tailings destroyed 10 houses (Mambulaoans Worldwide Buzz, 2012)*.

321 | A sinkhole in the dam at the HB mine site south of Salmo has been identified as the primary cause of the slough that posed a threat to the stability of the tailings pond last week. Heavy rainfall throughout the month of June played a contributing role in some seepage and the initial slough. In 1998, the Regional District of Central Kootenay acquired the 6-hectare tailings area as part of their central landfill area (Black Press Media, 2012; Larrauri, 2020*).

322 | A total of 20.6 million tonnes were released due to heavy rains, resulting in severe pollution of the Balog and Agno Rivers (NASSA & CCCP*; Larrauri, 2020*).

323 | A leak from a gypsum pond occurred through a "funnel-shaped hole," causing environmental concerns. The concentrations of nickel and zinc in the nearby Snow River exceeded values harmful to organisms by tenfold or even a hundredfold, while uranium concentrations exceeded acceptable levels by more than tenfold. The incident is linked to a heap-leach operation, and leakage from the gypsum pond was reported on multiple occasions, including April 8, 2013 (the 4^{th} leak since 2008), and again on May 21, 2013, after restarting operations. The leak from the gypsum pond resulted in the release of hundreds of thousands of m^3 of contaminated wastewater (Larrauri, 2020).

324 | At 7:45 am on Monday, December 17, the tailings dam at the former Gullbridge copper mine in central Newfoundland failed while stabilization work was in progress. The failure led to a breach in the 7 m high dam, approximately 25 m wide. The dam had been impounding mine tailings, partially covered by water, forming a tailings pond. A non-consumption water advisory has been issued for the Town of South Brook (Caldwel, 2013; CDA, 2017*; Rana et al., 2007*).

325 | Tragically, 4 people lost their lives, and one person sustained injuries. The Los Remedios River in Durango, San Lorenzo River, and El Comedero reservoir in Sinaloa were contaminated. The contamination resulted in the death of fish in the Los Remedios River, extending 130 km downstream. Furthermore, 300 families faced the loss of their incomes from a tilapia fish farm.

326 | The breach of an internal tailings dyke resulted in a surge of liquids and suspended solids over the external tailings dyke (Caldwell, 2014).

327 | The coal processing plant experienced a malfunction on Saturday, necessitating the drainage of plant water into a detention pond. Unfortunately, the tailings then overflowed into an emergency pond, with the material entering the Tulameen River.

328 | A breach in the wall of the containment pond led to the release of a plume of slurry containing fine coal particles, clay, and heavy metals into the Apetowun and Plate creeks, eventually reaching the Athabasca River. An allocation of $52.2

million has been set aside for addressing the aftermath. Additionally, an undocumented description of the plume has been reported 113 miles away from the source (Caldwell, 2014).

329 | Damage to a tailings pipeline resulted in the continuous flow of tailings into the Norashenik River for several days (Green Program)*.

330 | Between May 2013 and April 2014, leaks from the company's tailings pipeline and a dike failure at the tailings storage basin had an impact on more than 15 acres of wetland.

331 | Between May 2013 and April 2014, leaks from the company's tailings pipeline and a dike failure at the tailings storage basin had an impact on more than 15 acres of wetland (Jeffries et al., 2019; Newcrest, 2019).

332 | No details provided.

333 | The collapse of an old drainage pipe beneath a 27-acre ash waste pond resulted in the flow of ash through the drainage pipe into the Dan River. Approximately 82,000 short tons (74,400 t) of toxic coal ash and 27 million gallons (100,000 m^3) of contaminated water were released as a consequence (Caldwell, 2014).

334 | A release of 56,000 to 105,000 yrd^3 occurred. Several days of unauthorised uncontrolled releases were reported, with warnings of inadequate capacity dating back to 2012. These warnings were allegedly ignored, and a complex financial background, along with deferred maintenance under BHP, became evident before the transfer to Palmer in liquidation, leaving the cleanup bill in question.

335 | When the rains hit in 2014, the Stolice tailings dams held an estimated 1.2 million tons of mine waste. The heavy rains triggered a landslide that damaged parts of the drainage system, allowing rain to accumulate inside one of the tailings dams, pushing it beyond capacity. A site review by the Serbian water management agency, Srbijavode, revealed that the existing tailings dumps lacked adequate protection from external waters, leading to uncontrolled drainage and the washing away of tailings. One hundred thousand m^3 of tailings were released into the Kostajnik River, creating a downstream wave 50 to 75 m wide and leaving everything in its path covered in a layer of toxic mud 5-10 cm thick. Following another storm on July 17, tailings again spilled out of the damaged dam and into the Kostajnik. The collapse of the abandoned flotation tailings dam was attributed to damage to the dam's drainage system caused by a landslide triggered by heavy rain (Mining Weekly)*.

336 | A total of 7.3 million m^3 of tailings, 10.6 million m^3 of water, and 6.5 million m^3 of interstitial water were involved in the incident (Expert Panel Report)*.

337 | The flow affected the 420 km-long Bacanuchi River waterway, a tributary of the Sonora River, directly impacting approximately 800,000 people. (CDA, 2017)*.

338 | A significant amount of waste was released, burying vehicles and workers. Among those affected, a truck driver, a bulldozer operator, and the driver of a Fiat Uno were all buried in the incident (Larrauri, 2020).

339 | Between May 2013 and April 2014, leaks from the company's tailings pipeline and a dike failure at the tailings storage basin had an impact on more than 15 acres of wetland.

340 | The tailings travelled approximately 900 m, impacting the El Charcas or Pánuco stream and posing a threat to the drinking water supply in the area.

341 | The release occurred into the upper Pilcomayo basin.

342 | The newly formed company restarted past production, but a pipe failure occurred, leading to a runout that was contained by a berm. The company faced a fine of $180,000 in connection with the incident.

343 | Effluent and mine waste leaked from a pair of underground mine sites, including from a "non-engineered" containment berm and a concrete plug at an old underground site. The discharge reached the ocean through a creek, several beaver-dam-created wetlands, and Banks Lake before entering the ocean at Surrey Bay (Vancouver Sun)*.

344 | There was a release of approximately 3,000,000 gallons of mine wastewater from the Gold King Mine near Silverton (USEPA).

345 | The Fundão dam breached, causing its tailings to impact the nearby Santarém dam and partially erode its right shoulder. The Selinha dike, one of the side walls of the Germano dam, was also damaged. Unfortunately, 19 people were killed, including 14 who were working on the dams at the time. The waste discharge reached the Atlantic Ocean. The failure was attributed to insufficient drainage, leading to liquefaction of the tailings sands shortly after a small earthquake. A slurry wave flooded the town of Bento Rodrigues, destroying 158 homes, resulting in at least 17 confirmed deaths and 2 reported missing. The slurry further polluted the north Gualaxo River, Carmel River, and Rio Doce over a distance of 663 km, destroying 15 km^2 of land along the rivers and cutting residents off from a potable water supply. The estimated damage is at least 6.7 billion.

346 | Collapse of a waste rock pile in jade mining.

347 | One worker lost their life, and around 20 others are currently missing.

348 | By January 2017, 10.7 km of the total 11.5 km of the aging tailings pipeline had been replaced. The corrosion, exceeding initial expectations, resulted in alterations to the chemistry of the tailings (MG 2017 Sustainability Report)*.

349 | A failure in a drainage well resulted in the flow of tailings and water into the nearby Taishi River, a tributary of the Xihan River, which is the primary branch of the Jialing River. The contamination stemming from the tailings spread into Gansu, Shanxi, and Sichuan provinces along the Jialing River, causing severe environmental pollution in these areas.

350 | On May 22, 2016, inert tailing slurry was discharged into the Filippovka River from the Talovsky TSF, which was previously discontinued and sealed. The discharge resulted from the failure of a water collector, formerly used before 1979 to regulate surface water on the tailings dam. The Talovsky TMF is associated with the Ridder Ore Concentrator at the Kazzinc operation in the town of Ridder, Kazakhstan. Pollution extended into the Ulba and Filippovka rivers, flowing near the Kazakhstan-Russian border and heading toward the Siberian city of Omsk. Visuals of the polluted river resembled wet concrete replacing freshwater. Local reports suggested that the waste contained cyanide and excess minerals such as zinc, lead, copper, and manganese. However, mining and government officials downplayed the severity of the spill and the presence of toxins. The ore from Tishinsky, Shubinsky, and Ridder-Sokolny mines, along with gold-bearing tailings, accumulated in the abandoned TSF, are treated at the Ridder Concentrator.

351 | On the evening of August 8th, a landslide occurred in the southwest corner of the red-mud dam at Xiangjiang Wanji Aluminium, posing a threat of a red-mud slide. The dam, approximately 1.5 km in length, held about 2 million m^3 of red mud. Xiangjiang Wanji Aluminium, a private alumina refinery established in 2005, has an annual capacity of 1.2 million tonnes of alumina. The incident resulted in the complete submersion of a village in red mud, leading to the evacuation of around 300 villagers, with many farm and domestic animals reported killed.

352 | A 14 m wide sinkhole appeared in a phosphogypsum stack, creating a pathway for contaminated liquid to enter the underground. This liquid subsequently reached the Floridan Aquifer, a significant drinking water resource.

353 | Hurricane Matthew flooded a coal ash pond, causing leaked tailings to flow into the Liang, Ambalanga, and Agno rivers. The rivers were visibly impacted, with fly ash coating tree branches as much as 7 feet above the river surface.

354 | During the onslaught of the Super Typhoon, 50,000 metric tons of tailings material leaked into the Liang River. The tailings flowed through the drain tunnel of the underground mine after heavy rains. The leaked tailings subsequently entered the Liang River, then the Ambalanga River before reaching the Agno River.

355 | The failure of a waste rock pile in jade mining resulted in the disappearance of approximately 50 workers (Emmerman, 2021).

356 | The drainage channels around the red mud basin overflowed after heavy rain.

357 | A breakage occurred in a tailings transport chute, purportedly caused by an earthquake in the area. The spilled toxic material flowed into an ancestral grazing area, posing a threat to 4 specimens of Vicuna, a protected camelid species, and contaminating the groundwater.

358 | A partial dam failure occurred at the northwestern corner of the tailings pond, leading to the flooding of a downstream fish pond covering approximately 27 hectares. The incident resulted in the reported deaths of two individuals, with one person reported missing (Rana et al., 2021).

359 | A 4.5 m deep and 6 m wide trench appeared down the face of the 140 m high dam. Contaminated water was collected in the containment system at the base of the dam. The leak in the water pipeline went unnoticed for three hours.

360 | A pump failure during commissioning resulted in initial overtopping, which was initially denied by a miner. Fortunately, the overtopping was fully contained near the perimeter, with no release onto the unlined area.

361 | On June 30, a dike partially collapsed at Pool 3, utilized for the accumulation of phosphogypsum water. Approximately 100,000 m^3 (26.4 million gallons) of highly acidic wastewater surged through a dry Ashalim riverbed in southern Israel, leaving a wake of ecological destruction more than 20 km (12 miles) long (Rabinovitch, 2017; Rana et al., 2021).

362 | During the commissioning, a pump failure resulted in initial overtopping, which was initially denied by a miner. Fortunately, the overtopping was fully contained near the perimeter, with no release onto the unlined area.

363 | A total of 115 acres of agricultural land were covered by ash, with layers ranging from 0.5 m to 3 m in depth. Additionally, officials discovered evidence of severe water pollution in the Bheden River.

364 | A section of the geo-membrane layer of the tailing storage dam at the MNG Gold mines in Kokoya, Bong County, ruptured, leading to an uncontrollable discharge of slurry-containing cyanide from the dam into Sien Creek. A total of 34 persons were reportedly affected and admitted to major medical centres. The TSF holds approximately 300,000 m^3 of water, and the amount spilled was estimated to be 3 million gallons (11,356 m^3).

365 | An employee lost its life in a coal ash slide while working on the removal of ash from the pond to allow for its reuse.

366 | There was a V-shaped failure of the side wall of compartment 2 of the tailings dam. The wall failure was resealed on the same day by Hernic. Fortunately, the spillage was contained on the adjacent property, which had been previously used as an opencast mining area (Reuters, 2018)*.

367 | The area identified as high risk and scheduled for the statutorily required relocation of contents and closure experienced a breach due to overtopping caused by hurricane floods.

368 | Collapse of a waste rock pile in jade mining.

369 | High levels of lead, aluminium, sodium, and other toxins have been detected in drinking water up to two km away from the Norsk Hydro property, according to the Ministry of Health. The recorded pH in the waters was 10. Although the company denied the spill on its website, there was an overflow of the red mud basin after heavy rain. The company maintains that no overflow occurred. Unfortunately, this incident resulted in a local environmental activist being shot dead in front of his house. Highly alkaline and metal-laden liquids flooded the surrounding residential areas, rendering the drinking water supply in the area unusable.

370 | The collapse of the embankment of tailings dam No. 2 occurred after heavy rain. This incident resulted in the contamination of crops, the Sipchoc Creek, and the Santa River.

371 | The central mechanism in the development of the embankment failure was load redistribution within the dam and its foundation, causing zones to become over-stressed. A section of the northern dam wall collapsed into the southern tailings dam. The upstream embankment raises that had extended onto the tailings surface became unstable when static liquefaction was triggered by foundation deformation along a brittle layer. Two earthquakes were recorded in the area, 10 seconds apart and just over 2 km from the mine the day before the failure. The earthquake had a magnitude of 2.7 with 0.15g loading, which did affect the failure. The tailings dam failure was mainly due to the existence of a low-density foundation layer in the vicinity of the slump. The embankment failure resulted in a 'limited breakthrough' of tailings material from the northern to the southern tailings dam, and this breakthrough has been contained within the southern tailings dam (Rana et al., 2021).

372 | During spring snowmelt, a tributary stream meandered into an abandoned mine pit, causing the partially filled mine pit to completely fill and overtop its natural earth embankment. The embankment subsequently failed, draining the pit into the Embarass River and causing damage to utilities, along with water quality issues on Embarass Lake. There is uncertainty regarding whether the embankment that failed was man-made or natural (ASDSO).

373 | The waste rock pile for jade mining experienced a failure.

374 | A dam failure resulted in the release of tailings into Cañitas Creek for 26 km. 7 workers were reported missing, and most of the tailings have been deposited along the course of the Carnitas River. The federal attorney's Office for Environmental Protection stated that the tailings don't contain cyanide or any heavy metals. Unfortunately, three workers were killed, two were wounded, and 4 are still missing.

375 | A tailings spill has led to the shutdown of processing, resulting in a $1 billion impairment.

376 | Heavy rains caused a breach in the stopper boards of a penstock.

377 | The dam imperils two unlined coal ash ponds on site, containing a combined 2.1 million m^3 of coal ash. During Hurricane Florence, the ponds were overtopped.

378 | Three older inactive storage sites, covered by soil and vegetation, including tall trees, were submerged by Hurricane Florence. These sites hold 1.3 million tons of ash.

379 | The drainage pond for the newly commissioned TSFis overtopping due to heavy rains.

380 | The seal of the spring within the impoundment failed, allowing tailings to flow into the spring water.

381 | The tailings wave wreaked havoc on the mine's loading station and administrative area, proceeding downhill for approximately 7 km until it reached the Rio Paraopeba. Along its destructive path, the wave obliterated a railway bridge and infiltrated sections of the local community, Vila Ferteco, near the town of Brumadinho. The disaster resulted in 259 confirmed deaths and 11 missing individuals. Additionally, the wave caused extensive damage to two smaller sediment retention basins (Quelopana, 2019).

382 | After heavy rainfall, an inactive tailings dam experienced a failure, resulting in a spill that damaged 7 bridges and left 50 families isolated. Fortunately, no deaths or injuries were reported. Upon reviewing several photos depicting the aftermath of the incident, it is evident that the spill release is substantial enough to merit a Severity Code rating of 2. In a similar occurrence, another inactive tailings dam failed after heavy rain, causing a spill that damaged 7 bridges and isolated 100 families. Miraculously, there were no reported deaths or injuries in this incident.

383 | A spill of red mud has affected an area spanning 35 acres, including a nearby railway line, and has resulted in several casualties, though the exact number remains unclear. The incident unfolded as the boundary wall of a caustic pond, constructed by Hindalco Ltd, collapsed in Muri near the railway tracks. This collapse triggered a landslide-like situation, and preliminary investigations suggest that it may be attributed to the stacking of dry tailings to an excessive height.

384 | A waste heap failure has occurred, resulting in the tragic loss of three lives, while 54 individuals are currently reported as missing.

385 | The tailings spread across an expanse of 41,574 m^2 and reached the Mantaro River. The runoff from the tailings has reportedly caused a significant pollution event in the Rio Mantaro. Concerns are rising about potential contamination with cyanide in a segment of the river spanning 375 km (Rana et al., 2021).

386 | Tailings flowed for a distance of 1-2 km, causing disruption to a power line.

387 | A tailings wave surged over the Ananea-La Rinconada highway, resulting in the tragic death of a motorcyclist.

388 | Water and tailings flowed through the surrounding area, reaching the Yijimi River after 3 km, posing a threat to the drinking water supply of 68,000 people in Tieli City. By April 4, 2020, the pollution had extended 208 km downstream. The ”No. 4 overflow well” of the tailings dam tilted, leading to the release of supernatant water and tailings (WISE). Water testing in the Hulan River, located approximately 110 km southwest of the mining site in Yichun, revealed molybdenum levels 2.8 times higher than standard levels. The AGU Blogosphere presented two hypotheses: (1) that it was a decant tower constructed for dewatering the tailings, and (2) that it was part of a reclaim system. Despite the tilting of the overflow well, the tailings dam's embankment itself remained intact during the incident.

389 | On the evening of April 10, 2020, a fly ash dam at the Sasan Ultra Mega Power Project, owned by Reliance Company, breached near the village of Harrahva in the Singrauli district of Madhya Pradesh. This tragic event resulted in the loss of 6 lives and extensive damage to downstream rivers and fields. Subsequent to the breach, a substantial flash flood of coal ash mixed sludge occurred, impacting hundreds of villages and causing destruction to crops across thousands of acres. The overflow of liquid fly ash reached the nearby river and Rihind reservoir. According to a report by Amar Ujala, the incident led to the destruction of crops on 200 acres of land, affecting numerous villages with flash floods, and debris flow entering many houses in the area.

390 | Tailings spilled onto a nearby road and an area of 8,000 m^2 of land, eventually reaching the San Bernabé stream after covering a distance of 5 km. The spill also impacted the town of the same name.

391 | After heavy rainfall, mining waste collapsed into a lake, resulting in a catastrophic event where a 6.1 m (20 ft) wave of mud and water engulfed the area, burying numerous workers. Tragically, at least 174 people lost their lives, and 100 individuals remain missing.

392 | In the southern Azuay province, a small tailings dam breached, leading to the release of approximately 50 tonnes of pollutants into the Tenguel river, causing the death of fish in the affected area.

393 | The underflow/overflow point is directed towards the Tagil River. In January, the environmental prosecutor's office stated that there were no indications of destruction or uncontrolled water overflow. However, in response to a recent wave of media publications, experts conducted a new inspection of the mine on July 13.

394 | Central Asia Metals has reported a short-term leakage of tailings from Sasa's TSF4 into the local river. Additionally, the company stated that structural dam repairs are currently underway. To ensure the facility's safe reopening, a comprehensive understanding of the incident's causes is crucial, enabling the implementation of any necessary engineering solutions in the future.

395 | The failure of the Lagoa do Pirocáua dam at the Equinox Gold Aurizona mine on the Atlantic coast of Maranhão State, northeast Brazil, occurred on March 25, 2021, at 4:00 am local time. This incident led to the contamination of the water supply in the village of Aurizona. The 7 m high earthen dam was designed to capture sediments from open pits and store water for use in mining operations. The failure was attributed to the overtopping of the dam, triggered by 426 mm of rainfall over March 23-24, which corresponds to a 10,000-year precipitation event. It is important to note that the dam did not hold tailings.

396 | Following a breach in the spillway for the mine waste dam, the Tshikapa River, located across the border in the Democratic Republic of Congo, underwent a disturbing transformation, turning red and causing the death of hippos, fish, and other wildlife. The leak also resulted in a human tragedy, with at least 12 people confirmed dead and 4,500 individuals reported as sick, as stated by a minister in the neighbouring Democratic Republic of Congo. The river's pollution extended 100 km downstream, rendering drinking water unsafe. The breach in the spillway duct led to a massive spill of 'rejected pulp,' exacerbating the environmental and health impacts of the incident.

397 | Highly toxic mining tailings were discharged into the Florido stream, a tributary of the Pánuco River, in the municipality of Concordia, Sinaloa. The overflow of mining waste is suspected to be a consequence of the heavy rains induced by Hurricane Pamela, which impacted Sinaloa territory on October 13. As of now, the responsible company for the spill has not been identified.

398 | On November 19, the ponds in the flotation facility owned by Yıldızlar Holding's Nesko Mining experienced a collapse, leading to the release of waste into nearby rivers in the Şebinkarahisar district. The discharged cyanide waste has also made its way to the Kılıçkaya Dam in the region. This incident transpired during the rehabilitation of the old tailings dam, where the dam's structure failed, causing the spillage of tailings into the new dam, subsequently resulting in its overflow. Thousands of tons of hazardous chemicals entered the Darabul River and reached the Kılıçkaya Dam. Notably, the incident occurred at a closed mine that had previously been impacted by Hurricane Pamela and was owned by Rio Panusco SA de CV.

399 | In the foothills of the Andes, the continuous rainfall in the Ananea district led to the overflow of mining tailings ponds, resulting in the sweeping away of vehicles, flooded streets, and the destruction of roads. The tailings wave caused significant damage, destroying approximately 400 m of the national road leading to the La Rinconada town center and spilling into three residential areas (Progreso, Central, and Santiago). This overflow event occurred at 8:30 in the morning and was seemingly attributed to one of the sedimentation ponds of the San Antonio mining cooperative, situated on the Q'oñiunu hill. The failure of the tailings dam, or settling pond, occurred after heavy rainfall in the region.

400 | The coal slurry dam collapsed amid heavy rains on December 24, 2021, around 2 pm. The incident occurred shortly after the installation of a new end wall for the slurry pond, following the loading out of dry slurry in November 2021. The collapse was preceded by heavy rainfall 4 days prior, totalling 66mm. This event resulted in extensive pollution of the Black Umfolozi River within the wilderness zone of the 96,000-ha Hluhluwe-iMfolozi Park.

401 | The waste pile, initially registered as a tailings dam with the ANM, was a co-disposal stack containing waste rock and tailings. The overflow from this pile flooded a major highway, sweeping away cars and necessitating a two-day road closure. Furthermore, it prompted the evacuation of a staff member and 400 animals from the Wild Animal Rehabilitation Center located below the mine. In response to the spill, Brazilian regulators imposed a fine of $51.6 million on the company and suspended operations at the mine. The incident occurred after heavy rainfall, causing a slope failure involving three banks of the Cachoeirinha mine waste pile, resulting in the release of mine waste into the Lisa water retention dam. Although the dam overflowed along its entire embankment length, its stability remained uncompromised. The mud wave from the retention dam also blocked the highway, leading to one reported injury.

402 | A leak in the impoundment had been observed for a period of 20 days. The resulting spill into the Deliçay Stream carried toxic wastes through the Taurus Mountains and into the Mediterranean Sea. It's noteworthy that the smelter in question was inaugurated in 2013.

403 | There was a breach in the wall of a tailings pond containing iron slurry produced from a beneficiation plant. Approximately 20-30 acres of farmland in Banjhiberana village were submerged under the iron ore slurry. The spillage also contaminated two ponds, resulting in a fish kill. Additionally, a security guard is reported missing in connection to the incident.

404 | The basin overflowed due to the absence of a protective wall to contain the water. The incident lasted for an hour and had the potential to impact the drinking water supply for Fort Dauphin. Following this event, QMM released an additional one million m^3 of wastewater, resulting in a substantial fish kill.

405 | The tailings pond was put into operation around 2018. As a result, 7.5 mu of arbour forest land was buried, over 200 m of seasonal ditches and rural roads were blocked, and part of the surrounding walls of adjacent enterprises were washed away. Fortunately, no casualties were reported. The incident led to the formation of a large pit in the tailings pond, with the dam body experiencing flushing with a fap of about 70 to 80 m. This resulted in the burial of 0.5 hectares of arbour forest and land, blocking more than 200 m of seasonal ditches and rural roads, and washing away part of the surrounding walls of adjacent enterprises.

406 | A mud wave containing unrecovered minerals and chemical elements reached the La Rivera River and the Quebrada de Tarapaya, which connects with the Pilcomayo River. In response to this environmental incident, Argentina's Salta province has issued an order prohibiting the use of water from the Pilcomayo River.

407 | In 2010, De Beers sold the Jagersfontein mine and tailings to a consortium, which aimed to reprocess the tailings waste in the hope of discovering diamonds that were overlooked during the initial mining phase. Jagersfontein had been a prolific producer of some of the world's largest gems during its operation from 1870 to 1971. Tragically, disaster struck when the dam collapsed, causing a mud wave up to 1.5 km wide to travel approximately 8.5 km. This resulted in the seeping away and/or destruction of 51 houses, affecting another 103 homes, sweeping away cars, disrupting power lines, killing two individuals, injuring 76, and displacing more than 300 residents. Additionally, at least 500 animals lost their lives in the aftermath of the incident.

408 | The failure mechanism involved the subsidence of a section of the east wall of the tailings storage facility by approximately 1.5 meters, allowing water to exceed the wall's height and triggering the breach. The resulting plume extended over 8 km in length and had a width of about 1.2 km. A small community bore the brunt of the waste, with a total area of 3.57 km^2 covered within Williamson's mine lease area and an additional 1.52 km^2 outside the mine lease area. 13 dwellings and farmland were impacted, resulting in three reported injuries. The Ngw'wanholo village, with approximately 115 citizens, experienced severe effects from the incident.

409 | The failure occurred due to seepage in the tailings, leading to the breach of the storage facility.

410 | There was an overflow in the process water drainage pond.

411 | A failure occurred in a low berm constructed along the rim of an abandoned clay pit, which was repurposed for the retention and clarification of process water. The berm, constructed without proper compaction and incorporating brush and debris, experienced uncontrolled seepage at the foundation contact after a rapid rise in impoundment. This resulted in the release of approximately 80,000 gallons of process water (Division of Water Pollution Control, Tennessee, Department of Health and Envirionment)*.

412 | The liquefaction and flow of coarse, saturated tailings into underground mine workings beneath an impoundment occurred in an abandoned open pit. The incident is believed to have been triggered by voids in the rock above the workings, which propagated upward to the impoundment. This propagation may have resulted from unequal extraction of ore or the differential settlement of caving rock during ongoing mining operations (Brawner, 1979).

413 | Tailings were constrained by dikes primarily constructed with tailings fill using a dragline and leveled with a bulldozer. The fill underwent little or no compaction, and the dike slopes ranged from 33 to 38 degrees, closely aligning with or approaching the angle of repose for the material. As a consequence of these factors, multiple failures of the dikes transpired, leading to the release of impounded tailings into the nearby Avoca River (Brawner, 1979).

414 | A grout curtain, implemented in alluvial deposits, was employed to manage seepage containing radium-226 from an existing, reactivated tailings dam. This curtain was constructed by injecting a mixture of clay, water, cement, bentonite, and occasionally calcium chloride through slotted pipes installed in small-diameter boreholes drilled through the alluvium and into bedrock. Pump tests conducted after completing the grout curtain revealed that a thin zone along the bedrock surface remained ungrouted, and seepage through only the upper part of the alluvium was delayed. Despite observing that the curtain had a minimal overall effect on reducing seepage, it was noted that the dissolved radium-226 content in the groundwater significantly decreased as it passed through and beneath the grout curtain. This decrease in contaminant concentrations was attributed to the exchange between the effluent seepage and the chemicals in the grout curtain (Dodds,1978).

415 | The impoundment was built in the 1940s and 1950s, featuring a metal culvert designed to convey perennial streamflows beneath the dam and impoundment. However, the corrosive influence of acidic tailings effluent led to the corrosion and partial collapse of the culvert. Although no embankment breach occurred, suspended tailings were discharged downstream during periods of high flow through the damaged culvert (Montana Department State Lands)*.

416 | The dam was built using uncompacted clayey sand and gravel, featuring downstream slopes with a ratio of 1:1. Significant seepage at the embankment toe was observed, accompanied by damage manifesting as multiple cracks and scarps parallel to the crest. The cumulative vertical displacement of these cracks and scarps reached up to one m (Ash, 1976).

417 | A series of tailings dams, reaching heights of up to 350 feet, were developed over the course of a 50-year mine life in steep and narrow valleys. These dams incorporated a complex network of pipe-type decant structures and inadequately sized stream bypass channels. Unfortunately, the inadequacies in these bypass or decant systems led to the failure of 5 separate dams (Brawner, 1979).

418 | Several tailings dams, reaching heights of up to 350 feet, were constructed over the 50-year mine life in steep and narrow valleys. Unfortunately, one of these dams experienced failure due to seismic liquefaction. Regrettably, no further details regarding the specific circumstances of the failure were reported (Brawner, 1979).

419 | The initial phase of the tailings dam involved constructing it across a bay of a large lake by depositing mine waste, and tailings were discharged into the bay from the dam crest. A sudden piping failure occurred when the tailings beach reached a level one foot above the lake tailwater elevation, leading to the transport of a significant quantity of tailings and effluent through the mine waste and into the lake. To address the issue, a repair was implemented by placing a wide zone of cycloned sand over the spigotted tailings beach, effectively pushing ponded water back from the dam. This combination of draining through cycloned sands and reducing internal seepage gradients prevented further piping. Subsequent dam raises incorporated an upstream filter zone against the placed mine waste to enhance stability and prevent similar failures (Klohn, 1979; Klohn, 1980).

420 | The dam was initially constructed as a starter dike for subsequent upstream embankment raising. Initially used to retain water, the structure experienced excessive seepage at the contact point between the wooden spillway and the foundation. This seepage was attributed to the poor quality of construction during the winter period (Biyanov, 1976).

421 | Extensive damage to the embankment took place as a result of seepage-related slumping and ravelling of the face, accompanied by piping and erosional transport of tailings materials from the embankment (Hazen, 1924).

422 | During the raising of the dam using cycloned sand tailings, a foundation drainage system was installed, comprising a 6-inch diameter perforated corrugated metal pipe surrounded by filter gravel. When the cycloned sand fill reached a height of 55 feet above the pipe, a sinkhole, 25 feet in diameter and 20 feet deep, developed on the landfill surface. The sinkhole was attributed to the collapse of the drainage pipe, and investigations revealed severe corrosion caused by the slightly acidic pH of the seepage effluent. To address this issue, the pipe ends were plugged, and internal drainage was redirected to the pervious in-situ foundation soils downstream of the dam toe (Brawner, 1979).

423 | The dam had been built on a foundation containing old tailings. Lateral spreading and foundation strains induced liquefaction, leading to a tailings flowslide (Smith, 1969).

424 | An embankment slope failure that breached the crest of the dam occurred following an unusually heavy rainfall. At the time of the failure, ponded water was well back from the embankment crest, and no slimes or water were released (Klohn, 1972).

425 | A liquefaction flow slide is depicted, believed to be associated with lateral strains, differential movements, and cracking that occurred at a high-angle corner of the tailings embankment (Casagrande, 1971).

426 | The dam was comprised of a homogeneous section of well-compacted clay shale and sandstone-derived fill. The embankment failure occurred rapidly when the decant pipe, which penetrated the embankment, ruptured due to minor differential settlement (Casagrande, 1971).

427 | A reinforced concrete decant conduit extended beneath the tailings dam and impoundment. Due to the deterioration of the conduit, timber supports were added. However, the conduit collapsed under excessive external water pressures, forming a crater on the surface of the impounded slimes. Tailings and timber debris created a plug inside the collapsed conduit, allowing water pressures within the plugged section to increase. This, in turn, cracked the conduit, generating concentrated seepage within the coarse tailings comprising the embankment. The seepage led to piping of tailings into the rockfill starter dike at the downstream embankment toe. To address the damage, the debris plug was removed, the conduit was repaired, and filter zones were added to the rockfill (Smith & Connell, 1979).

428 | The upstream embankment was undergoing a raising process with an overall slope of 4:1 through the construction of perimeter dikes using hauled fill. The instability of the embankment was attributed to vibrations caused by the mine railroad, which transported and dumped fill for the perimeter dike. This led to tailings flow sliding (Casagrande, 1971).

429 | A large piping cavity developed in the embankment due to a seepage breakout on the embankment face. Piping progressed through the entire width of the perimeter dike in one day, and severe damage was narrowly averted (Casagrande, 1971).

430 | The freezing and growth of ice lenses on the embankment face resulted in extensive sloughing of the embankment slope during the first few days of spring thaw. This process was accompanied by the development of piping (Casagrande, 1971).

431 | The impoundment was lined with a 40-mil PVC geomembrane without an overlying soil cover. During the initial tailings deposition, when the tailings had accumulated over the liner to an average depth of less than one foot, an air bubble developed beneath the liner, lifting it about 20 feet over a 100-ft diameter area. The cause of bubble formation was not determined but may have been related to the formation of water vapor from subgrade soil moisture. The liner over the bubble ruptured, allowing a small amount of tailings and retained fluid to escape. The liner was repaired after decontamination and cleanup. Other smaller bubble areas were vented using a special apparatus (Anecdotal)*.

432 | An initial zoned earth fill dam was constructed using borrow material excavated from within the impoundment. The impoundment, which was not lined, could not guarantee a complete cutoff of foundation seepage at the chosen dam site. Seepage mitigation measures included an extensive underdrain system within the impoundment, a trench drain along the downstream toe of the dam, and extensive piezometer instrumentation. However, filling the impoundment led to excessive seepage around the abutments and beneath the trench drain, through interconnected zones of sand and gravel within the impoundment area. Remedial measures involved the construction of a deep trench drain system incorporating pump-back wells downstream from the raised dam toe (Anecdotal)*.

433 | A concrete-faced rockfill starter dike was constructed on a karstic limestone foundation. Despite placing a grout blanket in overexposed limestone within the impoundment area, several sinkholes developed during the initial filling, leading to the draining of the reservoir. One area of sinkhole formation was at the upstream toe of the concrete facing, and investigations revealed interconnected solution cavities in this area, as well as extensive caverns in the dam abutment near the crest. Repairs involved careful excavation of solution features and plugging with a mixture of mine waste and concrete. Additionally, a 10-foot thick mine waste layer was placed over treated areas to bridge and plug potential future sinkholes that might develop (Robinson & Toland, 1979).

434 | Wedge-type sliding on a thin layer of very soft foundation soil led to the instability of the embankment. However, the crest was not breached, and no tailings were released (Donaldson et al., 1976).

435 | Severe seepage and piping eroded a significant portion of the embankment slope, leaving near-vertical scarps (Donaldson et al., 1976).

436 | A failure is described where a rotational slide in the embankment face triggered partial liquefaction of the retained slimes. The slide was related to the long-term retention of water on the impoundment surface, which deviated from conventional operating practices in South Africa (Blight & Steffen, 1979).

437 | Slope instability caused a 15 m wide section of the embankment slope to drop 8 m. This condition occurred when saturated material was bulldozed in an oversteepened condition on the upper portion of the slope. Shortly after, seepage emerged on the unstable section, initiating retrogressive failure. However, a dam breach was averted by prompt remedial action (Schlick & Wahler, 1976).

438 | Confining dikes were constructed on soft tidal flats foundation materials by casting fill with a dragline and later hauling it with trucks and spreading it with bulldozers. The dikes experienced severe deformation and cracking, slumping, and bulging at the toe. Emergency remedial action averted failure (Schlick & Wahler, 1976).

439 | An old tailings dam was constructed within a quarry, and it was subsequently repaired. The specific cause for the need for repairs is not reported (Little & Beavan, 1972).

440 | Sliding of the upstream slope of the dam occurred during the excavation of the impounded tailings to a depth of 40 feet, intended to allow re-use of the impoundment. The failure was attributed to rapid-drawdown conditions on the upstream slope following the removal of the tailings (Tompson & Rodin, 1972).

441 | The initial starter dike was constructed to a height of 45 feet using relatively impervious sand and gravel on an impermeable foundation. Upstream raising involved using cycloned sands spigotted from the dam crest, with slimes discharged in the rear of the impoundment. When the embankment reached a height of 60 feet, a malfunction of the stationary cyclone system caused uncycloned tailings to be discharged from the rear of the impoundment, leading to an accumulation of ponded water and slimes near the embankment face. This caused seepage to emerge on the embankment face above the starter dike crest and raised the phreatic surface within the embankment to critical levels. Remedial measures included the installation of French drains on the embankment face to collect surface seepage and instituting perimeter discharge of whole tailings from the embankment crest to eliminate the accumulation of ponded water in this area (Robinson & Toland, 1979).

442 | A soil-bentonite slurry cutoff was constructed to reduce unacceptable quantities of contaminated foundation under seepage. The cutoff was installed to the greatest depth possible without extensive rock excavation. The remaining zones of under seepage through the fractured rock below the bottom of the cutoff were identified by piezometers and locally grouted, effectively stopping the seepage (Taylor & Ackhorner, 1984).

443 | An abandoned coal slurry impoundment was breached by overtopping during heavy rains. Unfortunately, no further details are available (Wobber et al., 1974).

444 | The dam was constructed to retain tailings and evaporate effluent from trona processed for soda ash, and it included a cutoff to reduce seepage through highly fractured foundation bedrock. Approximately 150 gallons per minute of under seepage occurred, which was somewhat greater than anticipated quantities and raised environmental concerns due to deposits it produced on the ground surface. No remedial measures were adopted because there was a secondary pond downstream where seepage was collected and returned to the main impoundment (Robinson & Toland, 1979).

445 | Piping developed at the abutment of a cyclone sand tailings dam when ponded water rose in response to spring runoff and came into direct contact with the sand tailings embankment fill. This condition had been predicted, and an upstream impervious zone had been added to prevent its occurrence. However, careless spigotting of tailings had eroded this zone at the abutment contact. Repairs consisted of dumping impervious fill on the upstream dam face and filling the downstream eroded piping exit area with sand and gravel filter material (Klohn, 1979; Klohn, 1980).

446 | Piping developed at the abutment of a cyclone sand tailings dam when ponded water rose in response to spring runoff and came into direct contact with the sand tailings embankment fill. This condition had been predicted, and an upstream impervious zone had been added to prevent its occurrence. However, careless spigotting of tailings had eroded this zone at the abutment contact. Repairs consisted of dumping impervious fill on the upstream dam face and filling the downstream eroded piping exit area with sand and gravel filter material (Klohn, 1979).

447 | An embankment of coal refuse, constructed with uncompacted, train-dumped fill, retained impounded coal tailings and water. Downstream slope movements of 20 meters per year, accompanied by a high phreatic surface and large quantities of seepage, resulted in severe cracking and deformation of the embankment slope (Schlick & Wahler, 1976).

448 | No details provided.

449 | The dam had not been raised since 1984. A central berm had been built to divide the impoundment. Tailings were placed in one while the other drained and dried. Dried tailings were then dug out and placed elsewhere. A truck was on the crest and became stuck in the mud. Two others were sent to help, and while this was going on, slip failure began. The crest was 2 m above the tailings, but they were placed away from the dam, which had water against it. The rotational movements soon allowed overtopping. A strong noise was heard, and the staff of a laboratory 500 m downstream ran for their lives up the valley side. The liquefied tailings swept down the zigzag valley like water, outstripping all vegetation. Downstream slope of the dam was 1:1.1 (ICOLD Tailings Committee)*.

450 | The lower impoundment of this disposal scheme was under construction in a valley adjacent to the active upper one. A saddle between the two valleys had a small dam to prevent overflow. At a time of maximum water level in the upper impoundment, a piping failure occurred at the left end of the saddle dam, releasing water into the lower impoundment, causing overtopping of the tailings dam under construction, and washing out a considerable amount of fill. The accident caused significant delays in the operation of the scheme(ICOLD Tailings Committee)*.

A.2.2. References

A list of references for the incident descriptions is presented here. Not for every recorded incident references are available or could be traced back.

Abadjiev, C., & Dimitrov, N. (1997). Taking warnings by the failure of" maritsa istok i" ash tailings dam. In *Transaction of the international congress on large dams* (Vol. 4, pp. 1–10).

Ash, R. (1976). Investigation for Remedial Works at the Retention Dams and Tailings Dumps at Captains Flat near Canberra, Australia. In *Douzième Congrès des Grands Barrages Mexico*.

Avadjiev, C. (1990). Improvement of a tailings dam stability after nine years of operation. In *International Symposium on Safety and Rehabilitation of Tailings Dams* (pp. 146–155).

Beavers, C. (2013). *An Overview of Phosphate Mining and Reclamation in Florida.* (Thesis)

Berti, G., Villa, F., Dover, D., Genevois, R., & Brauns, J. (1988). The Disaster of Stava/Northern Italy. In *Hydraulic Fill Structures* (pp. 492–510).

Bertrand, M. (2014, December 26). *Record $7.5-Million Environmental Fine Levied: Subsidiary of U.S. Company Pleads Guilty over Infractions at Northeastern Quebex Mining Operations that is Being Abandoned.* (Globe and Mail)

Bishop, A. W. (1973). The Stability of Tips and Spoil Heaps. *Quarterly Journal of Engineering Geology and Hydrogeology*, *6*(3-4), 335–376.

Biyanov, G. (1976). *Dams on Permafrost.*

Black Press Media. (2012, July 9). *Sinkhole to Blame for Slough at Mine Site Near Salmo.* Retrieved from https://www.nelsonstar.com/news/sinkhole-to-blame-for-slough-at-mine-site-near-salmo-4834299

Blight, G. (2000). Management and Operational Background to Three Tailings Dam Failure in South Africa. In W. Hustrulid, M. McCarter, D. Amponsah-Dacosta, & F. Zyl (Eds.), *Slope Stability in Surface Mining* (pp. 383–390).

Blight, G., & Fourie, A. (2003). A Review of Catastrophic Flow Failures of Deposits of Mine Waste and Municipal Refuse. In *International Workshop on Occurrence and Mechanisms of Flow in Natural Slopes and Earthfills.*

Blight, G., & Steffen, K. (1979). *Geotechnics of Gold Mining Waste Disposal.*

Brawner, C. (1979a). Concepts and Experience for Subsurface Storage of Tailings. In *Tailings Disposal Today: Subsurfface of Tailings* (pp. 153–177).

Brawner, C. (1979b). Design, Construction and Repair of Tailings Dams for MEtal Mine Waste Disposal. In *Mine Waste Disposal: Metal Mines* (pp. 53–87).

Caldwell, J. (2013). *Tailings Facility Failure in 2012.*

Caldwell, J. (2014). Tailing Facility Failures in 2013/2014. In *Proceedings Tailings and Mine Waste 2014.*

Caldwell, J. (2015). Tailing Facility Failures in 2014 and Update on Failure Statistics. In *Proceedings Tailings and Mine Waste 2015.*

Cardoso Duque, M. (2011). *Reconstitution of the Failure of the Fonte Santa Mine Tailings Dam: Modelling of the Dam Breaching Process*. (Thesis)

Casagrande, L. (1971). Design and Construction of Tailings Dams. In (pp. 181–203).

Castro, G., & Troncoso, J. (1989). Effects of 1985 Chilean Earthquake on Three Tailings Dams. In *5th Chilean Conference on Seismology and Earthquake Engineering, Santiago, Chile*.

Chakravatti, J., La Rocque, E., Reades, D., & Robinsky, E. (1982). Thickened Tailings Experiment for Close-Out of Uranium Mill Tailings at Denison Mines Limited. In *Management of Wastes from Uranium Mining and Milling*.

Chandler, R., & Tosatti, G. (2013). The Stava Tailings Dams Failure, Italy, July 1985. *Geotechnical Engineering*, *113*, 67–79.

Clark, M., Weitz, T., Banning, W., Turk, D., & Paterson, J. (1989). Montana Tunnels-Start-up Efficiencies Improved, Expansion Considered. *Mining Engineering*.

Csagoly, P. (2000). The Cyanide Spill at Baia Mare, Romania: Before, during and after. *Regional Environmental Center for Central and Eastern Europe*.

Dobry, R., & Alvarez, L. (1967). Seismic Gailures of Chilean Tailings Dams. *Journal of the Soil Mechanics and Foundations Division*, *93*(6), 237–260.

Dodds, R. (1979). Control of Seepage of Radium 226 Using an Alluvial Grout Curtain. In *Symposium on Uranium Mill Tailings Management, Fort Collins, Colorado* (pp. 245–261).

Donaldson, G., Adamson, R., & Clausen, H. (1976). Slimes Dams for Gold Mine Tailings and Other Residues in South Africa. In *ICOLD Meeting Mexico* (pp. 709–729).

Emerman, S. (2021). *Cause of Failure of the Lagoa do Pirocáua Dam at the Aurizona Mine on March 25, 2021, Maranhão State, Northeast Brazil*.

Fernández-Naranjo, F., Rodriguez-Gomez, V., Rodríguez-Pacheco, R., Alberruche, E., Arranz-González, J., Sarro, R., ... Vadillo, L. (2017). Analysis of Tailings Dam Failure Based on Historical Documents: the Case Study of "La Luciana", Spain. In *JTC1 Workshop on Advances in Landslide Understanding, Barcelona*.

Franca, J., M., Gezero, L., Ferreira, R., Amaral, S., & Montenegro, H. (2008). The Failure of the Fonte Santa Mine Tailing Dam (Northeast Portugal). *Proceedings and Monographs in Engineering Water and Earth Sciences*, 1153–1160.

Garino, L., Oldecop, L., & Rodari, G. (2016). Caracterización Geotécnica de Residuos Mineros. In *Congreso Argentino de Mecánica De Suelos e Ingeniería Geotéchnica*.

GESAMP. (2015). Proceedings of the Gesamp International Workshop on the Impacts of Mine Tailings in the Marine Envirionment.. (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection)

Gil, C. (2012). Accidentes y Fallas en Presas de Relave. *Geotecnia de Los Suelos Peruanos*.

Glotov, V., Chlachula, J., Glotova, L., & Little, E. (2018). Causes and Environmental Impact of the Gold-Tailings Dam Failure at Karamken, the Russian Far East. *Engineering Geology*, *245*, 236–247. https://doi.org/10.1016/j.enggeo.2018.08.012

Harder Jr, L., & Stewart, J. (1996). Failure of Tapo Canyon Tailings Dam. *Journal of Performance of Constructed Facilities*, *10*(3), 109–114.

Hazen, A., Sanborn, J., Haines, E., Pratt, A., Wiggin, T., Holmes, J., ... Gourley, H. (1924). Discussion on the Design of Earth Dams. *Transactions of the American Society of Civil Engineers*, *87*(1), 62–124.

Hollinger Mill Staff. (1951). Mill Tailings Disposal at Hollinger. *The Canadian Mining and Metallurgical*, *54*, 403–411.

Hutchison, I., Ash, W., & Fisher, J. (1984). Cyanide Control Options: Lessons from Case Histories. In *Proceedings of the Conference on Cyanide and the Environment, Tucson, AZ* (pp. 11–14).

Ishihara, K. (1984). *Post-Earthquake Failure of a Tailings Dam due to Liquefaction of Pond Deposit.* University of Missouri–Rolla.

Ishihara, K., Yasuda, S., & Yoshida, Y. (1990). Liquefaction-Induced Flow Failure of Embankments and Residual Strength of Silty Sands. *Soils and Foundations*, *30*(3), 69–80.

Jefferies, M., Morgenstern, N., van Zyl, D., & Wates, J. (2019). *Report on NTSF Embankment Failure Cadia Valley Operations for Ashurst Australia.*

Jennings, J. (1979). Mechanisms of Failure and Associated Design Considerations: the Failure of a Slimes Dam at Bafokeng. *Civil Engineer in South Africa*, *21*(6), 135–141.

Jigins, R. (1957). Tailings disposal at braden-copper-co. *Transactions of the Americal Institute of Mining and Metallurgical Engineers*, *208*(5), 1135–1140.

Kent, D., Ellinger, E., & Clifton, A. (1983). IMC K2's Brine Pond System: A Review After Seventeen Years. In *Waste Management and Containment Systmes* (pp. 775–781).

Kleiner, D. (1976). Design and Construction of an Embankment Dam to Impound Gypsum Wastes. In *Proceedings of the 12th International Congress on Large Dams, Mexico City* (Vol. 29, pp. 235–249).

Klohn, E. (1972). Design and Construction of Tailings Dams. *CIM Transactions*, *75*, 50–66.

Klohn, E. (1980). *Geotechnical Investigation for Siting Uranium Tailings Dams.*

Klohn, J. (1979). Seepage Control for Tailings Dams. In *Tailings and Waste Disposal.*

Larrauri, P., & Lall, U. (2018). Tailings Dams Failures: Updated Statistical Model for Discharge Volume and Runout. *Environments*, *5*(2), 28.

Lenhart, W. (1950). Control of Tailings from Washing Plants. *Rock Products*, *53*, 73–80.

Little, A., & Beavan, G. (1976). The Construction and Maintenance of Dams to Retain Industrial Waste. *Proceedings of the 12th ICOLD Conference, Mexico*, *1*, 515–519.

Londe, P., Guerber, P., Laplace, G., & Poutot, G. (1976). *Barrages de Berrien Pour le Stockage de Stériles.*

Luino, F., & De Graff, J. (2012). The Stava Mudflow of 19 July 1985 (Northern Italy): a Disaster that Effective Regulation Might have Prevented. *Natural Hazards and Earth System Sciences*, *12*(4), 1029–1044.

Macías, J., Corona-Chávez, P., Sanchez-Nuñez, J., Martínez-Medina, M., Garduño-Monroy, V., Capra, L., ... Cisneros-Máximo, G. (2015). The 27 May 1937 Catastrophic Flow Failure of Gold Tailings at Tlalpujahua, Michoacán, Mexico. *Natural Hazards and Earth System Sciences*, *15*(5), 1069–1085.

MacIver, B. (1961). How the Soils Engineer Can Help the Mill Man In the Construction of Proper Tailings Dams. *Engineering and Mining Journal*.

Martín-Crespo, T., Gómez-Ortiz, D., Martín-Velázquez, S., Martínez-Pagán, P., De Ignacio, C., Lillo, J., & Faz, A. (2018). Geoenvironmental Characterization of Unstable Abandoned Mine Tailings Combining Geophysical and Geochemical Methods (Cartagena-La Union district, Spain). *Engineering Geology*, *232*, 135–146.

McLemore, V., Smith, K., & Russell, C. (2014). *Sampling and monitoring for the mine life cycle* (Vol. 6). Society for Mining, Metallurgy, and Exploration.

Mittal, H., & Hardy, R. (1977). Geotechnical Aspects of a Rar Sand Tailings Dyke. In *Geotechnical Practice for Disposal of Solid Waste Materials* (pp. 327–347).

Morgenstern, N., Fair, A., & McRoberts, E. (1988). Geotechnical engineering beyond soil mechanics: A case study. *Canadian Geotechnical Journal*, *25*(4), 637–661.

Morgenstern, N., & Kupper, A. (1988). Hydraulic Fill Structures: A Perspective. In *Hydraulic Fill Structures* (pp. 1–31).

Morrill, J. (2021, February 25). *History of Mine Waste Failure in Serbia Sheds Light on New Threats.* Retrieved from https://earthworks.org/blog/history-of-mine-waste-failures-in-serbia-sheds-light-on-new-threats/

National Wildlife Federation. (2012). *Hale Mine, South Carlina.*

Nelson, J., & Kane, J. (1980). Failure of the Church Rock Tailings Dam. In *Proceedings of the 3rd Symposium on Uranium Mill Tailings Management, Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo* (pp. 24–25).

Newcrest. (2019). *Expert Review of Cadia Tailings Facility Completed.*

Okusa, S., & Anma, S. (1980). Slope Failures and Tailings Dam Damage in the 1978 Izu-Ohshima-Kinkai Earthquake. *Engineering Geology*, *16*(3-4), 195–224.

Okusa, S., Anma, S., & Maikuma, H. (1980). Liquefaction of mine tailings in the 1978 Izu-Ohshima-Kinkai earthquake, central Japan. In *7th world conference on earthquake engineering* (pp. 8–13).

Oldecop, L., & Pacheco, R. (2007). Liquefacción de Los Relaves Mineros. Riesgo Ambiental.. https://doi.org/10.13140/RG.2.1.1795.2409

Pacheco, R. (2019). Static Liquefaction in Tailings Dam and Flow Failure. *Madrid, SP..*.

Peck, P. (2007). *Avoiding tailings dam failures: Good practise in prevention.* (Lund University)

Penman, A., & Charles, J. (1991). The Safety of Tailings Dams and Lagoons in Britain. In *The Embankment Dam: Proceedings of the Sixth Conference of the British Dam Society* (pp. 53–58).

Piplinks. (2007, July 10). *Chronology of tailings dam failures in the philippines (1982-2007).*

Quelopana, H. (2019). Released Volume Estimation for Dam Break Analysis. In *6th International Seminar on Tailings Management*.

Rabinovitch, A. (2017, July 4). *'Tsunami' of Toxic Wastewater Kills Plants, Animals in Israel's Desert*. Retrieved from https://www.reuters.com/article/us-israel-environment-icl-idUSKBN19P1P6/#:~:text='Tsunami'%20of%20toxic%20wastewater%20kills%20plants%2C%20animals%20in%20Israel's%20desert,-By%20Ari%20Rabinovitch&text=MISHOR%20ROTEM%2C%20Israel%20(Reuters),km%20(12%20miles)%20long.

Rana, N., Ghahramani, N., Evans, S., McDougall, S., Small, A., & Take, W. (2021). Catastrophic Mass Flows Resulting from Tailings Impoundment Failures. *Engineering Geology*, *292*, 106262. https://doi.org/10.1016/j.enggeo.2021.106262

Reades, D., Davis, J., Goldby, H., & Stanlick, R. (1981). Remedial Works at Dam No. 1 Elliot Lake, Ontario. In *Symposium on Uranium Mill Tailings Management, Fort Collins, Colorado.*

Reid, D., & Fourie, A. (2017). Back analyses of the August 2016 Luoyang Red Mud Tailings Facility Failure..

Rico, M., Benito, G., Salgueiro, A., Díez-Herrero, A., & Pereira, H. (2007). Reported Tailings Dam Failures. A Review of the European Incidents in the Worldwide Context. *Journal of Hazardous Materials*, *152*(2), 846–852. https://doi.org/10.1016/j.jhazmat.2007.07.050

Ripley, M. (1972). The Disposal of Micaceous China Clay Waste in Southwest England. *Tailings Disposal Today*.

Robinson, K., & Toland, G. (1979). Case Histories of Different Seepage Problems for Nine Tailings Dams. In *Tailings and Waste Disposal*.

Robinson, P. (2004). *Partizansk Coal Ash Dam Break and Spill*.

Robinson, P. (2012). *Karamken Dam Break Information*.

Rodríguez, R., García, C., Zarroca, M., Roqué i Pau, C., Linares Santiago, R., & Oldecop, L. (2011). Características geológicas y geotécnicas de los lodos de flotación de la sierra minera de cartagena-la unión (se españa). *Boletín Geológico y Minero*, *122*(2), 127-144.

Rudd, R. (1979). The Bafokeng Disaster and its Legal Implications: the Failure of a Slimes Dam at Bafokeng. *Civil Engineer in South Africa*, *21*(6), 146–150.

Rudolph, T., & Coldewey, W. (1971). *Implications of Earthquakes on the Stability of Tailings Dams*.

Samarco. (2016). *Biennial Report: 2015-2016*.

Sandy, J., Piesold, D., Fleischer, V., & Forbes, P. (1976). Failure and Subsequent Stabilization of No. 3 Dump, Mufulira Mine, Zambia. *Transactions of the Institution of Mining and Metallurgical Engineers*.

Sautter, C. (1984). An Independent Review of the Environmental Health Aspects of the Church Rock, NM Tailings Spill. *Management of Uranium Mill Tailings*.

Scandic, G. (1979). Tailings Dam for Zletovo Mine. In (pp. 254–265).

Schlick, D., & Wahler, W. (1977). *Mine Refuse Impoundments in the United States* (Vol. 1028). Department of the Interior, Mining Enforcement and Safety Administration.

Simeoni, L., Tosatti, G., Lucchi, G., & Longo, M. (2018). *The Stava Catastrophic Failure of 19th July 1985 (Italy): Technical-Scientific Data and Socioeconomic Aspects*.

Small, A., James, M., & Al-Mamun, M. (2017). Advancing the State of Practice for Tailings Dam Breach Assessment using Empirical Correlations. In *Proceedings of the Canadian Dam Association, CDA 2017 Annual Conference, Kelowna, BC, Canada* (pp. 16–18).

Smith, E. (1969). Tailings Disposal and Liquefaction. *Transactions Society of Mining Engineers (AIME)*, *244*, 179–187.

Smith, E., & Connell, D. (1979). The Role of Water in the Failure of Tailings Dams. In *Tailings and Waste Disposal*.

Smith, E., Poindexter, D., & Bleikamp, R. (1977). Observational Approach to Tailings Dam Enlargement. In *Geotechnical Practice for Disposal of Solid Waste Materials* (pp. 461–474).

Swedisch Mining Association. (2001). *Seminar on Safe Tailings Dam Constructions*.

Tallin, J., Pufahl, D., & Barbour, S. (1990). Waste Management Schemes of Potash Mines in Saskatchewan. *Canadian Journal of Civil Engineering*, *17*(4), 528–542.

Taylor, M., & Achhorner, F. (1984). Corrective Measure Development and Construction Contaminant Migration Control. In *Management of Uranium Mill tailings*.

Thienenkamp, M. (2004). Post-Closure Mine Hydrology and its Impact on Underground Tailings Disposal at the Thalanga mine, Queensland, Australia. *Mine water*, 85–90.

Thomas, J., & Osterloh, E. (1917). The Construction and Maintenance of Slime Dams. *The Journal of The Chemical, Metallurgical and Mining Society of South Africa*, 214–215.

Thomson, G., & Rodin, S. (1972). *Colliery Spoil Tips: After Aberfan.* The Institution Civil Engineerings, London.

Toland, G. (1977). Case History of Failure and Reconstruction of the Mike Horse Tailings Dam Near Lincoln, Montana. In *15th Annual Engineering Geology and Soils Engineering Symposiumy*.

Troncoso, J. (1988). Evaluation of Seismic Behavior of Hydraulic Fill Structures. In *Hydraulic Fill Structures* (pp. 475–491).

Troncoso, J. (1990). Failure Risks of Abandoned Tailing Dams. In *International Symposium on Safety and Rehabilitation of Tailings Dams* (pp. 34–47).

United States Environmental Protection Agency (EPA). (1997a). *ASARCO Ray Complex: Breaches in Tailings Impoundment Containment Dike Contaminates Eleven Miles of River Sediment*.

United States Environmental Protection Agency (EPA). (1997b). *Magma Copper Mine: Repeated Release of Tailings into Pinto Creek*.

United States Environmental Protection Agency (EPA). (1997c). *Multiple Overflows Result in Major Fish Kill in Pinto Creek*.

van den Berghe, J., Ballard, J., Jewell, R., Pirson, M., & Reh, U. (2009). Importance of shear stress anisotropy and bottom drainage on tailings dam stability: A case history. In *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering* (pp. 1626–1629).

Veinott, G., Hynes, T., Anderson, M., Payne, J., Sylvester, P., Kwong, J., ... Meade, J. (2002). *A Chemical and Exotoxicological Assessment of Marine Tailings Disposal at Two Former Copper Mine Sites in Newfoundland.* (Canadian Technical Report of Fisheries and Aquatic Sciences)

Veinott, G., Sylvester, P., Hamoutene, D., Anderson, M., Meade, J., & Payne, J. (2003a). State of the Marine Environment at Little Bay Arm, Newfoundland and Labrador, Canada, 10 Years after a "Do Nothing" Response to a Mine Tailings Spill. *Journal of Environmental Monitoring : JEM*, *5*, 626-634. https://doi.org/10.1039/B301629N

Veinott, G., Sylvester, P., Hamoutene, D., Anderson, M., Meade, J., & Payne, J. (2003b). State of the Marine Environment at Little Bay Arm, Newfoundland and Labrador, Canada, 10 years after a "Do Nothing" response to a Mine Tailings Spill. *Journal of Environmental Monitoring*, *5*(4), 626–634.

Vick, S. (1996). Failure of the Omai tailings dam. *Geotechnical News*, *14*, 34–40.

Villavicencio, G., Espinace, R., Palma, J., Fourie, A., & Valenzuela, P. (2014). Failures of Sand Tailings Dams in a Highly Seismic Country. *Canadian Geotechnical Journal*, *51*(4), 449–464.

Vrhovnik, P., Dolenec, T., Serafimovski, T., Dolenec, M., & Rogan Šmuc, N. (2013). The Occurence of Heavy Metals and Metalloids in Surficial Lake Sediments before and after a Tailings Dam Failure. *Polish Journal of Environmental Studies*, *22*(5), 1525–1538.

Vrhovnik, P., Šmuc, N., Dolenec, T., Serafimovski, T., Tasev, G., & Dolenec, M. (2011). Geochemical Investigation of Sasa Tailings Dam Material and its Influence on the Lake Kalimanci Surficial Sediments (Republic of Macedonia)-Preliminary Study. *Geologija*, *54*(2), 169–176.

Wei, Z., Yin, G., Wang, J., Wan, L., & Li, G. (2013). Design, Construction and Management of Tailings Storage Facilities for Surface Disposal in China: Case Studies of Failures. *Waste management & Research: the Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *31*(1), 106–112. https://doi.org/10.1177/0734242X12462281

Williams, M. (1979). Tailing Dam Failure Case History. In *Proceedings, 2nd International Tailing Symposium* (pp. 428–433).

Wobber, F., Wier, C., Leshendok, T., & Beeman, W. (1974). Survey of Coal Refuse Banks and Slurry Ponds for the Indiana State Legislature Using Aerial and Orbital Inventory Techniques. In *First Symposium on Mine and Preparation Plant Refuse Disposal* (pp. 65–77).

Wolski, W., Mioduszewski, W., & Furstenberg, A. (1976). Some Aspects of Designs of Mine Tailings Dams. In *Douzième Congrès des Grands Barrages Mexico.*

Wood, H. (2012). Disasters and Minewater. *Good Practice and Prevention, London.*

Zabala, F., Navarta, G., & Oldecop, L. (2018). Modelling of Castaño Viejo Tailings Flow Case History. In *Proceedings of China-Europe Conference on Geotechnical Engineering* (pp. 1556–1560).

Zanbak, C. (2010). *Failure Mechanism and Kinematics of Ajka Tailings Pond Incident.*

A.3. Statistics

Critical details for the available failure records are displayed on the global map. Additionally, a comprehensive overview of attribute cross-correlations within the database is provided.

Geographical Locations

The world maps below depict the database records' locations, along with their classification into incidents or accidents, dam construction method, operational status, and failure category. While a more detailed analysis would be intriguing, it falls beyond the scope of this study.

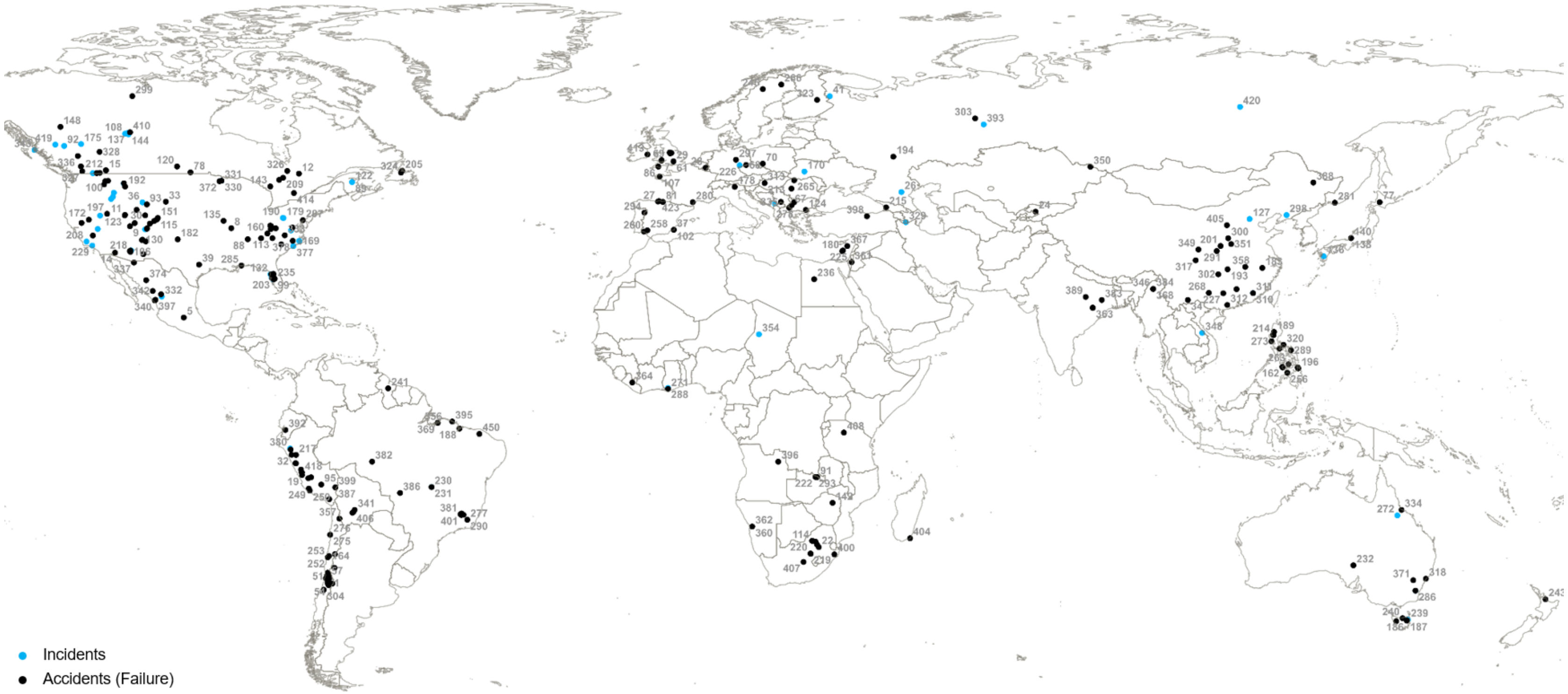


Figure A.1: Incidents and Accidents (Failure)

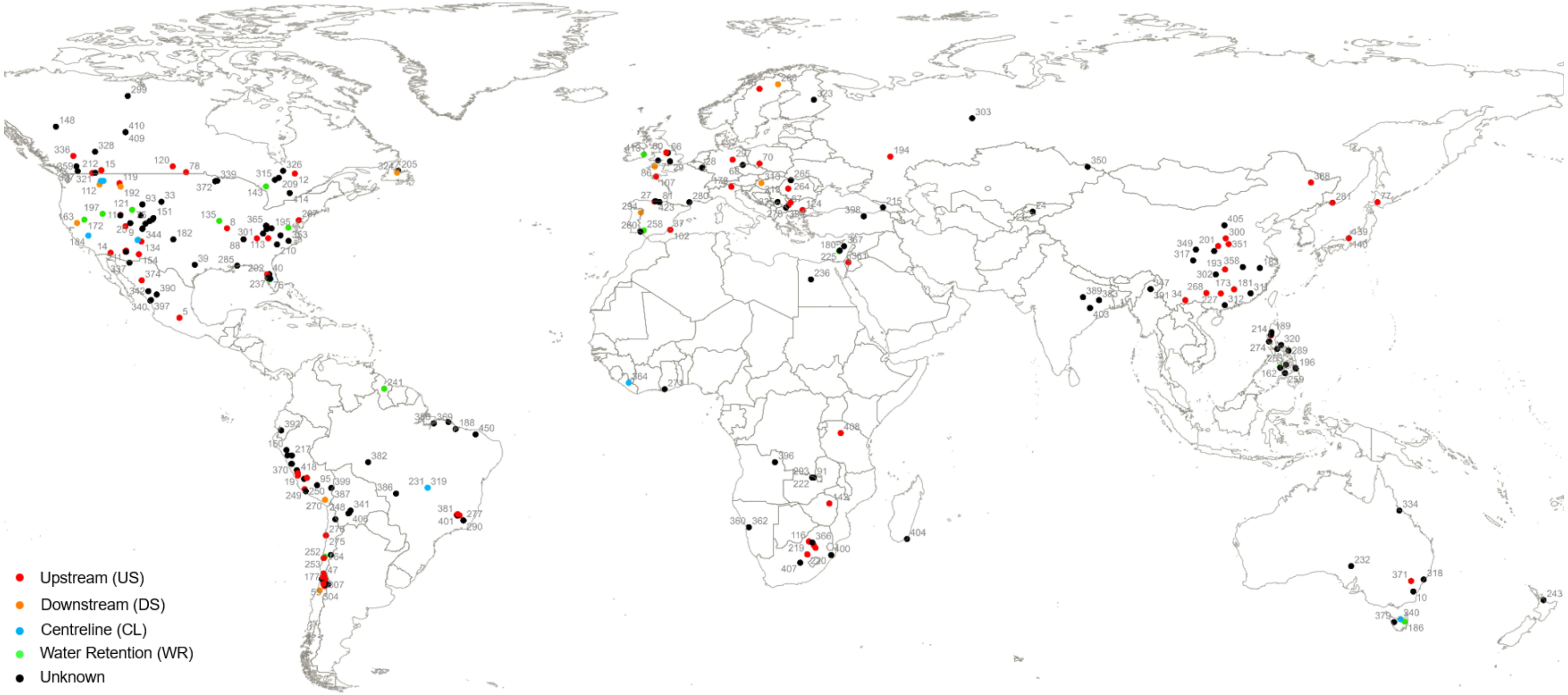


Figure A.2: Dam Construction Method

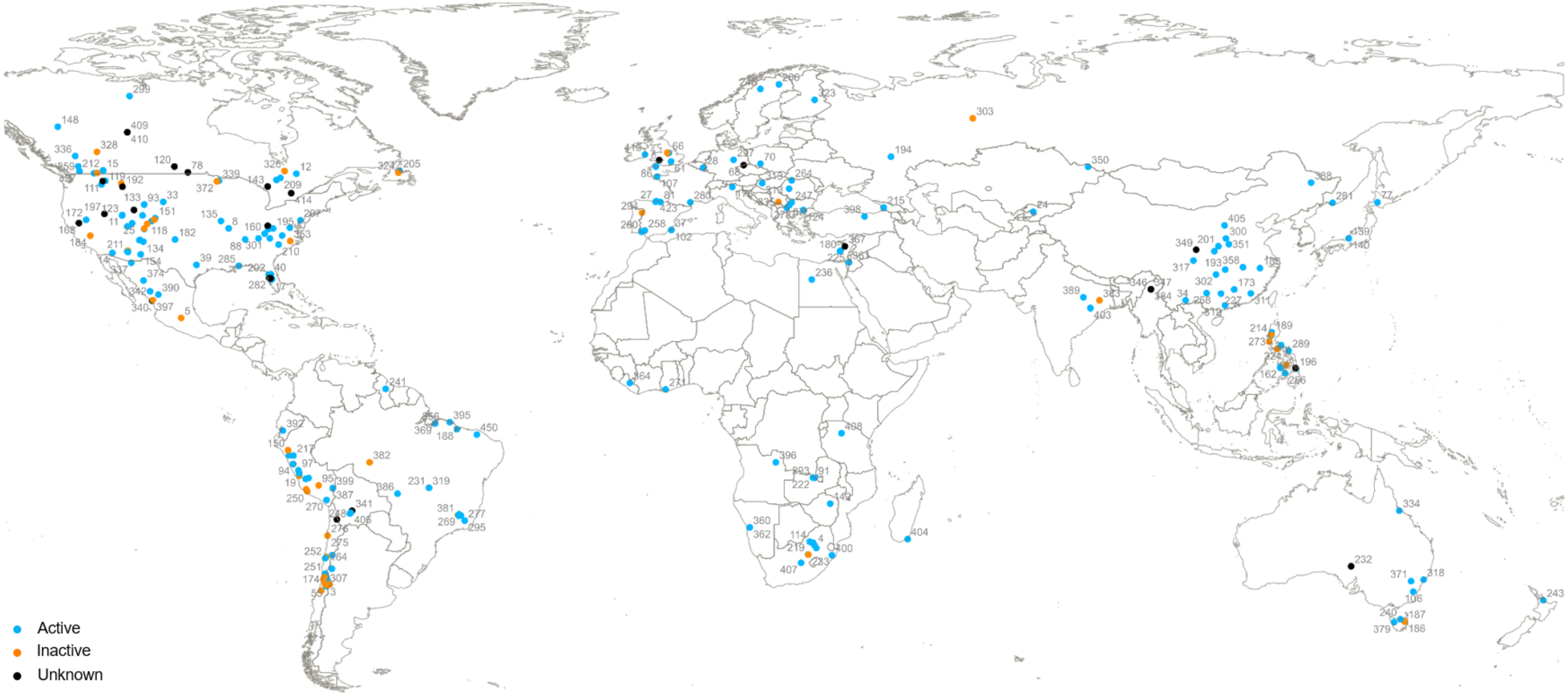


Figure A.3: Operational Status

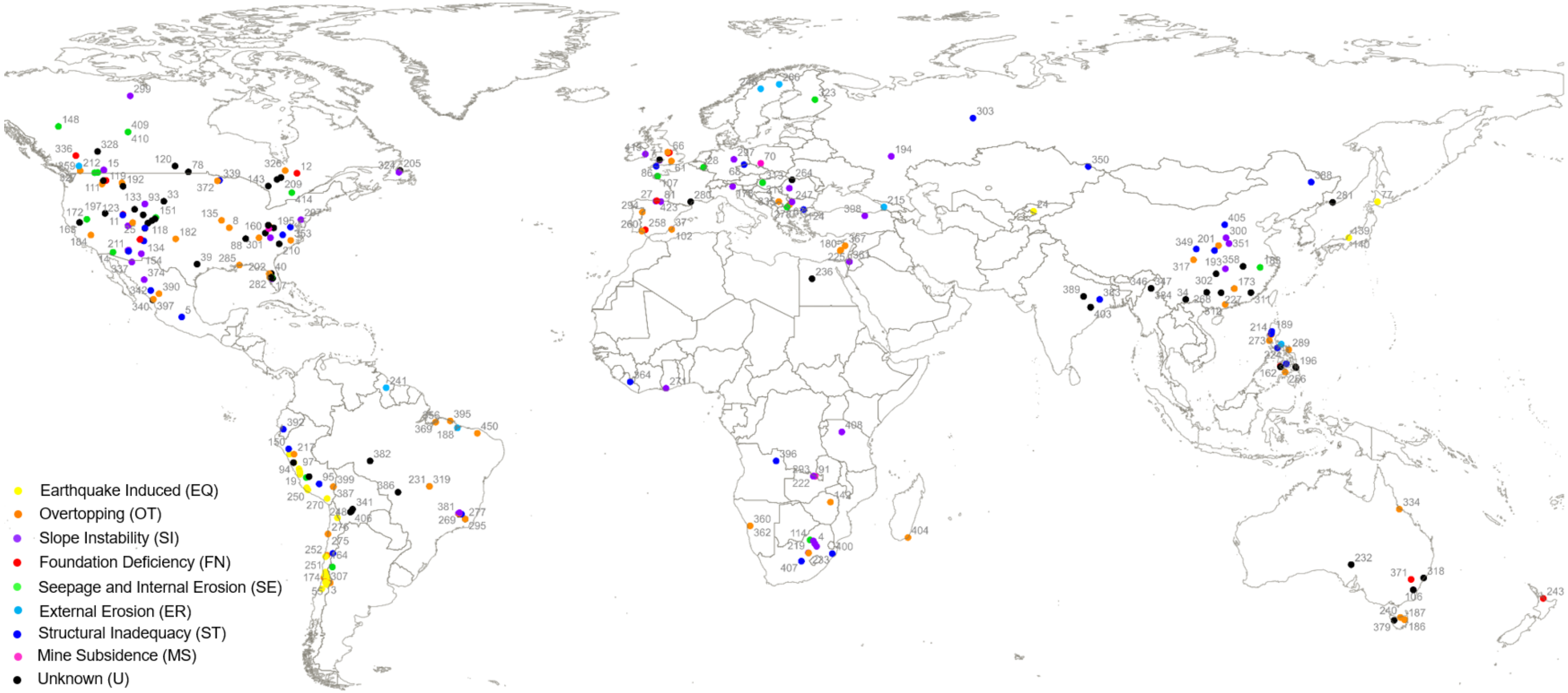


Figure A.4: Failure Category

Cross-Correlations

Cross-correlations among various attributes in the database are presented. Additional patterns or correlations may exist. A more in-depth analysis could be valuable, but it is not within the scope of this project.

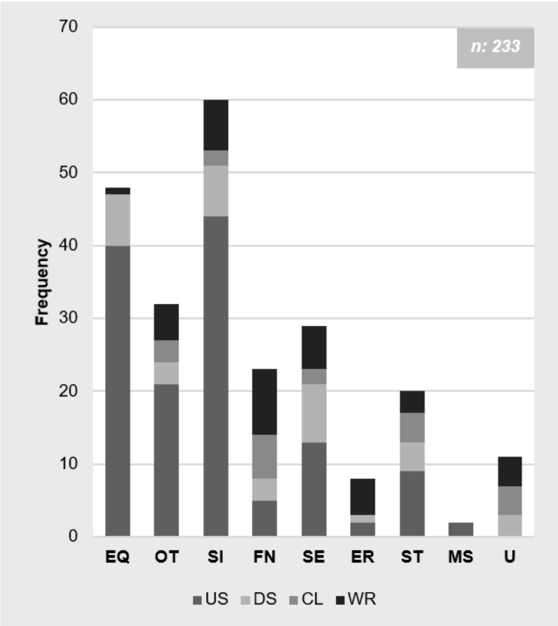


Figure A.5: Dam Construction Method by Failure Category
(US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, U: Unknown)

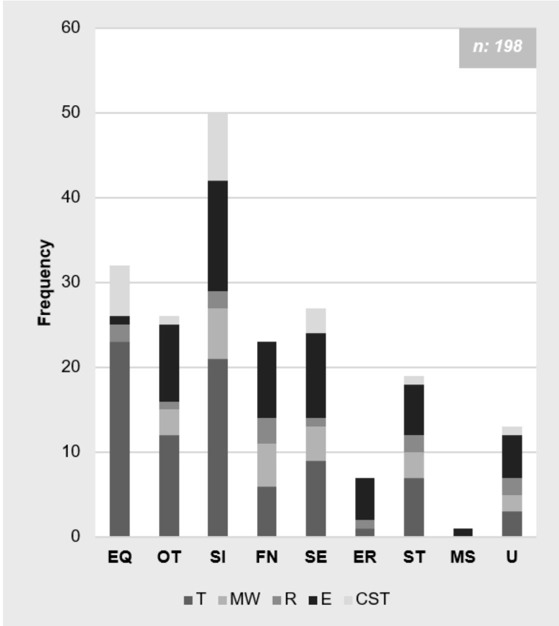


Figure A.6: Dam Fill Material by Failure Category
(E: Earthfill, R: Rockfill, T: Tailings, MW: Mine Waste, CST: Cycloned Sand Tailings, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, U: Unknown)

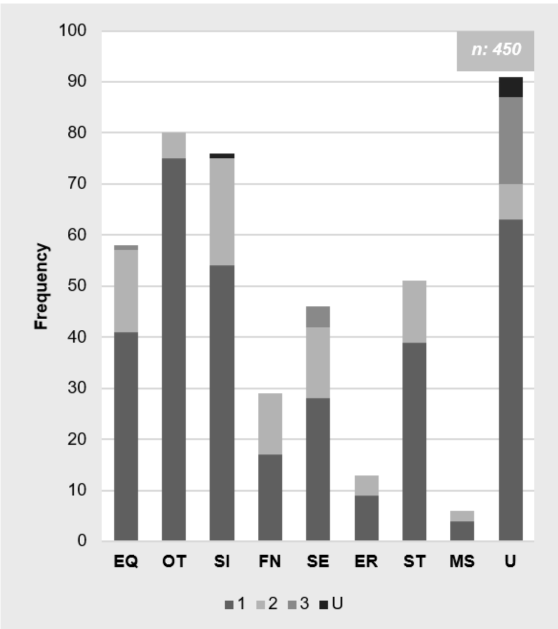


Figure A.7: Incident Type by Failure Category
(1: Accident, 2: Incident, 3: Groundwater Issue, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, U: Unknown)

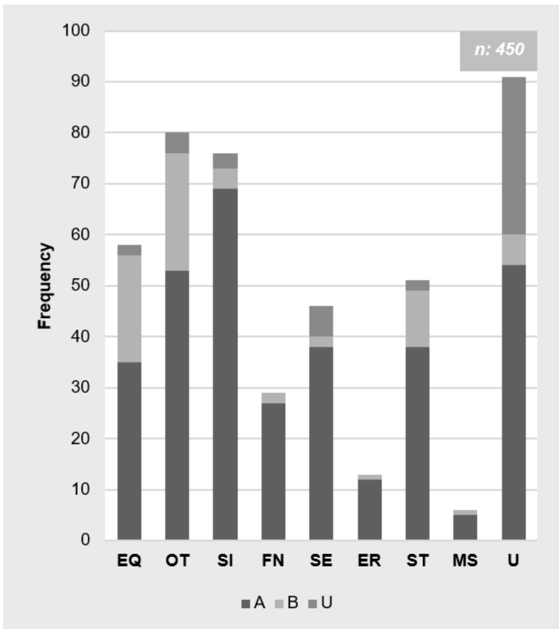


Figure A.8: Operational Status by Failure Category
(A: Active, B: Inactive, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, U: Unknown)

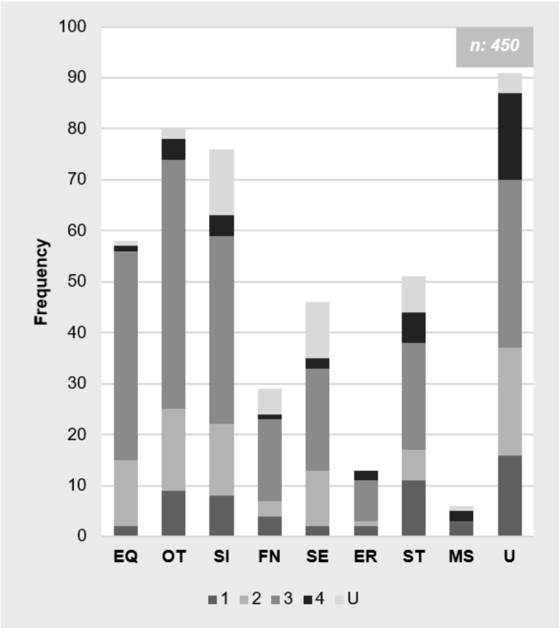


Figure A.9: Severity by Failure Category
(1: Very Serious, 2: Serious, 3: Minor, 4: Potential, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, U: Unknown)

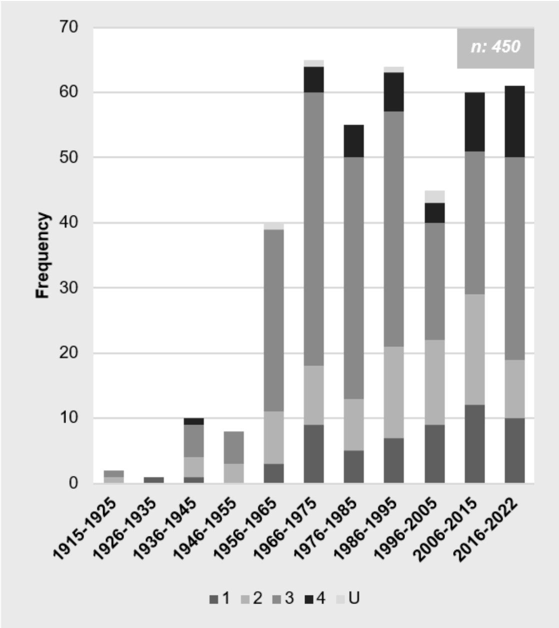


Figure A.10: Severity over Time
(1: Very Serious, 2: Serious, 3: Minor, 4: Potential)

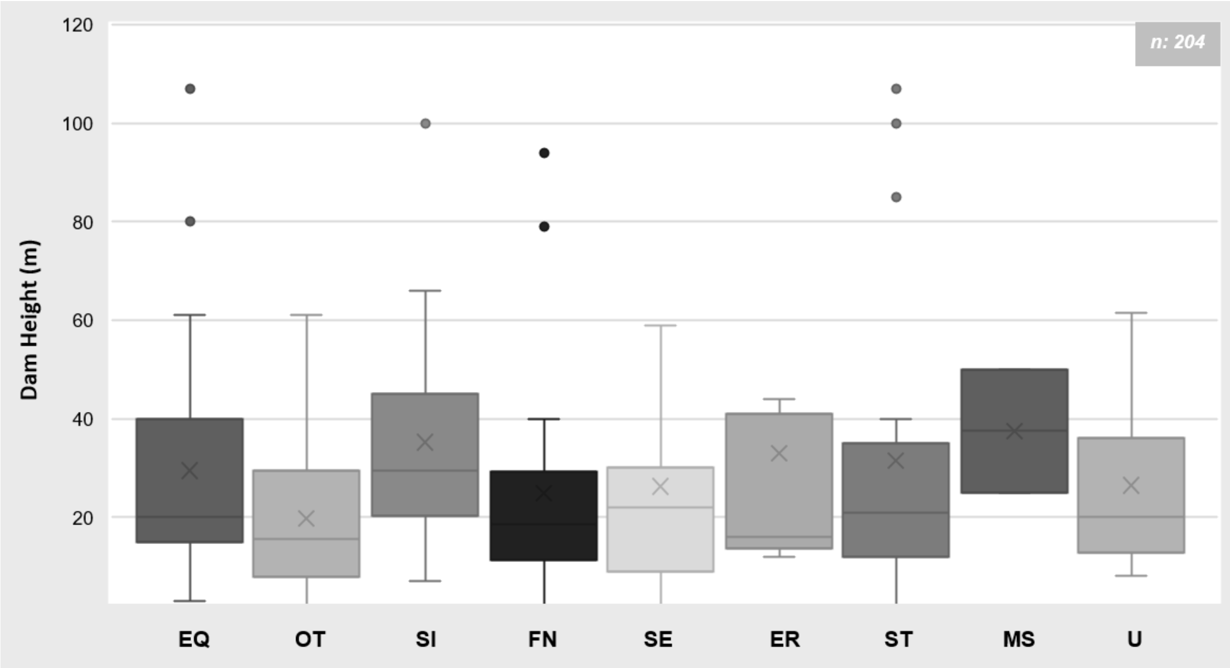


Figure A.11: Dam Height by Failure Category
(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, U: Unknown)

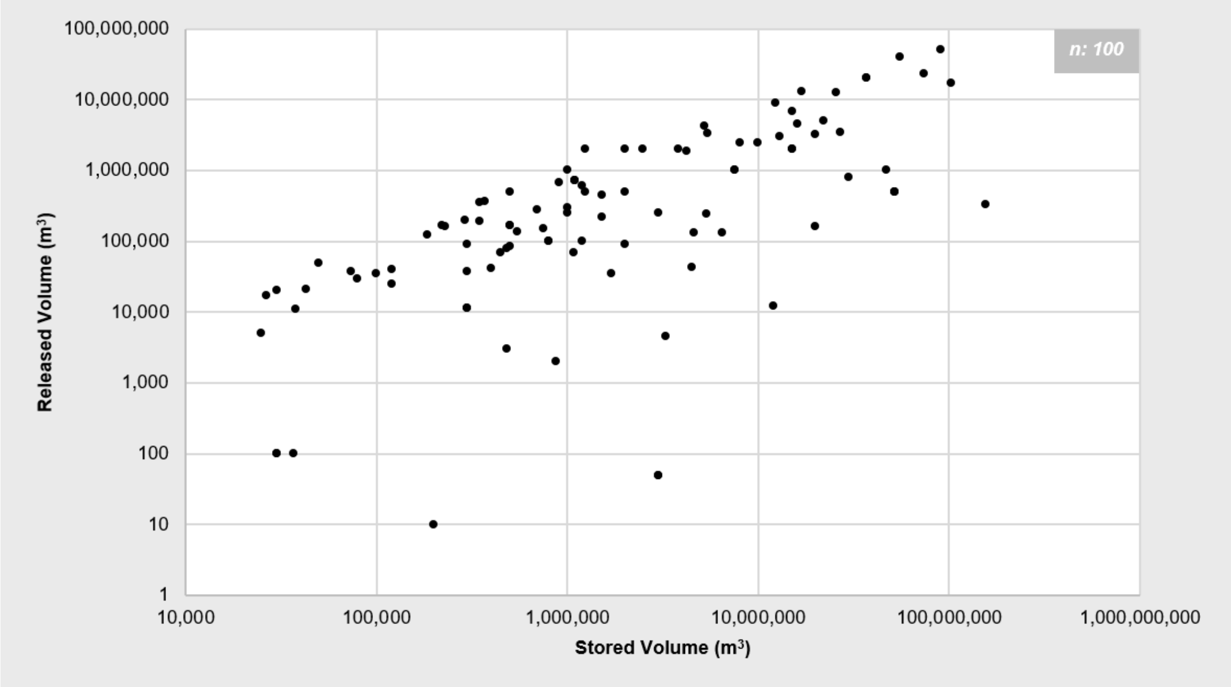


Figure A.12: Stored Volume versus Released Volume

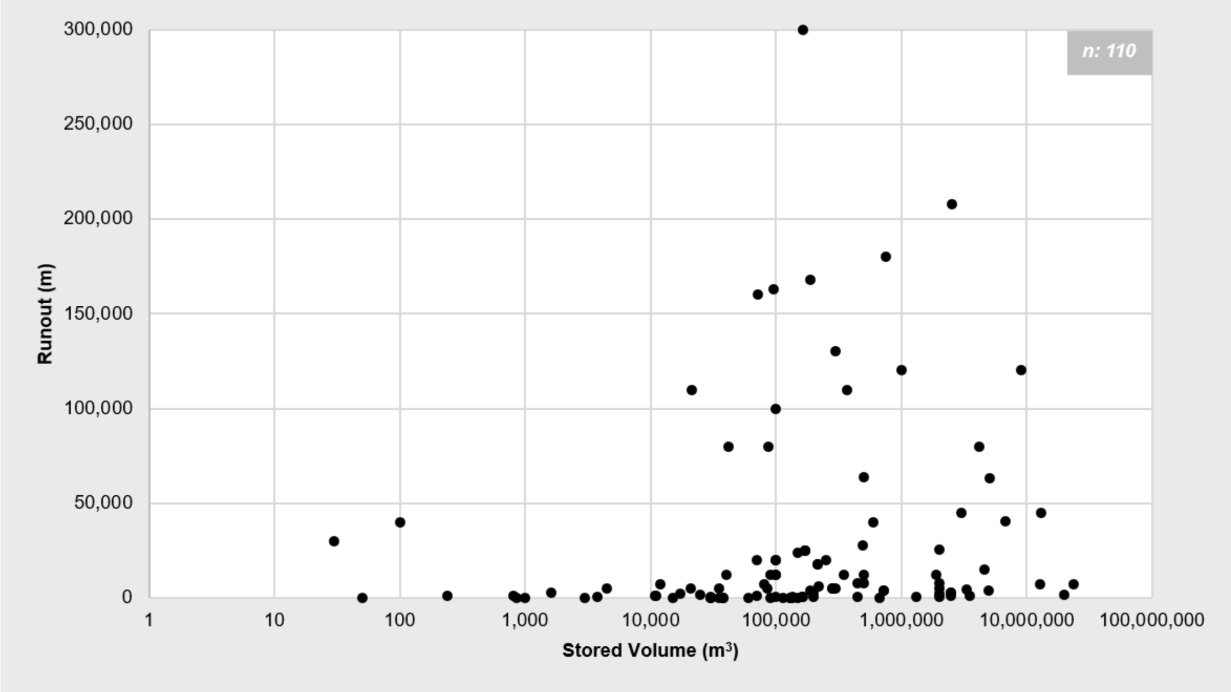


Figure A.13: Stored Volume versus Runout

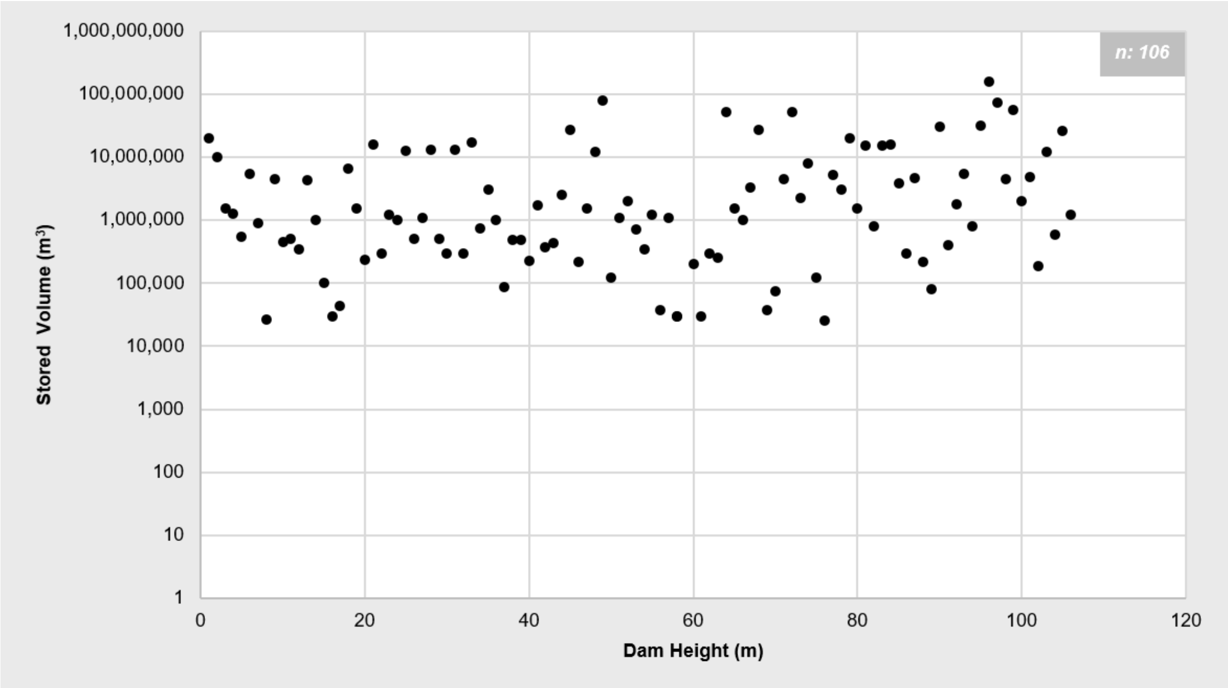


Figure A.14: Dam Height versus Stored Volume

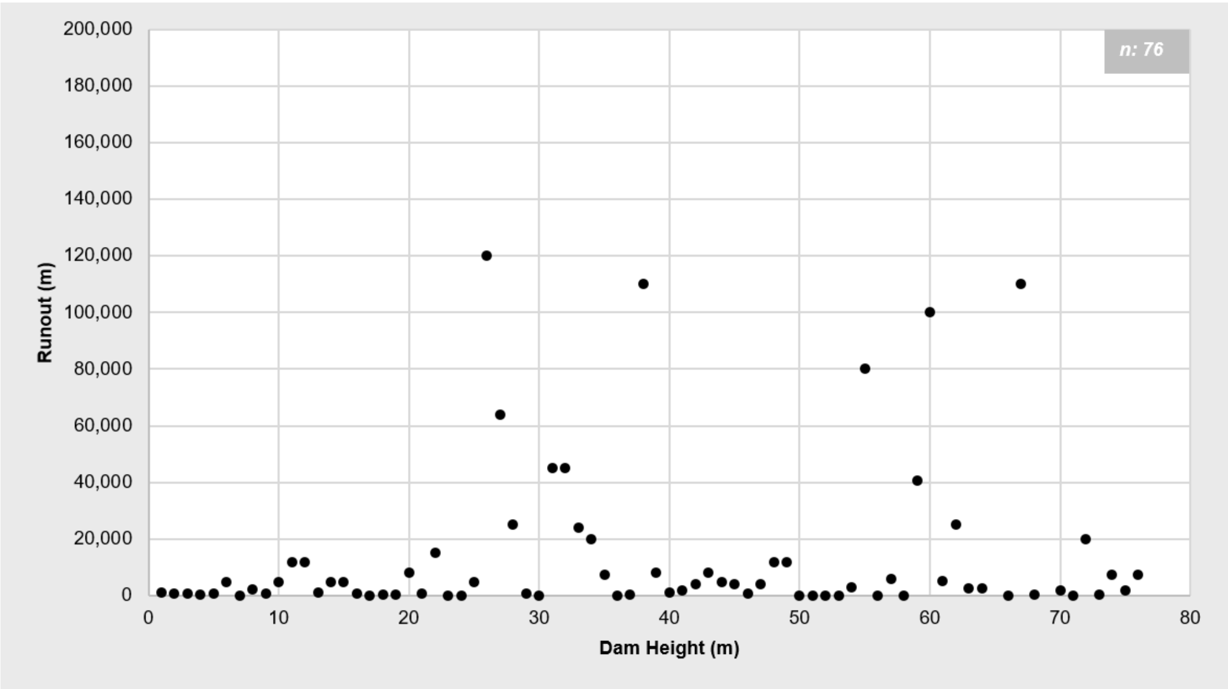


Figure A.15: Dam Height versus Runout

B

The Tool

The factors influencing the PoF are outlined in Appendix B.1 **(**Page 186**), covering site conditions, design elements, and LoP.** Appendix B.3 **(**Page 212**) details the corresponding inputs and options, categorised by site conditions, design elements, and LoP as well. It also highlights dependencies between inputs.** Appendix B.4 **(**Page 218**) features maps that can aid in determining inputs. The weight of inputs for each failure category and dam construction method is presented in** Appendix B.2 **(**Page 198**), again categorised by site conditions, design elements, and LoP.**

B.1. Contributing Factors

The factors incorporated into the tool are delineated below, categorised into site conditions, design elements, and LoP. Each factor is assigned a level of prevalence relative to different failure categories. These indications are rough estimates and serve as guidance for the weight determination using the AHP method. The resulting contribution to the total PoF for each dam construction method is also indicated. Moreover, there are 64 potential alternative factors for the LoP presented.

Site Conditions

Table B.1: Description of Contributing Site Factors, Including Indication of Relative Prevalence for Each Failure Category and Contribution to Total Probability of Failure (PoF) *(H: High, M: Medium, L: Low, -: Not, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention) – Colour Scale: Highest Contribution (Red) - Lowest Contribution (Green)*

		Prevalence Indication								Contribution to PoF			
ID	**Factor Description**	**EQ**	**OT**	**SI**	**FN**	**SE**	**ER**	**ST**	**MS**	**US**	**DS**	**CL**	**WR**
1.1	The TSF is located in a **seismically active region** where large-magnitude earthquakes can potentially generate strong ground motions.	H	-	-	-	-	-	-	-	7.62%	5.93%	1.48%	0.63%
1.2	Ground motions can potentially be induced by the **presence of (active) faults** that either cross the embankment or TSF or exist in close proximity.	M	-	-	-	-	-	-	-	1.99%	1.55%	0.39%	0.16%
1.3	Potential significant water inflow at the site due to the **catchment area** of the TSF being considerably larger than the TSF footprint.	-	H	M	-	-	L	L	-	1.22%	0.79%	1.17%	1.05%
1.4	The occurrence of **atmospheric rivers** or **intense rainfall events** at the site can create significant water inflow and has the potential to result in the rapid rise of the pond water level, the development of a high hydraulic gradient, and/or saturation of materials, but may also trigger landslides.	-	H	M	-	L	H	L	-	2.38%	1.78%	2.94%	2.52%
1.5	The site is prone to **rain-on-snow events**, potentially resulting in a rapid rise of pond water level, an enhanced runoff, elevated pore water pressures and slumping or sliding.	-	H	L	-	L	L	M	-	1.56%	1.09%	1.64%	1.48%
1.6	The potential for **significant snowmelt** at the site exists, which can lead to the rapid rise of the pond water level, the development of a high hydraulic gradient, and/or saturation of materials.	-	H	M	-	L	M	M	-	0.70%	0.58%	0.67%	0.73%
1.7	The site is susceptible to **thawing of permafrost**, which can result in a loss of stability or significant settlement of the foundation, as well as changes in pore water pressures that can alter the drainage patterns.	-	-	-	H	M	-	-	-	0.25%	0.53%	1.10%	0.98%
1.8	The TSF is prone to the potential occurrence of **hurricanes, cyclones, and typhoons** (or **tsunamis**), with destructive nature of strong winds and intense rainfall.	-	H	M	-	L	H	L	-	0.87%	0.72%	0.92%	0.90%
1.9	The site is prone to the **generation of high waves** in the ponded water due to extreme winds, which may lead to overtopping and erosion.	-	M	-	-	-	H	-	-	0.23%	0.31%	0.44%	0.44%
1.1	The site is prone to **adjacent landslides** that have the potential to cause significant damage to the slopes of the site, or may cause wave generation in the ponded water.	-	M	L	-	-	L	-	-	0.51%	0.28%	0.37%	0.36%
1.11	The location of the site and the project constraints imposes limitations on the minimum **embankment height,** e.g. the topography and the volume of production of tailings require to construct higher embankments, whereas for example open, flat terrain without infrastructure limitations allows for the use of lower embankments for tailings storage.	-	-	M	H	L	L	L	-	1.52%	0.85%	1.23%	1.08%
1.12	The location prevents building a **stable permanent spillway**, risking flood control and erosion. **Unstable walls** could lead to collapse and dysfunction. Without an **emergency spillway**, there's no backup plan.	-	M	-	-	-	H	-	-	0.20%	0.21%	0.28%	0.21%
1.13	The site is prone to **material** or **debris**, **vegetation**, as well as **ice damming** which could potentially block spillway or drainage structures.	-	H	M	L	M	-	M	-	2.23%	1.38%	1.57%	1.66%
1.14	**Artesian pressures** are likely to be present at the site, which may potentially create significant pore water pressures and increase in hydraulic gradients.	-	-	L	M	M	-	-	-	0.50%	0.56%	0.74%	0.86%
1.15	The **foundation** underlying the TSF is characterised by **strain-softening** or **contractive material,** which may cause the foundation to be unable to support the embankment's weight, resulting in instability, significant settlement, or liquefaction.	H	-	-	H	-	-	-	-	3.56%	2.91%	1.69%	0.90%
1.16	The **foundation** underlying the TSF potentially contains **collapsible or dispersive material** such as karst or salt domes, which may result in significant seepage, internal erosion, and eventual collapse of the embankment foundation.	-	-	-	H	H	-	-	-	0.32%	0.69%	1.14%	1.19%
1.17	The **foundation** underlying the dam potentially contains compressible material such as peat, which is unable to sustain the forces acting on the foundation, which may lead to significant settlement or sliding.	-	M	-	H	-	-	-	-	1.08%	0.87%	2.43%	1.61%
1.18	There is a **weakness plane** present between two adjacent material units in the natural foundation, which may reduce the structural stability and bearing capacity.	-	-	-	H	-	-	-	-	0.13%	0.24%	1.02%	0.61%
1.19	The foundation material is potentially **geochemically incompatible**, posing change in performance, which may result in strength loss or clogging of drains.	-	L	-	M	L	-	L	-	0.22%	0.29%	0.50%	0.42%

1.20.a	A high **permeability** may result in an increased potential for excessive seepage and internal erosion and may reduce the foundation strength.	-	-	-	M	H	-	-	-	0.21%	0.49%	0.28%	0.67%
1.20.b	A low **permeability** may result in the generation of excess pore pressure upon surface loading.	L	-	-	M	-	-	-	-	0.81%	0.64%	0.21%	0.10%
1.21	The foundation underlying the TSF is **non-uniform** with different characteristics for strength and permeability. The non-uniformity may lead to structural instability, unexpected seepage, unexpected erosion and/or differential settlement.	-	L	-	H	L	-	-	-	0.23%	0.32%	0.61%	0.55%
1.22	**Gap-graded soils** are present in the natural soil foundation, which may give rise to internal erosion.	-	-	-	-	H	-	-	-	0.19%	0.45%	0.11%	0.58%
1.23	**Culverts, and pipes** are present in the foundation, which have the potential to weaken the foundation, induce differential settlement, and result in concentrated leaks.	-	-	-	M	H	-	H	-	0.42%	0.88%	1.03%	1.12%
1.24	Significant **cracks** are present in the foundation, which have the potential to weaken the foundation, and may result in an increased permeability and increasing risk of internal erosion.	-	-	-	M	H	-	-	-	0.24%	0.54%	0.51%	0.81%
1.25	There is a **boundary** in the foundation between two units with a significant difference in **grain size**, coupled with potential **water flow** along the boundary, which may potentially lead to contact erosion.	-	-	-	-	H	-	-	-	0.19%	0.45%	0.11%	0.58%
1.26	The **available materials** for the dam **core**, **filters**, and **shell** of the TSF are potentially **internally instable**, posing risks filters not meeting filter compatibility, which may lead to internal erosion, deformation, settlement that can compromise the overall stability of the dam.	-	-	L	-	H	L	-	-	1.09%	0.92%	0.33%	1.06%
1.27	The **available materials** for the dam **core**, **filters**, and **shell** of the TSF are potentially **geochemically incompatible**, posing change in performance, which may result in strength loss or the clogging of drains (with as result an increased phreatic surface).	-	-	H	-	L	-	-	-	0.72%	0.67%	0.19%	0.78%
1.28	The **available materials** for the dam **shell** have a **low erosional resistance** and are susceptible to erosion by water flow, wave action, or wind.	-	H	M	-	-	H	-	-	0.54%	0.52%	0.55%	0.67%
1.29	The site had **previous disturbances** and land uses which likely included **excavations** and **fills** that have not been characterised and documented.	-	-	-	M	L	L	-	M	0.05%	0.14%	0.29%	0.25%
1.30.a	The presence of **underground mine workings** directly below or adjacent to the tailings impoundment poses a risk of seepage and potential collapse and surface subsidence.	-	-	-	-	-	-	-	H	0.30%	2.17%	3.26%	1.39%
1.30.b	The use of **unsupported mining methods**, such as longwall mining, sublevel caving, block caving, increases the risk of collapse and surface subsidence.	-	-	-	-	-	-	-	L	0.09%	0.66%	0.99%	0.42%
1.30.c	The presence of **weak host rock** increases the likelihood of subsidence.	-	-	-	-	-	-	-	M	0.09%	0.66%	0.99%	0.42%
1.30.d	**Selective extraction** practices at the underground mine can possibly result in differential settlement.	-	-	-	-	-	-	-	L	0.09%	0.66%	0.99%	0.42%
1.30.e	**Dewatering operations** at the mine, potentially cause suction forces and/or high difference in phreatic pressures.	-	-	-	-	-	-	-	L	0.03%	0.24%	0.36%	0.15%
1.30.f	The presence of **significant vibrations** from mining and blasting activities from the underground mine, which may cause instabilities.	-	-	-	-	-	-	-	M	0.05%	0.38%	0.57%	0.24%
1.31	The presence of **significant loads and/or vibrations** from workings on the dam crest or nearby construction works, open pit mining, or vibrations generated by machinery or vehicles on a nearby road may cause instability.	-	-	M	L	-	-	-	-	1.41%	0.60%	0.38%	0.64%
									Total	*34.84 %*	*32.93 %*	*33.47 %*	*28.65 %*

Design Elements

Table B.2: Description of Contributing Design Factors, Including Indication of Relative Prevalence for Each Failure Category and Contribution to Total Probability of Failure (PoF) *(H: High, M: Medium, L: Low, -: Not, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention) – Colour Scale: Highest Contribution (Red) - Lowest Contribution (Green)*

		Prevalence Indication								Contribution to PoF			
ID	**Factor Description**	**EQ**	**OT**	**SI**	**FN**	**SE**	**ER**	**ST**	**MS**	**US**	**DS**	**CL**	**WR**
2.1	By considering the specific characteristics of the **natural seismicity** at the site during the **design** phase, tailings dams can be engineered with heightened structural resilience, reducing the vulnerability to potential seismic hazards.	H	-	-	-	-	-	-	-	1.67%	1.30%	0.33%	0.14%

2.2	Incorporating **active faults** into the **design** enables engineers to account for the geological complexities associated with fault activity and develop robust engineering solutions. (If Faults)	M	-	-	-	-	-	-	-	0.27%	0.21%	0.05%	0.02%
2.3.a	The consideration of **water balance** in the design of tailings dams is essential. By carefully evaluating and integrating the water balance parameters, such as inflows, outflows, precipitation, evaporation, and seepage, engineers can ensure the effective management of water within the dam system, minimizing the risk of overtopping, structural instability, and contamination of surrounding ecosystems.	L	H	M	-	L	M	M	-	0.75%	0.71%	1.02%	0.88%
2.3.b	The integration of the **catchment area** into the water balance design of tailings dams is crucial engineers can effectively evaluate the inflow and outflow components of the water balance, including rainfall, runoff, and evapotranspiration. (If Incorporation Water Balance)	-	H	M	-	-	L	L	-	0.20%	0.19%	0.31%	0.26%
2.3.c	The consideration of the **Maximum Probable Flood (MPF)** in the **water balance**, including atmospheric river and intense rainfall events enables engineers to account for potential high-water volumes during extreme weather conditions. (If Incorporation Water Balance)	-	H	M	-	L	H	L	-	0.39%	0.38%	0.60%	0.52%
2.3.d	The consideration of **rain-on-snow events** in the **water balance** design allows engineers to manage increased loads. (If Incorporation Water Balance)	-	H	L	-	L	L	M	-	0.21%	0.20%	0.32%	0.27%
2.3.e	Accounting for **significant snowmelt** in the **water balance** design is essential as it allows engineers to manage increased water inflows resulting from rapid snowmelt. (If Incorporation Water Balance)	-	H	M	-	L	M	M	-	0.21%	0.20%	0.32%	0.27%
2.4.a	The **construction** of an (emergency) **spillway** with stable walls, provides an outlet for excess water during high-flow events.	-	M	-	-	-	-	M	-	0.77%	0.70%	1.12%	0.83%
2.4.b	By **designing** tailings dams without **relying** on an **emergency spillway** engineers prioritize the design of the main dam structure to ensure it has sufficient capacity and resilience to handle anticipated water inflows.	-	M	-	-	-	-	M	-	0.38%	0.35%	0.56%	0.41%
2.5	The consideration of **hurricanes**, **cyclones**, and **typhoons** (and **tsunamis**) in the **design** of tailings dams is crucial as engineers can develop structures that can withstand the associated high winds, intense rainfall, storm surges, and other related hazards. (If Credible Event)	-	M	M	-	-	H	-	-	0.39%	0.59%	0.71%	0.80%
2.6	By the consideration of **wind-generated wave** scenarios in the **design** engineers can assess the potential impact of wind-generated waves on the dam structure, determine the required freeboard height to account for wave run-up, and implement erosion control measures to protect the dam slopes and prevent soil erosion.	-	L	-	-	-	M	-	-	0.34%	0.56%	0.70%	0.78%
2.7	The consideration of adjacent **landslide-generated wave** scenarios in the **design** engineers can assess the potential wave heights and forces generated by nearby landslides and eventual choose to reinforce instable slopes. (If Credible Event)	-	L	L	-	-	-	-	-	0.34%	0.21%	0.43%	0.32%
2.8	The consideration of **permafrost** in the **design** engineers can assess the thermal regime, ground stability, and potential thawing effects on the dam foundation, allowing for the implementation of appropriate measures. (If Credible Condition)	-	-	-	H	L	-	-	-	0.21%	0.40%	1.49%	0.93%
2.9	Ensuring **compliance** with industry standards of practice for drained and undrained **factors of safety** under both **static** and **dynamic loads** for potential failure surfaces through the **foundation** is crucial in the design. Engineers can evaluate the stability of the dam foundation and assess the adequacy of the factors of safety to withstand various loading conditions.	-	-	-	H	-	-	-	-	0.18%	0.33%	1.48%	0.84%
2.1	The specific **material properties** are considered in the **design** of the **foundation**. engineers can accurately assess the behaviour and characteristics of the foundation materials. Allowing for the selection of appropriate foundation design techniques, reinforcement methods and construction considerations.	-	-	-	H	-	-	-	-	0.18%	0.33%	1.48%	0.84%
2.11	The **foundation design** accounts for **time-dependent, deformation-dependent and stress-path dependent processes** that may affect **material properties**. This allows engineers to take account for the potential changes in material behaviour over time, under different deformation conditions and along different stress paths. (If Material Properties of Foundation Considered)	-	-	-	H	-	-	-	-	0.18%	0.33%	1.48%	0.84%
2.12	The **foundation design** is considered throughout the **project lifecycle**, so engineers can ensure the integrity and safety of the dam structure from initial construction to subsequent raises.	-	-	-	M	-	-	-	-	0.18%	0.33%	1.48%	0.84%
2.13	Insufficient **compaction** of the **foundation** can lead to settlement, seepage, slope instability, and an increased susceptibility to liquefaction.	L	L	L	M	M	-	-	-	0.87%	0.82%	1.42%	1.10%
2.14	Ensuring **compliance** with industry standards of practice for drained and undrained **factors of safety** under both **static** and **dynamic loads** for potential failure surfaces through the **embankment** is crucial in the design. Engineers can accurately assess the stability of the embankment under the different loading conduits.	-	-	H	-	-	-	-	-	0.69%	0.28%	0.10%	0.27%
2.15	The specific **material properties** are considered in the **design** of the **embankment**. engineers can accurately assess the behaviour and characteristics of the foundation materials. Allowing for the selection of appropriate embankment design techniques, reinforcement methods and construction considerations.	-	-	H	-	-	-	-	-	0.69%	0.28%	0.10%	0.27%
2.16	The **embankment design** accounts for **time-dependent, deformation-dependent and stress-path dependent processes** that may affect **material properties**. This allows engineers to take account for the potential changes in material behaviour over time, under different deformation conditions and along different stress paths. (If Material Properties of Embankment Considered)	-	-	H	-	-	-	-	-	0.69%	0.28%	0.10%	0.27%

2.17	The **embankment design** is considered throughout the **project lifecycle**, so engineers can ensure the integrity and safety of the dam structure from initial construction to subsequent raises.	-	-	M	-	-	-	-	-	0.69%	0.28%	0.10%	0.27%
2.18	Insufficient **compaction** of the **embankment** can lead to settlement, seepage, slope instability, and an increased susceptibility to liquefaction.	-	L	M	-	M	L	-	-	0.80%	0.60%	0.58%	0.77%
2.19.a	The **excavation** of **tailings** may lead to slope instability, foundation discrepancies, but may also lead to an increase change of contamination and leaching.	-	-	H	M	L	-	-	-	0.05%	0.05%	0.08%	0.08%
2.19.b	The **excavation** of **tailings** is considered in the **design** and engineers address the potential impact of the excavation operations on the slope stability, foundation, and leaching.	-	-	H	M	L	-	-	-	0.05%	0.05%	0.08%	0.08%
2.2	The **rapid drawdown downstream** introduces a range of challenges, encompassing the generation of suction forces, heightened vulnerability to liquefaction, and escalated sediment transport and deposition.	L	-	L	L	M	-	-	-	0.12%	0.09%	0.06%	0.05%
2.21.a	The **absence** of a **tailings beach** may introduce hydraulic concerns as a tailings beach can serves as a natural buffer to prevent seepage and wave erosion.	L	L	M	-	M	M	-	-	0.98%	0.81%	1.10%	1.11%
2.21.b	Wide zones of **beaches** in tailings dams are not adequately compacted to a dilative state and are not free of contractive tailings, which may result in settlement and instability, uncontrolled seepage, liquefaction and slope erosion and material loss.	L	L	M	-	M	M	-	-	0.60%	0.48%	0.57%	0.56%
2.22	The **rate of raising** the dam is not sufficiently slow, hindering the dissipation of excess pore pressures and consolidation process within the supporting zone.	-	-	H	L	L	L	-	-	0.83%	0.59%	1.05%	0.91%
2.23	**Structural elements** are designed to **accommodate tailings** and **embankment** consolidation, deformation, and ice loads, preventing structural integrity, for example, upon differential settlement.	-	-	L	-	M	-	H	-	0.91%	1.49%	1.05%	1.04%
2.24	There is no **filter underdrainage system** incorporated at the basal level in the tailings dam, which may result in seepage problems, insufficient pore pressure dissipation, material saturation and internal erosion.	L	L	M	L	H	-	-	-	1.04%	0.98%	1.49%	1.34%
2.25	The **drainage capacity** is insufficient throughout lifecycle. This may result in significant pore pressure built up and saturation of material and consolidation delays.	L	L	M	M	H	-	-	-	1.24%	1.11%	1.34%	1.24%
2.26	The **blockage** of a **drainage system** in a tailings dam, caused by factors such as sediment, vegetation, or ice, can give rise to several complications, including pore pressure built up, material saturation and consolidation delays, but also damaging forces on infrastructure.	L	L	H	M	M	-	-	-	1.25%	1.11%	1.23%	1.18%
2.27	When the **materials** used in a drainage system do not meet **filter compatibility** requirements, this may result in clogging, reduced permeability, erosion and piping.	L	L	M	M	M	-	-	-	0.94%	0.86%	1.17%	1.15%
2.28	The **drainage system** is **designed** to accommodate settlement during dam construction and deformation under seismic loads, preventing potentially impeded drainage, pore pressure built up and ensuring structural integrity.	-	-	-	-	L	-	-	-	0.04%	0.11%	0.03%	0.14%
2.29.a	The presence of a tailings pond may could impact the embankment, especially when directly against the embankment.	-	-	M	-	M	-	-	-	0.30%	0.20%	0.06%	0.20%
2.29.b	The **pond** is (temporarily) in **contact with** the upstream **dam** face, which may result in e.g. significant seepage, material saturation.	-	-	M	-	M	-	-	-	0.25%	0.18%	0.06%	0.20%
2.3	The designed **embankment slopes** of a dam are **steep** and approach or exceed the natural angle of repose, increasing the change of slope instability and erosion.	-	-	H	-	-	H	-	-	0.71%	0.42%	0.21%	0.45%
2.31	The **embankments** are of **significant height**, which may increase the slope instability, high foundation stresses and elevated pore pressures.	L	-	M	H	L	-	-	-	1.80%	1.37%	1.77%	1.24%
2.32	There are **high flowrate pipelines** on the dams, without having secondary containment, may result in significant erosion due to the potential turbulent flow, hydraulic jump, and jetting effects.	-	-	-	-	-	H	-	-	0.03%	0.24%	0.18%	0.31%
2.33	The dam **design** considers the **artesian pressures**, allowing engineers to assess the impact of the artesian conditions on the stability and implement appropriate measures. (If Pressures are Credible)	-	-	L	M	M	-	-	-	0.29%	0.36%	0.93%	0.69%
2.34	The **embankment** is characterised by **strain-softening** or **contractive material**, which may cause the foundation to be unable to support the embankment's weight, resulting in instability, significant settlement, or liquefaction.	-	-	H	-	L	-	-	-	0.45%	0.22%	0.08%	0.22%
2.35	The **embankment** potentially contains **collapsible or dispersive material** such as karst or salt domes, which may result in significant seepage, internal erosion, and eventual collapse of the embankment foundation.	-	-	H	-	M	-	-	-	0.51%	0.36%	0.11%	0.40%
2.36	The **embankment** potentially contains compressible material such as peat, which is unable to sustain the forces acting on the foundation, which may lead to significant settlement or sliding.	-	-	H	-	-	-	-	-	0.43%	0.18%	0.07%	0.17%
2.37	There is a **weakness plane** present between two adjacent material units in the dam face, which may reduce the structural stability and bearing capacity.	-	-	H	-	-	-	-	-	0.43%	0.18%	0.07%	0.17%
2.38	The **tailings** are **susceptible** to **liquefaction**, allowing the tailings to liquefy upon credible earthquakes and anthropogenic vibrations. It, for example, consists of low-density, loose, contractive material that is uniformly graded, has a high silt content, and exhibits low permeability. Regular slurry deposited tailings often exhibit these characteristics, while, for example, paste fill tailings have a higher liquefaction resistance.	H	-	M	-	-	-	-	-	1.38%	0.89%	0.24%	0.23%
2.39.a	A fairly **high permeability** may result in an increased potential for excessive seepage and internal erosion and may reduce the foundation strength.	-	-	M	-	H	-	-	-	0.09%	0.11%	0.03%	0.14%
2.39.b	A fairly **low permeability** may result in the generation of excess pore pressure upon surface loading.	-	-	M	-	H	-	-	-	0.09%	0.11%	0.03%	0.14%

2.4	The **embankments** are constructed of **non-uniform** materials with different characteristics for strength and permeability. The uniformity may lead to structural instability, unexpected seepage, unexpected erosion and/or differential settlement.	-	-	M	-	M	-	-	-	0.24%	0.19%	0.06%	0.21%
2.41	**Gap-graded soils** are present in the embankment, which may give rise to internal erosion.	-	-	-	-	H	-	-	-	0.13%	0.30%	0.08%	0.39%
2.42	**Culverts, and pipes** are present in the embankment, which have the potential to weaken the foundation, induce differential settlement, and result in concentrated leaks.	-	-	M	-	-	-	-	-	0.30%	0.12%	0.05%	0.12%
2.43	Significant **cracks** are present in the embankment, which have the potential to weaken the foundation, and may result in an increased permeability and increasing risk of internal erosion.	-	-	-	M	H	-	-	-	0.14%	0.30%	0.61%	0.55%
2.44	There is a **boundary** in the embankment between two units with a significant difference in **grain size**, coupled with potential **water flow** along the boundary, which may potentially lead to contact erosion.	-	-	-	-	H	-	-	-	0.13%	0.30%	0.08%	0.39%
2.45	The **materials** used for the dam **core**, **filters**, and **shell** of the TSF are potentially **internally instable**, posing risks of internal erosion.	-	-	H	-	-	H	-	-	0.21%	0.14%	0.08%	0.16%
2.46	The **available materials** for the dam **core**, **filters**, and **shell** of the TSF are potentially **geochemically incompatible**, posing risks of chemical reactions and potential leaching of harmful substances when in contact with the tailings.	-	-	H	-	M	-	-	-	0.27%	0.26%	0.07%	0.30%
2.47	The **materials** of the dam **shell** are susceptible to **external erosion** by water flow, wave action, or wind.	-	-	-	-	-	H	-	-	0.05%	0.38%	0.28%	0.48%
2.48.a	The potential seepage or collapse by underground mine workings is considered in the design, allowing for assessment of the potential impact. (If Underground Mine Workings)	-	-	-	-	-	-	-	H	0.05%	0.36%	0.54%	0.23%
2.48.b	The use of **unsupported mining methods**, such as longwall mining, sublevel caving, block caving, are considered in the design, allowing for assessment of the potential impact. (If Underground Mine Workings)	-	-	-	-	-	-	-	L	0.02%	0.11%	0.16%	0.07%
2.48.c	The presence of **weak host rock** is considered in the design, allowing for assessment of the potential impact. (If Underground Mine Workings)	-	-	-	-	-	-	-	M	0.02%	0.11%	0.16%	0.07%
2.48.d	**Selective extraction** practices at the underground mine are considered in the design, allowing for assessment of the potential impact. (If Underground Mine Workings)	-	-	-	-	-	-	-	L	0.02%	0.11%	0.16%	0.07%
2.48.e	**Dewatering operations** at the mine are considered in the design, allowing for assessment of potential impact. (If Underground Mine Workings)	-	-	-	-	-	-	-	L	0.01%	0.04%	0.06%	0.03%
2.48.f	The vibrations from active underground mining activities are considered in the design.	-	-	-	-	-	-	-	M	0.01%	0.06%	0.09%	0.04%
2.49	**Anthropogenic vibrations** (e.g. from nearby open pit mining and blasting, construction works, machinery or vehicles) are considered in the **design**, allowing engineers to evaluate their potential effects on the dam and implement appropriate measures.	-	-	M	L	-	-	-	-	0.30%	0.16%	0.23%	0.21%
2.5	The **previous disturbances** (e.g. excavations) at the site are considered in the design.	-	-	-	M	L	L	-	M	0.09%	0.21%	0.61%	0.43%
2.51	There are measures in place for **monitoring pore water pressures** within the **foundation**. The results confirm the design assumptions and are within the design standards.	M	-	-	H	M	-	-	-	0.96%	1.29%	1.91%	1.38%
2.52	There are measures in place for **monitoring pore water pressures** within the **embankment**. The results confirm the design assumptions and are within the design standards.	M	-	H	-	M	-	-	-	1.40%	0.95%	0.27%	0.55%
2.53	There are measures in place for **monitoring deformations** within the **foundation**. The results confirm the design assumptions and are within the design standards.	M	-	-	H	L	L	M	M	1.17%	1.87%	2.32%	1.94%
2.54	There are measures in place for **monitoring deformations** within the **embankment**. The results confirm the design assumptions and are within the design standards.	M	-	H	-	L	L	M	M	1.62%	1.70%	0.92%	1.21%
								Total		*33.19 %*	*31.34 %*	*38.1 %*	*34.98 %*

Level of Practise (LoP)

Table B.3: Description of Contributing Level of Practise (LoP) Factors, Including Indication of Relative Prevalence for Each Failure Category and Contribution to Total Probability of Failure (PoF) *(H: High, M: Medium, L: Low, -: Not, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention) – Colour Scale: Highest Contribution (Red) - Lowest Contribution (Green)*

		Prevalence Indication								Contribution to PoF			
ID	**Factor Description**	**EQ**	**OT**	**SI**	**FN**	**SE**	**ER**	**ST**	**MS**	**US**	**DS**	**CL**	**WR**
3.1.1.a	**Evaluate uncertainties associated with climate change that may impact upon the safety of the tailings facility (see also GISTM requirement 3.1).**	L	H	M	L	M	H	L	L	1.13%	1.47%	1.47%	1.75%
3.1.1.b	Operator **updates** the above information at least at five-year intervals, and whenever there is a material change to the tailings facility or related **environmental**, **social** or economic **context**.	L	H	M	L	M	H	L	L	0.76%	0.83%	0.86%	0.89%
3.1.2.a	A detailed **site characterisation** of the tailings facility site(s) **exists** and it **is updated** as warranted throughout the lifecycle to reflect material changes in conditions and new knowledge.	H	H	M	H	M	M	L	L	0.76%	0.92%	0.76%	0.84%

3.1.2.b	**Site characterisation** is **supported by data** including site-specific climate, geomorphology, geology, geochemistry, hydrology, and hydrogeology (surface and groundwater flow and quality), geotechnical, and seismicity	H	H	M	H	M	M	L	L	0.84%	0.99%	0.92%	0.95%
3.1.2.c	**Tailings characterisation exists**, considering the physical and geochemical properties, and it is updated throughout the lifecycle to account for variability in ore properties, processing, and tailings deposition.	M	L	M	L	H	L	M	L	0.44%	0.30%	0.25%	0.26%
3.2.1	To enhance resilience, **climate change** knowledge is regularly updated and used to evaluate risks and opportunities to the tailings facility lifecycle, in accordance with the principles of adaptive management, with the aim of enhancing resiliency to climate change.	L	H	M	L	M	H	L	L	0.73%	0.82%	0.91%	1.01%
3.2.2	For existing facilities that are not in a state of safe closure, there are **periodic reviews** of the **tailings technologies**, **design** and **management** strategies, and assessments of the potential to implement improvements arising from the reviews.	M	M	M	M	M	M	M	M	0.78%	0.89%	0.65%	0.74%
3.3.1.a	**Extreme** loads are already in place.	H	M	H	H	H	M	M	M	0.16%	0.13%	0.10%	0.14%
3.3.1.b	If Extreme Consequence Classification external loading criteria are not adopted, the **Accountable Executive** shall take the **decision** to **adopt** a **design** for the current Consequence Classification criteria and maintain flexibility to upgrade the design for the highest classification criteria later in the tailings facility lifecycle.	H	M	H	H	H	M	M	M	0.17%	0.14%	0.11%	0.14%
3.3.2.a	**Select** and **identify design criteria** that are appropriate to **minimise risk** for all credible failure modes during each phase of the tailings facility lifecycle	H	H	H	H	H	H	H	H	1.22%	1.00%	0.77%	1.03%
3.3.2.b	**Document** the **rationale** for the design criteria selected to minimise risk.	H	H	H	H	H	H	H	H	0.41%	0.33%	0.26%	0.34%
3.3.3.a	**Develop** and **apply design criteria** such as factors of safety for slope stability and seepage management, for each lifecycle phase that considers: the estimated operational properties of materials and expected performance of the design elements, and; the quality of the implementation of the risk management systems.	H	M	H	H	M	M	L	M	0.36%	0.30%	0.23%	0.30%
3.3.3.b	**Account for** these **design** and **implementation issues** in assessments that are based on deformation analyses.	H	M	H	H	M	M	L	M	0.36%	0.30%	0.23%	0.30%
3.3.4.a	An **assessment** of the **potential** for **brittle failure modes** is **documented** and the analyses are addressed in the Design Basis Report (DBR).	M	M	H	H	M	H	M	M	0.30%	0.24%	0.19%	0.25%
3.3.5.a	Existing tailings facilities shall **conform** with the **Requirements** under Principle 4, **except** for those **aspects** where the Engineer of Record (EOR), with review by the ITRB or a senior independent technical reviewer, as appropriate, determines **that** the **upgrade** of an existing tailings facility is **not required, or viable, or cannot be retroactively applied**.	H	H	H	H	H	H	H	H	0.13%	0.10%	0.08%	0.11%
3.3.5.b	If the condition in (a.) above applies, the Accountable Executive shall **approve** and **document** the implementation of measures to reduce both the probability and the consequences of a tailings facility failure to reduce the risk to a level **as low as reasonably practicable (ALARP)**.	H	H	H	H	H	H	H	H	0.13%	0.10%	0.08%	0.11%
3.3.5.c	The basis and timing for addressing the **upgrade** of existing tailings facilities shall be **risk-informed** and **carried out as soon as reasonably practicable.**	H	H	H	H	H	H	H	H	0.38%	0.31%	0.24%	0.32%
3.3.6.a	The EOR shall prepare a **Design Basis Report (DBR)** that details the **design assumptions** and **criteria**, including operating constraints, and that provides the basis for the design of all phases of the tailings facility lifecycle.	M	M	M	M	M	M	M	M	0.34%	0.28%	0.21%	0.29%
3.3.6.b	The DBR shall be **reviewed** by the ITRB or senior independent technical reviewer.	M	M	M	M	M	M	M	M	0.34%	0.28%	0.21%	0.29%
3.3.6.c	The EOR shall **update** the DBR every time there is a **material change** in the design **assumptions**, **design criteria**, **design** or the **knowledge base** and confirm internal consistency among these elements.	M	M	M	M	M	M	M	M	0.34%	0.28%	0.21%	0.29%
3.4.1.a	For expansions to existing facilities, **assess** the **outcomes** of periodic **reviews** of potential refinements to tailings technologies and design approaches (as per Requirement 3.2).	M	M	M	M	M	M	M	M	0.10%	0.12%	0.09%	0.12%
3.4.1.b	Where the **design differs** from the **alternatives analysis**, there is a **rationale** that incorporates the goal of **minimising risks** to people and the environment throughout the tailings facility lifecycle.	M	M	M	M	M	M	M	M	0.10%	0.12%	0.09%	0.12%
3.4.2.a	A **robust design** that considers: The technical, social, environmental, and local economic context of the tailings facility. The Consequence Classification, site conditions, water management, mine plant operations, tailings operational and construction issues. The design demonstrates the feasibility of safe closure of the tailings facility.	H	M	H	H	H	H	H	L	0.33%	0.39%	0.29%	0.39%
3.4.2.b	The **design** is **reviewed** and updated as performance and site data become available throughout the tailings facility lifecycle and / or in response to material changes.	H	M	H	H	H	H	H	L	0.33%	0.39%	0.29%	0.39%
3.4.3.a	A **water management plan** that **takes into account** the **knowledge base**, the mine plan for the current state of the tailings facility lifecycle, upstream and downstream hydrological and hydrogeological basins, and the potential for climate change.	M	H	H	L	M	H	H	L	0.08%	0.10%	0.09%	0.10%
3.4.3.b	A **water balance model** that considers the **overall water management plan**.	M	H	H	L	M	H	H	L	0.08%	0.10%	0.09%	0.10%
3.4.3.c	The **water management plan** and water balance address the **safety** of the **tailings facility** and the prevention of unintentional releases.	M	H	H	L	M	H	H	L	0.08%	0.10%	0.09%	0.10%
3.4.4.a	**Potential failure modes** to the structure, its foundation, abutments, reservoir (tailings deposit and pond), Reservoir rim, and appurtenant structures are **identified**, **categorized** by risk assessments, and addressed through preventative measures incorporated into the design and/or through operational controls.	H	H	H	H	M	M	M	H	0.33%	0.39%	0.29%	0.39%

3.4.4.b	**Risk assessments** are used to **inform** the **design** to **minimise risk to ALARP**. Risk assessments should be used to determine whether the potential credible failure mode(s)/scenario are credible.	H	H	H	H	M	M	M	H	0.33%	0.39%	0.29%	0.39%
3.4.5	**Develop** a **design** for **each stage of construction** of the tailings facility, including but not limited to start-up, partial raises and interim configurations, final raise, and all closure stages.	H	H	M	M	M	M	M	L	0.38%	0.45%	0.34%	0.46%
3.4.6.a	The **closure design meets** all the **Requirements** of the Standard with sufficient detail to demonstrate the feasibility of the closure scenario.	H	H	H	H	H	H	H	H	0.12%	0.14%	0.11%	0.14%
3.4.6.b	The **closure design allows implementation** of elements of the closure design during construction and operation, as appropriate.	H	H	H	H	H	H	H	H	0.12%	0.14%	0.11%	0.14%
3.4.6.c	The **design** includes **progressive closure** and reclamation during operations.	H	H	H	H	H	H	H	H	0.12%	0.14%	0.11%	0.14%
3.4.7.a	Confirm that the **design satisfies ALARP**.	H	H	H	H	H	H	H	H	0.07%	0.08%	0.06%	0.08%
3.4.7.b	Seek to **identify** and **implement additional reasonable** steps that may be taken to further reduce potential consequences to people and the environment.	H	H	H	H	H	H	H	H	0.07%	0.08%	0.06%	0.08%
3.4.7.c	**Explain** and **document** the **decisions with respect to ALARP** and additional consequence reduction measures, in consultation with external parties as appropriate.	M	M	M	M	M	M	M	M	0.07%	0.08%	0.06%	0.08%
3.5.1.a	The **design intent**, established in the DBR, is **understood** and **implemented** for construction, operation and closure for each phase of the tailings facility lifecycle.	H	M	H	M	M	L	H	L	0.48%	0.41%	0.33%	0.43%
3.5.1.b	**Construction** and **operating** personnel **assigned** to tailings-related tasks are qualified based on the qualifications defined in the Tailings Management System (TMS).	L	L	M	M	M	L	H	L	0.16%	0.14%	0.11%	0.14%
3.5.1.c	Throughout **all stages** of the tailings facility lifecycle the **appropriate methodology, equipment and procedures**, data acquisition methods, are used and incorporated into the TMS and the Environmental and Social Management System (ESMS) for the mine and associated infrastructure.	L	L	M	M	M	L	H	L	0.48%	0.41%	0.33%	0.43%
3.5.1.d	The **TMS** and the **ESMS** are **implemented during construction, operation, and closure.**	L	L	M	M	M	L	H	L	0.16%	0.14%	0.11%	0.14%
3.5.2.a	**Quality Control** (QC) and **Quality Assurance** (QA) **programmes** are **established** to monitor the quality and adequacy of the construction and operation processes.	H	M	H	M	M	L	H	L	0.41%	0.27%	0.19%	0.28%
3.5.2.b	A **CDIV programme** that confirms that the design intent is met if site conditions vary from design assumptions.	H	M	H	M	M	L	H	L	0.41%	0.27%	0.19%	0.28%
3.5.3.a	**Construction Records Reports** (CRR) are **up to date** and are prepared when there is a material change to the tailings facility, its infrastructure, or its monitoring system.	M	L	M	M	M	L	H	L	0.36%	0.31%	0.24%	0.32%
3.5.3.b	The **CRRs** are **signed** by the **RTFE and the EOR.**	M	L	M	M	M	L	H	L	0.12%	0.10%	0.08%	0.11%
3.5.4.a	An **Operation, Maintenance and Surveillance** (OMS) Manual is **implemented**, covers each tailings facility and includes the requirements for the OMS activities necessary for the effective risk management based on best practice.	M	M	M	M	M	M	M	M	0.16%	0.14%	0.11%	0.14%
3.5.4.b	The **OMS** is **reviewed annually or more frequently** if there are any updates following a material change as defined by the Operator.	M	M	M	M	M	M	M	M	0.16%	0.14%	0.11%	0.14%
3.5.4.c	The **OMS provides clear context** and includes the inspection, maintenance and monitoring of the requirements identified including critical controls for safe operation and is reviewed for effectiveness.	M	M	M	M	M	M	M	M	0.05%	0.05%	0.04%	0.05%
3.5.4.d	The RTFE ensures that **personnel** involved in the TMS have **access** to the **OMS** Manual.	M	M	M	M	M	M	M	M	0.05%	0.05%	0.04%	0.05%
3.5.5.a	A **Change Management System** has been **established**.	M	L	M	M	M	L	H	L	0.05%	0.05%	0.04%	0.05%
3.5.5.b	The **Change Management System includes** processes for the **identification** of **changes** and **processes** for **evaluation**, **review**, **approval** and **documentation** of changes throughout the facility lifecycle.	M	L	M	M	M	L	H	L	0.06%	0.05%	0.04%	0.05%
3.5.5.c	The **Change Management System addresses** and documents **material changes** to design, construction, operations, or monitoring.	M	L	M	M	M	L	H	L	0.02%	0.02%	0.01%	0.02%
3.5.5.d	A **DAR** is **periodically prepared** and updated by the EOR that addresses the cumulative impact of material changes to the as-constructed facility.	M	L	M	M	M	L	H	L	0.02%	0.02%	0.01%	0.02%
3.5.5.e	**Recommendations** from the **DAR** have been **implemented** through updates to the construction, operations, design, DBR, OMS Manual and the monitoring programme.	H	H	H	H	H	H	H	H	0.06%	0.05%	0.04%	0.05%
3.5.5.f	The **Accountable Executive** has **approved** the **DAR**.	M	M	M	M	M	M	M	M	0.02%	0.02%	0.01%	0.02%
3.5.6.a	**Reviews** of **new** and **emerging technologies** and **approaches** for tailings management are carried out considering the tailings facility lifecycle.	H	H	H	H	H	H	H	H	0.02%	0.02%	0.01%	0.02%
3.5.6.b	Material **results** of the **reviews** have been **incorporated** into **refinements** of the facility design, construction and operations.	H	H	H	H	H	H	H	H	0.64%	0.55%	0.44%	0.57%
3.6.1.a	A **comprehensive** and **integrated performance monitoring programme** for the tailings facility and its appurtenant structures has been **developed**, and forms part of the TMS, and includes activities for inspection, reviews, and monitoring requirements in alignment with the facility OMS.	H	H	H	H	H	H	H	H	0.64%	0.55%	0.44%	0.57%
3.6.1.b	Aspects of the ESMS that are **linked** to tailings facility's **performance monitoring** are identified and included in the performance monitoring programme.	H	H	H	H	H	H	H	H	0.35%	0.42%	0.32%	0.42%
3.6.1.c	The **performance monitoring** programme is **integrated** and **reflects other programmes** such as the OMS and is updated in keeping with the principles of Adaptive Management.	H	H	H	H	H	H	H	H	0.12%	0.14%	0.11%	0.14%
3.6.2.a	A **comprehensive** and **integrated engineering monitoring system** has been **designed** and used to **verify design assumptions** and to monitor potential failure modes.	H	H	H	H	H	H	H	H	0.12%	0.14%	0.11%	0.14%

3.6.2.b	**Monitoring procedures** for non-brittle failure modes are **developed** and implemented to support the Observational Method.	M	H	H	H	H	H	H	M	1.04%	1.26%	0.96%	1.27%
3.6.2.c	**Brittle failure** modes are **addressed** by **conservative design criteria**.	M	M	H	H	M	H	M	M	0.35%	0.42%	0.32%	0.42%
3.6.3.a	**Performance objectives**, **indicators** and **criteria** are set that measure the performance of the tailings facility. These are specific and measurable and included in the monitoring programmes.	H	H	H	H	H	H	H	H	0.35%	0.42%	0.32%	0.42%
3.6.3.b	**Routine** and **regular inspecting**, **monitoring**, **testing**, **recording**, **evaluating** and **reporting** of the data from the monitoring programmes is conducted according to the established appropriate frequency.	H	H	H	H	H	H	H	H	0.58%	0.70%	0.53%	0.70%
3.6.3.c	The **monitoring programme** is **updated** throughout the tailings facility lifecycle based on the evaluation of the data to confirm that the performance objectives, indicators and criteria remain effective to manage risk.	H	H	H	H	H	H	H	H	0.58%	0.70%	0.53%	0.70%
3.6.4.a	The tailings facility **performance is assessed** by **analysing** technical **monitoring data** at a frequency established by the EOR.	H	H	H	H	H	H	H	H	0.58%	0.70%	0.53%	0.70%
3.6.4.b	The **analysis** of tailings facility technical monitoring data clearly **identifies** and presents **evidence** on **deviations** from the **expected** performance **objectives** and deterioration of the tailings facility performance over time.	H	H	H	H	H	H	H	H	0.22%	0.26%	0.20%	0.26%
3.6.4.c	The **results** from the tailings facility performance monitoring analysis are **promptly reported** to the EOR.	H	H	H	H	H	H	H	H	0.68%	0.83%	0.63%	0.83%
3.6.4.d	The EOR **promptly reviews** the tailings facility performance monitoring analysis **results** and **if required**, directs that the risk assessment and design be **updated**.	H	H	H	H	H	H	H	H	0.22%	0.26%	0.20%	0.26%
3.6.4.e	Performance expectations are incorporated into **Trigger Action Response Plans** or **critical controls** as criteria to state when action is or is not needed.	H	H	H	H	H	H	H	H	0.41%	0.49%	0.38%	0.50%
3.6.5.a	The **results** of the monitoring programmes are **reported** at a frequency that meets company expectations and regulatory requirements and at a minimum is completed annually.	M	M	M	M	M	M	M	M	0.22%	0.26%	0.20%	0.26%
3.6.5.b	Technical monitoring reports are **reviewed** and approved **by the RTFE and the EOR**.	M	M	M	M	M	M	M	M	0.29%	0.35%	0.27%	0.35%
3.7.1.a	A **documented** corporate tailings **management policy** that commits the Operator to the **safe management** of **tailings**, development of **emergency response plans**, and mechanisms for recovery after failure. This may be in the form of a standalone policy or embedded in a document that the Board of Directors adopts.	M	M	M	M	M	M	M	M	0.29%	0.35%	0.27%	0.35%
3.7.1.b	The **policy** and its endorsement by the Board of Directors is in writing and is **publicly available**.	L	L	L	L	L	L	L	L	0.06%	0.08%	0.06%	0.08%
3.7.2.a	A **performance based TMS** , follows established Plan-Do-Check-Act processes and is suitable for the organisation and its tailings facilities.	M	M	M	M	M	M	M	M	0.02%	0.03%	0.02%	0.03%
3.7.2.b	**Accountabilities**, **responsibilities** and **associated competencies** for the implementation of that framework are **defined** that supports appropriate identification and management of tailings facility risks.	M	M	M	M	M	M	M	M	0.02%	0.03%	0.02%	0.03%
3.7.2.c	The governance framework **supports** the **TMS**, its relevant critical systems and other related ESMS.	M	M	M	M	M	M	M	M	0.02%	0.03%	0.02%	0.03%
3.7.2.d	The **linkages** between the TMS and other systems such as the ESMS are **clear** to ensure effective integrated management of the tailings facility.	M	M	M	M	M	M	M	M	0.02%	0.03%	0.02%	0.03%
3.7.3.a	For persons with responsibility for tailings facilities, their **performance** reviews and or incentive payments are **based** in part, **on public safety and the integrity** of the tailings facilities.	L	L	L	L	L	L	L	L	0.02%	0.03%	0.02%	0.03%
3.7.3.b	Where **incentive payments** are used, they are based on the **degree** to **which public safety** and tailing facility integrity are a component of that role.	L	L	L	L	L	L	L	L	0.03%	0.03%	0.03%	0.03%
3.7.3.c	**Long-term incentives**, as part of executive compensation, **take tailings management, facility performance, and public safety into account**.	L	L	L	L	L	L	L	L	0.01%	0.01%	0.01%	0.01%
3.7.4.a	**Accountable Executive**(s) who is **directly answerable** to the **CEO** have been identified and assigned the safety aspects of a tailings facility and for avoiding or minimising the social and environmental consequences of a tailings facility failure.	M	M	M	M	M	M	M	M	0.02%	0.02%	0.01%	0.02%
3.7.4.b	The **accountability** referred to in (a) includes **developing** and **implementing** a **programme** of tailings management training, and for **emergency preparedness** and response.	M	M	M	M	M	M	M	M	0.05%	0.06%	0.04%	0.06%
3.7.4.c	The **Accountable Executive**(s) has **regular** and **scheduled communications** with the **EOR** and **Board of Directors** which can be initiated either by the Accountable Executive or the Board.	M	M	M	M	M	M	M	M	0.05%	0.06%	0.04%	0.06%
3.7.4.d	The process by which the **Board of Directors** holds the **Accountable Executive**(s) **responsible** is documented.	M	M	M	M	M	M	M	M	0.05%	0.06%	0.04%	0.06%
3.7.5.a	A **Responsible Tailings Facility Engineer** (RTFE) is appointed to the role.	M	M	M	M	M	M	M	M	0.02%	0.02%	0.01%	0.02%
3.7.5.b	**Roles** and **responsibilities** are **clearly defined** and documented for the RTFE position including accountability for the integrity of the tailings facility.	M	M	M	M	M	M	M	M	0.04%	0.05%	0.04%	0.05%
3.7.5.c	The **RTFE liaises** with the **EOR** and internal teams.	M	M	M	M	M	M	M	M	0.01%	0.02%	0.01%	0.02%
3.7.5.d	The RTFE must be **familiar** with the **DBR**, relevant design reports, and the construction and operations/performance of the tailings facility.	M	M	M	M	M	M	M	M	0.04%	0.05%	0.04%	0.05%
3.7.5.e	**Communication** occurs between the **RTFE** and the **Accountable Executive**, or designee.	M	M	M	M	M	M	M	M	0.01%	0.02%	0.01%	0.02%
3.7.6.a	**Qualification** and **experience requirements** for all **personnel** with **safety critical roles** are clearly defined and are appropriate to the level of responsibility for that position. This includes but is not limited to critical roles such as the RTFE, EOR and Accountable Executives.	M	M	M	M	M	M	M	M	0.04%	0.05%	0.04%	0.05%
3.7.6.b	**Succession plans** are **developed** for safety-critical roles.	M	M	M	M	M	M	M	M	0.14%	0.16%	0.13%	0.17%
3.7.7.a	For a tailings facility with a consequence classification of failure of 'Very High' to 'Extreme', the Operator has appointed an **Independent Tailings Review Board** (ITRB).	M	M	M	M	M	M	M	M	0.14%	0.16%	0.13%	0.17%

3.7.7.b	For a tailings facility with a consequence classification of **failure** of 'High' or lower, in the **absence** of an **ITRB**, the Operator has **appointed** a **senior independent technical reviewer**.	M	M	M	M	M	M	M	M	0.03%	0.04%	0.03%	0.04%
3.7.7.c	The **ITRB** or a **senior independent technical reviewer report to the Accountable Executive** for the tailings facility or delegate.	M	M	M	M	M	M	M	M	0.03%	0.04%	0.03%	0.04%
3.7.7.d	The **ITRB** or a **senior independent technical reviewer** is **appointed** during the early phase of tailings facility site investigation and design engineering (suggested pre-feasibility).	M	M	M	M	M	M	M	M	0.03%	0.04%	0.03%	0.04%
3.8.1.a	For all operating tailings facilities, and for closed facilities with consequence categories of 'High', 'Very High' and 'Extreme' an **engineering firm** which has the **design** and **construction expertise** for tailings facilities of comparable complexity has been **engaged**.	M	M	M	M	M	M	M	M	0.03%	0.04%	0.03%	0.04%
3.8.1.b	The **appointed Engineer** of **Record** (EOR) has **experience** and **expertise** commensurate with the complexity of the tailings facility and the consequence class and the appointment has been approved by the Operator.	M	M	M	M	M	M	M	M	0.03%	0.04%	0.03%	0.04%
3.8.1.c	A **DOR**, if appropriate either due to selection of an EOR internal to the Operator or other circumstances, is **appointed** that meets the essential qualifications and requirements of the EOR.	M	M	M	M	M	M	M	M	0.20%	0.24%	0.19%	0.24%
3.8.2.a	An **EOR** is **appointed** and in place at all times throughout the tailings facility lifecycle. The appointed EOR may change during the tailings facility lifecycle.	L	L	L	L	L	L	L	L	0.20%	0.24%	0.19%	0.24%
3.8.2.b	The EOR is **appointed through** a **written agreement** that clearly **describes** their **authority**, **role** and **responsibilities** throughout the tailings facility lifecycle, and during change of ownership of mining properties.	L	L	L	L	L	L	L	L	0.07%	0.08%	0.06%	0.08%
3.8.2.c	The **written agreement** clearly **describes** the **obligations** of the Operator to the EOR, to support the effective performance of the EOR during the tailings facility lifecycle.	L	L	L	L	L	L	L	L	0.04%	0.05%	0.04%	0.05%
3.8.3.a	A **programme** is **established** to manage the **quality** of all **engineering work and interactions** between the EOR, the RTFE and the Accountable Executive.	M	M	M	M	M	M	M	M	0.02%	0.03%	0.02%	0.03%
3.8.3.b	The established **programme** is **implemented** to manage the quality of all engineering work and the interactions between the EOR, the RTFE and the Accountable Executive.	M	M	M	M	M	M	M	M	0.01%	0.02%	0.01%	0.02%
3.8.3.c	The **programme**, developed by the Operator, **covers** the **involvement** of the **EOR**, the **RTFE** and the **Accountable Executive** in the tailings facility lifecycle as necessary to confirm that both the implementation of the design and the design intent are met.	M	M	M	M	M	M	M	M	0.09%	0.11%	0.09%	0.11%
3.8.4.a	The **risks** and **associated potential impacts** with a tailings facility are **considered** by the Accountable Executive in selecting the EOR.	L	L	L	L	L	L	L	L	0.09%	0.11%	0.09%	0.11%
3.8.4.b	The **selection** of the **EOR** shall be **decided** by the **Accountable Executive** and informed, but not decided, by procurement personnel.	L	L	L	L	L	L	L	L	0.03%	0.04%	0.03%	0.04%
3.8.4.c	EOR selection is **consistent** with **Requirement 9.1.**	L	L	L	L	L	L	L	L	0.05%	0.06%	0.04%	0.06%
3.8.5.a	A **succession plan** is in place when it is necessary to change the EOR (whether a firm or within a firm, or an in-house employee).	M	M	M	M	M	M	M	M	0.02%	0.02%	0.01%	0.02%
3.8.5.b	The **succession plan includes** the comprehensive **transfer of data**, **information**, **knowledge and experience** with the construction procedures and materials.	M	M	M	M	M	M	M	M	0.02%	0.02%	0.01%	0.02%
3.9.1.a	A **risk assessment process** is **in place** for the tailings facility and is based on an up to date knowledge base for the tailings facility.	H	H	H	H	H	H	H	H	0.07%	0.08%	0.06%	0.08%
3.9.1.b	The **risk assessment** is **updated** at least every three years and more frequently whenever there is a material change either to the tailings facility or to the social, environmental and local economic context.	H	H	H	H	H	H	H	H	0.07%	0.08%	0.06%	0.08%
3.9.1.c	**Risk assessment** scope to **include** the **full potential area** of influence of the tailings facility, and to actively incorporate industry experience in risk assessment	H	H	H	H	H	H	H	H	0.18%	0.21%	0.16%	0.22%
3.9.1.d	**Sources** of **risk** are **regularly identified**, **assessed** and **managed** at all phases of the tailings facility lifecycle, including projected climate change impacts under a range of credible future climate scenarios.	H	H	H	H	H	H	H	H	0.10%	0.12%	0.09%	0.12%
3.9.1.e	A **multi-disciplinary team** is qualified to **undertake** the **risk assessment** specific to the phase of the tailings facility lifecycle (i.e. construction, operation, suspension, expansion, closure) and has the ability to apply best practice methodology in a cross-functional manner.	H	H	H	H	H	H	H	H	0.10%	0.12%	0.09%	0.12%
3.9.1.f	Following **review** by the **ITRB** or **senior independent** technical **reviewer**, **action plans** are prepared, **implemented** and **reported** when risk assessments identify unacceptable tailings facility risks.	H	H	H	H	H	H	H	H	0.18%	0.21%	0.16%	0.22%
3.9.2.a	The TMS and **components** of the ESMS are **reviewed sufficiently often** to assure that the tailings facility management system is effective and applicable for the risks across the full lifecycle of the facility.	M	M	M	M	M	M	M	M	0.05%	0.06%	0.05%	0.07%
3.9.2.b	The **outcomes** of the TMS and ESMS **reviews** are **documented** and **reported** to the Accountable Executive, Board of Directors and project-affected people.	M	M	M	M	M	M	M	M	0.05%	0.06%	0.05%	0.07%
3.9.2.c	The **review** shall be **undertaken** by **senior technical reviewers** with the appropriate qualifications, expertise and resources.	M	M	M	M	M	M	M	M	0.13%	0.15%	0.11%	0.15%
3.9.2.d	For tailings facilities with 'High', 'Very High' or 'Extreme' Consequence Classification, the **review** is **conducted at least every three years.**	M	M	M	M	M	M	M	M	0.06%	0.07%	0.06%	0.08%
3.9.3	**Internal audits** are **completed** at a frequency to ensure consistent **implementation** of established **requirements** that related to company procedures, guidelines and corporate governance1 requirements that is consistent with the TMS and aspects of the ESMS relating to tailings facility risks.	M	M	M	M	M	M	M	M	0.13%	0.15%	0.11%	0.15%

3.9.4	An **annual tailings facility review** is conducted throughout the **construction** and **operational periods** to assess condition and performance. The reviews are performed by the EOR or the senior independent technical reviewer, as assigned for the tailings facility, and the review is documented. Reviews may be conducted more frequently, if required by identified issues or the implementation of necessary measures.	M	M	M	M	M	M	M	M	0.06%	0.07%	0.06%	0.08%
3.9.5.a	**DSRs** are **conducted** and **documented**: — every five years for tailings facilities with 'Very High' or 'Extreme' Consequence Classifications. Every 10 years for all other facilities, or, more frequently as recommended by the ITRB.	M	M	M	M	M	M	M	M	0.21%	0.24%	0.19%	0.25%
3.9.5.b	**DSRs include technical**, **operational** and **governance aspects** of the tailings facility and shall be completed according to best practice .	M	M	M	M	M	M	M	M	0.67%	0.79%	0.60%	0.80%
3.9.5.c	**DSR individuals cannot conduct consecutive DSRs** on the same facility.	M	M	M	M	M	M	M	M	0.09%	0.11%	0.09%	0.11%
3.9.5.d	**DSR individuals certify** in **writing** that they follow **best practices** for engineers in avoiding conflicts of interest.	M	M	M	M	M	M	M	M	0.09%	0.11%	0.09%	0.11%
3.9.6.a	For tailings facilities with 'Very High' or 'Extreme' Consequence Classifications, the ITRB 1 , reporting to the **Accountable Executive provides** ongoing **senior independent technical review** of the planning, siting, design, construction, operation, water and mass balance, maintenance, monitoring, performance and risk management at appropriate intervals across all phases of the tailings facility lifecycle.	M	M	M	M	M	M	M	M	0.09%	0.11%	0.09%	0.11%
3.9.6.b	For tailings facilities with other Consequence Classifications, this review can alternatively be performed by a **senior independent technical reviewer**.	M	M	M	M	M	M	M	M	0.09%	0.11%	0.09%	0.11%
3.9.6.c	The ongoing reviews are **conducted at appropriate intervals** across all phases of the tailings facility lifecycle.	M	M	M	M	M	M	M	M	0.07%	0.08%	0.06%	0.08%
3.9.7.a	A **process** and **governance mechanisms** have been **established** for **closure planning** and **closure cost estimating**.	L	L	L	L	L	L	L	L	0.07%	0.08%	0.06%	0.08%
3.9.7.b	A closure plan for the tailings facility has been established and associated closure cost estimates has been prepared.	L	L	L	L	L	L	L	L	0.07%	0.08%	0.06%	0.08%
3.9.7.c	**Closure cost estimates** are **reviewed** periodically and public disclosure is made annually to confirm that adequate financial capacity is in place to meet the closure requirements and expected timing for the tailings facility in their current state.	L	L	L	L	L	L	L	L	0.06%	0.07%	0.06%	0.07%
3.9.7.d	If any of an Operator's assets involving a tailings facility **underwent** a **change** in Ownership since the last review, the **Operator** must **provide documentation** that they **assessed** and took into account the capability of an acquirer to maintain this Standard (subject to provisions of local/national regulations).	L	L	L	L	L	L	L	L	0.06%	0.07%	0.06%	0.07%
3.10.1.a	The Operator has developed an **educational programme** inclusive of job procedures and responsibilities for prevention of a failure.	M	M	M	M	M	M	M	M	0.06%	0.07%	0.06%	0.07%
3.10.1.b	Those with **roles** for **preventing** a **failure** in any phase of the tailing facility lifecycle **is included** in the education programme.	M	M	M	M	M	M	M	M	0.02%	0.02%	0.02%	0.02%
3.10.2	**Mechanisms** have been established that **incorporate** workers' **experience-based knowledge** into planning, design and operations for all phases of the tailings facility lifecycle.	M	M	M	M	M	M	M	M	0.36%	0.43%	0.33%	0.43%
3.10.3	The Operator has **established mechanisms** that **promote cross-functional collaboration** to support public safety and the integrity of the tailings facility through: effective data and knowledge sharing, effective communication, and implementation of management measures.	M	M	M	M	M	M	M	M	0.18%	0.21%	0.16%	0.22%
3.10.4.a	The Operator has **identified** and **implemented lessons** from **internal incident investigations**.	M	M	M	M	M	M	M	M	0.54%	0.64%	0.49%	0.65%
3.10.4.b	The Operator has **identified** and **implemented lessons** from relevant **external incident reports**.	M	M	M	M	M	M	M	M	0.54%	0.64%	0.49%	0.65%
3.10.4.c	Internal and external incident lessons learned pay particular **attention to human and organisational factors**.	M	M	M	M	M	M	M	M	0.18%	0.21%	0.16%	0.22%
3.10.5.a	The Operator has established a **documented mechanism** that **recognises**, **rewards** and **protects** employees and contractors **who report problems** or **identify opportunities** for **improving** tailings facility management.	M	M	M	M	M	M	M	M	0.18%	0.21%	0.16%	0.22%
3.10.5.b	The Operator has **responded** in a **timely manner**, and **communicated** to employees and contractors the **actions taken** in response to concerns and opportunities raised.	M	M	M	M	M	M	M	M	0.18%	0.21%	0.16%	0.22%
3.11.1	Accountable Executive has **established** a **formal**, **confidential** and **written process to receive**, **investigate** and **promptly address concerns** from employees and contractors related to the tailings facility, including possible permit violations or other matters related to regulatory compliance, public safety, tailings facility integrity or the environment.	L	L	L	L	L	L	L	L	0.36%	0.43%	0.33%	0.43%
3.11.2	The Operator **maintains** whistleblower **protection practices** that do not discharge, discriminate or retaliate against a whistleblower who in good faith reports possible violations relating to regulatory compliance, public safety, tailings facility integrity or the environment.	L	L	L	L	L	L	L	L	0.18%	0.21%	0.16%	0.22%
3.12.1.a	All of the disclosures specified in **15.1(A) and (B)** above are **addressed**.	M	M	M	M	M	M	M	M	0.72%	0.87%	0.67%	0.88%
3.12.1.b	The disclosures specified in **15.1(C)** are **addressed**.	M	M	M	M	M	M	M	M	0.24%	0.29%	0.22%	0.29%
3.12.2.a	The **Operator maintains** a **systematic** and **timely approach** to responding to requests from project-affected people for information material to public safety and integrity of a tailings facility.	M	M	M	M	M	M	M	M	0.24%	0.29%	0.22%	0.29%
3.12.2.b	In instances where such **requests** are **denied** by the Operator, an **explanation shall be provided** to the requesting project-affected people in a reasonable timeframe and records shall be kept of relevant explanations provided to the requesting project-affected people.	M	M	M	M	M	M	M	M	0.24%	0.29%	0.22%	0.29%
									Total	***32.96 %***	***35.73 %***	***28.44 %***	***36.37 %***

Alternative Level of Practise (LoP) Factors

Table B.4: Alternative Contributing Level of Practise (LoP), Including Indication of Relative Prevalence for Each Failure Category *(H: High, M: Medium, L: Low, -: Not, EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy)*

		Prevalence Indication							
ID	**Factor Description**	**EQ**	**OT**	**SI**	**FN**	**SE**	**ER**	**ST**	**MS**
3.1	**Site Investigation & Material Characterisation**								
3.1.1	The site of the TSF is selected carefully (historically) taking into account various environtmental conditions (e.g. seismicity, hydro(geo)logical conditions and geotechnical characteristics of native material), following a process of detailed consultation and review.	-	M	L	M	L	L	-	M
3.1.2	Thorough evaluations are conducted to assess and gain a comprehensive understanding of the natural seismic activity at the site.	H	-	-	-	-	-	-	M
3.1.3	The anthropogenic seismic activity at the site is evaluated and comprehensively understood through detailed assessments.	-	-	-	L	H	-	-	H
3.1.4	A comprehensive hydrological assessment is performed, relying on field data to analyse the water balance and account for the catchment area. The evaluation incorporates site-specific climate data and is calibrated with local stations to strengthen the findings. Potential uncertainties arising from climate change are carefully considered throughout the assessment process.	-	H	M	-	M	H	M	-
3.1.5	Extensive studies and long-term field data collection have provided a solid understanding of groundwater conditions and hydrogeology.	M	L	H	H	M	M	L	L
3.1.6	The geotechnical and geochemical properties of the native soil profile and bedrock are characterised through through field investigations and laboratory tests. The material behavior is understood in a high level of detail. Spatial variability is mapped and critical zones are identified. The results of the laboratory tests align with the field observations.	L	-	H	H	L	M	-	H
3.1.7	The geotechnical and geochemical properties of the tailings and other contained material are characterised through through field investigations and laboratory tests. The material behavior is understood in a high level of detail. Spatial variability is mapped and critical zones are identified. The results of the laboratory tests align with the field observations.	M	-	H	-	L	-	-	L
3.1.8	The geotechnical and geochemical properties of the construction borrow material are characterised through through field investigations and laboratory tests. The material behavior is understood in a high level of detail. Spatial variability is mapped and critical zones are identified. The quality of the borrow material is examined and verified. The results of the laboratory tests align with the field observations.	M	-	M	M	H	H	-	-
3.1.9	The results of the field investigation and laboratory tests are reported. The results of the field investigation and laboratory tests are unambigiously documented. The report is complete, transpirant and accessible.	H	L	H	H	M	L	L	L
3.1.10	A comprehensive QA/QC program to verify quality/validity of the results of the field investigation and laboratory testing is in place. There are limited uncertainties and gaps, and the data and site characteristation is reviewed.	M	M	M	M	M	M	M	M
3.1.11	A dedicated investigative program has been implemented or is presently under development to rectify any deficiencies or gaps identified in the site investigation and material characterization.	M	M	M	M	M	M	M	M
3.1.12	The site investigation and material characterization program undergoes regular updates to integrate any significant changes, evolving conditions, and newly acquired knowledge, including information related to climate change. This ensures that the program remains up-to-date and responsive to the latest developments.	M	M	M	M	M	M	M	M
3.2	**Design**								
3.2.1	Throughout its lifespan, the project maintains a thorough detailed Design Basis Report (DBR) that outlines assumptions, criteria, and operational limitations. This report serves as a fundamental document for designing all stages of the tailings facility and undergoes regular evaluations conducted by the Independent Tailings Review Board (ITRB) or a senior independent technical reviewer.	M	M	M	M	M	M	M	M
3.2.2	The design of the tailings facility adheres to the latest industry standards and best practices, ensuring its robustness. It considers a range of factors, including technical specifications, social aspects, environmental consequences, and the local economic landscape. The design process takes into careful account site conditions, water management, mining plant operations, tailings operations, and construction challenges. Furthermore, the design incorporates strategies for progressive closure and reclamation during the facility's operational phase. This comprehensive design approach guarantees the feasibility of a secure facility closure.	M	M	M	M	M	M	M	M
3.2.3	Tailings facility designs are developed for each stage of the construction process, including start-up, partial raises, interim configurations, final raise, and pre-construction closure. The level of intricacy in the design corresponds to the specific phase of the tailings facility's lifecycle, ensuring that it aligns appropriately with the corresponding stage.	M	M	M	M	M	M	M	-
3.3	**Analysis**								
3.3.1	**Stability Analysis**								
3.3.1.1	For every section of the dam, a stability analysis is carried out, taking into consideration any raises or changes in materials that may occur during the lifespan of the facility. These analyses undergo regular reviews and specifically focus on identifying potential failure modes. The analysis takes into account operational characteristics, the performance of design elements, and the systems in place for risk management. Criteria are established, such as factors of safety for slope stability, to ensure the integrity of the design.	M	M	M	M	M	M	M	M
3.3.1.2	To evaluate different failure modes and conditions, a thorough sensitivity analysis is performed, taking into account the insights acquired from the investigation, construction, and operational stages.	H	H	H	H	H	H	H	H
3.3.1.3	The findings of the stability analysis have been thoroughly documented and presented in a comprehensive and easily understandable report. The report offers a thorough account of the obtained results from the analysis, along with an explanation of the underlying assumptions utilised in the process.	M	M	M	M	M	M	M	M

3.3.2	**Hydro(geological) Analysis**								
3.3.2.1	A water management plan is developed, considering hydrogeological basins both upstream and downstream, and potential climate change effects. Regular evaluations are conducted to assess its short- and long-term performance, and the plan is calibrated using representative field data.	L	H	M	L	M	M	L	-
3.3.2.2	The water balance model within the plan demonstrates a thorough understanding of the overall water management strategy. It encompasses measures to prevent unintentional releases and ensures comprehensive water management practices.	L	H	M	L	M	M	L	-
3.3.2.3	The outcomes of the hydro(geo)logical analysis are documented and presented in a comprehensive report that is readily accessible. The report provides a detailed description of the obtained results and assumptions.	L	M	M	L	M	M	M	-
3.3.3	**Risk Analsysis**								
3.3.3.1	An in-depth risk analysis is in place, based on the current understanding derived from investigations and failure modes. It provides an overview of the various risks and their corresponding mitigations. The report details the criteria required to effectively minimise risks across all failure modes during each phase of the tailings facility's lifecycle. In addition, the knowledge of climate change is consistently updated and utilized to assess risks and identify opportunities throughout the lifecycle of the tailings facility.	H	H	H	H	H	H	H	H
3.3.3.2	The outcomes of the risk analysis are reported, presenting a comprehensive and easily accessible report where the results are explained in a clear and comprehensible manner. The decisions made based on the analysis are logically justified, and any risks that are deemed unacceptable are appropriately reported.	H	H	H	H	H	H	H	H
3.3.3.3	The results of the risk analysis are effectively followed up, and proactive measures are implemented based on the action plans to mitigate and reduce risks.	M	M	M	M	M	M	M	M
3.3.3.4	The risks are effectively communicated and conveyed in a comprehensive manner.	M	M	M	M	M	M	M	M
3.3.3.5	The risk assessment undergoes regular updates, with a minimum frequency of every three years, and more frequent revisions are conducted whenever there are significant changes to the tailings facility or the social, environmental, and local economic context. A qualified team thoroughly reviews the risk assessment and formulates action plans accordingly.	M	M	M	M	M	M	M	M
3.4	**Operations**								
3.4.1	A well-defined and easily comprehensible project management plan is established and diligently adhered to throughout all construction phases. The plan is regularly updated as necessary to ensure its relevance. The design intent is thoroughly understood and effectively implemented during the construction process.	L	L	M	L	M	L	M	-
3.4.2	The construction process is overseen by a qualified supervisor who is present full-time, ensuring clear roles and responsibilities are assigned throughout all construction phases.	L	L	M	L	M	L	M	-
3.4.3	The construction and operating personnel are appropriately qualified in accordance with the qualifications outlined in the management program.	L	L	M	L	M	L	M	-
3.4.4	A quality assurance and quality control (QA/QC) program is implemented to ensure the monitoring of construction and operation processes for their adequacy and quality. The use of appropriate methodologies, equipment, procedures, and data acquisition methods is consistently followed throughout all stages of the tailings facility's lifecycle, in alignment with the QA/QC program. Additionally, deviations from the design intent and assumptions are monitored.	L	L	M	L	M	L	M	-
3.4.5	The construction reports through the life of construction are up to date, accessible, include drawings, photos, etc. The reports are promptly updated in the event of any significant change or modification to the monitoring system. Deviations from the design intent and assumptions are duly reported and documented in the construction reports.	L	L	M	L	M	L	M	-
3.4.6	The construction process undergoes regular review by qualified individuals throughout its duration, ensuring diligent oversight. Effective communication channels are established between the owner and contractor, facilitating discussions on critical aspects of the construction project.	L	L	M	L	M	L	M	-
3.4.7	The Engineer of Record (EOR) periodically prepares and updates a comprehensive report that addresses the cumulative impact of material changes to the as-constructed facility. Acceptance of these changes involves all relevant parties, ensuring a collaborative approach to managing and addressing modifications.	L	L	L	L	L	L	L	L
3.4.8	Implemented recommendations have resulted in updates to the construction, operations, design, OMS manual, and monitoring program. The accountable executive has provided approval for the Documented Action Report (DAR).	L	L	L	L	L	L	L	L
3.4.9	A comprehensive Operation, Maintenance, and Surveillance (OMS) Manual is implemented, encompassing each tailings facility and outlining the necessary OMS activities for effective risk management based on industry best practices. The OMS undergoes annual reviews or more frequent updates in response to material changes as defined by the Operator. It provides clear guidance and includes inspections, maintenance, and monitoring requirements, along with critical controls for safe operation. The effectiveness of the OMS is regularly reviewed and assessed.	L	L	L	L	L	L	L	L
3.4.10	Personnel engaged in the Tailings Management System (TMS) are granted access to the OMS Manual.	L	L	L	L	L	L	L	L
3.5	**Monitoring Programme**								
3.5.1	A comprehensive performance monitoring program is in place for the tailings facility and its associated structures. It is integrated into the Tailings Management System (TMS) and encompasses inspection, reviews, and monitoring activities aligned with the facility's Operation, Maintenance, and Surveillance (OMS) requirements. The engineering monitoring system is designed to validate design assumptions and monitor potential failure modes.	H	H	H	H	H	H	H	H
3.5.2	Regular inspections, monitoring, testing, recording, evaluation, and reporting of data from the monitoring programs are carried out at appropriate intervals as per established protocols.	H	H	H	H	H	H	H	H
3.5.3	The monitoring program is regularly updated during the lifecycle of the tailings facility, considering data evaluation to ensure the effectiveness of performance objectives, indicators, and criteria in risk management.	M	M	M	M	M	M	M	M
3.6	**Performance Objectives**								
3.6.1	Specific and measurable performance objectives, indicators, and criteria are established to evaluate the performance of the tailings facility. These are integrated into the monitoring programs.	M	M	M	M	M	M	M	M
3.6.2	The performance of the tailings facility is evaluated by analysing technical monitoring data as per the frequency determined by the Engineer of Record (EOR).	L	L	L	L	L	L	L	L
3.6.3	The analysis of technical monitoring data for the tailings facility provides clear identification and evidence of any deviations from the expected performance objectives and the deterioration of facility performance over time.	M	M	M	M	M	M	M	M

3.6.4	The geotechnical performance of the infrastructure meets expectations and remains within design allowances, including factors such as movement, settlement, tension cracks, and more.	M	L	H	H	L	L	L	-
3.6.5	The hydrological performance of the infrastructure meets expectations and remains within design allowances, including factors such as seepage, piezometric level, internal erosion, and impact to groundwater.	-	-	M	L	H	-	-	-
3.6.6	The hydrological performance of the infrastructure consistently meets expectations and adheres to the Design Basis Manual (DBM) at all times. This includes proper management and operations of features such as the feeboard, beach, and spillway.	-	H	M	-	-	M	H	-
3.6.7	The foundation performance meets expectations and remains within the design allowances for movement and settlement.	M	-	-	H	M	-	-	-
3.6.8	Appropriate actions are taken based on the results, including updates to the risk assessment and design if necessary.	H	H	H	H	H	H	H	H
3.6.9	The findings from the monitoring analysis of the tailings facility's performance are reviewed, comprehensively reported and promptly communicated to the EOR.	M	M	M	M	M	M	M	M
3.7	**Education Programme**								
3.7.1	The Operator has implemented an educational program that includes job procedures and responsibilities aimed at preventing failures. The educational programme includes individuals with roles in preventing failures at any phase of the tailings facility lifecycle	H	H	H	H	H	H	H	H
3.7.2	Mechanisms are in place to integrate workers' experiential knowledge into planning, design, and operations throughout all stages of the tailings facility lifecycle. The Operator has implemented mechanisms to foster cross-functional collaboration through effective data and knowledge sharing, effective communication and implementation of management measures.	M	M	M	M	M	M	M	M
3.7.3	The Operator has identified and applied insights from internal incident investigations and external incident reports.	L	L	L	L	L	L	L	L
3.7.4	The Operator has implemented a documented mechanism that acknowledges, incentivises, and safeguards employees and contractors who report issues or suggest improvements in tailings facility management.	H	H	H	H	H	H	H	H
3.7.5	The Operator promptly addresses and communicates the actions taken in response to concerns and opportunities raised by employees and contractors.	M	M	M	M	M	M	M	M
3.8	**Management System and Governance**								
3.8.1	A change management system is in place to address and document significant changes to the design, construction, operations, or monitoring aspects. This system incorporates processes for change identification, evaluation, review, approval, and documentation, ensuring comprehensive coverage throughout the lifecycle of the facility.	L	L	L	L	L	L	L	L
3.8.2	The Engineer of Record (EOR) periodically prepares and updates a comprehensive report that addresses the cumulative impact of material changes to the as-constructed facility. Acceptance of these changes involves all relevant parties, ensuring a collaborative approach to managing and addressing modifications.	M	M	M	M	M	M	M	M
3.8.3	Implemented recommendations have resulted in updates to the construction, operations, design, OMS manual, and monitoring program. The accountable executive has provided approval for the Documented Action Report (DAR).	L	L	L	L	L	L	L	L
3.8.4	A comprehensive corporate tailings management policy is established, committing the Operator to ensuring the safe management of tailings, developing emergency response plans, and implementing mechanisms for recovery in the event of failure. This policy is publicly available and may be in the form of a standalone document or integrated within a document adopted by the Board of Directors. The implemented program effectively manages the quality of all engineering work and facilitates the interactions between the Engineer of Record (EOR), the Responsible Tailings Facility Engineer (RTFE), and the Accountable Executive.	M	M	M	M	M	M	M	M
3.8.5	A well-defined succession plan is established, encompassing the thorough transfer of data, information, knowledge, and experience related to construction procedures and materials.	L	L	L	L	L	L	L	L
3.8.6	A comprehensive closure plan for the tailings facility has been developed, accompanied by the preparation of estimated closure costs. Furthermore, a robust process and governance mechanisms have been established to facilitate effective closure planning.	M	M	M	M	M	M	M	M
3.8.7	Clear definitions are established for accountabilities, responsibilities, and the corresponding competencies required to implement the framework, ensuring the proper identification and management of risks associated with the tailings facility. Roles and responsibilities for the Responsible Tailings Facility Engineer (RTFE) position are explicitly outlined and documented, highlighting their accountability for maintaining the integrity of the tailings facility.	M	M	M	M	M	M	M	M
3.8.8	The interconnections between the Tailings Management System (TMS) and other systems, such as the Environmental and Social Management System (ESMS), are well-defined to ensure seamless integration and effective management of the tailings facility.	L	L	L	L	L	L	L	L
3.8.9	The Accountable Executive(s), reporting directly to the CEO, is responsible for the safety of the tailings facility and minimizing its social and environmental consequences in case of a failure. Regular communication takes place between the Accountable Executive(s), the Engineer of Record (EOR), and the Board of Directors, initiated by either party. Clear qualification and experience requirements are defined for safety critical roles, including the RTFE, EOR, and Accountable Executives.	L	L	L	L	L	L	L	L
3.8.10	Regular assessments of innovative technologies and approaches for tailings management are conducted, taking into account the entire lifecycle of the tailings facility.	M	M	M	M	M	M	M	M
3.8.11	The Operator promptly and systematically responds to information requests from project-affected individuals regarding the public safety and integrity of the tailings facility. In cases where requests are denied, an explanation is provided to the individuals within a reasonable timeframe, and records of explanations are maintained.	L	L	L	L	L	L	L	L

B.2. Weights

Each contributing factor is assigned a weight, determined for each dam construction method and failure category using the AHP weighting method. While not all matrices within the AHP method are presented here, an overview of the resulting weights is provided.

Site Conditions

Table B.5: Weights of Site Conditions Factors
(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention) – Colour Scale: Highest Contribution (Grey) - Lowest Contribution (White)

ID	Factors		EQ	OT	SI	FN	SE	ER	ST	MS	*Total*
1.1	The TSF is located in a seismically active region where large-magnitude earthquakes can potentially generate strong ground motions.	US	0.297								0.297
		DS	0.297								0.297
		CL	0.297								0.297
		WR	0.297								0.297
1.2	Ground motions can potentially be induced by the presence of (active) faults that either cross the embankment or TSF or exist in close proximity to it.	US	0.077								0.077
		DS	0.077								0.077
		CL	0.077								0.077
		WR	0.077								0.077
1.3	Potential significant water inflow at the site due to the catchment area of the TSF being considerably larger than the TSF footprint.	US		0.033	0.016			0.015	0.003		0.067
		DS		0.033	0.016			0.015	0.003		0.067
		CL		0.033	0.016			0.015	0.003		0.067
		WR		0.033	0.016			0.015	0.003		0.067
1.4	The occurrence of atmospheric rivers or intense rainfall events at the site can create significant water inflow and has the potential to result in the rapid rise of the pond water level, the development of a high hydraulic gradient, and/or saturation of materials, but may also trigger landslides.	US		0.086	0.016		0.004	0.040	0.005		0.151
		DS		0.086	0.016		0.004	0.040	0.005		0.151
		CL		0.086	0.016		0.004	0.040	0.005		0.151
		WR		0.086	0.016		0.004	0.040	0.005		0.151
1.5	The site is prone to rain-on-snow events, potentially resulting in a rapid rise of pond water level, an enhanced runoff, elevated pore water pressures and slumping or sliding.	US		0.047	0.016		0.004	0.016	0.005		0.088
		DS		0.047	0.016		0.004	0.016	0.005		0.088
		CL		0.047	0.016		0.004	0.016	0.005		0.088
		WR		0.047	0.016		0.004	0.016	0.005		0.088
1.6	The potential for significant snowmelt at the site exists, which can lead to the rapid rise of the pond water level, the development of a high hydraulic gradient, and/or saturation of materials.	US		0.016	0.009		0.004	0.016	0.005		0.050
		DS		0.016	0.009		0.004	0.016	0.005		0.050
		CL		0.016	0.009		0.004	0.016	0.005		0.050
		WR		0.016	0.009		0.004	0.016	0.005		0.050
1.7	The site is susceptible to thawing of permafrost, which can result in a loss of stability or significant settlement of the foundation, as well as changes in pore water pressures that can alter the drainage patterns.	US				0.036	0.015				0.051
		DS				0.036	0.015				0.051
		CL				0.034	0.015				0.049
		WR				0.036	0.015				0.051
1.8	The TSF is prone to the potential occurrence of hurricanes, cyclones, and typhoons (or tsunamis), with destructive nature of strong winds and intense rainfall.	US		0.023	0.009		0.003	0.016	0.010		0.061
		DS		0.023	0.009		0.003	0.016	0.010		0.061
		CL	0.023	0.009		0.003	0.016	0.010		0.061	0.122
		WR		0.023	0.009		0.003	0.016	0.010		0.061
1.9	The site is prone to the generation of high waves in the ponded water due to extreme winds, which may lead to overtopping and erosion.	US		0.010				0.026			0.036
		DS		0.010				0.026			0.036
		CL		0.010				0.026			0.036
		WR		0.010				0.026			0.036
1.10	The site is prone to adjacent landslides that have the potential to cause significant damage to the slopes of the site, or may cause wave generation in the ponded water.	US		0.010	0.009			0.003			0.023
		DS		0.010	0.009			0.003			0.023
		CL		0.010	0.009			0.003			0.023
		WR		0.010	0.009			0.003			0.023
1.11	The location of the site and the project constraints imposes limitations on the minimum embankment height, e.g. the topography and the volume of production of tailings require to construct higher embankments, whereas for example open, flat terrain without infrastructure limitations allows for the use of lower	US			0.042	0.022	0.004	0.006	0.002		0.076
		DS			0.042	0.022	0.004	0.006	0.002		0.076
		CL			0.042	0.032	0.004	0.006	0.002		0.086
		WR			0.042	0.022	0.004	0.006	0.002		0.076
1.12	The location prevents building a stable permanent spillway, risking flood control and erosion. Unstable walls could lead to collapse and dysfunction. Without an emergency spillway, there's no backup plan.	US		0.006					0.009		0.015
		DS		0.006					0.009		0.015
		CL	0.006					0.009		0.015	0.031
		WR		0.006					0.009		0.015
1.13	The site is prone to material or debris, vegetation, as well as ice damming which could potentially block spillway or drainage structures.	US		0.033	0.042	0.007	0.008		0.014		0.103
		DS		0.033	0.042	0.007	0.008		0.014		0.103
		CL		0.033	0.042	0.007	0.008		0.014		0.103
		WR		0.033	0.042	0.007	0.008		0.014		0.103
1.14	Artesian pressures are likely to be present at the site, which may potentially create significant pore water pressures and increase in hydraulic gradients.	US			0.009	0.022	0.015				0.045
		DS			0.009	0.022	0.015				0.045
		CL			0.009	0.021	0.015				0.044
		WR			0.009	0.022	0.015				0.045
1.15	The foundation underlying the TSF is characterised by strain-softening or contractive material, which may cause the foundation to be unable to support the embankment's weight, resulting in instability, significant settlement or liquefaction.	US	0.134			0.036					0.170
		DS	0.134			0.036					0.170
		CL	0.134			0.034					0.168
		WR	0.134			0.036					0.170
1.16	The foundation underlying the TSF potentially contains collapsible or dispersive material such as karst or salt domes, which may result in significant seepage, internal erosion and eventual collapse of the embankment foundation.	US				0.036	0.023				0.059
		DS				0.036	0.023				0.059
		CL				0.034	0.023				0.057
		WR				0.036	0.023				0.059
1.17	The foundation underlying the dam potentially contains compressible material such as peat, which is unable to sustain the forces acting on the foundation, which may lead to significant settlement or sliding.	US		0.047		0.036					0.083
		DS		0.047		0.036					0.083
		CL		0.047		0.034					0.081
		WR		0.047		0.036					0.083

1.18	There is a weakness plane present between two adjacent material units in the natural foundation, which may reduce the structural stability and bearing capacity.	US				0.036					0.036
		DS				0.036					0.036
		CL				0.034					0.034
		WR				0.036					0.036
1.19	The foundation material is potentially geochemically incompatible, posing change in performance, which may result in strength loss or clogging of drains.	US		0.006		0.009	0.004		0.005		0.024
		DS		0.006		0.009	0.004		0.005		0.024
		CL	0.006		0.008	0.004		0.005		0.024	0.047
		WR		0.006		0.009	0.004		0.005		0.024
1.20.a	A fairly high permeability may result in an increased potential for excessive seepage and internal erosion, and may reduce the foundation strength.	US				0.005	0.023				0.028
		DS				0.005	0.023				0.028
		CL				0.005	0.023				0.028
		WR				0.005	0.023				0.028
1.20.b	A fairly low permeability may result in the generation of excess pore pressure upon surface loading.	US	0.031			0.002					0.033
		DS	0.031			0.002					0.033
		CL	0.031			0.002					0.033
		WR	0.031			0.002					0.033
1.21	The foundation underlying the TSF is non-uniform with different characteristics for strength and permeability. The non-uniformity may lead to structural instability, unexpected seepage, unexpected erosion and/or differential settlement.	US		0.006		0.014	0.008				0.027
		DS		0.006		0.014	0.008				0.027
		CL		0.006		0.013	0.008				0.027
		WR		0.006		0.014	0.008				0.027
1.22	Gap-graded soils are present in the natural soil foundation, which may give rise to internal erosion.	US					0.023				0.023
		DS					0.023				0.023
		CL					0.023				0.023
		WR					0.023				0.023
1.23	Culverts, and pipes are present in the foundation, which have the potential to weaken the foundation, induce differential settlement, and result in concentrated leaks.	US				0.022	0.023		0.021		0.065
		DS				0.022	0.023		0.021		0.065
		CL				0.024	0.023		0.021		0.067
		WR				0.022	0.023		0.021		0.065
1.24	Significant cracks are present in the foundation, which have the potential to weaken the foundation, and may result in an increased permeability and increasing risk of internal erosion.	US				0.014	0.023				0.036
		DS				0.014	0.023				0.036
		CL				0.013	0.023				0.036
		WR				0.014	0.023				0.036
1.25	There is a boundary in the foundation between two units with a significant difference in grain size, coupled with potential water flow along the boundary, which may potentially lead to contact erosion.	US					0.023				0.023
		DS					0.023				0.023
		CL					0.023				0.023
		WR					0.023				0.023
1.26	The available materials for the dam core, filters, and shell of the TSF are potentially internally instable, posing risks filters not meeting filter compatibility, which may lead to internal erosion, deformation, settlement that can compromise the overall stability of the dam.	US			0.027		0.023	0.016			0.066
		DS			0.027		0.023	0.016			0.066
		CL			0.027		0.023	0.016			0.066
		WR			0.027		0.023	0.016			0.066
1.27	The available materials for the dam core, filters, and shell of the TSF are potentially geochemically incompatible, posing change in performance, which may result in strength loss or the clogging of drains (with as result an increased phreatic surface).	US			0.016		0.023				0.039
		DS			0.016		0.023				0.039
		CL			0.016		0.023				0.039
		WR			0.016		0.023				0.039
1.28	The available materials for the dam shell have a low erosional resistance and are susceptible to erosion by water flow, wave action, or wind.	US		0.010	0.009			0.040			0.059
		DS		0.010	0.009			0.040			0.059
		CL		0.010	0.009			0.040			0.059
		WR		0.010	0.009			0.040			0.059
1.29	The site had previous disturbances and land uses which likely included excavations and fills that have not been characterised and documented.	US				0.009	0.002	0.006			0.016
		DS				0.009	0.002	0.006			0.016
		CL				0.008	0.002	0.006			0.016
		WR				0.009	0.002	0.006			0.016
1.30.a	The presence of underground mine workings directly below or adjacent to the tailings impoundment poses a risk of seepage and potential collapse and surface subsidence.	US								0.326	0.326
		DS								0.326	0.326
		CL								0.326	0.326
		WR								0.326	0.326
1.30.b	The use of unsupported mining methods, such as longwall mining, sublevel caving, block caving, increases the risk of collapse and surface subsidence.	US								0.099	0.099
		DS								0.099	0.099
		CL								0.099	0.099
		WR								0.099	0.099
1.30.c	The presence of weak host rock increases the likelihood of subsidence.	US								0.099	0.099
		DS								0.099	0.099
		CL								0.099	0.099
		WR								0.099	0.099
1.30.d	Selective extraction practices at the underground mine can possibly result in differential settlement.	US								0.099	0.099
		DS								0.099	0.099
		CL								0.099	0.099
		WR								0.099	0.099
1.30.e	Dewatering operations at the mine, potentially cause suction forces and/or high difference in phreatic pressures.	US								0.036	0.036
		DS								0.036	0.036
		CL								0.036	0.036
		WR								0.036	0.036
1.30.f	The presence of significant vibrations from mining and blasting activities from the underground mine, which may cause instabilities.	US								0.057	0.057
		DS								0.057	0.057
		CL								0.057	0.057
		WR								0.057	0.057
1.31	The presence of significant loads and/or vibrations from workings on the dam crest or nearby construction works, open pit mining, or vibrations generated by machinery or vehicles on a nearby road may cause instability.	US			0.042	0.006					0.048
		DS			0.042	0.006					0.048
		CL			0.042	0.006					0.048
		WR			0.042	0.006					0.048

Design Elements

Table B.6: Weights of Design Element Factors
(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention) – Colour Scale: Highest Contribution (Grey) - Lowest Contribution (White)

ID	Factors		EQ	OT	SI	FN	SE	ER	ST	MS	*Total*
2.1	By considering the specific characteristics of the natural seismicity at the site during the design phase, tailings dams can be engineered with heightened structural resilience, reducing the vulnerability to potential seismic hazards.	US	0.065								0.065
		DS	0.065								0.065
		CL	0.065								0.065
		WR	0.065								0.065
2.2	Incorporating active faults into the design enables engineers to account for the geological complexities associated with fault activity and develop robust engineering solutions.	US	0.010								0.010
		DS	0.010								0.010
		CL	0.010								0.010
		WR	0.010								0.010
2.3.a	The consideration of water balance in the design of tailings dams is essential. By carefully evaluating and integrating the water balance parameters, such as inflows, outflows, precipitation, evaporation, and seepage, engineers can ensure the effective management of water within the dam system, minimizing	US	0.004	0.027	0.001		0.002	0.022	0.006		0.062
		DS	0.004	0.027	0.001		0.002	0.022	0.006		0.062
		CL	0.004	0.027	0.001		0.002	0.022	0.006		0.062
		WR	0.004	0.027	0.001		0.002	0.022	0.006		0.062
2.3.b	The integration of the catchment area into the water balance design of tailings dams is crucial engineers can effectively evaluate the inflow and outflow components of the water balance, including rainfall, runoff, and evapotranspiration.	US		0.009	0.000			0.007	0.002		0.018
		DS		0.009	0.000			0.007	0.002		0.018
		CL		0.009	0.000			0.007	0.002		0.018
		WR		0.009	0.000			0.007	0.002		0.018
2.3.c	The consideration of the Maximum Probable Flood (MPF) in the water balance, including atmospheric river and intense rainfall events enables engineers to account for potential high water volumes during extreme weather conditions.	US		0.016	0.001		0.001	0.013	0.004		0.034
		DS		0.016	0.001		0.001	0.013	0.004		0.034
		CL		0.016	0.001		0.001	0.013	0.004		0.034
		WR		0.016	0.001		0.001	0.013	0.004		0.034
2.3.d	The consideration of rain-on-snow events in the water balance design allows engineers to manage increased loads.	US		0.009	0.000		0.001	0.007	0.002		0.018
		DS		0.009	0.000		0.001	0.007	0.002		0.018
		CL		0.009	0.000		0.001	0.007	0.002		0.018
		WR		0.009	0.000		0.001	0.007	0.002		0.018
2.3.e	Accounting for significant snowmelt in the water balance design is essential as it allows engineers to manage increased water inflows resulting from rapid snowmelt.	US		0.009	0.000		0.001	0.007	0.002		0.018
		DS		0.009	0.000		0.001	0.007	0.002		0.018
		CL		0.009	0.000		0.001	0.007	0.002		0.018
		WR		0.009	0.000		0.001	0.007	0.002		0.018
2.4.a	The construction of an (emergency) spillway with stable walls, provides an outlet for excess water during high-flow events.	US		0.030					0.023		0.052
		DS		0.030					0.023		0.052
		CL		0.030					0.023		0.052
		WR		0.030					0.023		0.052
2.4.b	By designing tailings dams without relying on an emergency spillway engineers prioritize the design of the main dam structure to ensure it has sufficient capacity and resilience to handle anticipated water inflows.	US		0.015					0.011		0.026
		DS		0.015					0.011		0.026
		CL		0.015					0.011		0.026
		WR		0.015					0.011		0.026
2.5	The consideration of hurricanes, cyclones, and typhoons (and tsunamis) in the design of tailings dams is crucial as engineers can develop structures that can withstand the associated high winds, intense rainfall, storm surges, and other related hazards.	US		0.014	0.002			0.056			0.072
		DS		0.014	0.002			0.056			0.072
		CL		0.014	0.002			0.056			0.072
		WR		0.014	0.002			0.056			0.072
2.6	By the consideration of wind-generated wave scenarios in the design engineers can assess the potential impact of wind-generated waves on the dam structure, determine the required freeboard height to account for wave run-up, and implement erosion control measures to protect the dam slopes and	US		0.014				0.056			0.071
		DS		0.014				0.056			0.071
		CL		0.014				0.056			0.071
		WR		0.014				0.056			0.071
2.7	The consideration of adjacent landslide-generated wave scenarios in the design engineers can assess the potential wave heights and forces generated by nearby landslides and eventual choose to reinforce instable slopes.	US		0.014	0.002						0.016
		DS		0.014	0.002						0.016
		CL		0.014	0.002						0.016
		WR		0.014	0.002						0.016
2.8	The consideration of permafrost in the design engineers can assess the thermal regime, ground stability, and potential thawing effects on the dam foundation, allowing for the implementation of appropriate measures.	US				0.049	0.004				0.053
		DS				0.049	0.004				0.053
		CL				0.049	0.004				0.053
		WR				0.049	0.004				0.053
2.9	Ensuring compliance with industry standards of practice for drained and undrained factors of safety under both static and dynamic loads for potential failure surfaces through the foundation is crucial in the design. Engineers can evaluate the stability of the dam foundation and assess the adequacy of the	US				0.049					0.049
		DS				0.049					0.049
		CL				0.049					0.049
		WR				0.049					0.049
2.10	The specific material properties are taken into account in the design of the foundation. engineers can accurately assess the behaviour and characteristics of the foundation materials. Allowing for the selection of appropriate foundation design techniques, reinforcement methods and	US				0.049					0.049
		DS				0.049					0.049
		CL				0.049					0.049
		WR				0.049					0.049
2.11	The foundation design accounts for time-dependent, deformation-dependent and stress-path dependent processes that may affect material properties. This allows engineers to take account for the potential changes in material behaviour over time, under different deformation conditions and along different	US				0.049					0.049
		DS				0.049					0.049
		CL				0.049					0.049
		WR				0.049					0.049
2.12	The foundation design is considered throughout the project lifecycle, so engineers can ensure the integrity and safety of the dam structure from initial construction to subsequent raises.	US				0.049					0.049
		DS				0.049					0.049
		CL				0.049					0.049
		WR				0.049					0.049
2.13	Insufficient compaction of the foundation can lead to settlement, seepage, slope instability, and an increased susceptibility to liquefaction.	US	0.010	0.014	0.004	0.029	0.009				0.067
		DS	0.010	0.014	0.004	0.029	0.009				0.067
		CL	0.010	0.014	0.004	0.029	0.009				0.067
		WR	0.010	0.014	0.004	0.029	0.009				0.067

2.14	Ensuring compliance with industry standards of practice for drained and undrained factors of safety under both static and dynamic loads for potential failure surfaces through the embankment is crucial in the design. Engineers can accurately assess the stability of the embankment under the different	**US**			0.021						0.021
		DS			0.021						0.021
		CL			0.021						0.021
		WR			0.021						0.021
2.15	The specific material properties are taken into account in the design of the embankment. engineers can accurately assess the behaviour and characteristics of the foundation materials. Allowing for the selection of appropriate embankment design techniques, reinforcement methods and	**US**			0.021						0.021
		DS			0.021						0.021
		CL			0.021						0.021
		WR			0.021						0.021
2.16	The embankment design accounts for time-dependent, deformation-dependent and stress-path dependent processes that may affect material properties. This allows engineers to take account for the potential changes in material behaviour over time, under different deformation conditions and along different	**US**			0.021						0.021
		DS			0.021						0.021
		CL			0.021						0.021
		WR			0.021						0.021
2.17	The embankment design is considered throughout the project lifecycle, so engineers can ensure the integrity and safety of the dam structure from initial construction to subsequent raises.	**US**			0.021						0.021
		DS			0.021						0.021
		CL			0.021						0.021
		WR			0.021						0.021
2.18	Insufficient compaction of the embankment can lead to settlement, seepage, slope instability, and an increased susceptibility to liquefaction.	**US**		0.014	0.013		0.009	0.009			0.046
		DS		0.014	0.013		0.009	0.009			0.045
		CL		0.014	0.013		0.009	0.009			0.045
		WR		0.014	0.013		0.009	0.009			0.045
2.19.a	The excavation of tailings is may lead to slope instability, foundation discrepancies, but may also lead to an increase change of contamination and leaching.	**US**			0.001	0.002	0.001				0.004
		DS			0.001	0.002	0.001				0.004
		CL			0.001	0.002	0.001				0.004
		WR			0.001	0.002	0.001				0.004
2.19.b	The excavation of tailings is considered in the design and engineers address the potential impact of the excavation operations on the slope stability, foundation and leaching.	**US**			0.001	0.002	0.001				0.004
		DS			0.001	0.002	0.001				0.004
		CL			0.001	0.002	0.001				0.004
		WR			0.001	0.002	0.001				0.004
2.20	The rapid drawdown downstream introduces a range of challenges, encompassing the generation of suction forces, heightened vulnerability to liquefaction, and escalated sediment transport and deposition.	**US**	0.004		0.001	0.001	0.000				0.006
		DS	0.004		0.001	0.001	0.000				0.006
		CL	0.004		0.001	0.001	0.000				0.006
		WR	0.004		0.001	0.001	0.000				0.006
2.21.a	The absence of a tailings beach may introduce hydraulic concerns as a tailings beach can serves as a natural buffer to prevent seepage and wave erosion.	**US**	0.001	0.030	0.009		0.006	0.024			0.070
		DS	0.001	0.030	0.009		0.006	0.024			0.070
		CL	0.001	0.030	0.009		0.006	0.024			0.070
		WR	0.001	0.030	0.009		0.006	0.024			0.070
2.21.b	Wide zones of beaches in tailings dams are not adequately compacted to a dilative state and are not free of contractive tailings, which may result in settlement and instability, uncontrolled seepage, liquefaction and slope erosion and material loss.	**US**	0.004	0.015	0.004		0.003	0.012			0.039
		DS	0.004	0.015	0.004		0.003	0.012			0.039
		CL	0.004	0.015	0.004		0.003	0.012			0.039
		WR	0.004	0.015	0.004		0.003	0.012			0.039
2.22	The rate of raising a the dam is not sufficiently slow, hindering the dissipation of excess pore pressures and consolidation process within the supporting zone.	**US**			0.021	0.029	0.003	0.009			0.062
		DS			0.021	0.029	0.003	0.009			0.062
		CL			0.021	0.029	0.003	0.009			0.062
		WR			0.021	0.029	0.003	0.009			0.062
2.23	Structural elements are designed to accommodate tailings and embankment consolidation, deformation, and ice loads, preventing structural integrity, for example, upon differential settlement.	**US**			0.004		0.005		0.100		0.109
		DS			0.004		0.005		0.100		0.109
		CL			0.004		0.005		0.100		0.109
		WR			0.004		0.005		0.100		0.109
2.24	There is no filter underdrainage system incorporated at the basal level in the tailings dam, which may result in seepage problems, insufficient pore pressure dissipation, material saturation and internal erosion.	**US**	0.007	0.026	0.004	0.019	0.015				0.072
		DS	0.007	0.026	0.004	0.019	0.015				0.072
		CL	0.007	0.026	0.004	0.019	0.015				0.072
		WR	0.007	0.026	0.004	0.019	0.015				0.072
2.25	The drainage capacity is insufficient throughout lifecycle. This may result in significant pore pressure built up and saturation of material and consolidation delays.	**US**	0.016	0.026	0.004	0.013	0.015				0.074
		DS	0.016	0.026	0.004	0.013	0.015				0.074
		CL	0.016	0.026	0.004	0.013	0.015				0.074
		WR	0.016	0.026	0.004	0.013	0.015				0.074
2.26	The blockage of a drainage system in a tailings dam, caused by factors such as sediment, vegetation, or ice, can give rise to several complications, including pore pressure built up, material saturation and consolidation delays, but also damaging forces on infrastructure.	**US**	0.017	0.026	0.004	0.009	0.015				0.071
		DS	0.017	0.026	0.004	0.009	0.015				0.071
		CL	0.017	0.026	0.004	0.009	0.015				0.071
		WR	0.017	0.026	0.004	0.009	0.015				0.071
2.27	When the materials used in a drainage system do not meet filter compatibility requirements, this may result in clogging, reduced permeability, erosion and piping.	**US**	0.005	0.026	0.004	0.009	0.015				0.059
		DS	0.005	0.026	0.004	0.009	0.015				0.059
		CL	0.005	0.026	0.004	0.009	0.015				0.059
		WR	0.005	0.026	0.004	0.009	0.015				0.059
2.28	The drainage system is designed to accommodate settlement during dam construction and deformation under seismic loads, preventing potentially impeded drainage, pore pressure built up and ensuring structural integrity.	**US**					0.005				0.005
		DS					0.005				0.005
		CL					0.005				0.005
		WR					0.005				0.005
2.29.a	The presence of a tailings pond may could impact the embankment, especially when directly against the embankment.	**US**			0.007		0.005				0.011
		DS			0.007		0.005				0.011
		CL			0.007		0.005				0.011
		WR			0.007		0.005				0.011
2.29.b	The pond is (temporarily) in contact with the upstream dam face, which may result in e.g. significant seepage, material saturation.	**US**			0.007		0.005				0.011
		DS			0.007		0.005				0.011
		CL			0.007		0.005				0.011
		WR			0.007		0.005				0.011
2.30	The designed embankment slopes of a dam are steep and approach or exceed the natural angle of repose, increasing the change of slope instability and erosion.	**US**			0.021			0.021			0.042
		DS			0.021			0.021			0.042
		CL			0.021			0.021			0.042
		WR			0.021			0.021			0.042

2.31	The embankments are of significant height, which may increase the slope instability, high foundation stresses and elevated pore pressures.	US	0.035		0.021	0.049	0.003				0.108
		DS	0.035		0.021	0.049	0.003				0.108
		CL	0.035		0.021	0.049	0.003				0.108
		WR	0.035		0.021	0.049	0.003				0.108
2.32	There are high flowrate pipelines on the dams, without having secondary containment, may result in significant erosion due to the potential turbulent flow, hydraulic jump and jetting effects.	US						0.036			0.036
		DS						0.036			0.036
		CL						0.036			0.036
		WR						0.036			0.036
2.33	The dam design considers the artesian pressures, allowing engineers to assess the impact of the artesian conditions on the stability and implement appropriate measures.	US			0.004	0.029	0.005				0.039
		DS			0.004	0.029	0.005				0.039
		CL			0.004	0.029	0.005				0.039
		WR			0.004	0.029	0.005				0.039
2.34	The embankment is characterised by strain-softening or contractive material, which may cause the foundation to be unable to support the embankment's weight, resulting in instability, significant settlement or liquefaction.	US			0.013		0.002				0.015
		DS			0.013		0.002				0.015
		CL			0.013		0.002				0.015
		WR			0.013		0.002				0.015
2.35	The embankment potentially contains collapsible or dispersive material such as karst or salt domes, which may result in significant seepage, internal erosion and eventual collapse of the embankment foundation.	US			0.013		0.009				0.022
		DS			0.013		0.009				0.022
		CL			0.013		0.009				0.022
		WR			0.013		0.009				0.022
2.36	The embankment potentially contains compressible material such as peat, which is unable to sustain the forces acting on the foundation, which may lead to significant settlement or sliding.	US			0.013						0.013
		DS			0.013						0.013
		CL			0.013						0.013
		WR			0.013						0.013
2.37	There is a weakness plane present between two adjacent material units in the dam face, which may reduce the structural stability and bearing capacity.	US			0.013						0.013
		DS			0.013						0.013
		CL			0.013						0.013
		WR			0.013						0.013
2.38	The tailings are susceptible to liquefaction, allowing the tailings to liquefy upon credible earthquakes and anthropogenic vibrations. It, for example, consists of low-density, loose, contractive material that is uniformly graded, has a high silt content, and exhibits low permeability. Regular slurry deposited tailings often	US	0.036		0.013						0.050
		DS	0.036		0.012						0.048
		CL	0.036		0.012						0.048
		WR	0.036		0.012						0.048
2.39.a	A fairly high permeability may result in an increased potential for excessive seepage and internal erosion, and may reduce the foundation strength.	US			0.002		0.005				0.006
		DS			0.002		0.005				0.006
		CL			0.002		0.005				0.006
		WR			0.002		0.005				0.006
2.39.b	A fairly low permeability may result in the generation of excess pore pressure upon surface loading.	US			0.002		0.005				0.006
		DS			0.002		0.005				0.006
		CL			0.002		0.005				0.006
		WR			0.002		0.005				0.006
2.40	The embankments are constructed of non-uniform materials with different characteristics for strength and permeability. The uniformity may lead to structural instability, unexpected seepage, unexpected erosion and/or differential settlement.	US			0.006		0.005				0.011
		DS			0.006		0.005				0.011
		CL			0.006		0.005				0.011
		WR			0.006		0.005				0.011
2.41	Gap-graded soils are present in the embankment, which may give rise to internal erosion.	US					0.015				0.015
		DS					0.015				0.015
		CL					0.015				0.015
		WR					0.015				0.015
2.42	Culverts, and pipes are present in the embankment, which have the potential to weaken the foundation, induce differential settlement, and result in concentrated leaks.	US			0.009						0.009
		DS			0.009						0.009
		CL			0.009						0.009
		WR			0.009						0.009
2.43	Significant cracks are present in the embankment, which have the potential to weaken the foundation, and may result in an increased permeability and increasing risk of internal erosion.	US				0.019	0.009				0.028
		DS				0.019	0.009				0.028
		CL				0.019	0.009				0.028
		WR				0.019	0.009				0.028
2.44	There is a boundary in the embankment between two units with a significant difference in grain size, coupled with potential water flow along the boundary, which may potentially lead to contact erosion.	US					0.015				0.015
		DS					0.015				0.015
		CL					0.015				0.015
		WR					0.015				0.015
2.45	The materials used for the dam core, filters, and shell of the TSF are potentially internally instable, posing risks of internal erosion.	US			0.006			0.009			0.015
		DS			0.006			0.009			0.015
		CL			0.006			0.009			0.015
		WR			0.006			0.009			0.015
2.46	The available materials for the dam core, filters, and shell of the TSF are potentially geochemically incompatible, posing risks of chemical reactions and potential leaching of harmful substances when in contact with the tailings.	US			0.006		0.009				0.015
		DS			0.006		0.009				0.015
		CL			0.006		0.009				0.015
		WR			0.006		0.009				0.015
2.47	The materials of the dam shell are susceptible to external erosion by water flow, wave action, or wind.	US						0.056			0.056
		DS						0.056			0.056
		CL						0.056			0.056
		WR						0.056			0.056
2.48.a	The potential seepage or collapse by underground mine workings is considered in the design, allowing for assessment of the potential impact.	US								0.054	0.054
		DS								0.054	0.054
		CL								0.054	0.054
		WR								0.054	0.054
2.48.b	The use of unsupported mining methods, such as longwall mining, sublevel caving, block caving, are considered in the design, allowing for assessment of the potential impact.	US								0.016	0.016
		DS								0.016	0.016
		CL								0.016	0.016
		WR								0.016	0.016

2.48.c	The presence of weak host rock is considered in the design, allowing for assessment of the potential impact.	US								0.016	0.016
		DS								0.016	0.016
		CL								0.016	0.016
		WR								0.016	0.016
2.48.d	Selective extraction practices at the underground mine are considered in the design, allowing for assessment of the potential impact.	US								0.016	0.016
		DS								0.016	0.016
		CL								0.016	0.016
		WR								0.016	0.016
2.48.e	Dewatering operations at the mine are considered in the design, allowing for assessment of potential impact.	US								0.006	0.006
		DS								0.006	0.006
		CL								0.006	0.006
		WR								0.006	0.006
2.48.f	The vibrations from active underground mining activities are taken into account in the design.	US								0.009	0.009
		DS								0.009	0.009
		CL								0.009	0.009
		WR								0.009	0.009
2.49	Anthropogenic vibrations (e.g. from nearby open pit mining and blasting, construction works, machinery or vehicles) are considered in the design, allowing engineers to evaluate their potential effects on the dam and implement appropriate measures.	US			0.009	0.006					0.015
		DS			0.009	0.006					0.015
		CL			0.009	0.006					0.015
		WR			0.009	0.006					0.015
2.50	The previous disturbances (e.g. excavations) at the site are considered in the design.	US				0.019	0.002	0.008			0.028
		DS				0.019	0.002	0.008			0.028
		CL				0.019	0.002	0.008			0.028
		WR				0.019	0.002	0.008			0.028
2.51	There are measures in place for monitoring pore water pressures within the foundation. The results confirm the design assumptions and are within the design standards.	US	0.025			0.049	0.015			0.024	0.113
		DS	0.025			0.049	0.015			0.024	0.113
		CL	0.025			0.049	0.015			0.024	0.113
		WR	0.025			0.049	0.015			0.024	0.113
2.52	There are measures in place for monitoring pore water pressures within the embankment. The results confirm the design assumptions and are within the design standards.	US	0.025		0.021		0.009				0.055
		DS	0.025		0.021		0.009				0.055
		CL	0.025		0.021		0.009				0.055
		WR	0.025		0.021		0.009				0.055
2.53	There are measures in place for monitoring deformations within the foundation. The results confirm the design assumptions and are within the design standards.	US	0.016			0.049	0.015	0.022	0.058		0.161
		DS	0.016			0.049	0.015	0.022	0.058		0.161
		CL	0.016			0.049	0.015	0.022	0.058		0.161
		WR	0.016			0.049	0.015	0.022	0.058		0.161
2.54	There are measures in place for monitoring deformations within the embankment. The results confirm the design assumptions and are within the design standards.	US	0.016		0.021		0.009	0.022	0.058		0.126
		DS	0.016		0.021		0.009	0.022	0.058		0.126
		CL	0.016		0.021		0.009	0.022	0.058		0.126
		WR	0.016		0.021		0.009	0.022	0.058		0.126

Level of Practise (LoP)

Table B.7: Weights of Level of Practise (LoP) Factors
(EQ: Earthquake Induced, ER: External Erosion, FN: Foundation deficiency, MS: Mine Subsidence, OT: Overtopping: SE: Excessive Seepage and Internal Erosion, SI: Slope Instability, ST: Structural Inadequacy, US: Upstream, DS: Downstream, CL: Centreline, WR: Water Retention) – Colour Scale: Highest Contribution (Grey) - Lowest Contribution (White)

ID	Factors	GISTM ID		EQ	OT	SI	FN	SE	ER	ST	MS	*Total*
3.1.1.a	Evaluate uncertainties associated with climate change that may impact upon the safety of the tailings facility (see also GISTM requirement 3.1).	2.1.b	US	0.003	0.023	0.007	0.001	0.020	0.045	0.016	0.004	0.119
			DS	0.003	0.030	0.007	0.001	0.018	0.045	0.016	0.004	0.124
			CL	0.003	0.030	0.007	0.001	0.018	0.045	0.016	0.004	0.124
			WR	0.004	0.030	0.007	0.001	0.018	0.045	0.016	0.004	0.125
3.1.1.b	Operator updates the above information at least at five-year intervals, and whenever there is a material change to the tailings facility or related environmental, social or economic context.	2.1.c	US	0.003	0.012	0.007	0.002	0.007	0.015	0.016	0.004	0.066
			DS	0.003	0.015	0.007	0.002	0.006	0.015	0.016	0.004	0.068
			CL	0.003	0.015	0.007	0.002	0.006	0.015	0.016	0.004	0.068
			WR	0.004	0.015	0.007	0.002	0.006	0.015	0.016	0.004	0.069
3.1.2.a	A detailed site characterisation of the tailings facility site(s) exists and it is updated as warranted throughout the lifecycle to reflect material changes in conditions and new knowledge.	2.2.a	US	0.009	0.006	0.006	0.006	0.009	0.009	0.014	0.003	0.062
			DS	0.011	0.007	0.006	0.006	0.011	0.009	0.014	0.003	0.068
			CL	0.010	0.007	0.006	0.006	0.011	0.009	0.014	0.003	0.067
			WR	0.010	0.007	0.006	0.006	0.011	0.009	0.014	0.003	0.067
3.1.2.b	Site characterisation is supported by data including site-specific climate, geomorphology, geology, geochemistry, hydrology, and hydrogeology (surface and groundwater flow and quality), geotechnical, and seismicity.	2.2.b	US	0.009	0.010	0.006	0.006	0.009	0.009	0.014	0.003	0.066
			DS	0.011	0.013	0.006	0.006	0.011	0.009	0.014	0.003	0.073
			CL	0.010	0.013	0.006	0.006	0.011	0.009	0.014	0.003	0.072
			WR	0.010	0.013	0.006	0.006	0.011	0.009	0.014	0.003	0.072
3.1.2.c	Tailings characterisation exists, considering the physical and geochemical properties, and it is updated throughout the lifecycle to account for variability in ore properties, processing, and tailings deposition.	2.2.c	US	0.009	0.002	0.002	0.002	0.009	0.002	0.005	0.001	0.031
			DS	0.004	0.002	0.002	0.002	0.004	0.002	0.005	0.001	0.021
			CL	0.005	0.002	0.002	0.002	0.004	0.002	0.005	0.001	0.023
			WR	0.003	0.002	0.002	0.002	0.004	0.002	0.005	0.001	0.021
3.2.1	To enhance resilience, climate change knowledge is regularly updated and used to evaluate risks and opportunities to the tailings facility lifecycle, in accordance with the principles of adaptive management, with the aim of enhancing resiliency to climate change.	3.1.a	US	0.003	0.016	0.006	0.002	0.006	0.024	0.004	0.001	0.062
			DS	0.003	0.020	0.006	0.002	0.009	0.024	0.004	0.001	0.069
			CL	0.003	0.020	0.006	0.002	0.009	0.024	0.004	0.001	0.069
			WR	0.003	0.020	0.006	0.002	0.009	0.024	0.004	0.001	0.069

3.2.2	For existing facilities that are not in a state of safe closure, there are periodic reviews of the tailings technologies, design and management strategies, and assessments of the potential to implement improvements arising from the reviews.	3.2.b	**US**	0.010	0.005	0.006	0.002	0.006	0.008	0.019	0.004	0.060
			DS	0.010	0.007	0.006	0.002	0.009	0.008	0.019	0.004	0.064
			CL	0.010	0.007	0.006	0.002	0.009	0.008	0.019	0.004	0.064
			WR	0.010	0.007	0.006	0.002	0.009	0.008	0.019	0.004	0.064
3.3.1.a	Extreme loads are already in place.	4.3.a	**US**	0.000	0.002	0.002	0.001	0.002	0.001	0.002	0.001	0.011
			DS	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			CL	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			WR	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
3.3.1.b	If Extreme Consequence Classification external loading criteria are not adopted, the Accountable Executive shall take the decision to adopt a design for the current Consequence Classification criteria and maintain flexibility to upgrade the design for the highest	4.3.b.	**US**	0.001	0.002	0.002	0.001	0.002	0.001	0.002	0.001	0.011
			DS	0.001	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			CL	0.001	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			WR	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
3.3.2.a	Select and identify design criteria that are appropriate to minimise risk for all credible failure modes during each phase of the tailings facility lifecycle.	4.4.a	**US**	0.003	0.014	0.018	0.005	0.014	0.008	0.017	0.004	0.083
			DS	0.003	0.007	0.018	0.005	0.013	0.008	0.017	0.004	0.075
			CL	0.003	0.007	0.018	0.005	0.013	0.008	0.017	0.004	0.075
			WR	0.003	0.007	0.018	0.005	0.013	0.008	0.017	0.004	0.075
3.3.2.b	Document the rationale for the design criteria selected to minimise risk.	4.4.b	**US**	0.001	0.005	0.006	0.002	0.005	0.003	0.006	0.001	0.028
			DS	0.001	0.002	0.006	0.002	0.004	0.003	0.006	0.001	0.025
			CL	0.001	0.002	0.006	0.002	0.004	0.003	0.006	0.001	0.025
			WR	0.001	0.002	0.006	0.002	0.004	0.003	0.006	0.001	0.025
3.3.3.a	Develop and apply design criteria such as factors of safety for slope stability and seepage management, for each lifecycle phase that considers: the estimated operational properties of materials and expected performance of the design elements, and; the quality of	4.5.a	**US**	0.001	0.004	0.005	0.001	0.004	0.003	0.005	0.001	0.025
			DS	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.022
			CL	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.022
			WR	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.022
3.3.3.b	Account for these design and implementation issues in assessments that are based on deformation analyses.	4.5.b	**US**	0.001	0.004	0.005	0.001	0.004	0.003	0.005	0.001	0.025
			DS	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.022
			CL	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.022
			WR	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.022
3.3.4.a	An assessment of the potential for brittle failure modes is documented and the analyses are addressed in the Design Basis Report (DBR).	4.6.a	**US**	0.001	0.003	0.004	0.001	0.003	0.002	0.004	0.001	0.020
			DS	0.001	0.002	0.004	0.001	0.003	0.002	0.004	0.001	0.018
			CL	0.001	0.002	0.004	0.001	0.003	0.002	0.004	0.001	0.018
			WR	0.001	0.002	0.004	0.001	0.003	0.002	0.004	0.001	0.018
3.3.5.a	Existing tailings facilities shall conform with the Requirements under Principle 4, except for those aspects where the Engineer of Record (EOR), with review by the ITRB or a senior independent technical reviewer, as appropriate, determines that the upgrade of an existing	4.7.a	**US**	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.009
			DS	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.008
			CL	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.008
			WR	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.008
3.3.5.b	If the condition in (a.) above applies, the Accountable Executive shall approve and document the implementation of measures to reduce both the probability and the consequences of a tailings facility failure to reduce the risk to a level as low as reasonably practicable	4.7.b	**US**	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.009
			DS	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.008
			CL	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.008
			WR	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.008
3.3.5.c	The basis and timing for addressing the upgrade of existing tailings facilities shall be risk-informed and carried out as soon as reasonably practicable.	4.7.c	**US**	0.001	0.004	0.005	0.001	0.004	0.003	0.005	0.001	0.026
			DS	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.023
			CL	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.023
			WR	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.023
3.3.6.a	The EOR shall prepare a Design Basis Report (DBR) that details the design assumptions and criteria, including operating constraints, and that provides the basis for the design of all phases of the tailings facility lifecycle.	4.8.a	**US**	0.001	0.004	0.005	0.001	0.004	0.002	0.005	0.001	0.023
			DS	0.001	0.002	0.005	0.001	0.004	0.002	0.005	0.001	0.021
			CL	0.001	0.002	0.005	0.001	0.004	0.002	0.005	0.001	0.021
			WR	0.001	0.002	0.005	0.001	0.004	0.002	0.005	0.001	0.021
3.3.6.b	The DBR shall be reviewed by the ITRB or senior independent technical reviewer.	4.8.b	**US**	0.001	0.004	0.005	0.001	0.004	0.002	0.005	0.001	0.023
			DS	0.001	0.002	0.005	0.001	0.004	0.002	0.005	0.001	0.021
			CL	0.001	0.002	0.005	0.001	0.004	0.002	0.005	0.001	0.021
			WR	0.001	0.002	0.005	0.001	0.004	0.002	0.005	0.001	0.021
3.3.6.c	The EOR shall update the DBR every time there is a material change in the design assumptions, design criteria, design or the knowledge base and confirm internal consistency among these elements.	4.8.c	**US**	0.001	0.004	0.005	0.001	0.004	0.002	0.005	0.001	0.023
			DS	0.001	0.002	0.005	0.001	0.004	0.002	0.005	0.001	0.021
			CL	0.001	0.002	0.005	0.001	0.004	0.002	0.005	0.001	0.021
			WR	0.001	0.002	0.005	0.001	0.004	0.002	0.005	0.001	0.021
3.4.1.a	For expansions to existing facilities, assess the outcomes of periodic reviews of potential refinements to tailings technologies and design approaches (as per Requirement 3.2).	5.1.b	**US**	0.001	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			DS	0.001	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			CL	0.001	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			WR	0.001	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
3.4.1.b	Where the design differs from the alternatives analysis, there is a rationale that incorporates the goal of minimising risks to people and the environment throughout the tailings facility lifecycle.	5.1.c	**US**	0.001	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			DS	0.001	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			CL	0.001	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			WR	0.001	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
3.4.2.a	A robust design that considers: The technical, social, environmental, and local economic context of the tailings facility. The Consequence Classification, site conditions, water management, mine plant operations, tailings operational and construction issues. The design	5.2.a	**US**	0.002	0.002	0.004	0.001	0.007	0.003	0.008	0.002	0.028
			DS	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
			CL	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
			WR	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
3.4.2.b	The design is reviewed and updated as performance and site data become available throughout the tailings facility lifecycle and / or in response to material changes.	5.2.b	**US**	0.002	0.002	0.004	0.001	0.007	0.003	0.008	0.002	0.028
			DS	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
			CL	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
			WR	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
3.4.3.a	A water management plan that takes into account the knowledge base, the mine plan for the current state of the tailings facility lifecycle, upstream and downstream hydrological and hydrogeological basins, and the potential for climate change.	5.3.a	**US**	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.007
			DS	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.008
			CL	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.008
			WR	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.008
3.4.3.b	A water balance model that considers the overall water management plan.	5.3.b	**US**	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.007
			DS	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.008
			CL	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.008
			WR	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.008

3.4.3.c	The water management plan and water balance address the safety of the tailings facility and the prevention of unintentional releases.	5.3.c	US	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.007
			DS	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.008
			CL	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.008
			WR	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.000	0.008
3.4.4.a	Potential failure modes to the structure, its foundation, abutments, reservoir (tailings deposit and pond), Reservoir rim, and appurtenant structures are identified, categorized by risk assessments, and addressed through preventative measures incorporated into the	5.4.a	US	0.002	0.002	0.004	0.001	0.007	0.003	0.008	0.002	0.028
			DS	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
			CL	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
			WR	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
3.4.4.b	Risk assessments are used to inform the design to minimise risk to ALARP. Risk assessments should be used to determine whether the potential credible failure mode(s)/scenario are credible.	5.4.b	US	0.002	0.002	0.004	0.001	0.007	0.003	0.008	0.002	0.028
			DS	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
			CL	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
			WR	0.002	0.003	0.004	0.001	0.006	0.003	0.008	0.002	0.029
3.4.5	Develop a design for each stage of construction of the tailings facility, including but not limited to start-up, partial raises and interim configurations, final raise, and all closure stages.	5.5.a	US	0.002	0.003	0.004	0.001	0.007	0.005	0.009	0.002	0.033
			DS	0.002	0.004	0.004	0.001	0.007	0.005	0.009	0.002	0.033
			CL	0.002	0.004	0.004	0.001	0.007	0.005	0.009	0.002	0.033
			WR	0.002	0.004	0.004	0.001	0.007	0.005	0.009	0.002	0.033
3.4.6.a	The closure design meets all the Requirements of the Standard with sufficient detail to demonstrate the feasibility of the closure scenario.	5.6.a	US	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			DS	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			CL	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			WR	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
3.4.6.b	The closure design allows implementation of elements of the closure design during construction and operation, as appropriate.	5.6.b	US	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			DS	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			CL	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			WR	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
3.4.6.c	The design includes progressive closure and reclamation during operations.	5.6.c	US	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			DS	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			CL	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			WR	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
3.4.7.a	Confirm that the design satisfies ALARP.	5.7.d	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.4.7.b	Seek to identify and implement additional reasonable steps that may be taken to further reduce potential consequences to people and the environment.	5.7.e	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.4.7.c	Explain and document the decisions with respect to ALARP and additional consequence reduction measures, in consultation with external parties as appropriate.	5.7.f	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.5.1.a	The design intent, established in the DBR, is understood and implemented for construction, operation and closure for each phase of the tailings facility lifecycle.	6.1.a	US	0.002	0.006	0.006	0.002	0.006	0.004	0.007	0.002	0.035
			DS	0.002	0.003	0.006	0.002	0.006	0.004	0.007	0.002	0.031
			CL	0.002	0.003	0.006	0.002	0.006	0.004	0.007	0.002	0.031
			WR	0.002	0.003	0.006	0.002	0.006	0.004	0.007	0.002	0.031
3.5.1.b	Construction and operating personnel assigned to tailings-related tasks are qualified based on the qualifications defined in the Tailings Management System (TMS).	6.1.b	US	0.001	0.002	0.002	0.001	0.002	0.001	0.002	0.001	0.012
			DS	0.001	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			CL	0.001	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			WR	0.001	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
3.5.1.c	Throughout all stages of the tailings facility lifecycle the appropriate methodology, equipment and procedures, data acquisition methods, are used and incorporated into the TMS and the Environmental and Social Management System (ESMS) for the mine and associated	6.1.c	US	0.002	0.006	0.006	0.002	0.006	0.004	0.007	0.002	0.035
			DS	0.002	0.003	0.006	0.002	0.006	0.004	0.007	0.002	0.031
			CL	0.002	0.003	0.006	0.002	0.006	0.004	0.007	0.002	0.031
			WR	0.002	0.003	0.006	0.002	0.006	0.004	0.007	0.002	0.031
3.5.1.d	The TMS and the ESMS are implemented during construction, operation, and closure.	6.1.d	US	0.001	0.002	0.002	0.001	0.002	0.001	0.002	0.001	0.012
			DS	0.001	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			CL	0.001	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			WR	0.001	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
3.5.2.a	Quality Control (QC) and Quality Assurance (QA) programmes are established to monitor the quality and adequacy of the construction and operation processes.	6.2.a	US	0.001	0.003	0.008	0.001	0.003	0.002	0.004	0.001	0.022
			DS	0.001	0.002	0.008	0.001	0.003	0.002	0.004	0.001	0.021
			CL	0.001	0.002	0.008	0.001	0.003	0.002	0.004	0.001	0.021
			WR	0.001	0.002	0.008	0.001	0.003	0.002	0.004	0.001	0.021
3.5.2.b	A CDIV programme that confirms that the design intent is met if site conditions vary from design assumptions.	6.2.b	US	0.001	0.003	0.008	0.001	0.003	0.002	0.004	0.001	0.022
			DS	0.001	0.002	0.008	0.001	0.003	0.002	0.004	0.001	0.021
			CL	0.001	0.002	0.008	0.001	0.003	0.002	0.004	0.001	0.021
			WR	0.001	0.002	0.008	0.001	0.003	0.002	0.004	0.001	0.021
3.5.3.a	Construction Records Reports (CRR) are up to date and are prepared when there is a material change to the tailings facility, its infrastructure, or its monitoring system.	6.3.a	US	0.001	0.004	0.005	0.001	0.004	0.003	0.005	0.001	0.026
			DS	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.023
			CL	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.023
			WR	0.001	0.002	0.005	0.001	0.004	0.003	0.005	0.001	0.023
3.5.3.b	The CRRs are signed by the RTFE and the EOR.	6.3.b	US	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.009
			DS	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.008
			CL	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.008
			WR	0.000	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.008
3.5.4.a	An Operation, Maintenance and Surveillance (OMS) Manual is implemented, covers each tailings facility and includes the requirements for the OMS activities necessary for the effective risk management based on best practice.	6.4.a	US	0.000	0.002	0.002	0.001	0.002	0.001	0.002	0.001	0.011
			DS	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			CL	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			WR	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
3.5.4.b	The OMS is reviewed annually or more frequently if there are any updates following a material change as defined by the Operator.	6.4.b	US	0.000	0.002	0.002	0.001	0.002	0.001	0.002	0.001	0.011
			DS	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			CL	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010
			WR	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.010

3.5.4.c	The OMS provides clear context and includes the inspection, maintenance and monitoring of the requirements identified including critical controls for safe operation and is reviewed for effectiveness.	6.4.c	**US**	0.000	0.001	0.001	0.000	0.001	0.000	0.001	0.000	0.004
			DS	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.003
			CL	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.003
			WR	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.003
3.5.4.d	The RTFE ensures that personnel involved in the TMS have access to the OMS Manual.	6.4.d	**US**	0.000	0.001	0.001	0.000	0.001	0.000	0.001	0.000	0.004
			DS	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.003
			CL	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.003
			WR	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.003
3.5.4.e	The RTFE should provide access to training to all levels of personnel involved in the TMS.	6.4.e	**US**	0.000	0.001	0.001	0.000	0.001	0.000	0.001	0.000	0.004
			DS	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.003
			CL	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.003
			WR	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.003
3.5.5.a	A Change Management System has been established.	6.5.a	**US**	0.000	0.001	0.001	0.000	0.001	0.000	0.001	0.000	0.004
			DS	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.004
			CL	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.004
			WR	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.004
3.5.5.b	The Change Management System includes processes for the identification of changes and processes for evaluation, review, approval and documentation of changes throughout the facility lifecycle.	6.5.b	**US**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.5.5.c	The Change Management System addresses and documents material changes to design, construction, operations, or monitoring.	6.5.c	**US**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.5.5.d	A DAR is periodically prepared and updated by the EOR that addresses the cumulative impact of material changes to the as-constructed facility.	6.5.d	**US**	0.000	0.001	0.001	0.000	0.001	0.000	0.001	0.000	0.004
			DS	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.004
			CL	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.004
			WR	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.004
3.5.5.e	Recommendations from the DAR have been implemented through updates to the construction, operations, design, DBR, OMS Manual and the monitoring programme.	6.5.e	**US**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.5.5.f	The Accountable Executive has approved the DAR.	6.5.f	**US**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.5.6.a	Reviews of new and emerging technologies and approaches for tailings management are carried out considering the tailings facility lifecycle.	6.6.a	**US**	0.002	0.008	0.008	0.003	0.008	0.005	0.010	0.002	0.046
			DS	0.002	0.004	0.008	0.003	0.008	0.005	0.010	0.002	0.042
			CL	0.002	0.004	0.008	0.003	0.008	0.005	0.010	0.002	0.042
			WR	0.002	0.004	0.008	0.003	0.008	0.005	0.010	0.002	0.042
3.5.6.b	Material results of the reviews have been incorporated into refinements of the facility design, construction and operations.	6.6.b	**US**	0.002	0.008	0.008	0.003	0.008	0.005	0.010	0.002	0.046
			DS	0.002	0.004	0.008	0.003	0.008	0.005	0.010	0.002	0.042
			CL	0.002	0.004	0.008	0.003	0.008	0.005	0.010	0.002	0.042
			WR	0.002	0.004	0.008	0.003	0.008	0.005	0.010	0.002	0.042
3.6.1.a	A comprehensive and integrated performance monitoring programme for the tailings facility and its appurtenant structures has been developed, and forms part of the TMS, and includes activities for inspection, reviews, and monitoring requirements in alignment with	7.1.a	**US**	0.002	0.003	0.004	0.001	0.007	0.004	0.008	0.002	0.031
			DS	0.002	0.004	0.004	0.001	0.006	0.004	0.008	0.002	0.031
			CL	0.002	0.004	0.004	0.001	0.006	0.004	0.008	0.002	0.031
			WR	0.002	0.004	0.004	0.001	0.006	0.004	0.008	0.002	0.031
3.6.1.b	Aspects of the ESMS that are linked to tailings facility's performance monitoring are identified and included in the performance monitoring programme.	7.1.b	**US**	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			DS	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			CL	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			WR	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
3.6.1.c	The performance monitoring programme is integrated and reflects other programmes such as the OMS and is updated in keeping with the principles of Adaptive Management.	7.1.c	**US**	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			DS	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			CL	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
			WR	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.010
3.6.2.a	A comprehensive and integrated engineering monitoring system has been designed and used to verify design assumptions and to monitor potential failure modes.	7.2.a	**US**	0.005	0.009	0.011	0.003	0.020	0.013	0.025	0.006	0.092
			DS	0.005	0.011	0.011	0.003	0.019	0.013	0.025	0.006	0.093
			CL	0.005	0.011	0.011	0.003	0.019	0.013	0.025	0.006	0.093
			WR	0.005	0.011	0.011	0.003	0.019	0.013	0.025	0.006	0.093
3.6.2.b	Monitoring procedures for non-brittle failure modes are developed and implemented to support the Observational Method.	7.2.b	**US**	0.002	0.003	0.004	0.001	0.007	0.004	0.008	0.002	0.031
			DS	0.002	0.004	0.004	0.001	0.006	0.004	0.008	0.002	0.031
			CL	0.002	0.004	0.004	0.001	0.006	0.004	0.008	0.002	0.031
			WR	0.002	0.004	0.004	0.001	0.006	0.004	0.008	0.002	0.031
3.6.2.c	Brittle failure modes are addressed by conservative design criteria.	7.2.c	**US**	0.002	0.003	0.004	0.001	0.007	0.004	0.008	0.002	0.031
			DS	0.002	0.004	0.004	0.001	0.006	0.004	0.008	0.002	0.031
			CL	0.002	0.004	0.004	0.001	0.006	0.004	0.008	0.002	0.031
			WR	0.002	0.004	0.004	0.001	0.006	0.004	0.008	0.002	0.031
3.6.3.a	Performance objectives, indicators and criteria are set that measure the performance of the tailings facility. These are specific and measurable and included in the monitoring programmes.	7.3.a	**US**	0.003	0.005	0.006	0.002	0.011	0.007	0.014	0.003	0.051
			DS	0.003	0.006	0.006	0.002	0.011	0.007	0.014	0.003	0.052
			CL	0.003	0.006	0.006	0.002	0.011	0.007	0.014	0.003	0.052
			WR	0.003	0.006	0.006	0.002	0.011	0.007	0.014	0.003	0.052
3.6.3.b	Routine and regular inspecting, monitoring, testing, recording, evaluating and reporting of the data from the monitoring programmes is conducted according to the established appropriate frequency.	7.3.b	**US**	0.003	0.005	0.006	0.002	0.011	0.007	0.014	0.003	0.051
			DS	0.003	0.006	0.006	0.002	0.011	0.007	0.014	0.003	0.052
			CL	0.003	0.006	0.006	0.002	0.011	0.007	0.014	0.003	0.052
			WR	0.003	0.006	0.006	0.002	0.011	0.007	0.014	0.003	0.052
3.6.3.c	The monitoring programme is updated throughout the tailings facility lifecycle based on the evaluation of the data to confirm that the performance objectives, indicators and criteria remain effective to manage risk.	7.3.c	**US**	0.003	0.005	0.006	0.002	0.011	0.007	0.014	0.003	0.051
			DS	0.003	0.006	0.006	0.002	0.011	0.007	0.014	0.003	0.052
			CL	0.003	0.006	0.006	0.002	0.011	0.007	0.014	0.003	0.052
			WR	0.003	0.006	0.006	0.002	0.011	0.007	0.014	0.003	0.052

3.6.4.a	The tailings facility performance is assessed by analysing technical monitoring data at a frequency established by the EOR.	7.4.a	US	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
			DS	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
			CL	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
			WR	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
3.6.4.b	The analysis of tailings facility technical monitoring data clearly identifies and presents evidence on deviations from the expected performance objectives and deterioration of the tailings facility performance over time.	7.4.b	US	0.004	0.006	0.007	0.002	0.013	0.009	0.017	0.004	0.060
			DS	0.004	0.007	0.007	0.002	0.013	0.009	0.017	0.004	0.061
			CL	0.004	0.007	0.007	0.002	0.013	0.009	0.017	0.004	0.061
			WR	0.004	0.007	0.007	0.002	0.013	0.009	0.017	0.004	0.061
3.6.4.c	The results from the tailings facility performance monitoring analysis are promptly reported to the EOR.	7.4.c	US	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
			DS	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
			CL	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
			WR	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
3.6.4.d	The EOR promptly reviews the tailings facility performance monitoring analysis results and if required, directs that the risk assessment and design be updated.	7.4.d	US	0.002	0.003	0.004	0.001	0.008	0.005	0.010	0.002	0.036
			DS	0.002	0.004	0.004	0.001	0.008	0.005	0.010	0.002	0.036
			CL	0.002	0.004	0.004	0.001	0.008	0.005	0.010	0.002	0.036
			WR	0.002	0.004	0.004	0.001	0.008	0.005	0.010	0.002	0.036
3.6.4.e	Performance expectations are incorporated into Trigger Action Response Plans or critical controls as criteria to state when action is or is not needed.	7.4.e	US	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
			DS	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
			CL	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
			WR	0.001	0.002	0.002	0.001	0.004	0.003	0.005	0.001	0.019
3.6.5.a	The results of the monitoring programmes are reported at a frequency that meets company expectations and regulatory requirements and at a minimum is completed annually.	7.5.a	US	0.001	0.002	0.003	0.001	0.006	0.004	0.007	0.002	0.025
			DS	0.001	0.003	0.003	0.001	0.005	0.004	0.007	0.002	0.026
			CL	0.001	0.003	0.003	0.001	0.005	0.004	0.007	0.002	0.026
			WR	0.001	0.003	0.003	0.001	0.005	0.004	0.007	0.002	0.026
3.6.5.b	Technical monitoring reports are reviewed and approved by the RTFE and the EOR.	7.5.b	US	0.001	0.002	0.003	0.001	0.006	0.004	0.007	0.002	0.025
			DS	0.001	0.003	0.003	0.001	0.005	0.004	0.007	0.002	0.026
			CL	0.001	0.003	0.003	0.001	0.005	0.004	0.007	0.002	0.026
			WR	0.001	0.003	0.003	0.001	0.005	0.004	0.007	0.002	0.026
3.7.1.a	A documented corporate tailings management policy that commits the Operator to the safe management of tailings, development of emergency response plans, and mechanisms for recovery after failure. This may be in the form of a standalone policy or embedded	8.1.a	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.7.1.b	The policy and its endorsement by the Board of Directors is in writing and is publicly available.	8.1.b	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
3.7.2.a	A performance based TMS , follows established Plan-Do-Check-Act processes and is suitable for the organisation and its tailings facilities.	8.2.a	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
3.7.2.b	Accountabilities, responsibilities and associated competencies for the implementation of that framework are defined that supports appropriate identification and management of tailings facility risks.	8.2.b	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
3.7.2.c	The governance framework supports the TMS, its relevant critical systems and other related ESMS.	8.2.c	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
3.7.2.d	The linkages between the TMS and other systems such as the ESMS are clear to ensure effective integrated management of the tailings facility.	8.2.d	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
3.7.3.a	For persons with responsibility for tailings facilities, their performance reviews and or incentive payments are based in part, on public safety and the integrity of the tailings facilities.	8.3.a	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
3.7.3.b	Where incentive payments are used, they are based on the degree to which public safety and tailing facility integrity are a component of that role.	8.3.b	US	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.7.3.c	Long-term incentives, as part of executive compensation, take tailings management, facility performance, and public safety into account.	8.3.c	US	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.7.4.a	Accountable Executive(s) who is directly answerable to the CEO have been identified and assigned the safety aspects of a tailings facility and for avoiding or minimising the social and environmental consequences of a tailings facility failure.	8.4.a	US	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			DS	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			CL	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			WR	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
3.7.4.b	The accountability referred to in (a) includes developing and implementing a programme of tailings management training, and for emergency preparedness and response.	8.4.b	US	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			DS	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			CL	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			WR	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
3.7.4.c	The Accountable Executive(s) has regular and scheduled communications with the EOR and Board of Directors which can be initiated either by the Accountable Executive or the Board.	8.4.c	US	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			DS	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			CL	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			WR	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
3.7.4.d	The process by which the Board of Directors holds the Accountable Executive(s) responsible is documented.	8.4.d	US	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001

3.7.5.a	A Responsible Tailings Facility Engineer (RTFE) is appointed to the role.	8.5.a	US	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			DS	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			CL	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			WR	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
3.7.5.b	Roles and responsibilities are clearly defined and documented for the RTFE position including accountability for the integrity of the tailings facility.	8.5.b	US	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.7.5.c	The RTFE liaises with the EOR and internal teams.	8.5.c	US	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			DS	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			CL	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			WR	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
3.7.5.d	The RTFE must be familiar with the DBR, relevant design reports, and the construction and operations/performance of the tailings facility.	8.5.d	US	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.7.5.e	Communication occurs between the RTFE and the Accountable Executive, or designee.	8.5.e	US	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			DS	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			CL	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			WR	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
3.7.6.a	Qualification and experience requirements for all personnel with safety critical roles are clearly defined and are appropriate to the level of responsibility for that position. This includes but is not limited to critical roles such as the RTFE, EOR and Accountable Executives.	8.6.a	US	0.001	0.001	0.002	0.000	0.002	0.002	0.003	0.001	0.011
			DS	0.001	0.001	0.002	0.000	0.002	0.002	0.003	0.001	0.012
			CL	0.001	0.001	0.002	0.000	0.002	0.002	0.003	0.001	0.012
			WR	0.001	0.001	0.002	0.000	0.002	0.002	0.003	0.001	0.012
3.7.6.b	Succession plans are developed for safety-critical roles.	8.6.b	US	0.001	0.001	0.002	0.000	0.002	0.002	0.003	0.001	0.011
			DS	0.001	0.001	0.002	0.000	0.002	0.002	0.003	0.001	0.012
			CL	0.001	0.001	0.002	0.000	0.002	0.002	0.003	0.001	0.012
			WR	0.001	0.001	0.002	0.000	0.002	0.002	0.003	0.001	0.012
3.7.7.a	For a tailings facility with a consequence classification of failure of 'Very High' to 'Extreme', the Operator has appointed an Independent Tailings Review Board (ITRB).	8.7.a	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.003
			DS	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			CL	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			WR	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
3.7.7.b	For a tailings facility with a consequence classification of failure of 'High' or lower, in the absence of an ITRB, the Operator has appointed a senior independent technical reviewer.	8.7.b	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.003
			DS	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			CL	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			WR	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
3.7.7.c	The ITRB or a senior independent technical reviewer report to the Accountable Executive for the tailings facility or delegate.	8.7.c	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.003
			DS	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			CL	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			WR	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
3.7.7.d	The ITRB or a senior independent technical reviewer is appointed during the early phase of tailings facility site investigation and design engineering (suggested pre-feasibility).	8.7.d	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.003
			DS	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			CL	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			WR	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
3.7.7.e	The ITRB members and a senior independent technical reviewer have certified in writing the absence of a conflict of interest with the tailings facility as defined by best practice.	8.7.e	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.003
			DS	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			CL	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			WR	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
3.8.1.a	For all operating tailings facilities, and for closed facilities with consequence categories of 'High', 'Very High' and 'Extreme' an engineering firm which has the design and construction expertise for tailings facilities of comparable complexity has been engaged.	9.1.a	US	0.001	0.002	0.002	0.001	0.002	0.002	0.005	0.001	0.016
			DS	0.001	0.002	0.002	0.001	0.004	0.002	0.005	0.001	0.018
			CL	0.001	0.002	0.002	0.001	0.004	0.002	0.005	0.001	0.018
			WR	0.001	0.002	0.002	0.001	0.004	0.002	0.005	0.001	0.018
3.8.1.b	The appointed Engineer of Record (EOR) has experience and expertise commensurate with the complexity of the tailings facility and the consequence class and the appointment has been approved by the Operator.	9.1.b	US	0.001	0.002	0.002	0.001	0.002	0.002	0.005	0.001	0.016
			DS	0.001	0.002	0.002	0.001	0.004	0.002	0.005	0.001	0.018
			CL	0.001	0.002	0.002	0.001	0.004	0.002	0.005	0.001	0.018
			WR	0.001	0.002	0.002	0.001	0.004	0.002	0.005	0.001	0.018
3.8.1.c	A DOR, if appropriate either due to selection of an EOR internal to the Operator or other circumstances, is appointed that meets the essential qualifications and requirements of the EOR.	9.1.c	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.8.2.a	An EOR is appointed and in place at all times throughout the tailings facility lifecycle. The appointed EOR may change during the tailings facility lifecycle.	9.2.a	US	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.003
			DS	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			CL	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
			WR	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.004
3.8.2.b	The EOR is appointed through a written agreement that clearly describes their authority, role and responsibilities throughout the tailings facility lifecycle, and during change of ownership of mining properties.	9.2.b	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
3.8.2.c	The written agreement clearly describes the obligations of the Operator to the EOR, to support the effective performance of the EOR during the tailings facility lifecycle.	9.2.c	US	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.8.3.a	A programme is established to manage the quality of all engineering work and interactions between the EOR, the RTFE and the Accountable Executive.	9.3.a	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.008
			DS	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			CL	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			WR	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
3.8.3.b	The established programme is implemented to manage the quality of all engineering work and the interactions between the EOR, the RTFE and the Accountable Executive.	9.3.b	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.008
			DS	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			CL	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			WR	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008

3.8.3.c	The programme, developed by the Operator, covers the involvement of the EOR, the RTFE and the Accountable Executive in the tailings facility lifecycle as necessary to confirm that both the implementation of the design and the design intent are met.	9.3.c	US	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.003
			DS	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			CL	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
			WR	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.003
3.8.4.a	The risks and associated potential impacts with a tailings facility are considered by the Accountable Executive in selecting the EOR.	9.4.a	US	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			DS	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			CL	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
			WR	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.004
3.8.4.b	The selection of the EOR shall be decided by the Accountable Executive and informed, but not decided, by procurement personnel.	9.4.b	US	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.8.4.c	EOR selection is consistent with Requirement 9.1.	9.4.c	US	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.8.5.a	A succession plan is in place when it is necessary to change the EOR (whether a firm or within a firm, or an in-house employee).	9.5.a	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.8.5.b	The succession plan includes the comprehensive transfer of data, information, knowledge and experience with the construction procedures and materials.	9.5.b	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.9.1.a	A risk assessment process is in place for the tailings facility and is based on an up to date knowledge base for the tailings facility.	10.1.a	US	0.001	0.001	0.002	0.001	0.004	0.002	0.004	0.001	0.016
			DS	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			CL	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			WR	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
3.9.1.b	The risk assessment is updated at least every three years and more frequently whenever there is a material change either to the tailings facility or to the social, environmental and local economic context.	10.1.b	US	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			DS	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			CL	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			WR	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
3.9.1.c	Risk assessment scope to include the full potential area of influence of the tailings facility, and to actively incorporate industry experience in risk assessment	10.1.c	US	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			DS	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			CL	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
			WR	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.001	0.009
3.9.1.d	Sources of risk are regularly identified, assessed and managed at all phases of the tailings facility lifecycle, including projected climate change impacts under a range of credible future climate scenarios.	10.1.d	US	0.001	0.001	0.002	0.001	0.004	0.002	0.004	0.001	0.016
			DS	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			CL	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			WR	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
3.9.1.e	A multi-disciplinary team is qualified to undertake the risk assessment specific to the phase of the tailings facility lifecycle (i.e. construction, operation, suspension, expansion, closure) and has the ability to apply best practice methodology in a cross-functional	10.1.e	US	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
3.9.1.f	Following review by the ITRB or senior independent technical reviewer, action plans are prepared, implemented and reported when risk assessments identify unacceptable tailings facility risks.	10.1.f	US	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
3.9.2.a	The TMS and components of the ESMS are reviewed sufficiently often to assure that the tailings facility management system is effective and applicable for the risks across the full lifecycle of the facility.	10.2.a	US	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011
			DS	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011
			CL	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011
			WR	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011
3.9.2.b	The outcomes of the TMS and ESMS reviews are documented and reported to the Accountable Executive, Board of Directors and project-affected people.	10.2.b	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.9.2.c	The review shall be undertaken by senior technical reviewers with the appropriate qualifications, expertise and resources.	10.2.c	US	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011
			DS	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011
			CL	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011
			WR	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011
3.9.2.d	For tailings facilities with 'High', 'Very High' or 'Extreme' Consequence Classification, the review is conducted at least every three years.	10.2.d	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.9.3	Internal audits are completed at a frequency to ensure consistent implementation of established requirements that related to company procedures, guidelines and corporate governance requirements that is consistent with the TMS and aspects of the ESMS relating to	10.3.a	US	0.001	0.002	0.002	0.001	0.004	0.002	0.005	0.001	0.018
			DS	0.001	0.002	0.002	0.001	0.004	0.002	0.005	0.001	0.018
			CL	0.001	0.002	0.002	0.001	0.004	0.002	0.005	0.001	0.018
			WR	0.001	0.002	0.002	0.001	0.004	0.002	0.005	0.001	0.018
3.9.4	An annual tailings facility review is conducted throughout the construction and operational periods to assess condition and performance. The reviews are performed by the EOR or the senior independent technical reviewer, as assigned for the tailings facility,	10.4.a	US	0.003	0.005	0.007	0.002	0.013	0.008	0.016	0.003	0.058
			DS	0.003	0.007	0.007	0.002	0.012	0.008	0.016	0.003	0.058
			CL	0.003	0.007	0.007	0.002	0.012	0.008	0.016	0.003	0.058
			WR	0.003	0.007	0.007	0.002	0.012	0.008	0.016	0.003	0.058
3.9.5.a	DSRs are conducted and documented: — every five years for tailings facilities with 'Very High' or 'Extreme' Consequence Classifications. Every 10 years for all other facilities, or, more frequently as recommended by the ITRB.	10.5.a	US	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			DS	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			CL	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			WR	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
3.9.5.b	DSRs include technical, operational and governance aspects of the tailings facility and shall be completed according to best practice.	10.5.b	US	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			DS	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			CL	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			WR	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008

3.9.5.c	DSR individuals cannot conduct consecutive DSRs on the same tailings facility.	10.5.c	US	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			DS	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			CL	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			WR	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
3.9.5.d	DSR individuals certify in writing that they follow best practices for engineers in avoiding conflicts of interest.	10.5.d	US	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			DS	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			CL	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
			WR	0.000	0.001	0.001	0.000	0.002	0.001	0.002	0.000	0.008
3.9.6.a	For tailings facilities with 'Very High' or 'Extreme' Consequence Classifications, the ITRB 1 , reporting to the Accountable Executive provides ongoing senior independent technical review of the planning, siting, design, construction, operation, water and mass	10.6.a	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.9.6.b	For tailings facilities with other Consequence Classifications, this review can alternatively be performed by a senior independent technical reviewer.	10.6.b	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.9.6.c	The ongoing reviews are conducted at appropriate intervals across all phases of the tailings facility lifecycle.	10.6.c	US	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.000	0.006
3.9.7.a	A process and governance mechanisms have been established for closure planning and closure cost estimating.	10.7.a	US	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
3.9.7.b	A closure plan for the tailings facility has been established and associated closure cost estimates has been prepared.	10.7.b	US	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
3.9.7.c	Closure cost estimates are reviewed periodically and public disclosure is made annually to confirm that adequate financial capacity (including insurance, to the extent commercially reasonable) is in place to meet the closure requirements and	10.7.c	US	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			DS	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			CL	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
			WR	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.005
3.9.7.d	If any of an Operator's assets involving a tailings facility underwent a change in Ownership since the last review, the Operator must provide documentation that they assessed and took into account the capability of an acquirer to maintain this Standard (subject to	10.7.d	US	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
			DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
			CL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
			WR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
3.10.1.a	The Operator has developed an educational programme inclusive of job procedures and responsibilities for prevention of a failure.	11.1.a	US	0.002	0.003	0.004	0.001	0.007	0.004	0.009	0.002	0.031
			DS	0.002	0.004	0.004	0.001	0.007	0.004	0.009	0.002	0.032
			CL	0.002	0.004	0.004	0.001	0.007	0.004	0.009	0.002	0.032
			WR	0.002	0.004	0.004	0.001	0.007	0.004	0.009	0.002	0.032
3.10.1.b	Those with roles for preventing a failure in any phase of the tailing facility lifecycle is included in the education programme.	11.1.b	US	0.001	0.001	0.002	0.001	0.004	0.002	0.004	0.001	0.016
			DS	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			CL	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			WR	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
3.10.2	Mechanisms have been established that incorporate workers' experience-based knowledge into planning, design and operations for all phases of the tailings facility lifecycle.	11.2.a	US	0.003	0.004	0.006	0.002	0.011	0.006	0.013	0.003	0.047
			DS	0.003	0.005	0.006	0.002	0.010	0.006	0.013	0.003	0.047
			CL	0.003	0.005	0.006	0.002	0.010	0.006	0.013	0.003	0.047
			WR	0.003	0.005	0.006	0.002	0.010	0.006	0.013	0.003	0.047
3.10.3	The Operator has established mechanisms that promote cross-functional collaboration to support public safety and the integrity of the tailings facility through: effective data and knowledge sharing, effective communication, and implementation of management	11.3.a	US	0.003	0.004	0.006	0.002	0.011	0.006	0.013	0.003	0.047
			DS	0.003	0.005	0.006	0.002	0.010	0.006	0.013	0.003	0.047
			CL	0.003	0.005	0.006	0.002	0.010	0.006	0.013	0.003	0.047
			WR	0.003	0.005	0.006	0.002	0.010	0.006	0.013	0.003	0.047
3.10.4.a	The Operator has identified and implemented lessons from internal incident investigations.	11.4.a	US	0.001	0.001	0.002	0.001	0.004	0.002	0.004	0.001	0.016
			DS	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			CL	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			WR	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
3.10.4.b	The Operator has identified and implemented lessons from relevant external incident reports.	11.4.b	US	0.001	0.001	0.002	0.001	0.004	0.002	0.004	0.001	0.016
			DS	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			CL	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			WR	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
3.10.4.c	Internal and external incident lessons learned pay particular attention to human and organisational factors.	11.4.c	US	0.001	0.001	0.002	0.001	0.004	0.002	0.004	0.001	0.016
			DS	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			CL	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			WR	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
3.10.5.a	The Operator has established a documented mechanism that recognises, rewards and protects employees and contractors who report problems or identify opportunities for improving tailings facility management.	11.5.a	US	0.002	0.003	0.004	0.001	0.007	0.004	0.009	0.002	0.031
			DS	0.002	0.004	0.004	0.001	0.007	0.004	0.009	0.002	0.032
			CL	0.002	0.004	0.004	0.001	0.007	0.004	0.009	0.002	0.032
			WR	0.002	0.004	0.004	0.001	0.007	0.004	0.009	0.002	0.032
3.10.5.b	The Operator has responded in a timely manner, and communicated to employees and contractors the actions taken in response to concerns and opportunities raised.	11.5.b	US	0.001	0.001	0.002	0.001	0.004	0.002	0.004	0.001	0.016
			DS	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			CL	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
			WR	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.001	0.016
3.11.1	Accountable Executive has established a formal, confidential and written process to receive, investigate and promptly address concerns from employees and contractors related to the tailings facility, including possible permit violations or other matters related to	12.1.a	US	0.004	0.007	0.008	0.002	0.009	0.009	0.017	0.004	0.059
			DS	0.004	0.007	0.008	0.002	0.013	0.009	0.017	0.004	0.065
			CL	0.004	0.007	0.008	0.002	0.013	0.009	0.017	0.004	0.065
			WR	0.004	0.007	0.008	0.002	0.013	0.009	0.017	0.004	0.065
3.11.2	The Operator maintains whistleblower protection practices that do not discharge, discriminate or retaliate against a whistleblower who in good faith reports possible violations relating to regulatory compliance, public safety, tailings facility integrity or the	12.2.a	US	0.001	0.002	0.003	0.001	0.003	0.003	0.006	0.001	0.020
			DS	0.001	0.002	0.003	0.001	0.004	0.003	0.006	0.001	0.022
			CL	0.001	0.002	0.003	0.001	0.004	0.003	0.006	0.001	0.022
			WR	0.001	0.002	0.003	0.001	0.004	0.003	0.006	0.001	0.022

3.12.1.a	All of the disclosures specified in 15.1(A) and (B) above are addressed.	15.1.a	US	0.001	0.002	0.003	0.001	0.003	0.003	0.006	0.001	0.020
			DS	0.001	0.002	0.003	0.001	0.004	0.003	0.006	0.001	0.022
			CL	0.001	0.002	0.003	0.001	0.004	0.003	0.006	0.001	0.022
			WR	0.001	0.002	0.003	0.001	0.004	0.003	0.006	0.001	0.022
3.12.1.b	The disclosures specified in 15.1(C) are addressed.	15.1.b	US	0.001	0.002	0.003	0.001	0.003	0.003	0.006	0.001	0.020
			DS	0.001	0.002	0.003	0.001	0.004	0.003	0.006	0.001	0.022
			CL	0.001	0.002	0.003	0.001	0.004	0.003	0.006	0.001	0.022
			WR	0.001	0.002	0.003	0.001	0.004	0.003	0.006	0.001	0.022
3.12.2.a	The Operator maintains a systematic and timely approach to responding to requests from project-affected people for information material to public safety and integrity of a tailings facility.	15.2.a	US	0.002	0.003	0.004	0.001	0.004	0.004	0.009	0.002	0.030
			DS	0.002	0.004	0.004	0.001	0.007	0.004	0.009	0.002	0.032
			CL	0.002	0.004	0.004	0.001	0.007	0.004	0.009	0.002	0.032
			WR	0.002	0.004	0.004	0.001	0.007	0.004	0.009	0.002	0.032
3.12.2.b	In instances where such requests are denied by the Operator, an explanation shall be provided to the requesting project-affected people in a reasonable timeframe and records shall be kept of relevant explanations provided to the requesting project-affected	15.2.b	US	0.001	0.001	0.001	0.000	0.001	0.001	0.003	0.001	0.010
			DS	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011
			CL	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011
			WR	0.001	0.001	0.001	0.000	0.002	0.001	0.003	0.001	0.011

B.3. Input Questions and Options

The descriptions of inputs linked to contributing factors are outlined here. Input options, along with their effects, are also presented. Cells marked in green signify a favourable input, yellow denotes neutrality, red indicates an adverse impact, and orange designates an unknown effect. These effects are associated with various modifiers. Please be advised that in the case of the LoP, there are no questions; only statements of contributing factors. The input options remain consistent across all factors.

Site Conditions

Table B.8: Questions and Input Options Site Conditions, Showing Effects on the Baseline Probability of Failure (PoF) *– Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange)*

ID	Input Question	Input Options
1.1	What is the Peak Ground Acceleration (PGA) at the site? If unknown, utilise seismic hazard map (GSHAP, 2011), note at the map return period 475 years/10% probability of exceedance in 50 years. (see sheet 'Maps')	PGA ≤ 0.2 g (return period 475 years/10% probability of
		0.2 g < PGA ≤ 0.4 g (return period 475 years/10% probability
		PGA > 0.4 g (return period 475 years/10% probability of
1.2	Are (active) faults are crossing the TSF or exist in close proximity such that they may induce ground motions at the TSF?	No
		Yes, inactive, but very unlikely to cause ground motions
		Yes, inactive faults which may potentially cause ground
		Yes, active faults, which may cause ground motions
		Unknown
1.3	What is the estimated size of the catchment area of the TSF compared to the TSF Footprint?	Catchment area ≈ TSF footprint
		Catchment area ≈ 2 x TSF footprint
		Catchment area >> 2 x TSF footprint
		Unknown
1.4	What is the climate at site (according to Köppen Climate Classification)? If unknown, utilise climate map (Beck, 2018). B14(see sheet 'Maps')	Af (tropical; rainforest)
		Am (tropical; monsoon)
		Aw (tropical; savanna, dry winter)
		As (tropical; savanna, dry summer)
		B (arid)
		Cf (temperate; no dry season)
		Cw (temperate; dry winter)
		Cs (temperate; dry summer)
		Dfa (continental; no dry season; hot summer)
		Dfb (continental; no dry season; warm summer)
		Dfc (continental; no dry season; cold summer)
		Dfd (continental; dry winter; very cold winter)
		Dwa (continental; dry winter; hot summer)
		Dwb (continental; dry winter; warm summer)
		Dwc (continental; dry winter; cold summer)
		Dwd (continental; dry winter; very cold winter)
		Dsa (continental; dry summer; hot summer)
		Dsb (continental; dry summer; warm summer)
		Dsc (continental; dry summer; cold summer)
		Dsd (continental; dry winter; very cold winter)
		ET (polar; tundra)
		EF (polar; ice cap)

1.5	What is the climate at site (according to Köppen Climate Classification)? If unknown, utilise climate map (Beck, 2018). B14(see sheet 'Maps')	Af (tropical; rainforest) Am (tropical; monsoon) Aw (tropical; savanna, dry winter) As (tropical; savanna, dry summer) B (arid) Cf (temperate; no dry season) Cw (temperate; dry winter) Cs (temperate; dry summer) Dfa (continental; no dry season; hot summer) Dfb (continental; no dry season; warm summer) Dfc (continental; no dry season; cold summer) Dfd (continental; dry winter; very cold winter) Dwa (continental; dry winter; hot summer) Dwb (continental; dry winter; warm summer) Dwc (continental; dry winter; cold summer) Dwd (continental; dry winter; very cold winter) Dsa (continental; dry summer; hot summer) Dsb (continental; dry summer; warm summer) Dsc (continental; dry summer; cold summer) Dsd (continental; dry winter; very cold winter) ET (polar; tundra) EF (polar; ice cap)
1.6		Af (tropical; rainforest) Am (tropical; monsoon) Aw (tropical; savanna, dry winter) As (tropical; savanna, dry summer) B (arid) Cf (temperate; no dry season) Cw (temperate; dry winter) Cs (temperate; dry summer) Dfa (continental; no dry season; hot summer) Dfb (continental; no dry season; warm summer) Dfc (continental; no dry season; cold summer) Dfd (continental; dry winter; very cold winter) Dwa (continental; dry winter; hot summer) Dwb (continental; dry winter; warm summer) Dwc (continental; dry winter; cold summer) Dwd (continental; dry winter; very cold winter) Dsa (continental; dry summer; hot summer) Dsb (continental; dry summer; warm summer) Dsc (continental; dry summer; cold summer) Dsd (continental; dry winter; very cold winter) ET (polar; tundra) EF (polar; ice cap)
1.7	Is there permafrost present at the site and is there a potential for thawing? If unknown, utilise permafrost map (Brown et al., 2002). (see sheet 'Maps')	No Yes, with no anticipated thawing or freeze/thaw cycles in the Yes, with potential thawing in the next decades and/or Yes, but uncertain regarding thawing and/or freeze/thaw
1.8	Is the site susceptible to hurricanes, cyclones and typhoons? If unknown, utilise hurricanes, cyclones and typhoons map (Dilley et al., 2005;CHRR, 2005). (see sheet 'Maps')	No Perhaps, potential vulnerability falls within the 0-5th decile of Yes, vulnerability falls within the 5th-10th decile of hazard
1.9	Is the site prone to generation of high waves in ponded water due to strong winds? If unkown, utilise wind map (Global Wind Atlas, 2023). (see sheet 'Maps')	No, mean wind speed < 5 m/s, wind not in the direction of the Possibly Likely, mean wind speed > 10 m/s or Weibull k parameter>2
1.10	Is the site surrounded by steep terrain with potential collapse?	No Yes, but stable slopes Yes, potentially marginally stable to unstable slopes (e.g. Yes, but unknown stability
1.11	Do the location of the site and the project constraints require a minimum embankment height?	No, embankments < 25 m can be constructed Yes, embankments between 25 and 100 m are required Yes, embankments must be greater than 100 m
1.12	Does the location allow for the practical construction of a permanent or emergency spillway?	Yes Yes, but walls marginally stable to unstable (e.g. slopes with No, difficult to construct
1.13	Is the site prone to generation of material/debris accumulation or ice damming?	No Perhaps Yes Unknown
1.14	Are artesian pressures identified which may affect the embankment?	No Yes Unknown
1.15	Is the foundation underlying the TSF characterised by strain-softening or contractive material?	No Yes, but material only present in minor quantities Yes Unknown
1.16	Is there collapsible or dispersive material present within the foundation (e.g. karst or salt domes)?	No Yes Unknown

1.17	Is there compressible material present within the foundation (e.g. peat)?	No Yes, but material only present in minor quantities Yes Unknown
1.18	Is there potential for weakness planes to exist within the foundation materials (e.g. pre-sheared surfaces in clay)?	No Yes, but does not play a role in stability Yes Unknown
1.19	Is the foundation material potentially geochemically incompatible?	No Yes, but material only present in minor quantities Yes Unknown
1.20.a	Is the permeability of the foundation underlying the TSF significantly high enough to potentially elevate the risk of internal erosion or compromise foundation strength?	No Yes, but material only present in minor quantities Yes Unknown
1.20.b	Is the permeability of the foundation underlying the TSF relatively low, to the extent that it may significantly contribute to the generation of excessive pore pressures?	No Yes, but material only present in minor quantities Yes Unknown
1.21	Are foundation units potentially variable (in e.g. strength, stress history, and permeability) in both vertical and lateral extents within the TSF proximity?	No Yes, but insignificant variability Yes Unknown
1.22	Are gap-graded soils present in the foundation?	No Yes, but material only present in minor quantities Yes Unknown
1.23	Are there culverts or pipes present in the foundation?	No Yes Unknown
1.24	Are there significant discontinuities or cracks expected to be present in the foundation?	No Potentially Yes Unknown
1.25	Is there a boundary in the foundation between two units with a significant difference in grain size, where the presence of water flow along the boundary is possible?	No Yes Unknown
1.26	Do the available materials for the dam core, filters, and shell possess the potential for internal instability?	No Potentially Yes Unknown
1.27	Do the available materials for the dam core, filters, and shell possess the potential for geochemical incompatibility?	No Potentially Yes Unknown
1.28	Do the available materials for the dam shell exhibit a low resistance to erosion (e.g. wind, wave, water flow)?	No Potentially Yes Unknown
1.29	Did the site had previous disturbances, which likely included excavations and fills that have not been characterised and documented?	No Potentially Yes Unknown
1.30.a	Is the TSF located directly, partly above or in the very vicinity of underground mine workings?	No Yes, in the close vicinity Yes, partly/directly above
1.30.b	Are unsupported mining methods, such as longwall mining, sublevel caving, or block caving, utilised in the underground mine?	No Yes Unknown
1.30.c	Is the host rock within the mining location characterised as weak?	No Slightly Yes Unknown
1.30.d	Are selective extraction practices employed at the underground mine?	No Yes Unknown
1.30.e	Does the underground mine conduct extensive dewatering operations?	No Yes, but not extreme Yes Unknown
1.30.f	May the active mining process produce vibrations that could potentially affect the embankment?	No Potentially Yes Unknown
1.31	Do activities such as working on the embankment crest, nearby construction work, open-pit mining operations, or the operation of machinery and vehicles in close proximity to the TSF result in substantial loads or vibrations at the site?	No Potentially Yes Unknown

Design Elements

Table B.9: Questions and Input Options Design Elements, Showing Effects on the Baseline Probability of Failure (PoF) *– Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange)*

ID	Input Question	Input Options
2.1	Is the dam designed to maintain a FoS>1 under the maximum credible earthquake?	Yes No Unknown
2.2	Does the design incorporate the presence of active faults?	Yes No Unknown
2.3.a	Does the design consider a detailed water balance?	Yes No Unknown
2.3.b	Does the water balance consider the catchment area?	Yes No Unknown
2.3.c	Does the water balance account for the Maximum Probable Flood (MPF), including the consideration of atmospheric rivers and intense rainfall events?	Yes No Unknown
2.3.d	Does the water balance take into consideration rain-on-snow events?	Yes No Unknown
2.3.e	Does the water balance account for (significant) snowmelt?	Yes No Unknown
2.4.a	Has an permanent spillway with stable walls been constructed?	Yes Yes, but without stable walls No
2.4.b	Is the design reliant on the use of an emergency spillway?	No Yes Unknown
2.5	Does the design incorporate the potential occurrence of hurricanes, cyclones, and/or typhoons (or tsunamis)?	Yes No Unknown
2.6	Does the design account for wind-generated waves?	Yes No Unknown
2.7	Does the design take into consideration adjacent landslide-generated waves?	Yes No Unknown
2.8	Is the design specifically addressing permafrost and the potential for thawing?	Yes Yest, but potential for thawing not addressed No Unknown
2.9	Do the drained and undrained factors of safety, under both static and dynamic loads, for potential failure surfaces through the foundation, meet industry standards of practice?	Yes Partially No Unknown
2.10	Does the design of the foundation take into account the specific material properties?	Yes Partially No Unknown
2.11	Does the foundation design consider time-dependent, deformation-dependent, and stress-path dependent processes that may affect material properties?	Yes Partially No Unknown
2.12	Is the foundation design considered throughout all stages and raises?	Yes Partially No Unknown
2.13	In the presence, is soil or fill material origionally present in the foundaiton excavated?	Yes Partially No Unknown
2.14	Do the drained and undrained factors of safety, under both static and dynamic loads, for potential failure surfaces through the embankment, meet industry standards of practice?	Yes Partially No Unknown
2.15	Does the design of the embankment take into account the specific material properties?	Yes Partially No Unknown
2.16	Does the embankment design consider time-dependent, deformation-dependent, and stress-path dependent processes that may affect material properties?	Yes Partially No Unknown

2.17	Is the embankment design considered throughout all stages and raises?	Yes Partially No Unknown
2.18	Is the embankment sufficiently compacted?	Yes Partially No Unknown
2.19.a	Is the excavation/re-mining of tailings considered?	No Yes Unknown
2.19.b	Is the excavation of tailings taken into consideration in the design?	No Yes Unknown
2.20	Are there any examples of rapid drawdown downstream?	Yes Sometimes No Unknown
2.21.a	Is there a tailings beach present?	Yes, >20 m Yes, < 20 m No
2.21.b	Are wide zones of beaches compacted to a dilative state, free from contractive tailings?	Yes No Unknown
2.22	Is the rate of rising (demonstrated to be) sufficiently slow to allow for the dissipation of excess pore pressures and desaturation within the supporting zone?	Yes, Demonstrated Considered to be No Unknown
2.23	Are the structural elements designed to accommodate tailings and embankment consolidation, deformation, and ice loads?	Yes Partly No Unknown
2.24	Is there an underdrainage system installed at the basal level of the dam?	Yes No Unknown
2.25	Is the drainage capacity (demonstrated to be) sufficient over the lifespan of the dam?	Yes, Demonstrated Considered to be No Unknown
2.26	Are instances of blockage in the drainage systems (caused by factors such as sediment, vegetation, or ice, geochemical precipitation) observed or expected?	No Sometimes Yes Unknown
2.27	Do the filter materials meet the requirements for filter compatibility?	Yes Partly No Unknown No filter materials used
2.28	Are the filters designed to accommodate settlement during dam construction and deformation under seismic loads?	Yes Partly No Unknown
2.29.a	Is there a tailings pond present against or in the vicinity of the dam?	No Yes
2.29.b	Is the pond in temporary contact with the upstream dam face?	No Yes, but temporary (<1 month successively) Yes (longer >1 month successively) Unknown
2.30	Are the upstream and downstream embankment slopes steeply inclined?	No, << natural angle of repose Slightly, but < natural angle of repose Yes, close to or exceeding natural angle of repose Unknown
2.31	Are the embankments of significant height?	No, < 25 meters Moderately, 25-100 m Yes, > 100 m
2.32	Are there high flow pipelines on the dams that do not have secondary containment measures in place?	No Yes, but not having secondary containment Yes
2.33	Are artesian pressures considered in the design?	Yes No Unknown
2.34	Is the embankment characterised by strain-softening or contractive material?	No Yes, but material only present in minor quantities Yes Unknown
2.35	Is there dispersive material present or soluble material within the embankment (e.g. dispersive clays or soluable limestone)?	No Yes Unknown

2.36	Is there compressible material present within the embankment (e.g. peat)?	No Yes, but material only present in minor quantities Yes Unknown
2.37	Is there potential for weakness planes to exist within the embankment materials (e.g. pre-sheared surfaces in clay)?	No Yes, but does not play a role in stability Yes Unknown
2.38	Are the tailings lacking adequate liquefaction resistance (e.g. low-density, loose, contractive material that is uniformly graded, with high silt content, and low permeability)?	No (dry stack) Minor (e.g. paste fill) Yes ('regular tailings") Unknown
2.39.a	Is the permeability of the embankment material significantly high enough to potentially elevate the risk of internal erosion or compromise foundation strength?	No Yes, but material only present in minor quantities Yes Unknown
2.39.b	Is the permeability of the embankment material relatively low, to the extent that it may significantly contribute to the generation of excessive pore pressures?	No Yes, but material only present in minor quantities Yes Unknown
2.40	Is material within the embankment characterized by non-uniformity, exhibiting different characteristics in terms of strength and permeability?	No Yes, but insignificant variability Yes Unknown
2.41	Are gap-graded soils present in the embankment?	No Yes, but material only present in minor quantities Yes Unknown
2.42	Are culverts or pipes present in the embankment?	No Yes, a couple Yes Unknown
2.43	Have cracks been observed in the dam fill surface?	No Yes, but only minor Yes Unknown
2.44	Is there a boundary within the embankment between two units with a significant difference in grain size, where the presence of water flow along the boundary is possible?	No Yes Unknown
2.45	Do the materials of the dam core, filters, and shell have the potential for internal instability?	No Potentially Yes Unknown
2.46	Is the embankment material potentially geochemically incompatible?	No Potentially Yes Unknown
2.47	Do the materials of the dam shell exhibit high erosion resistance?	Yes Partly No Unknown
2.48.a	Is the potential seepage or collapse of the underground mine workings considered in the design?	Yes No Unknown
2.48.b	Is there consideration given to unsupported mining methods, such as longwall mining, sublevel caving, or block caving, utilized in the underground mine?	Yes No Unknown
2.48.c	Is the strength of the host rock taken into account?	Yes No Unknown
2.48.d	Does the design consider the selective extraction practices?	Yes No Unknown
2.48.e	Does the design consider the dewatering operations?	Yes No Unknown
2.48.f	Does the design consider vibrations from active mining operations?	Yes No Unknown
2.49	Are the potential significant anthropogenic vibrations created by mine works (both underground and open pit), construction works, machinery or vehicles in close proximity to the TSF considered in the design?	Yes No Unknown
2.50	Are the potential previous disturbances (e.g.) excavations at the site considered in the design?	Yes No Unknown
2.51	Are measures in place for monitoring pore water pressures within the foundation and do the results confirm the design assumptions and are within the design standards.	Measures in place meet design Measures in place, but do not meet design No/Limited measures in place Unknown

2.52	Are measures in place for monitoring pore water pressures within the embankment and do the results confirm the design assumptions and are within the design standards.	Measures in place meet design Measures in place, but do not meet design No/Limited measures in place Unknown
2.53	Are measures in place for monitoring deformations within the foundation and do the results confirm the design assumptions and are within the design standards?	Measures in place meet design Measures in place, but do not meet design No/Limited measures in place Unknown
2.54	Are measures in place for monitoring deformations within the embankment and do the results confirm the design assumptions and are within the design standards?	Measures in place meet design Measures in place, but do not meet design No/Limited measures in place Unknown

Level of Practise (LoP)

Table B.10: Input Options Level of Practise (LoP), Showing Effects on the Baseline Probability of Failure (PoF) – *Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange)*

ID	Input	GISTM ID	Input Options
3.x	Contributing Factors	x	Meets Partially Meets Does not Meet Unknown

Dependencies

Certain inputs become irrelevant based on the selection of specific inputs. The tool utilises dependencies to address this. Although it is recognised that there are more input options available, the ones currently integrated into the tool are listed below.

- If 1.30.a = No, no input required for 1.30.b, 1.30.c, 1.30.d, 1.30.e, 1.30.f and 2.48.a, 2.48.b, 2.48.c, 2.48.d, 2.48.e, 2.48.f
- If 1.30.b = No, no input required for 2.48.b
- If 1.30.c = No, no input required for 2.48.c
- If 1.30.d = No, no input required for 2.48.d
- If 1.40.e = No, no input required for 2.48.e
- If 1.40.f = No, no input required for 2.48.f.
- If 1.1 = PGA $\leq$, no input required for 2.1
- If 1.2 = No, no input required for 2.2
- If 1.7 = No, no input required for 2.8
- If 1.8 = No, no input required for 2.5
- If 1.10 = No, no input required for 2.7
- If 1.14 = No, no input required for 2.33
- If 1.26 = No, no input required for 2.45
- If 1.27 = No, no input required for 2.46
- If 1.28 = No, no input required for 2.47
- If 1.29 = No, no input required for 2.50
- If 1.31 = No, no input required for 2.49
- If 2.3.a = No, no input required for 2.3.b, 2.3.c, 2.3.d, 2.3.e
- If 2.4.a = Yes, no input required for 2.4.b
- If 2.19.a = No, no input required for 2.19.b
- If 2.21.a = No, no input required for 2.21.b
- If 2.27 = No filter materials used, no input required for 2.28
- If 2.29.a = No, no input required for 1.9 and 2.6 and 2.29.b

B.4. Maps

The tool includes various maps to aid in selecting input options, including seismicity; current and future climate; hurricanes, cyclones and typhoons; floods; permafrost ;and wind speeds. These maps are presented on the subsequent pages.

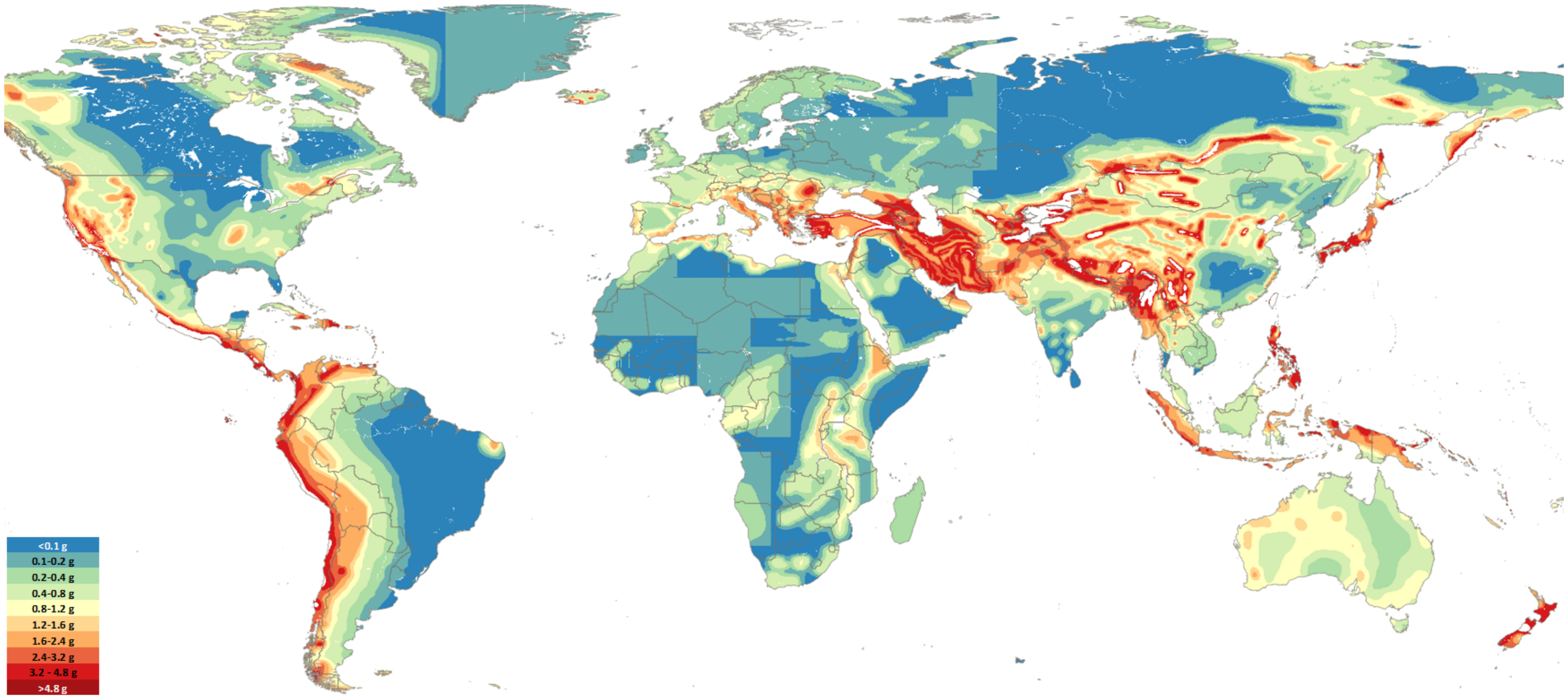


Figure B.1: Seismicity (Criteria 1.1) *(GSHAP, 2011)*

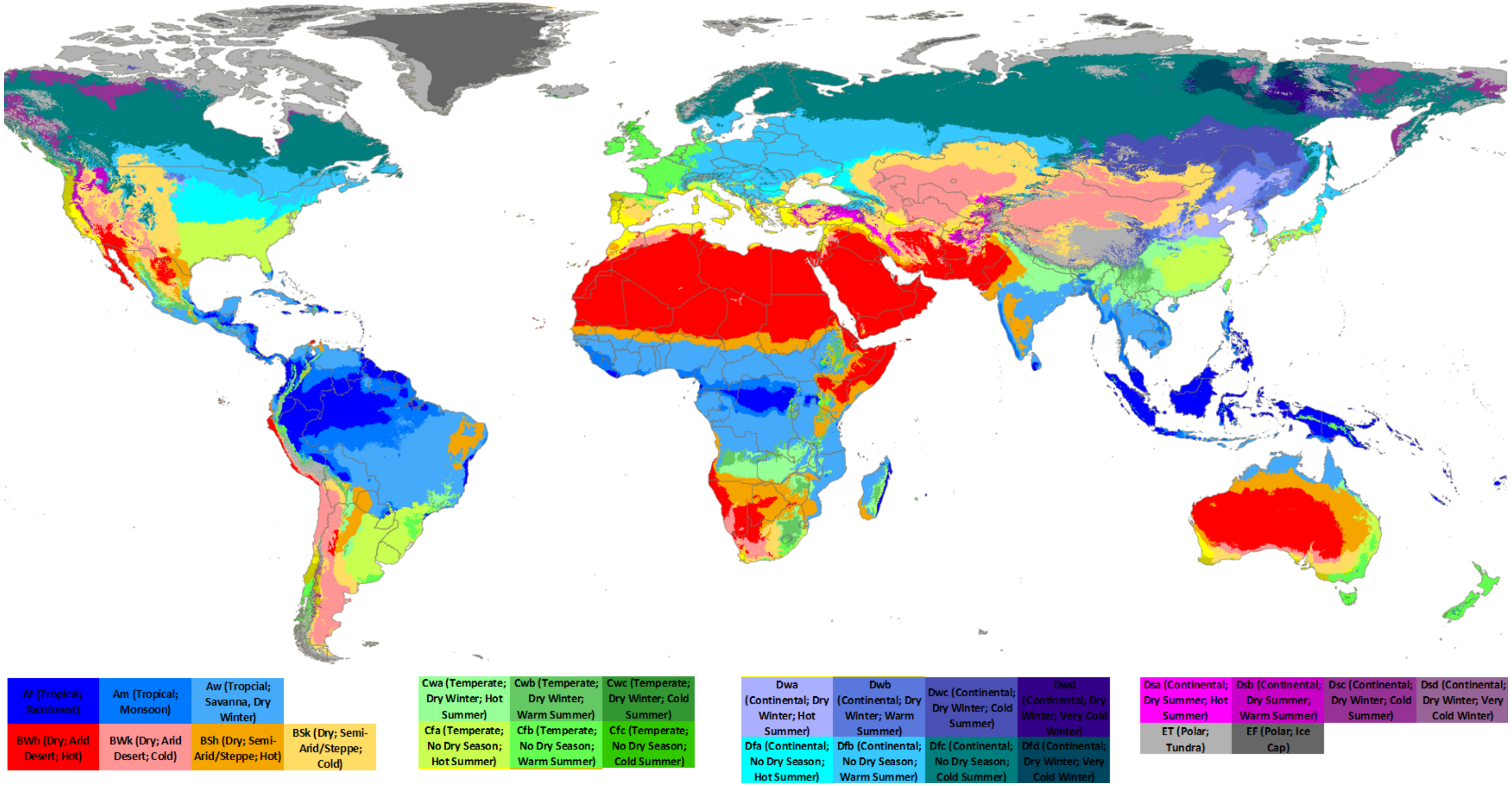


Figure B.2: Climate (Criteria 1.3, 1.4 and 1.5) *(Beck et al., 2018)*

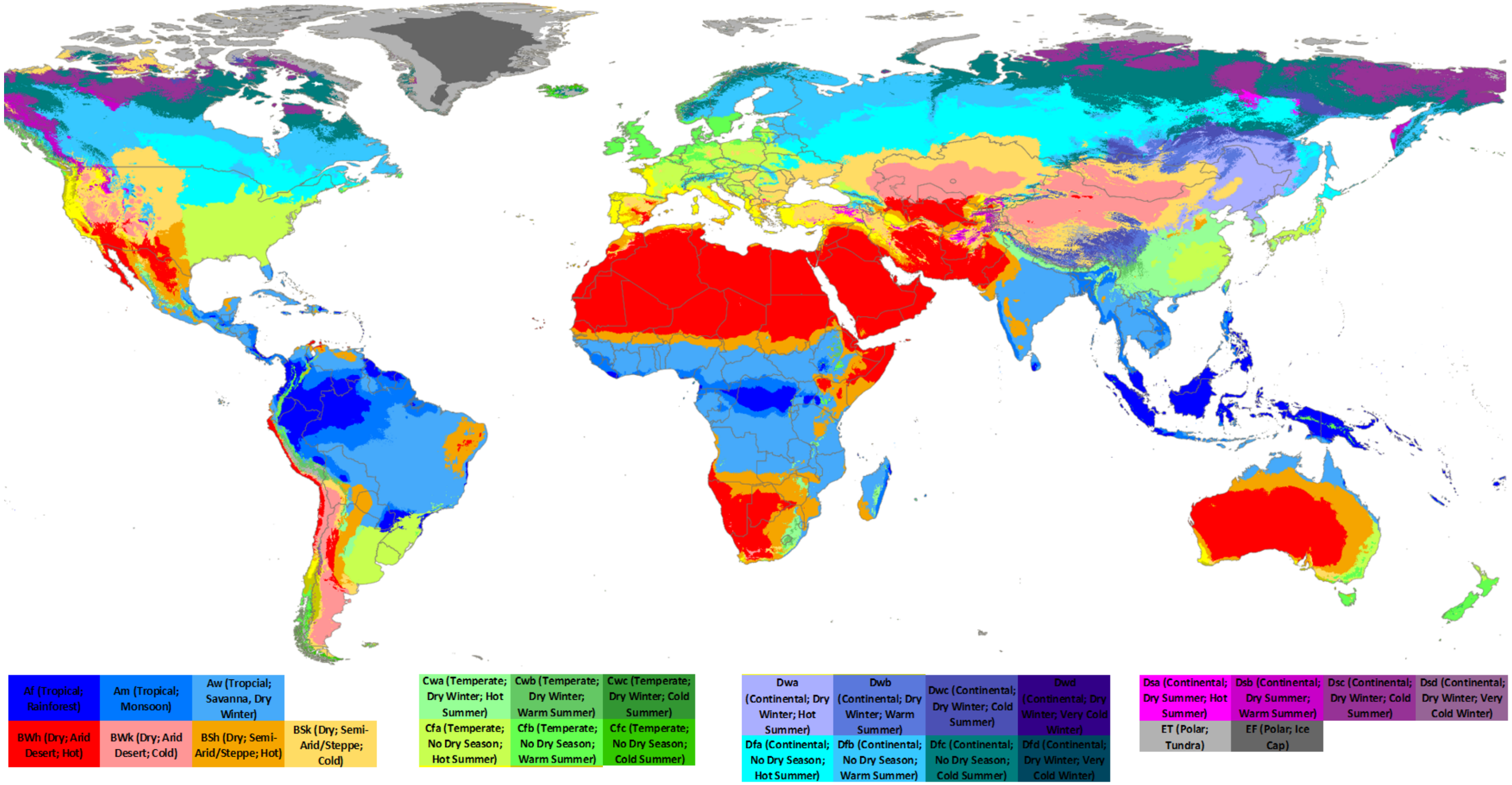


Figure B.3: Future Climate (Criteria 1.3, 1.4 and 1.5) (in 2080) *(Beck et al., 2018)*

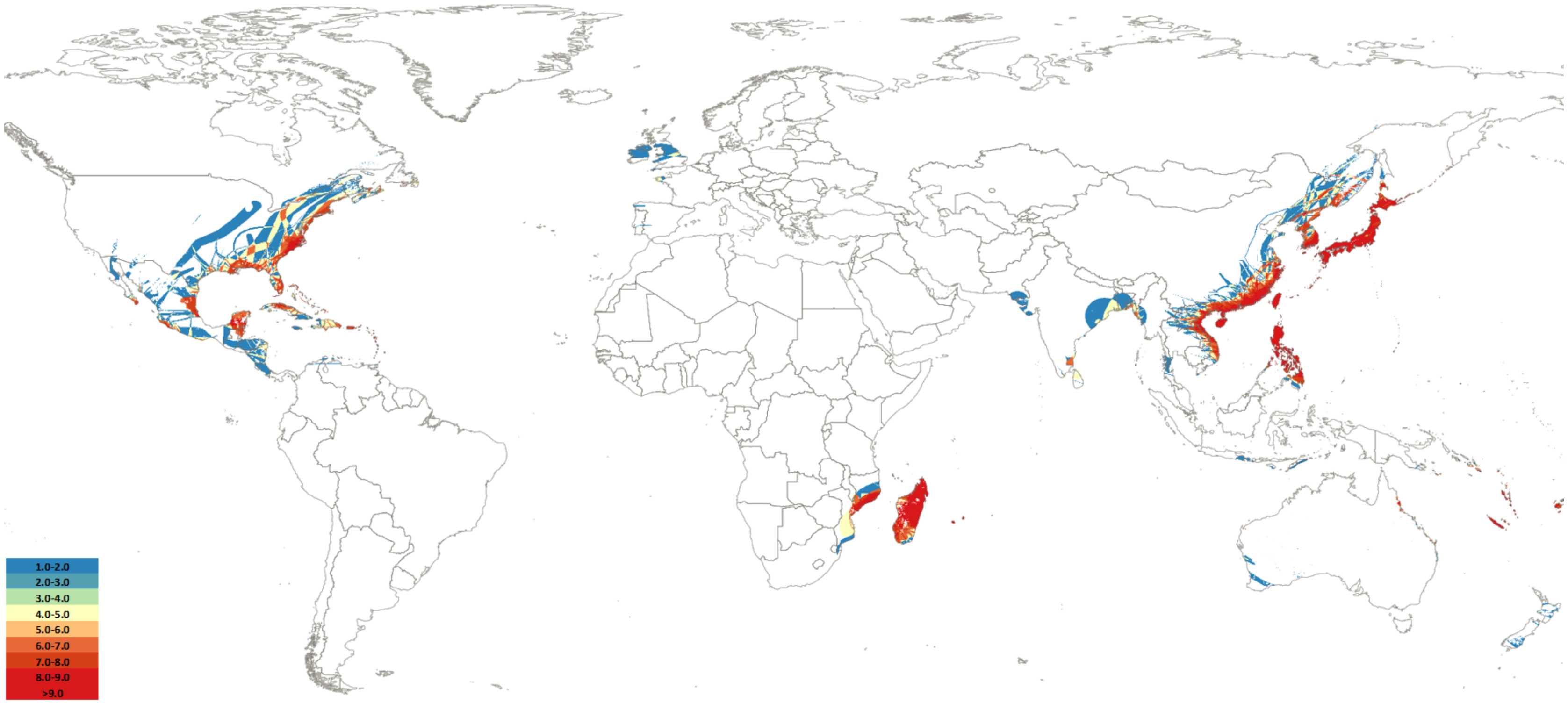


Figure B.4: Hurricanes, Cyclones and Typhoons, Showing Deciles in the period 1980 - 2000 (Criteria 1.8) *(CHRR et al., 2005; Agwe et al., 2005)*

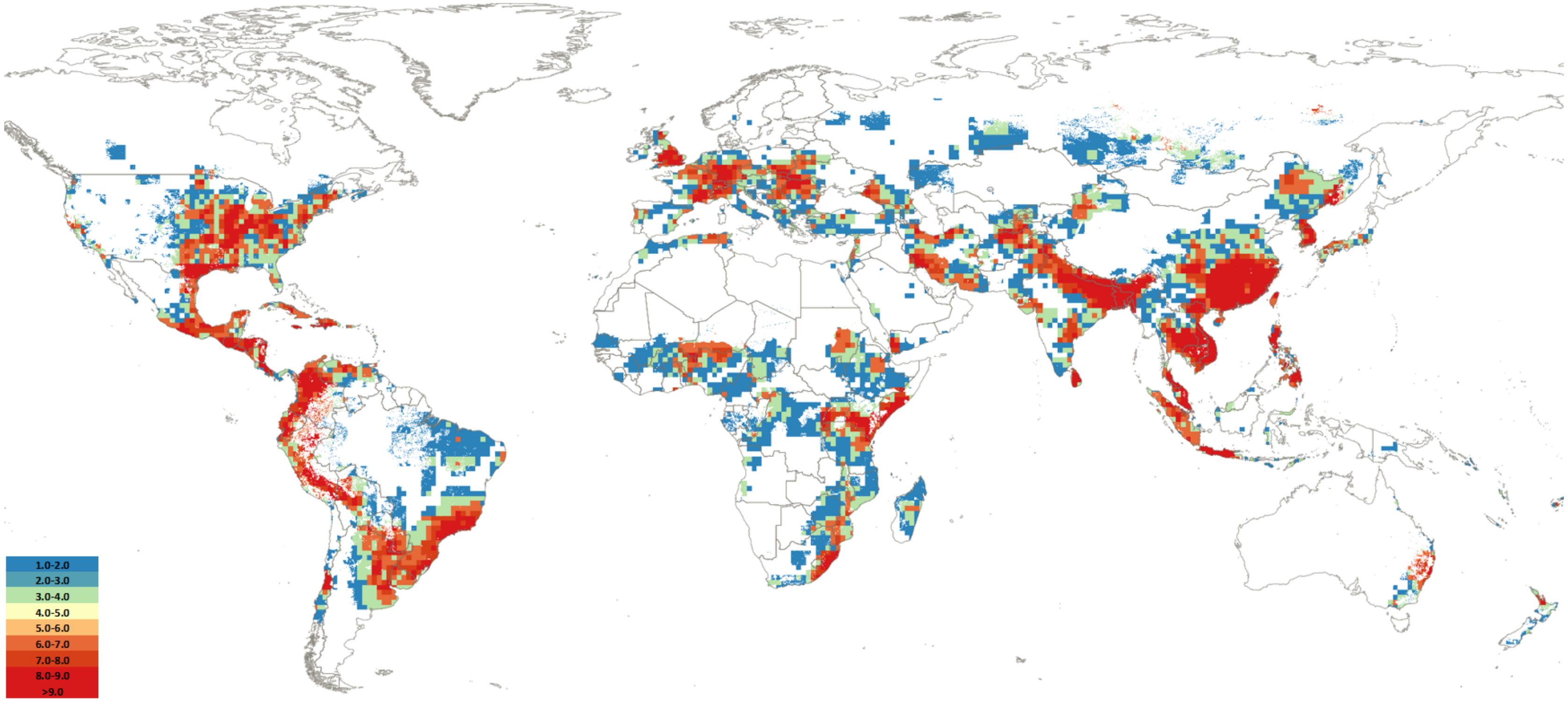


Figure B.5: Flood, Showing Deciles in the Period 1985 - 2003 (Criteria 1.8) *(CHRR et al., 2005; Dilley et al., 2005)*

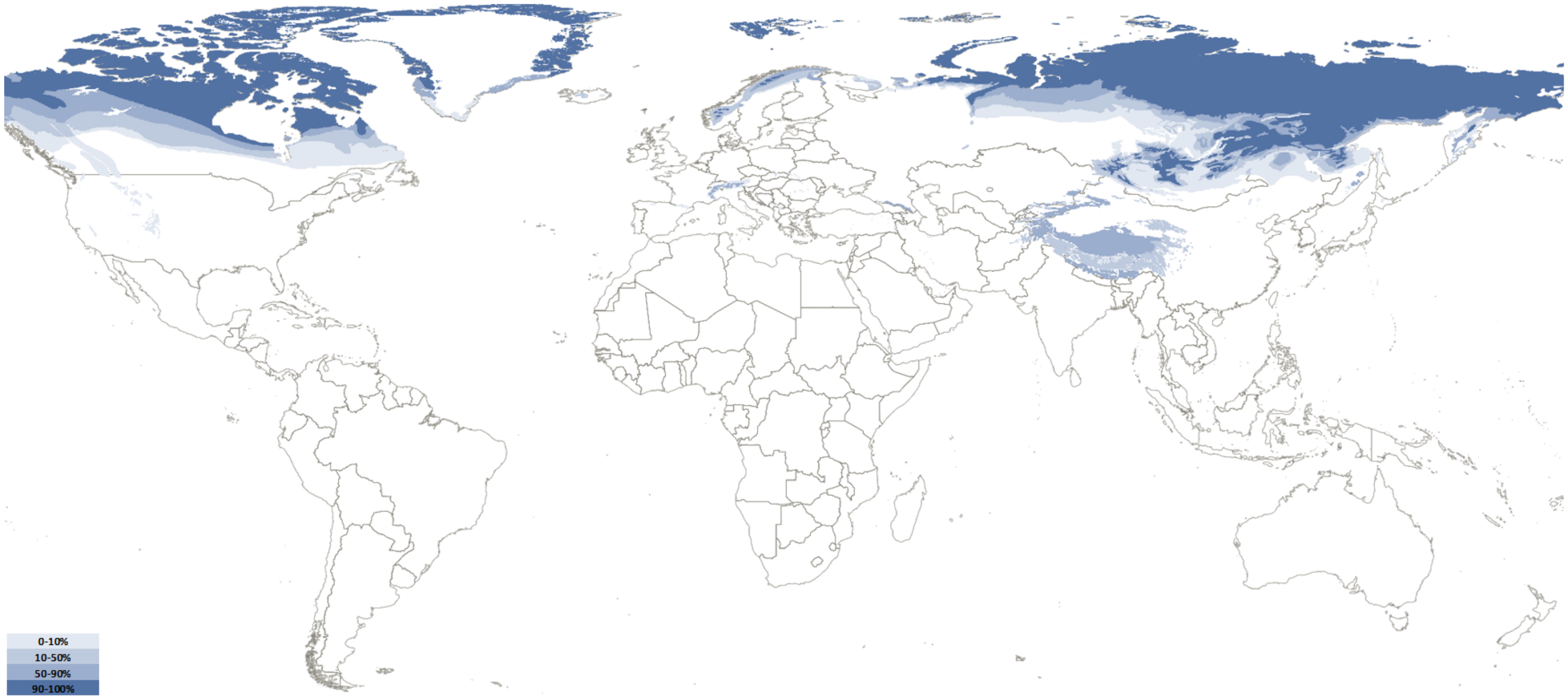


Figure B.6: Permafrost, Showing Percentage of Frozen Ground (Criteria 1.7) *(Brown et al., 2001)*

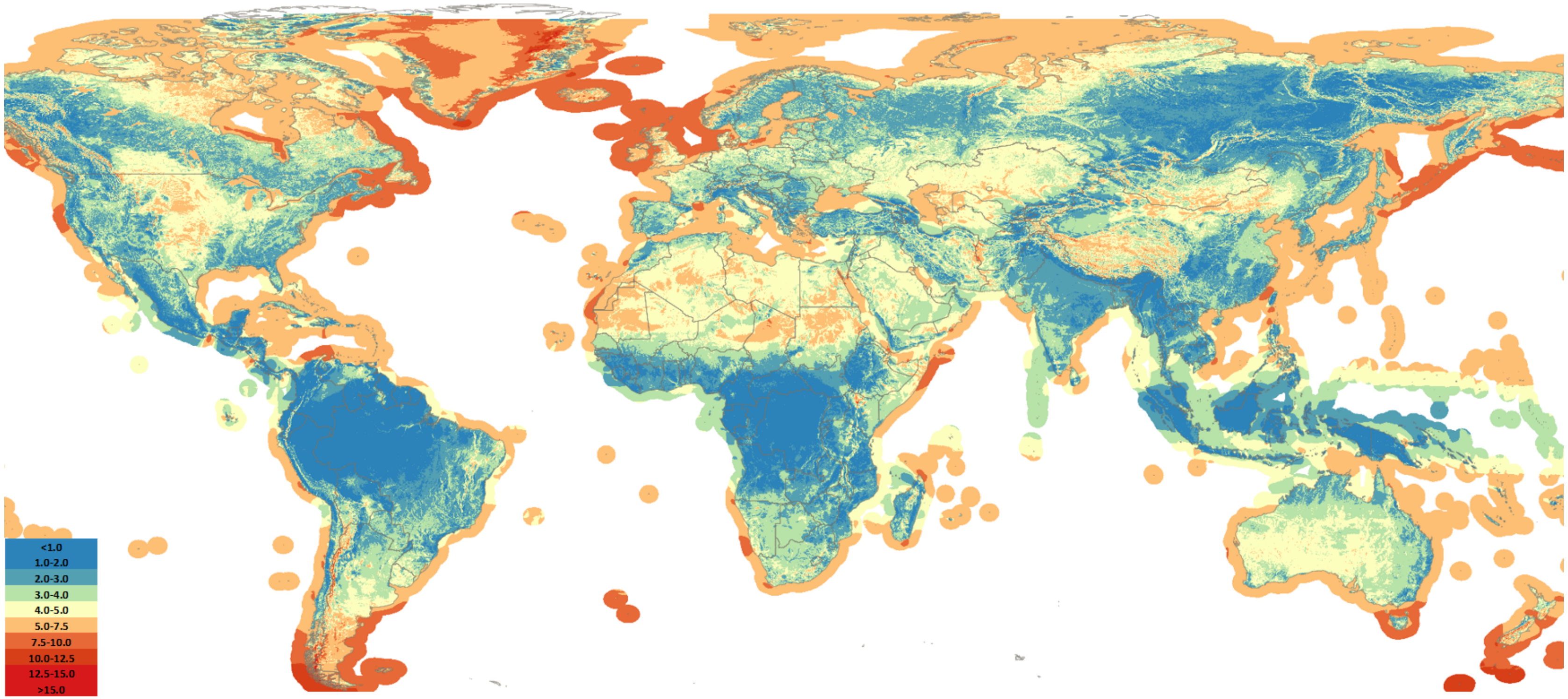


Figure B.7: Mean Wind Speed (10 m) (criteria 1.9) *(Badger et al., 2023)*

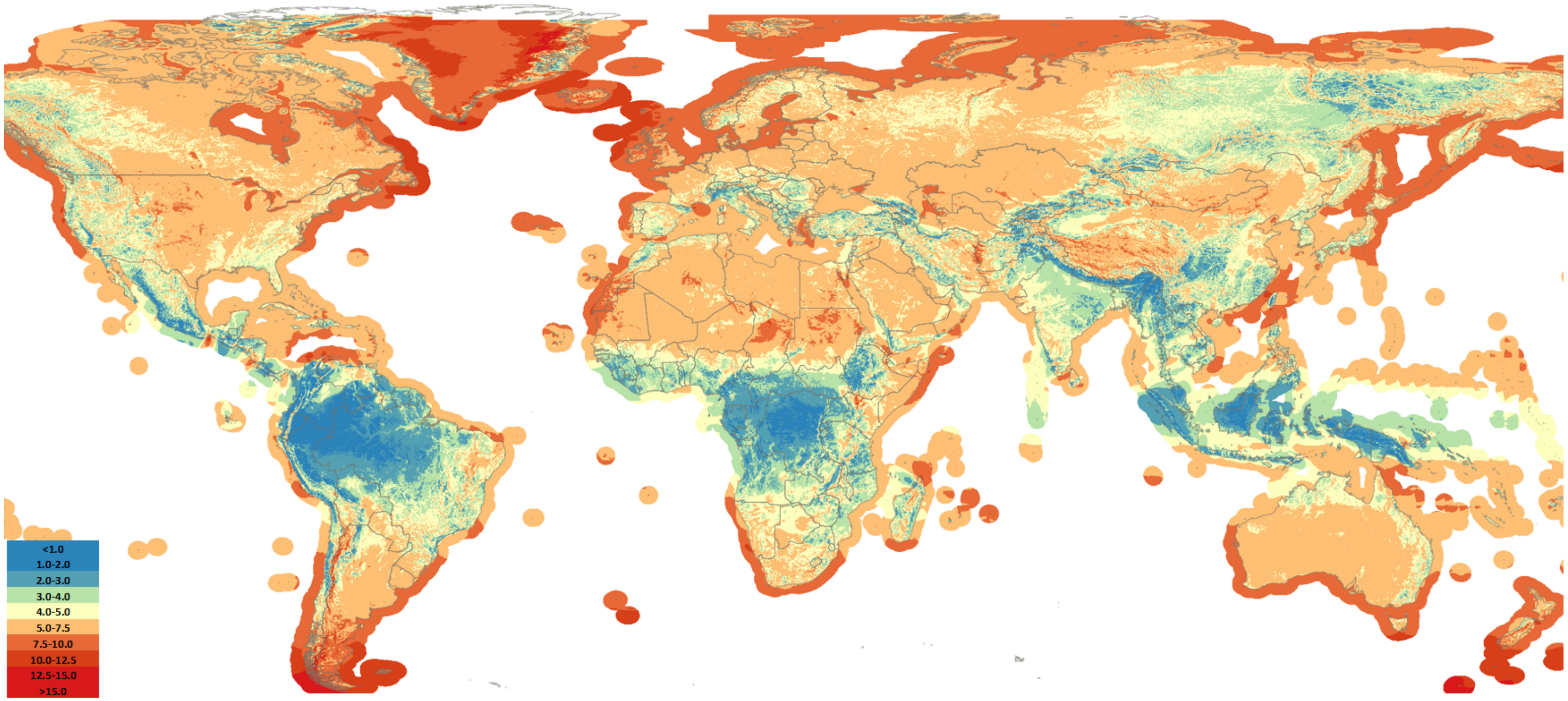


Figure B.8: Mean Wind Speed (50 m) (criteria 1.9) *(Badger et al., 2023)*

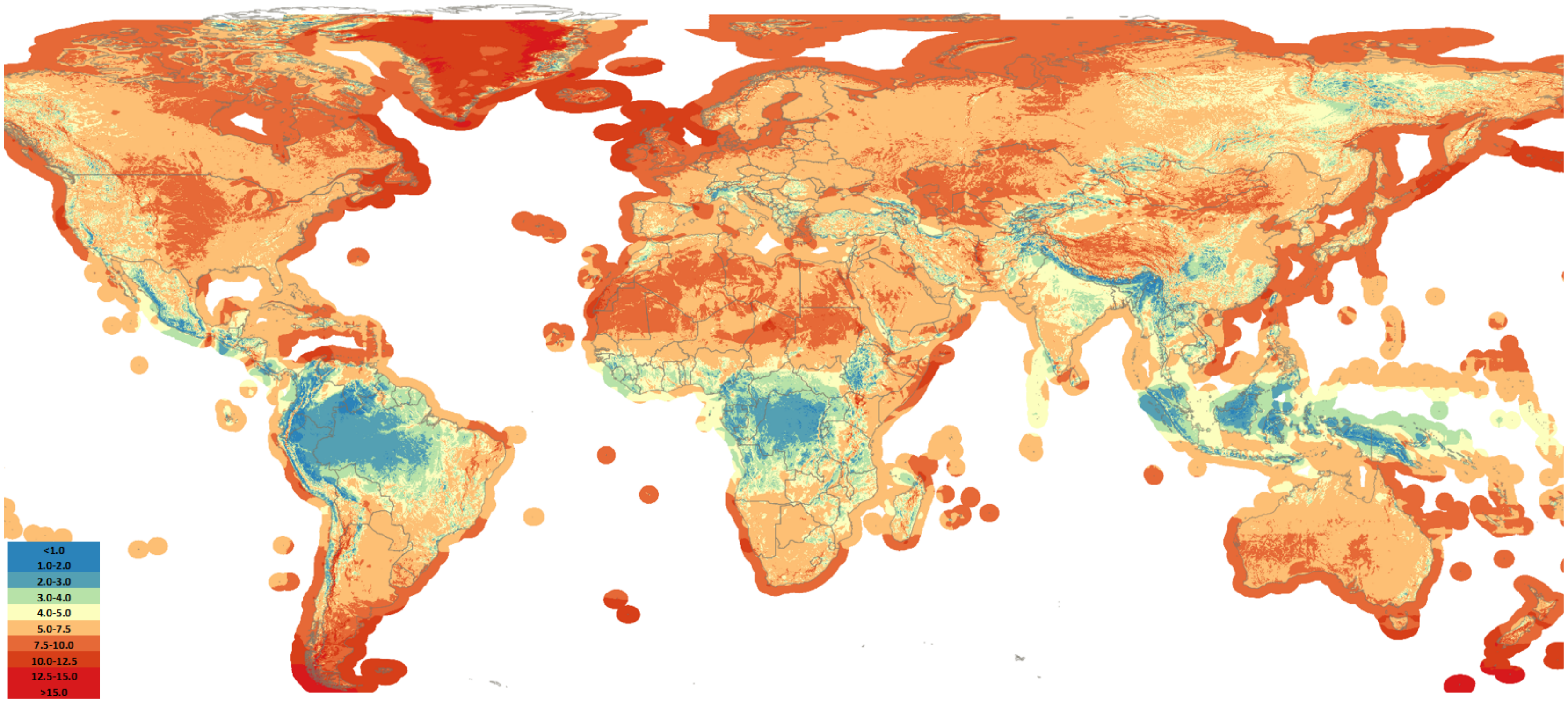


Figure B.9: Mean Wind Speed (100 m) (criteria 1.9) *(Badger et al., 2023)*

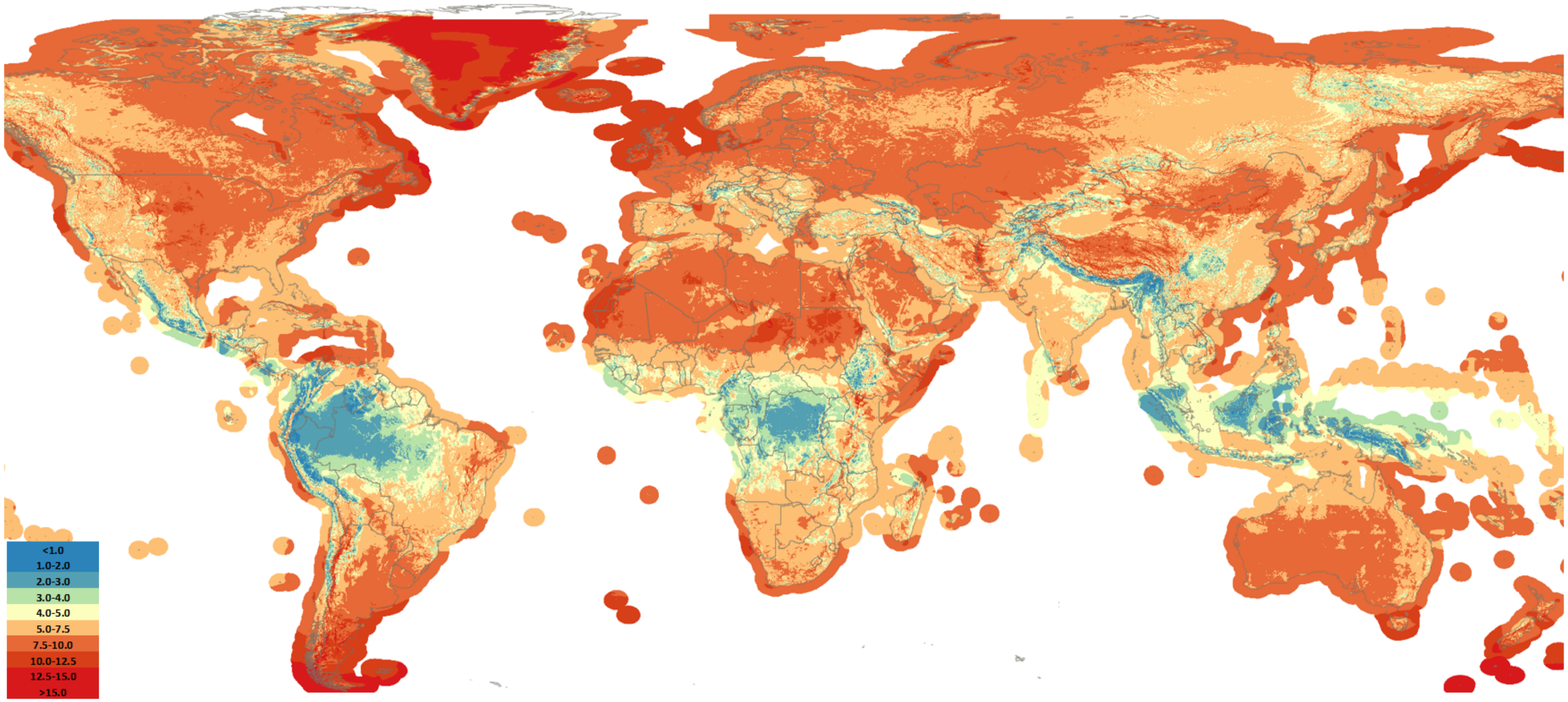


Figure B.10: Mean Wind Speed (150 m) (criteria 1.9) *(Badger et al., 2023)*

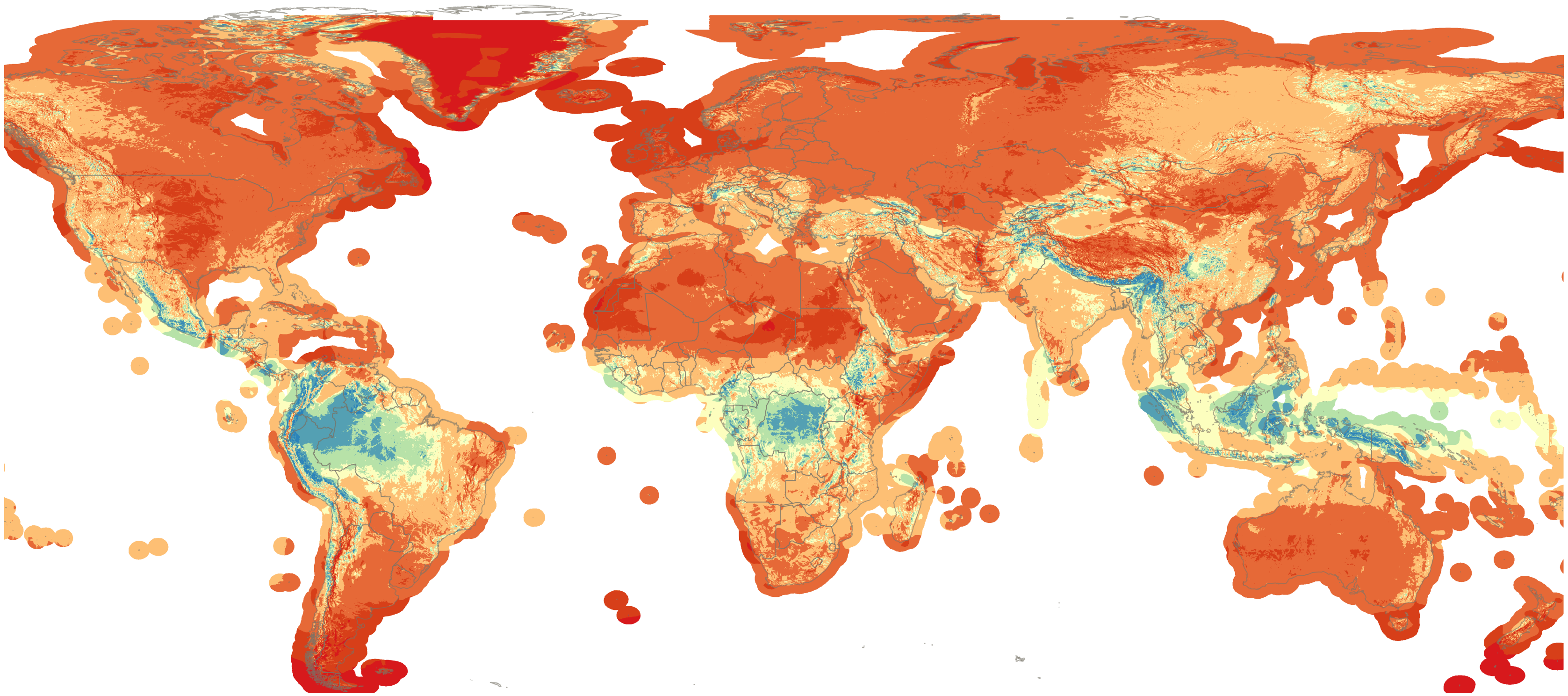


Figure B.11: Mean Wind Speed (200 m) (criteria 1.9) *(Badger et al., 2023)*

C

Case Studies

Information about the analysed case studies is provided, utilised as a foundation for selecting input options in the tool. Appendix C.1.1 **(**Page 231**) provides a background of Case 1: Failure Analysis.** Appendix C.2.1 **(**Page 237**) provides a background of Case 2: Project Improvement Example. The selected inputs and the results are also presented here in** Appendix C.1.2 **(**Page 236**) and** Appendix C.2.2 **(**Page Appendix C.2.2**), respectively.**

C.1. Case 1: Failure Analysis

This section presents a comprehensive background on the analysed failure case. The provided background information serves the purpose of delineating the inputs, with a corresponding overview included in this section as well.

C.1.1. Background

In April 1998, the Aznalcóllar tailings dam in southern Spain failed, leading to a significant release of toxic mine waste into the nearby Guadiamar River and the surrounding area. The tailings contained hazardous heavy metals like lead and zinc, posing a severe environmental threat. This chapter outlines the site's background and design, summarises the failure, discusses observed behaviour, details mitigation efforts, and outlines the consequences of the disaster brief.

There are several authors who investigated the failure, including Alonso & Gens (2006a,c,b); Alonso & Gens (2012); Alonso & Gens (2021); Alonso & Gens (2022). Their results are summarised below.

Site and Design Characteristics

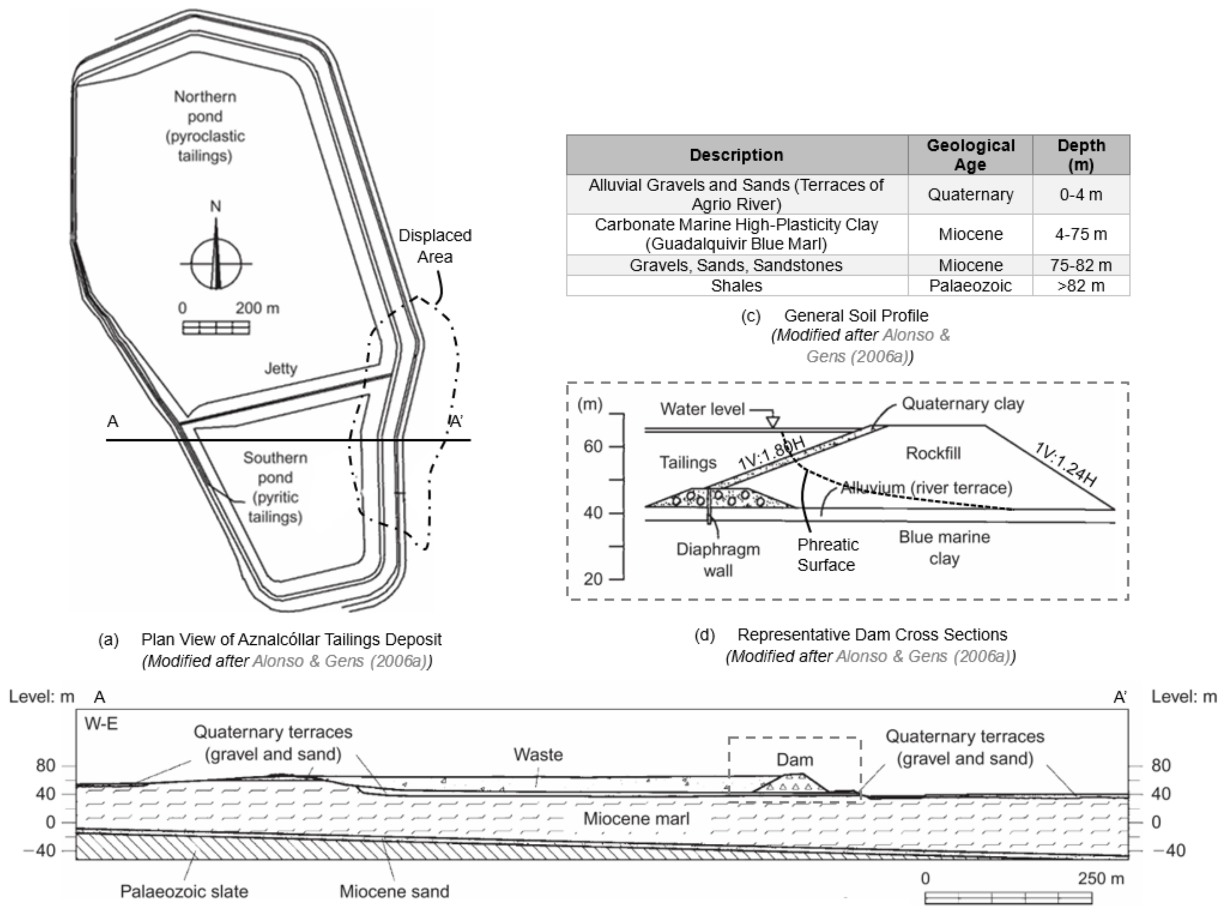
The Aznalcóllar TSF is situated in southern Spain's Guadalquivir basin. It utilises 85% of non-exploitable rock for a downstream perimeter embankment built on a thin granular alluvium ($\sim$ 4 m), covering thick Miocene carbonate, high-plasticity, overconsolidated, fine, low-permeability, marine clays (> 60 m). Below are Tertiary units (gravel, sand, sandstone), succeeded by Palaeozoic shales (>80 m), as evidenced by borehole data. Upstream a Quarternary clay blanket connects to a shallow bentonite diaphragm wall, designed to ensure imperviousness. The initial embankment slopes measured 1V:1.90H downstream and 1V:1.75H upstream. In 1985, the downstream slope was revised to 1V:1.24H, and in 1990, the crest width was expanded from 14 to 36.5 meters, while the 130-meter base width remained constant. A freeboard of 1 meter was consistently maintained.

The site encompasses a northern lagoon containing coarse pyroclastic material and a southern pond containing finer pyritic slimes, separated by a jetty. The commencement of tailings deposition dates back to 1978, with continuous embankment elevation over two decades. The finely ground waste is pumped, post-processing, in an aqueous suspension behind the tailings dam. The foundation clays, characterised by their substantial thickness and low permeability, gave rise to an extensive consolidation timeline. Seismic considerations were accounted for through a pseudo-static methodology, incorporating estimated horizontal (0.048g) and vertical (0.976g) accelerations. Steady-state water pressures were assumed. An overview of the TSF is presented in Figure C.1.

Failure

In 1996, following a comprehensive safety evaluation, the embankment height was augmented by 2 meters from its original design. Subsequent stability analysis indicated a low phreatic factor of safety, approximated at 1.17. Paradoxically, despite these measures, the tallest eastern embankment, rising 27 meters, suffered an abrupt failure in 1998, without prior signs of distress. 600 m of the embankment was affected by the failure.

Various potential factors for the failure were postulated, encompassing the expansive foundation clay, chemical erosion induced by the acidic pyritic slurry, and the effects of blasting activities in the proximate open pit mine. However, the eventual cause was determined to be a profound deep translational sliding motion. This sliding plane developed progressively at a depth of 26 meters, just north of the jetty structure. The sliding plane throughout the embankment is schematically shown in Figure C.2. The shear plane in the material is shown in Figure C.7. The magnitude of the failure, along with its depth and configuration, categorises this incident as exceptional. An aerial view of the failure is shown in Figure C.3.



Description	Geological Age	Depth (m)
Alluvial Gravels and Sands (Terraces of Agrio River)	Quaternary	0-4 m
Carbonate Marine High-Plasticity Clay (Guadalquivir Blue Marl)	Miocene	4-75 m
Gravels, Sands, Sandstones	Miocene	75-82 m
Shales	Palaeozoic	>82 m

(c) General Soil Profile *(Modified after Alonso & Gens (2006a))*

(a) Plan View of Aznalcóllar Tailings Deposit *(Modified after Alonso & Gens (2006a))*

(d) Representative Dam Cross Sections *(Modified after Alonso & Gens (2006a))*

(b) Cross-Section of Tailings Lagoon *(Modified after Alonso & Gens (2006a))*

Figure C.1: Overview Aznalcóllar Tailings Storage Facility (TSF)

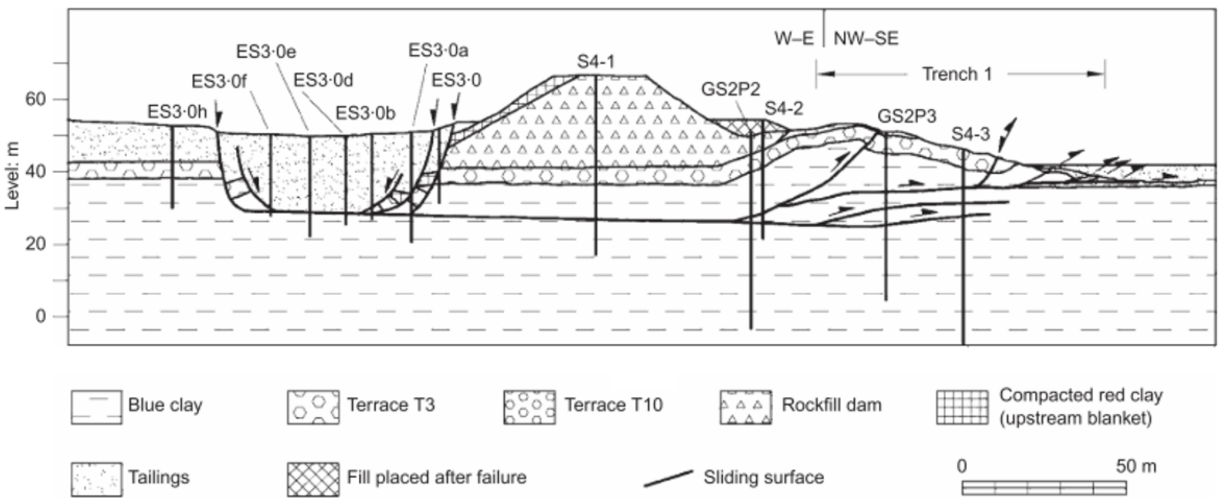


Figure C.2: Cross Section of Slide showing Failure Surfaces *(Alonso & Gens, 2006a)*

(a) View from the East *(Alonso & Gens, 2006a)*

(b) Detail of Breach *(Alonso & Gens, 2006a)*

Figure C.3: *Aerial View of Tailings*

Although, the homogenous characterisation of the clay would imply a rotational failure mode; however, the failure was controlled by failure surfaces. Two prominent discontinuity sets were identified in the clays: sub-horizontal bedding planes (shown in Figure C.4a), dipping at an angle of 2-4 degrees in an SSE direction, spaced at intervals of 2-2.5 meters; and a vertical jointing system aligned along the N-S/NE-SW directions (shown in Figure C.4b), characterised by a spacing of 2-5 meters, featuring smooth, slickensided joints (Shown in Figure C.5). These discontinuities were attributed to deep-seated fractures within the Paleozoic basement, facilitating the development of a failure plane.

(a) Horizontal Bedding Planes *(Alonso & Gens, 2006a)*

(b) Vertical Jointing *(Alonso & Gens, 2006a)*

Figure C.4: *Discontinuity Sets (Alonso & Gens, 2006a)*

Figure C.5: Slickensides *(Alonso & Gens, 2006a)*

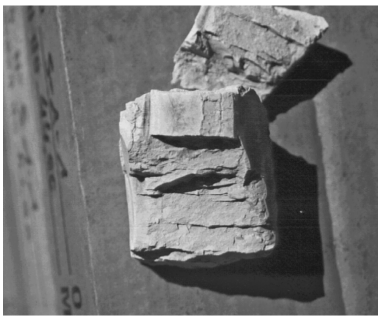


Figure C.6: Stratification of Clay *(Alonso & Gens, 2006a)*

Figure C.7: Sliding Plane *(Alonso & Gens, 2006a)*

The brittle nature of the clay and the low residual friction angle, identified by direct shear tests, played a significant role in reducing the available foundation strength. The strength experienced progressive diminishment with incremental deformations, culminating in an abrupt decline upon reaching its peak strength threshold. The liquefaction of tailings post-failure further escalated forces acting on the dam, thereby exacerbating the failure. Moreover, residual pore pressures are attributed to incomplete clay consolidation.

The strength was progressively reduced upon small deformations and suddenly dropped after it reached its peak strength. After a progression of the failure, the tailings liquefied, which significantly increased the forces on the dam, promoting further failure. Besides, the relatively high pore pressures left from the incomplete consolidation of the clay foundation, are thought to have contributed as well.

Behaviour and Mitigation

The embankment behaviour was always considered normal. Routine visual inspections were executed, even shortly preceding the failure. Some instrumentation damage was noted, which remained susceptible to impact from the dump trucks used during dam construction. An overview of the instrumentation is shown in Figure C.8.

No abnormal settlements were recorded. An overview of the displacements is shown in Figure C.9. Nevertheless, lateral displacements went unmeasured. Several piezometers were installed 2 m into the foundation clay, intended to measure pore water pressures developing in the granular alluvium. The piezometric head of the sands was at the ground surface. The piezometric readings were low and although the measurements show a more irregular pattern after November 1997, they are within the design limits and did not pose a concern, see Figure C.10.

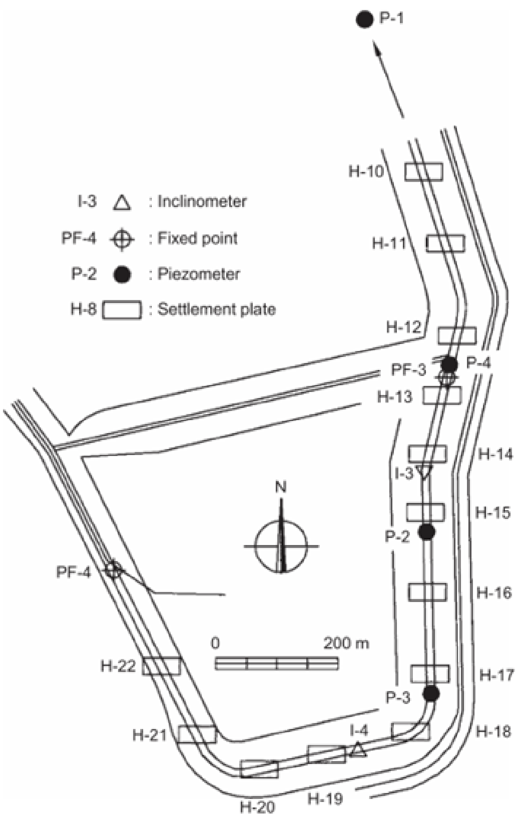


Figure C.8: Overview of Position of Monitoring Instruments *(Alonso & Gens, 2006a)*

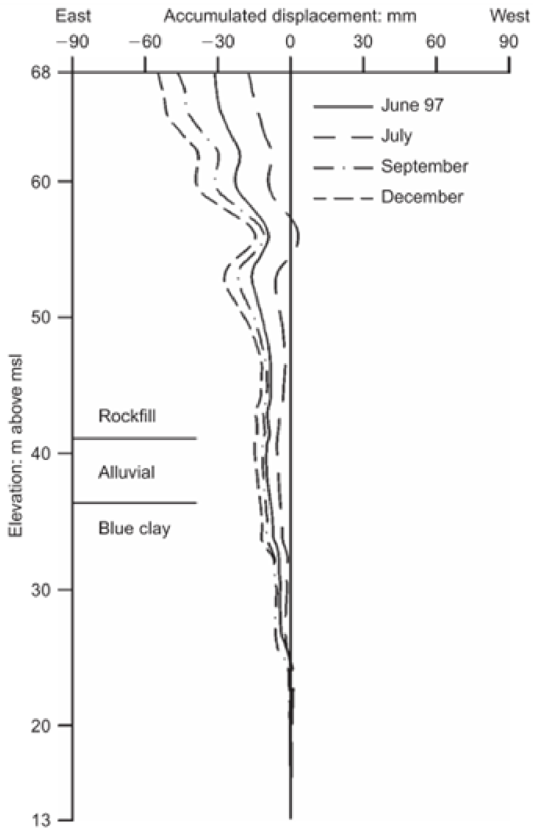


Figure C.9: Inclinomter Readings *(Alonso & Gens, 2006a)*

The piezometers did not yield any information about the consolidation progress in the foundation clays, while in the vicinity of the sliding surface, strong vertical pressure gradients existed, as a result of the slow consolidation process of the impervious clay. Although the clay was known to have low permeability, the designers assumed that there would be some preferential drainage paths that would guarantee sufficient dissipation of excess pore pressures. This assumption was wrong and should have been verified by installing piezometers into the clays. Broadening the dam's base could have distributed the embankment's load more effectively.

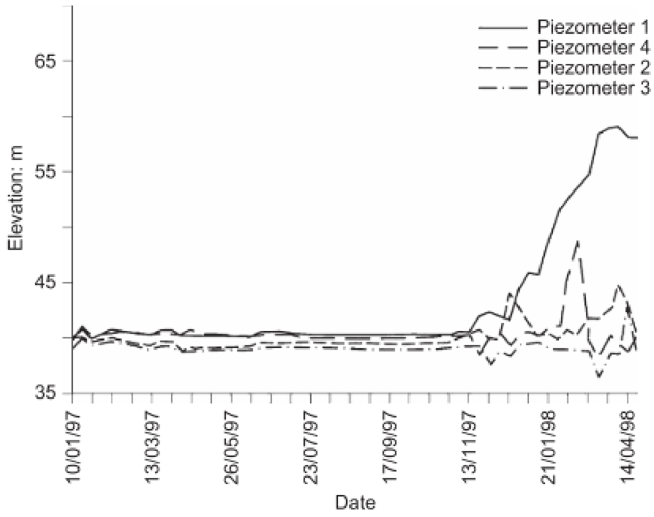


Figure C.10: Piezometric Readings *(Alonso & Gens, 2006a)*

The brittleness should have been better characterised so that it could be made sure that they would never exceed their peak strength. Safety factors should have been increased to decrease the chances of reaching the peak, because the consequences of doing so are far worse than with a ductile response. In this context, heightened inclinometer density or depth would not have forewarned of impending failure, as no discernible signs were evident. The only solution to this would have been to make sure the post-peak regime is not reached.

In hindsight, the failure should already have taken place sooner. Based on estimated safety factors, the dam operated near critical conditions during an extended portion of its construction timeline. The strength decrement, due to deformation along the failure surface, proceeded progressively. The dam height remained static between 1991 and 1995, enabling some pore pressure dissipation, facilitating the subsequent 2-meter height augmentation. Material properties used for that analysis are shown in Table C.1 (Alonso & Gens, 2006a,c,b).

Table C.1: Material Properties Utilised for Analysis *(Alonso & Gens, 2006c)*

Property - Symbol (Unit)	Symbol	Unit	Alluvial	Clay	Rockfill	Tailings
Dry Unit Weight	γ_d	kN/m^3	20	21	20	31
Unit Weight of Water	γ_w	kN/m^3	20	21	20	31
Young's Modulus	E	kPa	20 x 10^3	40 x 10^3	40 x 10^3	3 x 10^3
Poisson's Ratio	v	-	0.3	0.3	0.3	0.3
Effective Cohesion	c'	kPa	1	Variable	-	1
Effective Friction Angle	ϕ'	°	35	Variable	-	37
Dilatancy Angle	ψ	°	0	0	-	0
Type	-	-	Drained	Undrained	Drained	Drained
Hydraulic Conductivity	k	m/day	1.55 x 10^{-3}	1.55 x 10^{-6}	1.55 x 10^{-3}	1.55 x 10^{-3}

Consequences

Note that the displacement of the embankment decreased towards the south, because of a stabilising berm placed against the rock-fill embankment. The 'corner' conditions, also contributed to a reduction of the sliding risk.

The tailings, exhibiting an acidic pH (3-3.7) and hosting a mix of potentially toxic minerals, posed a significant environmental hazard. Consequently, the pyritic mud overlay posed an acute environmental hazard, culminating in the contamination of the Guadiamar River, with a devastating impact on aquatic life, claiming the lives of 37 tons of fish, crabs, and shellfish. The mining company successfully managed to seal the dam breach within 36 hours.

C.1.2. Input and Results

The selected inputs, the effect and the contribution to the PoF for each factor are displayed in Table C.2.

Table C.2: Inputs, Effects and Contribution to the Probability of Failure (PoF) Case 1: Failure Analysis – *Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange), Higest Contribution (Red) - Lowest Contribution (Green))*

ID	Selected Input	Effect	PoF
1.1	PGA > 0.4 g (return period 475 years/10%	Adverse	2.8 E-05
1.15	Yes	Adverse	1.4 E-05
2.51	No/Limited measures in place	Adverse	1.0 E-05
1.4	Cs (temperate; dry summer)	Adverse	8.3 E-06
2.54	No/Limited measures in place	Adverse	8.3 E-06
2.21.a	No	Adverse	6.9 E-06
3.1.1.a	Does Not Meet	Adverse	6.9 E-06
2.31	Moderately, 25-100 m	Adverse	6.7 E-06
2.27	No filter materials used	Adverse	4.3 E-06
2.38	Yes ("regular tailings")	Adverse	4.2 E-06
3.2.1	Does Not Meet	Adverse	3.8 E-06
2.4.a	No	Adverse	3.5 E-06
1.16	Yes	Adverse	3.2 E-06
1.20.b	Yes	Adverse	3.0 E-06
1.2	Unknown	Unknown	2.9 E-06
2.23	Unknown	Unknown	2.8 E-06
3.5.6.a	Does Not Meet	Adverse	2.6 E-06
3.5.6.a	Does Not Meet	Adverse	2.6 E-06
1.24	Yes	Adverse	2.5 E-06
3.6.4.d	Does Not Meet	Adverse	2.3 E-06
2.30	Yes, close to or exceeding natural angle of	Adverse	2.3 E-06
2.26	Unknown	Unknown	2.2 E-06
1.25	Yes	Adverse	2.1 E-06
3.6.2.b	Does Not Meet	Adverse	2.0 E-06
3.6.2.c	Does Not Meet	Adverse	2.0 E-06
2.24	Unknown	Unknown	1.9 E-06
3.4.4.b	Does Not Meet	Adverse	1.8 E-06
2.9	No	Adverse	1.7 E-06
2.11	No	Adverse	1.7 E-06
3.11.1	Unknown	Unknown	1.6 E-06
3.3.2.b	Does Not Meet	Adverse	1.6 E-06
3.9.4	Unknown	Unknown	1.5 E-06
2.6	Unknown	Unknown	1.5 E-06
2.14	No	Adverse	1.4 E-06
1.13	Perhaps	Neutral	1.3 E-06
1.27	Unknown	Unknown	1.2 E-06
2.1	Yes	Neutral	1.2 E-06
2.18	Unknown	Unknown	1.2 E-06
3.10.2	Unknown	Unknown	1.2 E-06
3.10.3	Unknown	Unknown	1.2 E-06
3.6.2.a	Partially Meets	Neutral	1.2 E-06
3.3.4	Does Not Meet	Adverse	1.1 E-06
2.25	Considered to be	Neutral	1.1 E-06
1.14	Unknown	Unknown	1.0 E-06
3.3.2.a	Partially Meets	Neutral	9.3 E-07
3.1.2.b	Partially Meets	Neutral	9.3 E-07
2.52	Measures in place, but do not meet design	Neutral	9.1 E-07
1.30.a	No	Favourable	8.9 E-07
3.1.2.a	Partially Meets	Neutral	8.6 E-07
2.29.b	Yes (longer >1 month successively)	Adverse	8.5 E-07
1.23	No	Neutral	8.2 E-07
3.12.2.a	Unknown	Unknown	8.2 E-07
3.10.1.a	Unknown	Unknown	8.0 E-07
3.10.5.a	Unknown	Unknown	8.0 E-07
3.6.4.b	Partially Meets	Neutral	7.7 E-07
2.33	Unknown	Unknown	7.2 E-07
2.4.b	Unknown	Unknown	6.9 E-07
2.32	Unknown	Unknown	6.9 E-07
2.35	Unknown	Unknown	6.8 E-07
3.6.3.c	Partially Meets	Neutral	6.5 E-07
3.6.5.b	Unknown	Unknown	6.5 E-07
2.22	Considered to be	Neutral	6.1 E-07
1.31	Yes	Adverse	5.6 E-07
3.3.3.b	Unknown	Unknown	5.5 E-07
2.16	Unknown	Unknown	5.5 E-07
3.11.2	Unknown	Unknown	5.4 E-07
3.12.1.a	Unknown	Unknown	5.4 E-07
3.12.1.b	Unknown	Unknown	5.4 E-07
2.2	Yes	Adverse	5.3 E-07
3.3.6.a	Unknown	Unknown	5.2 E-07
3.3.6.b	Unknown	Unknown	5.2 E-07
3.3.6.c	Unknown	Unknown	5.2 E-07
3.5.2.a	Unknown	Unknown	5.1 E-07
2.46	Unknown	Unknown	4.9 E-07
3.6.4.c	Unknown	Unknown	4.9 E-07
3.6.4.e	Unknown	Unknown	4.9 E-07
3.3.5.b	Does Not Meet	Adverse	4.8 E-07
3.9.3	Unknown	Unknown	4.6 E-07
3.8.1.a	Unknown	Unknown	4.5 E-07
3.8.1.b	Unknown	Unknown	4.5 E-07
1.18	Unknown	Unknown	4.5 E-07
3.10.1.b	Unknown	Unknown	4.0 E-07
3.10.4.a	Unknown	Unknown	4.0 E-07
3.10.4.b	Unknown	Unknown	4.0 E-07
3.10.4.c	Unknown	Unknown	4.0 E-07
3.10.5.b	Unknown	Unknown	4.0 E-07
3.5.1.c	Partially Meets	Neutral	3.9 E-07
2.2	Unknown	Unknown	3.9 E-07
2.53	Measures in place meet design	Favourable	3.7 E-07
3.4.4.a	Partially Meets	Neutral	3.7 E-07
3.4.2.a	Partially Meets	Neutral	3.7 E-07
3.4.7.a	Does Not Meet	Adverse	3.7 E-07
3.4.7.b	Does Not Meet	Adverse	3.7 E-07
3.4.7.c	Does Not Meet	Adverse	3.7 E-07
3.6.5.a	Partially Meets	Neutral	3.3 E-07
3.7.6.a	Unknown	Unknown	3.1 E-07
3.7.6.b	Unknown	Unknown	3.1 E-07
1.21	Yes, but insignificant variability	Neutral	3.0 E-07
2.49	Unknown	Unknown	3.0 E-07
3.3.5.c	Partially Meets	Neutral	2.9 E-07
3.9.2.a	Unknown	Unknown	2.8 E-07
3.9.2.c	Unknown	Unknown	2.8 E-07
3.1.2.c	Partially Meets	Neutral	2.8 E-07
3.3.3.a	Partially Meets	Neutral	2.8 E-07
2.15	Partially	Neutral	2.7 E-07
3.12.2.b	Unknown	Unknown	2.7 E-07
1.19	Potentially	Neutral	2.7 E-07
3.4.6.a	Unknown	Unknown	2.6 E-07
3.4.6.b	Unknown	Unknown	2.6 E-07
3.4.6.c	Unknown	Unknown	2.6 E-07
3.3.1.b	Unknown	Unknown	2.6 E-07
3.5.1.b	Unknown	Unknown	2.6 E-07
3.5.1.d	Unknown	Unknown	2.6 E-07
3.5.2.b	Partially Meets	Neutral	2.6 E-07
3.5.4.b	Unknown	Unknown	2.6 E-07
3.5.4.a	Unknown	Unknown	2.6 E-07
3.6.4.a	Partially Meets	Neutral	2.4 E-07
2.42	Unknown	Unknown	2.3 E-07
2.39.a	Unknown	Unknown	2.1 E-07
2.39.b	Unknown	Unknown	2.1 E-07
3.9.5.a	Unknown	Unknown	2.1 E-07
3.9.5.b	Unknown	Unknown	2.1 E-07
3.9.5.c	Unknown	Unknown	2.1 E-07
3.9.5.d	Unknown	Unknown	2.1 E-07
3.8.3.a	Unknown	Unknown	2.1 E-07
3.8.3.b	Unknown	Unknown	2.1 E-07
1.5	Cs (temperate; dry summer)	Favourable	2.0 E-07
3.9.1.a	Partially Meets	Neutral	2.0 E-07
3.9.1.d	Partially Meets	Neutral	2.0 E-07
3.3.5.a	Unknown	Unknown	1.9 E-07
3.5.3.b	Unknown	Unknown	1.9 E-07
1.26	No	Favourable	1.7 E-07
2.29.a	Yes	Neutral	1.7 E-07
3.2.2	Meets	Favourable	1.7 E-07
1.17	No	Favourable	1.6 E-07
1.11	No, embankments < 25 m can be	Favourable	1.6 E-07
3.1.1.b	Meets	Favourable	1.6 E-07
2.3.a	Yes	Favourable	1.6 E-07
3.9.6.a	Unknown	Unknown	1.5 E-07
3.9.6.b	Unknown	Unknown	1.5 E-07
3.9.6.c	Unknown	Unknown	1.5 E-07
3.8.1.c	Unknown	Unknown	1.5 E-07
1.3	Catchment area ≈ TSF footprint	Favourable	1.5 E-07
3.8.5.a	Unknown	Unknown	1.5 E-07
3.8.5.b	Unknown	Unknown	1.5 E-07
3.7.1.a	Unknown	Unknown	1.4 E-07
3.9.2.b	Unknown	Unknown	1.4 E-07
3.9.2.d	Unknown	Unknown	1.4 E-07
3.9.7.a	Unknown	Unknown	1.4 E-07
3.9.7.b	Unknown	Unknown	1.4 E-07

3.9.7.c	Unknown	Unknown	1.4 E-07
1.8	No	Favourable	1.4 E-07
3.6.1.c	Partially Meets	Neutral	1.3 E-07
3.6.3.a	Meets	Favourable	1.3 E-07
3.6.3.b	Meets	Favourable	1.3 E-07
3.3.1.a	Partially Meets	Neutral	1.2 E-07
3.9.1.e	Unknown	Unknown	1.2 E-07
3.9.1.f	Unknown	Unknown	1.2 E-07
3.7.1.b	Does Not Meet	Adverse	1.2 E-07
3.9.1.b	Partially Meets	Neutral	1.1 E-07
3.9.1.c	Partially Meets	Neutral	1.1 E-07
1.6	Cs (temperate; dry summer)	Favourable	1.1 E-07
3.7.4.a	Unknown	Unknown	1.1 E-07
3.7.4.b	Unknown	Unknown	1.1 E-07
3.7.4.c	Unknown	Unknown	1.1 E-07
3.8.4.a	Unknown	Unknown	1.0 E-07
1.7	No	Favourable	9.9 E-08
1.28	No	Favourable	9.8 E-08
3.5.5.d	Unknown	Unknown	9.7 E-08
3.5.5.a	Unknown	Unknown	9.7 E-08
3.7.5.a	Unknown	Unknown	9.6 E-08
3.7.5.c	Unknown	Unknown	9.6 E-08
3.7.5.e	Unknown	Unknown	9.6 E-08
3.8.2.a	Unknown	Unknown	9.2 E-08
1.20.a	No	Favourable	9.2 E-08
3.5.4.c	Unknown	Unknown	8.5 E-08
3.5.4.d	Unknown	Unknown	8.5 E-08
3.5.4.e	Unknown	Unknown	8.5 E-08
3.4.5	Meets	Favourable	8.5 E-08
1.22	No	Favourable	8.5 E-08
2.3.c	Yes	Favourable	8.5 E-08
3.6.1.a	Meets	Favourable	7.9 E-08
3.5.1.a	Meets	Favourable	7.8 E-08
2.19.a	No	Neutral	7.7 E-08
3.4.2.b	Meets	Favourable	7.3 E-08
3.7.7.e	Unknown	Unknown	7.0 E-08
3.7.7.b	Unknown	Unknown	7.0 E-08
3.7.7.a	Unknown	Unknown	7.0 E-08
3.7.7.c	Unknown	Unknown	7.0 E-08
3.7.7.d	Unknown	Unknown	7.0 E-08
2.1	Yes	Favourable	6.9 E-08
2.12	Yes	Favourable	6.9 E-08
3.8.3.c	Unknown	Unknown	6.9 E-08
3.7.3.a	Unknown	Unknown	6.3 E-08
2.43	No	Favourable	6.1 E-08
2.41	No	Favourable	6.0 E-08
2.44	No	Favourable	6.0 E-08
1.9	No, mean wind speed < 5 m/s, wind not in	Favourable	5.8 E-08
3.5.3.a	Meets	Favourable	5.7 E-08
2.17	Yes	Favourable	5.5 E-08
1.1	No	Favourable	5.3 E-08
3.8.2.b	Unknown	Unknown	5.1 E-08
3.7.2.a	Unknown	Unknown	4.8 E-08

3.7.2.b	Unknown	Unknown	4.8 E-08
3.7.2.c	Unknown	Unknown	4.8 E-08
3.7.2.d	Unknown	Unknown	4.8 E-08
3.9.7.d	Unknown	Unknown	4.6 E-08
2.3.d	Yes	Favourable	4.5 E-08
2.3.e	Yes	Favourable	4.5 E-08
2.3.b	Yes	Favourable	4.3 E-08
2.34	No	Favourable	4.1 E-08
1.12	Yes	Favourable	3.8 E-08
2.4	No	Favourable	3.6 E-08
3.7.4.d	Unknown	Unknown	3.5 E-08
3.7.3.c	Unknown	Unknown	3.5 E-08
3.8.4.b	Unknown	Unknown	3.4 E-08
3.8.4.c	Unknown	Unknown	3.4 E-08
2.37	No	Favourable	3.3 E-08
2.36	No	Favourable	3.3 E-08
3.5.5.b	Unknown	Unknown	3.2 E-08
3.5.5.e	Unknown	Unknown	3.2 E-08
3.5.5.f	Unknown	Unknown	3.2 E-08
3.5.5.c	Unknown	Unknown	3.2 E-08
3.7.5.b	Unknown	Unknown	3.2 E-08
3.7.5.d	Unknown	Unknown	3.2 E-08
3.8.2.c	Unknown	Unknown	2.8 E-08
3.6.1.b	Meets	Favourable	2.6 E-08
1.29	No	Favourable	2.6 E-08
3.7.3.b	Unknown	Unknown	1.9 E-08
3.4.3.a	Meets	Favourable	1.8 E-08
3.4.3.c	Meets	Favourable	1.8 E-08
3.4.3.b	Meets	Favourable	1.8 E-08
1.30.b	N/A	x	x
1.30.c	N/A	x	x
1.30.d	N/A	x	x
1.30.e	N/A	x	x
1.30.f	N/A	x	x
2.7	N/A	x	x
2.8	N/A	x	x
2.13	N/A	x	x
2.19.b	N/A	x	x
2.21.b	N/A	x	x
2.28	N/A	x	x
2.46	N/A	x	x
2.47	N/A	x	x
2.48.b	N/A	x	x
2.48.c	N/A	x	x
2.48.d	N/A	x	x
2.48.d	N/A	x	x
2.48.e	N/A	x	x
2.48.f	N/A	x	x
2.48.f	N/A	x	x
2.48.e	N/A	x	x
3.4.1.a	N/A	x	x
3.4.1.b	N/A	x	x
		Total	*2.1 E-04*

C.2. Case 2: Project Improvement Example

Over the last five years, substantial enhancements have been implemented to augment the safety measures of this TSF. In this section, the case study is introduced, providing contextual information required as input for the tool. Only information relevant to the inputs required for the tool is presented. Some aspects are not discussed in detail due to confidentiality reasons. For these privacy reasons, names have been generalised too. Subsequently, an overview of the inputs for the analysis at various time steps is provided.

C.2.1. Background

Prior to examining the targeted dam section of investigation, general information on the TSF is outlined, covering its operations, and addressing environmental factors such as surroundings, weather, climate, and the seismic setting. Subsequently, a comprehensive overview of the dam section under investigation is provided, including detailed explanations of its foundation and construction materials. The section finishes with a summary of the available data for analysis.

General Information

The tailings storage facility under investigation serves as a repository for roughly 100 million tonnes of copper, silver/gold, and zinc mill tailings from the nearby mining operations. It was commissioned in the late 1920s with the deposition of tailings in the natural lake adjacent to the mine and mill site. The current TSF covers much of the original lake basin. As storage capacity requirements increased over the years, containment structures (i.e., tailings and water dams) were constructed on an as-needed basis. At present, there are three main ponds (Pond 1, Pond 2, Pond 3) and fifteen dams that are part of the TSF. Production has recently ceased.

Since 2017 several site investigations have been completed to better characterise the foundation soils and estimate geotechnical parameters. Subsequently, stability assessments and dam breach analysis were completed. The results identified several dam structures, that did not meet the project criteria and the consequences of the dam breach were identified to include impacts to the population at risk and important infrastructure within the neighbouring community. Therefore, toe berms were recommended and constructed at several dam sections, including the dam section under investigation. The TSF also has a comprehensive monitoring plan, which has been expanded since 2017 as well.

A closure plan is currently being developed. The facility is expected to remain on care and maintenance for a period of up to several decades. Re-processing of the tailings is being considered prior to transitioning the facility into full closure.

Surroundings

The surrounding terrain comprises flat, low-lying regions, which have some standing water that form swamps. The ground is undulating with gentle to moderate slopes at higher altitudes, with an overall inclination towards the northeast. Moreover, in the surrounding area, there are several natural lakes that nearby communities depend on as their source of potable water. Small towns and a highway are located in close vicinity to the TSF.

Weather and Climate

The TSF is situated in a subarctic climate zone that is typically characterised by long, cold winters with relatively low precipitation. Temperatures typically peak in July and can reach 24 °C. The lowest temperatures are observed in January, when they can reach -23 °C. However, deviations up to 40 °C in summer and -46 °C in winter have been noted. The average daily temperature during the winter months is -19 °C, whereas during the summers the average daily temperature is a positive 19 °C. Winter is the season with the least amount of precipitation, with an average monthly precipitation of around 20 mm, mostly as snow. In contrast, summer has an average monthly precipitation of 70 mm. About 75% of the annual rainfall (450 mm), therefore, falls between the months of June and September. There is a possibility of heavy rainfall events. Snow typically accumulates to 60 - 90 cm. However, snow depths of more than 1.00 m have been observed throughout history. The lake usually completely freezes over by mid-November. Break-up usually begins in mid-May. Figure C.11 summarises the average monthly temperature and precipitation.

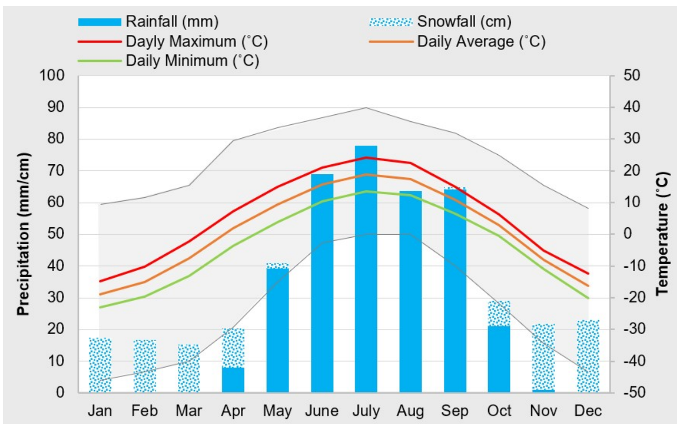


Figure C.11: Climate Normals (1981-2010)

Seismic Setting

The TSF is situated in an aseismic region. There are recorded earthquakes within 300 km of the site since 1985. The Peak Ground Acceleration (PGA) at an Annual Exceedance Probability (AEP) of 1:10,000 is estimated to be between 0.08 to 0.10g. For an AEP of 1:5,000, the PGA estimates lie between 0.05 to 0.065g. The closest recorded earthquake occurred in 1993, 300 km away from the site, with a magnitude of 2.5. Nonetheless, it appears that pore pressures in the dams have responded to high-magnitude earthquakes that took place at a considerable distance (>3,000 km) from the TSF.

Dam Section Under Investigation

The dam being assessed in this report is one of the oldest structures at the TSF. The history spans over 80 years. It is complex and was not well documented during the early periods of operations. The dam was originally constructed to provide tailings containment near the north end of the historical lake. It was constructed across a topographic low between bedrock ridges where the lake narrowed to approximately 50 m wide. The dam was progressively raised over bedrock ridges as tailings storage requirements increased; the alignment followed along the adjacent ridges of higher topography. The dam was constructed in several stages, with the main milestones related to operations and construction as described below:

- The dam was absent in the initial operational years of the 1930s and 1940s. During this time, tailings were deposited from single-point discharge, which occurred from a distal point from this structure ($\sim$ 1800 m away). Tailings were deposited and dispersed throughout the entire lake basin.
- An initial starter dam is believed to have been constructed in the 1940s and was subsequently raised in an upstream direction in the 1950s through 1970s. Tailings deposition continued to occur from the distal single-point discharge, with deposition occurring upstream of the dam.
- An upgrade was completed from 1979 to 1981 in response to observations of internal erosion (piping) at the downstream toe. A blanket filter was placed over the downstream slope/toe and extended downstream over the surface of the tailings that had been deposited within the lake basin. The dam shell was then widened in a downstream direction over the blanket filter. The widened shell was constructed of compacted tailings with a downstream slope of approximately 2.0H:1V to 2.5H:1V.
- Between 1981 and the mid-2000s, the dam was raised in a downstream direction.
- Between 2003 and 2006, the dam was raised in an upstream direction. This included the construction of a waste rock pad into the pond and deposited tailings upstream of the main dam and placement of compacted tailings, with an internal drainage network, to raise the crest elevation by 7 m. The downstream slope of the raised portion was approximately 4H:1V.
- In 2007, deposition at the facility transitioned from single-point discharge to spigotted tailings discharge from the perimeter embankments. This resulted in the deposition of tailings directly from the crest of this structure to achieve a uniform tailings beach around the perimeter.
- The crest continued to be raised in an upstream manner over the deposited tailings beach as required through the remainder of operations; typical annual raises were on the order of 0.5 m in height. The total height of the current dam is 25 m.
- From 2016 to 2017, a 75 m wide waste rock toe berm was constructed. Fill was placed directly into the downstream pond in a manner to displace soft sediments. The toe berm flattened the overall downstream slope from approximately 3.5H:1V to 6.0H:1V.

The dam fills comprise compacted tailings fill and waste rock fill with smaller amounts of slag fill and natural sand and gravel fill used to construct drains and filter layers. The dam foundation within the topographic low typically comprises the following stratigraphy listed below, from top to bottom. These soil layers gradually thin out (lenticular) toward the adjacent bedrock ridges and the dam fills transition to directly overlie bedrock.

1. Soft to firm hydraulically placed mill tailings silt (3 to 6 m thick)
2. Soft to firm amorphous peat (0 to 5 m thick)
3. Very soft to stiff glaciolacustrine clay (2 to 15 m thick)
4. Compact to dense glacial till sand/silt (0 to 3 m thick)
5. Bedrock

In 2017, hydraulically placed tailings as well as soft peat and glaciolacustrine clay were known to be present in the dam foundation. At that time, the stability assessment of the dam accounted for the presence of the peat and glaciolacustrine clay with drained and undrained strength parameters. However, the liquefaction potential of the tailings had not yet been assessed and effective strength (drained) strengths were used for modelling the tailings strength. The project stability FoS criteria developed were met based on these stability modelling inputs. The results of site investigations and engineering analyses that were initiated in 2017 showed the hydraulically placed tailings were potentially susceptible to liquefaction. A design was undertaken to upgrade the stability of the structure to meet minimum FoS criteria of 1.5 for peak undrained strength and 1.1 for post-peak undrained strength loading conditions.

Improvements

Between 2017 and 2022, a number of improvements were undertaken at the site to improve safety; these improvements were related to both design elements and LoP. The improvements included the following.

- The number of site investigation locations has increased. In 2017, 19 Drill Hole (DH)s were available. In 2022, 36 DHs were available. There has also been additional CPT testing. While in 2017 just 2 CPT profiles were made, 28 were available in 2022.
- The material characterisation of the foundation units has been improved; a significant number of thin-walled (Shelby) tube samples were collected for laboratory analysis. The analysis included characterisation units within the critical state soil mechanics framework. 3 Shelby tubes were collected in 2017, while in 2022 33 were collected.
- There has been an improvement in the monitoring of piezometric conditions and subsurface deformations. The number of VW piezometers has increased from 12 to 68. In 2017, there was 1 SAA, while in 2022 there were installed 2. Furthermore, 3 additional slope inclinometers were added to the existing one in 2017, totalling 4 slope inclinometers in 2022.
- The VW Piezometers and SAAs transmit data automatically to an online database platform for near-real-time viewing of instrumentation readings. This system has TARPs established for each instrument. The system was upgraded in 2019 to permit more frequent transmission of instrument readings (less than hourly frequency).
- The governance was enhanced in 2017, with the establishment of regular monthly meetings that involved tailings operations staff, key management personnel, and the EoR.
- In 2017, also an ITRB has been established. The board has bi-annual meetings, with an annual site visit to review the facility performance observations, design process and construction summaries.
- Several improvements were made to upgrade water management throughout the site in 2018, including upgrades of spillways and water management structures.
- A DBR was established for the site in 2019. It contains clear and consistent criteria for geotechnical, hydrogeological, hydrological and hydro technical considerations in design.
- An upgrade of the EPRP was undertaking in 2019. The upgrade includes engagement with external stakeholders and first responder groups.
- A major revision of the OMS manual was undertaken in 2021.

- In 2021, the construction of a toe berm was completed to buttress the structure and improve stability, particularly to provide sufficient resistance in consideration of post-liquefied strengths of loose contractive tailings in the foundation. Toe berm construction consisted of approximately 350,000 m^3 of fill; initial fill placement consisted of placement into the downstream pond in a manner to achieve displacement of soft sediment. Subsequent lifts occurred above pond level and resulted in an overall dam slope of approximately 12H:1V. The toe berm included erosion protection along the downstream slope in direct contact with pond water.

Cross-Section

Figure C.12 displays a sketch of the dam section in 2017 and Figure C.13 in 2022. In the subsequent section there is elaborated upon the characteristics of the foundation and construction materials.

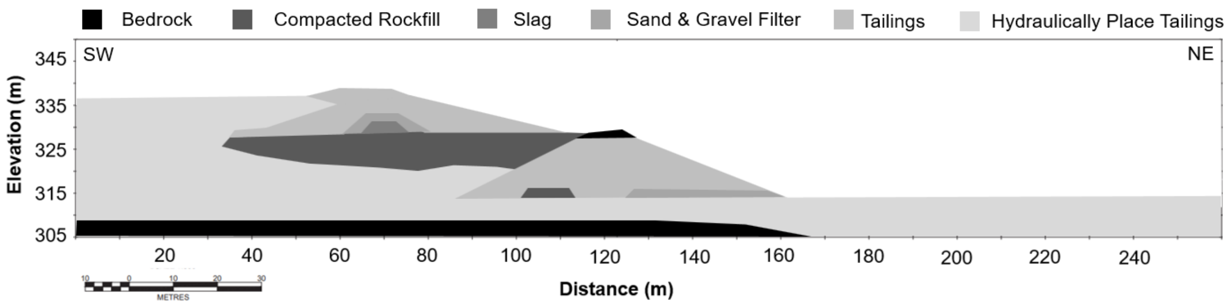


Figure C.12: Sketch of Cross Section 2017

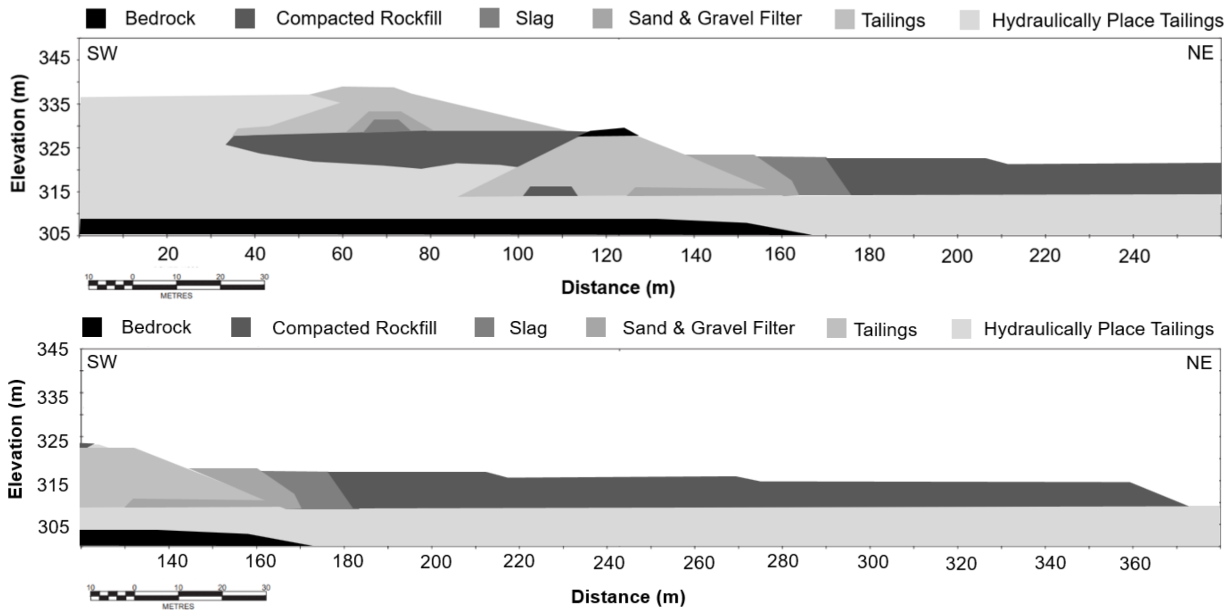


Figure C.13: Sketch of Cross Section 2022

Foundation Material

The bedrock is a Precambrian Shield, and at several locations exposed at the surface. Several rock types have been identified, including high-grade gneisses, a greenstone belt, and related intrusive rock suites. Moreover, volcanic, volcanoclastic and sedimentary rocks can be found. Large ore deposits that are classified as volcanogenic massive sulfide deposits are found in association with the felsic rocks and are distributed throughout the region. The rocks are generally strong and exhibit only slight degrees of weathering. Numerous faults and shear zones have been mapped. The two primary fault orientations identified include a set of north-northwest trending faults that bound the deposits and the tailings facility and a set of east-west trending thrust faults within this bounded zone. Nonetheless, the dams are generally constructed directly on top of natural soils, and to a lesser extent, bedrock.

The lithological sequence from bedrock to surface includes bedrock, glacial till, glaciofluvial soil, glaciolacustrine soil, and peat and organic soil, as shown in Figure C.14. A brief description of the characteristics of each unit:

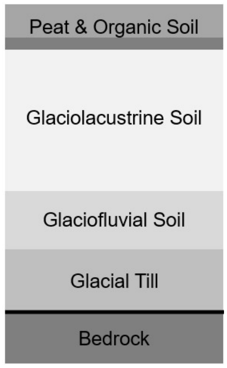


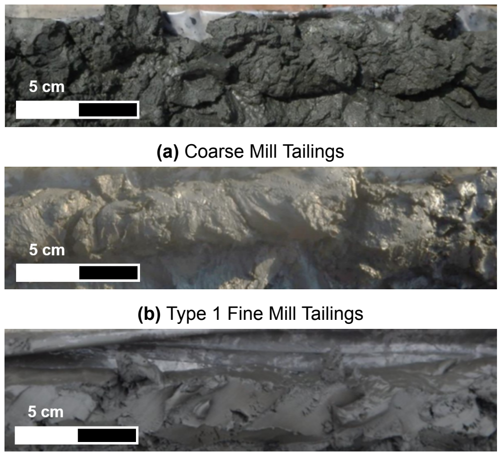
Figure C.14: Lithological Sequence

- **Glacial Till**
  The glacial till is directly overlying the bedrock, intermittently around the site. The thickness varies across the site, with the thickest deposits up to 5 m, typically located on the South-south western region due to the effects of glacier ice movement in the area. The glacial till comprises loose to dense well-graded sand to gravel with some traces of silt, clay, cobbles and boulders. Its structure is heterogeneous.
- **Glaciofluvial Soil**
  The glaciofluvial soils are generally overlying the glacial till, also found intermittently across the site. Generally, their thickness does not exceed 5 m, although in the Northern section of the site, a 10 m thick layer of glaciofluvial soil has been encountered. It is loose to dense well-graded sand, but at some locations it has been characterised as sandy silt or silty sand. The structure of the soil is stratified, alternating between fine and coarse layers. Particles are rounded to sub-angular.
- **Glaciolacustrine Soil**
  Glaciolacustrine soils have been encountered at various locations across the site, overlying either the bedrock, glacial till or glaciofluvial soil. The thickest deposits have been found in areas with flat, low-lying surface topography and where the depth of the bedrock is the greatest. The thickness typically ranges from 1 to 10 m. The plasticity, consistency, and relative clay-silt particle size fractions of the glaciolacustrine soils vary throughout the site. The soils can be classified as high to low-plasticity clay, which is usually normally consolidated. However, in many areas, an overconsolidated upper layer (crust) is present, believed to be caused by weathering. The overconsolidated layer has a thickness of up to 3 m and is generally blocky or fissured on a millimetre scale.
- **Peat and Organic Soil**
  Organic soils and peat are present within the top 0.3 to 2.5 m of the native ground. The peat is usually up to 2.5 m thick overlaying a thin layer of organic silt. The peat is non-plastic, very soft to soft and comprises root fragments and other organic material. The organic content ranges from 70 to 80% and water content from 300 to 400%. The organic silt is non-plastic to low plastic, soft and shows amorphous characteristics. The organic content typically ranges from 25 to 50%, with a water content of 120 to 240%. However, it should be emphasised that the exact composition of these layers may differ within the TSF.

Tailings Material

The dam section under investigation serves as a containment structure for fine mill tailings and is also partly built on top of these tailings. The mill tailings are generated through a flotation circuit and discharged as a slurry with concentrations ranging from 20 to 25% by weight. Cyclones are periodically operated for paste backfill to support underground mining operations and remove the coarsest fraction of the tailings prior to discharge. The mill tailings are generally non-plastic, with particles ranging from fine silty sand to sandy silt. Within the deposited mill tailings, three units can be identified (shown in Figure C.15):

- **Coarse Mill Tailings**: Having an equal proportion of poorly graded fine sand and non-plastic silt. These tailings are found in loose to compact states of relative density and show dilative behaviour.
- **Fine Mill Tailings (Type 1)**: Composed of non-plastic silts, with a fines content exceeding 90%. They have a soft to stiff consistency and are known to exhibit contractive behaviour.
- **Fine Mill Tailings (Type 2)**: Have similar characteristics to 'Type 1 Fine Mill Tailings', but composed of finer-grained materials and in a less compact state compared to Type 1.



(a) Coarse Mill Tailings

(b) Type 1 Fine Mill Tailings

(c) Type 2 Fine Mill Tailings

Figure C.15: Close-Up Picture Mill Tailings

Construction Material

Quite some variability is found within the construction material. Despite the variability of the material some general units can be distinguished, which are briefly described below.

- **Clay and Silt**
  The clay and silt serve as low permeability core fill of several dam sections. These materials are sourced from nearby borrow pits of glaciolacustrine soil and compacted to achieve a minimum dry density of 97%. Typically, they can be categorised as high-plastic clay.
- **Compacted Tailings**
  The compacted tailings are typically composed of non-plastic fine sandy silt to fine sand and silt. These materials are obtained either from designated tailings borrow pits or by 'scalping' deposited mill tailings from the beaches, with as a target obtaining the coarsest fraction of tailings. The tailings are compacted to obtain a minimum of 98% dry density.
- **Slag**
  The slag is a by-product of former smelting processes. The slag consists of cobble to gravel-sized particles with trace sand and has been used in dam construction for drains, dam shells, erosion protection and dust control.
- **Waste Rock**
  Waste rock is used for the construction of the downstream shells and buttresses. Besides, it has been used as rip rap protection along the upstream faces of various dams to prevent erosion due to wave action. When used in constructing the downstream faces, the material is compacted, whereas it is deposited in a loose state at the upstream face. The waste rock is obtained from various sources, including underground and open-pit mining operations. It has variable compositions of boulders, cobbles, gravel and sand with traces of fines. The waste rock is Potential Acid Generating (PAG).

- **Quarried and Transition Rockfill**
  Recently, quarried rockfill has been utilized for constructing the upstream and downstream shells of some perimeter dams as well as buttresses. This material is sourced from a nearby bedrock outcrop and consists of strong to very strong angular particles of fresh to slightly weathered bedrock. It comprises broadly graded particles ranging from 1,000 mm boulders to sand sizes, with zones of PAG material but low metal leaching potential. The rockfill is typically compacted. In addition to the quarried rockfill, finer transition rockfill materials have been produced by processing the quarried rockfill, resulting in a well-graded rockfill with a maximum particle size of 200 mm. This transition rockfill is placed as a transition zone between filter and rockfill zones and is also compacted.
- **Sand and Gravel Filters, and Coarse Filter**
  Materials from the sand and gravel filters have been collected at nearby open pit mines and are crushed to meet the gradation specifications. Various types of filters with different gradations have been utilised, although the same material properties have been applied for simplicity. They are clean granular fills with less than 5% fines content. The filters comprise clean granular fills with less than 5% fines content and are typically compacted.

Available Data

In this section, the available data utilised for the evaluation of the case is listed for reference.

- **OMS Manual**
  The OMS manual consists of a set of sections with general information about the facility, prepared by the TSF owner. The categories discussed are governance, facility description, tailings delivery system, tailings deposition plan, dam raise and construction plan, water management plan, dam safety program, instrumentation and monitoring plan, environmental monitoring plan, emergency action plan and an emergency preparedness plan.
- **Geotechnical Material Properties**
  This document gives a brief description of the native foundation materials and the non-native tailings and construction materials. Geotechnical properties of the different units are estimated, based on different laboratory and field tests. These include direct shear tests, CPTs, field vane shear tests and 1D consolidation tests, among others.
- **Dam Safety Inspections (DSIs)**
  DSIs from 2017-2022 provide a global overview of the TSF constructions. It includes the observations from the site investigations, the installed monitoring instruments and its most striking records. Furthermore, it contains general maintenance advice.
- **Dam Breach Assessment**
  The dam breach assessment includes a dam breach inundation study, which involves the generation of inundation maps. The study also facilitates dam consequence classifications.
- **Independent Peer Review Board (IPRB) Updates**
  A set of documents from the IPRB are available for the period of 2017-2022. It mainly includes presentations summarising stability analysis and planned or completed work.

It is understood that the mine owner has a risk management process in place, however, it is unclear in which detail this is done, which hazards and failure modes have been identified and which actions have been taken. The results have not been made available.

C.2.2. Input and Results

The selected inputs, effect and contribution to the PoF for each factor are shown in Table C.3 and Table C.4.

Table C.3: Inputs, Effects and Contribution to the Probability of Failure (PoF) (for 2017 and 2022)
Case 2: Example Improvement Case (Author) – *Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange), Higest Contribution (Red) - Lowest Contribution (Green))*

ID	2017			2022		
	Selected Input	Effect	PoF	Selected Input	Effect	PoF
1.15	Yes	Adverse	3.9 E-05	Yes	Adverse	3.9 E-05
1.13	Yes	Adverse	2.4 E-05	Yes	Adverse	2.4 E-05
2.31	Moderately, 25-100 m	Adverse	2.3 E-05	Moderately, 25-100 m	Adverse	2.3 E-05
2.38	Yes ("regular tailings")	Adverse	1.8 E-05	Yes ("regular tailings")	Adverse	1.8 E-05
2.52	No/Limited measures in place	Adverse	1.7 E-05	Measures in place, but do not meet design	Neutral	5.8 E-06
2.26	Yes	Adverse	1.5 E-05	Yes	Adverse	1.5 E-05
2.25	No	Adverse	1.5 E-05	Considered to be	Neutral	5.0 E-06
2.51	No/Limited measures in place	Adverse	1.3 E-05	Measures in place, but do not meet design	Neutral	4.2 E-06
3.1.1.a	Does Not Meet	Adverse	1.2 E-05	Does Not Meet	Adverse	1.2 E-05
1.26	Yes	Adverse	1.2 E-05	Yes	Adverse	1.2 E-05
1.17	Yes	Adverse	1.2 E-05	Yes	Adverse	1.2 E-05
2.13	No	Adverse	1.0 E-05	No	Adverse	1.0 E-05
1.31	Potentially	Neutral	1.0 E-05	Yes	Adverse	1.0 E-05
3.1.2.b	Does Not Meet	Adverse	9.1 E-06	Partially Meets	Neutral	3.0 E-06
2.4.a	No	Adverse	9.0 E-06	No	Adverse	9.0 E-06
1.4	Dfc (continental; no dry season; cold	Neutral	8.6 E-06	Dfc (continental; no dry season; cold	Neutral	8.6 E-06
3.1.2.a	Does Not Meet	Adverse	8.2 E-06	Partially Meets	Neutral	2.7 E-06
2.24	Unknown	Unknown	8.1 E-06	Unknown	Unknown	8.1 E-06
2.30	Yes, close to or exceeding natural angle of	Adverse	7.9 E-06	Slightly, but < natural angle of repose	Neutral	2.6 E-06
3.2.1	Does Not Meet	Adverse	7.9 E-06	Does Not Meet	Adverse	7.9 E-06
1.27	Yes	Adverse	7.8 E-06	Yes	Adverse	7.8 E-06
2.14	No	Adverse	7.7 E-06	No	Adverse	7.7 E-06
2.16	No	Adverse	7.7 E-06	Partially	Neutral	2.6 E-06
1.2	Yes, inactive faults which may potentially	Neutral	7.2 E-06	Yes, inactive faults which may potentially	Neutral	7.2 E-06
2.21.b	No	Adverse	7.1 E-06	No	Adverse	7.1 E-06
1.5	Dfc (continental; no dry season; cold	Neutral	5.6 E-06	Dfc (continental; no dry season; cold	Neutral	5.6 E-06
1.1	PGA ≤ 0.2 g (return period 475 years/10%	Favourable	5.5 E-06	PGA ≤ 0.2 g (return period 475 years/10%	Favourable	5.5 E-06
1.11	Yes, embankments between 25 and 100 m	Neutral	5.5 E-06	Yes, embankments between 25 and 100 m	Neutral	5.5 E-06
3.1.1.b	Unknown	Unknown	5.5 E-06	Unknown	Unknown	5.5 E-06
1.14	Yes	Adverse	5.4 E-06	Yes	Adverse	5.4 E-06
3.11.1	Unknown	Unknown	5.2 E-06	Unknown	Unknown	5.2 E-06
2.34	Yes	Adverse	4.9 E-06	Yes	Adverse	4.9 E-06
2.37	Yes	Adverse	4.7 E-06	Yes	Adverse	4.7 E-06
3.3.2.a	Partially Meets	Neutral	4.4 E-06	Meets	Favourable	8.8 E-07
3.10.2	Unknown	Unknown	3.9 E-06	Unknown	Unknown	3.9 E-06
3.10.3	Unknown	Unknown	3.9 E-06	Unknown	Unknown	3.9 E-06
3.3.3.a	Does Not Meet	Adverse	3.9 E-06	Partially Meets	Neutral	1.3 E-06
1.28	Unknown	Unknown	3.9 E-06	Unknown	Unknown	3.9 E-06
3.6.2.b	Does Not Meet	Adverse	3.8 E-06	Does Not Meet	Adverse	3.8 E-06
3.6.2.a	Partially Meets	Neutral	3.8 E-06	Meets	Favourable	7.5 E-07
3.3.6.a	Does Not Meet	Adverse	3.7 E-06	Partially Meets	Neutral	1.2 E-06
3.3.6.b	Does Not Meet	Adverse	3.7 E-06	Meets	Favourable	2.5 E-07
3.3.6.c	Does Not Meet	Adverse	3.7 E-06	Meets	Favourable	2.5 E-07
3.4.4.a	Does Not Meet	Adverse	3.6 E-06	Does Not Meet	Adverse	3.6 E-06
3.4.4.b	Does Not Meet	Adverse	3.6 E-06	Does Not Meet	Adverse	3.6 E-06
2.22	Considered to be	Neutral	3.1 E-06	Considered to be	Neutral	3.1 E-06
1.20.b	Yes, but material only present in minor	Neutral	2.9 E-06	Yes, but material only present in minor	Neutral	2.9 E-06
2.46	Yes	Adverse	2.9 E-06	Yes	Adverse	2.9 E-06
3.2.2	Partially Meets	Neutral	2.8 E-06	Meets	Favourable	5.6 E-07
1.7	Yes, with potential thawing in the next	Adverse	2.7 E-06	Yes, with potential thawing in the next	Adverse	2.7 E-06
3.10.1.a	Unknown	Unknown	2.6 E-06	Unknown	Unknown	2.6 E-06
3.10.5.a	Unknown	Unknown	2.6 E-06	Unknown	Unknown	2.6 E-06
3.12.2.a	Unknown	Unknown	2.6 E-06	Unknown	Unknown	2.6 E-06
2.17	Partially	Neutral	2.6 E-06	Partially	Neutral	2.6 E-06
1.21	Yes	Adverse	2.5 E-06	Yes	Adverse	2.5 E-06
1.6	Dfc (continental; no dry season; cold	Neutral	2.5 E-06	Dfc (continental; no dry season; cold	Neutral	2.5 E-06
3.6.4.b	Partially Meets	Neutral	2.5 E-06	Meets	Favourable	4.9 E-07
2.2	Unknown	Unknown	2.4 E-06	Unknown	Unknown	2.4 E-06
2.8	No	Adverse	2.3 E-06	No	Adverse	2.3 E-06
3.5.6.a	Partially Meets	Neutral	2.3 E-06	Meets	Favourable	4.6 E-07
3.5.6.a	Partially Meets	Neutral	2.3 E-06	Meets	Favourable	4.6 E-07
3.6.3.b	Partially Meets	Neutral	2.1 E-06	Meets	Favourable	4.2 E-07
3.6.3.c	Partially Meets	Neutral	2.1 E-06	Meets	Favourable	4.2 E-07
1.25	Yes	Adverse	2.0 E-06	Yes	Adverse	2.0 E-06
3.3.1.b	Does Not Meet	Adverse	1.9 E-06	Does Not Meet	Adverse	1.9 E-06
3.5.1.d	Does Not Meet	Adverse	1.7 E-06	Meets	Favourable	1.2 E-07
3.11.2	Unknown	Unknown	1.7 E-06	Unknown	Unknown	1.7 E-06

3.12.1.a	Unknown	Unknown	1.7 E-06	Unknown	Unknown	1.7 E-06
3.12.1.b	Unknown	Unknown	1.7 E-06	Unknown	Unknown	1.7 E-06
3.3.1.a	Does Not Meet	Adverse	1.7 E-06	Partially Meets	Neutral	5.8 E-07
3.5.4.b	Does Not Meet	Adverse	1.7 E-06	Partially Meets	Neutral	5.7 E-07
3.5.4.a	Does Not Meet	Adverse	1.7 E-06	Meets	Favourable	1.1 E-07
2.4	Unknown	Unknown	1.7 E-06	Unknown	Unknown	1.7 E-06
2.2	No	Adverse	1.6 E-06	No	Adverse	1.5 E-06
1.19	Unknown	Unknown	1.6 E-06	Unknown	Unknown	1.6 E-06
3.1.2.c	Partially Meets	Neutral	1.6 E-06	Partially Meets	Neutral	1.6 E-06
2.43	Yes	Adverse	1.6 E-06	Yes	Adverse	1.6 E-06
1.23	No	Neutral	1.5 E-06	No	Neutral	1.5 E-06
2.4.b	Yes	Neutral	1.5 E-06	Yes	Neutral	1.5 E-06
3.3.2.b	Partially Meets	Neutral	1.5 E-06	Meets	Favourable	2.9 E-07
3.6.4.d	Partially Meets	Neutral	1.5 E-06	Partially Meets	Neutral	1.5 E-06
1.18	Yes	Adverse	1.4 E-06	Yes	Adverse	1.4 E-06
3.4.5	Partially Meets	Neutral	1.4 E-06	Partially Meets	Neutral	1.4 E-06
3.9.2.a	Does Not Meet	Adverse	1.4 E-06	Does Not Meet	Adverse	1.4 E-06
3.3.5.a	Does Not Meet	Adverse	1.4 E-06	Does Not Meet	Adverse	1.4 E-06
2.6	Yes	Neutral	1.3 E-06	Yes	Neutral	1.3 E-06
3.10.1.b	Unknown	Unknown	1.3 E-06	Unknown	Unknown	1.3 E-06
3.10.4.a	Unknown	Unknown	1.3 E-06	Unknown	Unknown	1.3 E-06
3.10.4.b	Unknown	Unknown	1.3 E-06	Unknown	Unknown	1.3 E-06
3.10.4.c	Unknown	Unknown	1.3 E-06	Unknown	Unknown	1.3 E-06
3.10.5.b	Unknown	Unknown	1.3 E-06	Unknown	Unknown	1.3 E-06
3.3.3.b	Partially Meets	Neutral	1.3 E-06	Partially Meets	Neutral	1.3 E-06
3.5.3.b	Does Not Meet	Adverse	1.3 E-06	Does Not Meet	Adverse	1.3 E-06
3.4.6.a	Does Not Meet	Adverse	1.3 E-06	Does Not Meet	Adverse	1.3 E-06
3.4.6.b	Does Not Meet	Adverse	1.3 E-06	Partially Meets	Neutral	4.3 E-07
3.4.6.c	Does Not Meet	Adverse	1.3 E-06	Partially Meets	Neutral	4.3 E-07
2.54	Measures in place meet design	Favourable	1.3 E-06	Measures in place meet design	Favourable	1.3 E-06
3.6.1.a	Partially Meets	Neutral	1.3 E-06	Meets	Favourable	2.5 E-07
3.4.2.a	Partially Meets	Neutral	1.2 E-06	Partially Meets	Neutral	1.2 E-06
1.30.a	Yes, in the close vicinity	Neutral	1.1 E-06	Yes, in the close vicinity	Neutral	1.1 E-06
3.9.1.b	Does Not Meet	Adverse	1.1 E-06	Does Not Meet	Adverse	1.1 E-06
3.9.1.c	Does Not Meet	Adverse	1.1 E-06	Does Not Meet	Adverse	1.1 E-06
2.42	Yes, a couple	Neutral	1.1 E-06	Yes, a couple	Neutral	1.1 E-06
3.8.3.a	Does Not Meet	Adverse	9.9 E-07	Partially Meets	Neutral	3.3 E-07
3.7.6.a	Unknown	Unknown	9.8 E-07	Unknown	Unknown	9.8 E-07
3.7.6.b	Unknown	Unknown	9.8 E-07	Unknown	Unknown	9.8 E-07
2.53	Measures in place meet design	Favourable	9.3 E-07	Measures in place meet design	Favourable	9.3 E-07
2.29.a	Yes	Neutral	9.2 E-07	Yes	Neutral	9.2 E-07
2.41	Unknown	Unknown	9.2 E-07	Unknown	Unknown	9.2 E-07
3.9.2.c	Unknown	Unknown	9.1 E-07	Unknown	Unknown	9.1 E-07
1.3	Catchment area ≈ TSF footprint	Favourable	8.8 E-07	Catchment area ≈ TSF footprint	Favourable	8.8 E-07
3.12.2.b	Unknown	Unknown	8.7 E-07	Unknown	Unknown	8.7 E-07
1.24	Potentially	Neutral	8.5 E-07	Potentially	Neutral	8.5 E-07
1.9	Possibly	Neutral	8.3 E-07	Possibly	Neutral	8.3 E-07
3.6.4.a	Partially Meets	Neutral	7.8 E-07	Meets	Favourable	1.6 E-07
3.6.4.c	Partially Meets	Neutral	7.8 E-07	Meets	Favourable	1.6 E-07
2.21.a	Yes, >20 m	Favourable	7.6 E-07	Yes, >20 m	Favourable	7.6 E-07
2.45	Potentially	Neutral	7.3 E-07	Potentially	Neutral	7.3 E-07
2.27	Yes	Favourable	7.2 E-07	Yes	Favourable	7.2 E-07
3.8.5.a	Does Not Meet	Adverse	7.1 E-07	Does Not Meet	Adverse	7.1 E-07
3.8.5.b	Does Not Meet	Adverse	7.1 E-07	Does Not Meet	Adverse	7.1 E-07
3.7.1.a	Does Not Meet	Adverse	6.9 E-07	Partially Meets	Neutral	2.3 E-07
1.22	Yes, but material only present in minor	Neutral	6.7 E-07	Yes, but material only present in minor	Neutral	6.7 E-07
2.9	Partially	Neutral	6.7 E-07	Partially	Neutral	6.7 E-07
2.11	Partially	Neutral	6.7 E-07	Yes	Favourable	1.3 E-07
3.5.5.d	Does Not Meet	Adverse	6.7 E-07	Does Not Meet	Adverse	6.7 E-07
3.9.7.b	Does Not Meet	Adverse	6.7 E-07	Partially Meets	Neutral	2.2 E-07
3.9.7.c	Does Not Meet	Adverse	6.7 E-07	Does Not Meet	Adverse	6.7 E-07
1.30.c	Unknown	Unknown	6.5 E-07	Unknown	Unknown	6.5 E-07
2.23	Yes	Favourable	6.5 E-07	Yes	Favourable	6.5 E-07
3.9.1.a	Partially Meets	Neutral	6.5 E-07	Partially Meets	Neutral	6.5 E-07
3.9.1.d	Partially Meets	Neutral	6.5 E-07	Partially Meets	Neutral	6.5 E-07
2.39.a	Unknown	Unknown	6.4 E-07	Unknown	Unknown	6.4 E-07
2.39.b	Unknown	Unknown	6.4 E-07	Unknown	Unknown	6.4 E-07
1.8	No	Favourable	6.3 E-07	No	Favourable	6.3 E-07
2.3.a	Yes	Favourable	6.1 E-07	Yes	Favourable	6.1 E-07
2.18	Yes	Favourable	6.0 E-07	Yes	Favourable	6.0 E-07
3.9.1.e	Does Not Meet	Adverse	5.9 E-07	Does Not Meet	Adverse	5.9 E-07
3.9.1.f	Does Not Meet	Adverse	5.9 E-07	Does Not Meet	Adverse	5.9 E-07
3.5.4.c	Does Not Meet	Adverse	5.7 E-07	Meets	Favourable	3.8 E-08
3.5.4.d	Does Not Meet	Adverse	5.7 E-07	Meets	Favourable	3.8 E-08
3.5.4.e	Unknown	Unknown	5.7 E-07	Unknown	Unknown	3.8 E-08
1.30.f	Yes	Adverse	5.6 E-07	No	Favourable	3.8 E-08
2.15	Yes	Favourable	5.1 E-07	Yes	Favourable	5.1 E-07
3.9.4	Meets	Favourable	4.8 E-07	Meets	Favourable	4.8 E-07

3.9.2.b	Unknown	Unknown	4.6 E-07	Unknown	Unknown	4.6 E-07
3.9.2.d	Unknown	Unknown	4.6 E-07	Unknown	Unknown	4.6 E-07
3.6.1.b	Partially Meets	Neutral	4.2 E-07	Meets	Favourable	8.4 E-08
3.6.1.c	Partially Meets	Neutral	4.2 E-07	Meets	Favourable	8.4 E-08
3.6.3.a	Meets	Favourable	4.2 E-07	Meets	Favourable	4.2 E-07
3.4.1.a	Partially Meets	Neutral	3.7 E-07	Partially Meets	Neutral	3.7 E-07
3.4.1.b	Partially Meets	Neutral	3.7 E-07	Partially Meets	Neutral	3.7 E-07
2.35	No	Favourable	3.7 E-07	No	Favourable	3.7 E-07
1.1	No	Favourable	3.7 E-07	No	Favourable	3.7 E-07
3.5.1.a	Meets	Favourable	3.5 E-07	Meets	Favourable	3.5 E-07
3.5.1.c	Meets	Favourable	3.5 E-07	Meets	Favourable	3.5 E-07
3.7.7.e	Does Not Meet	Adverse	3.4 E-07	Does Not Meet	Adverse	3.4 E-07
3.7.4.a	Unknown	Unknown	3.4 E-07	Unknown	Unknown	3.4 E-07
3.7.4.b	Unknown	Unknown	3.4 E-07	Unknown	Unknown	3.4 E-07
3.7.4.c	Unknown	Unknown	3.4 E-07	Unknown	Unknown	3.4 E-07
3.8.3.b	Partially Meets	Neutral	3.3 E-07	Partially Meets	Neutral	3.3 E-07
3.8.4.a	Unknown	Unknown	3.3 E-07	Unknown	Unknown	3.3 E-07
2.36	No	Favourable	3.2 E-07	No	Favourable	3.2 E-07
2.3.c	Yes	Favourable	3.1 E-07	Yes	Favourable	3.1 E-07
3.7.5.c	Unknown	Unknown	3.1 E-07	Unknown	Unknown	3.1 E-07
2.19.a	No	Neutral	3.1 E-07	Yes	Adverse	5.5 E-07
3.5.2.a	Meets	Favourable	3.0 E-07	Meets	Favourable	3.0 E-07
3.5.2.b	Meets	Favourable	3.0 E-07	Meets	Favourable	3.0 E-07
3.4.3.a	Partially Meets	Neutral	2.9 E-07	Partially Meets	Neutral	2.9 E-07
3.4.3.c	Partially Meets	Neutral	2.9 E-07	Partially Meets	Neutral	2.9 E-07
3.3.5.c	Meets	Favourable	2.7 E-07	Meets	Favourable	2.7 E-07
3.5.3.a	Meets	Favourable	2.6 E-07	Meets	Favourable	2.6 E-07
3.6.2.c	Meets	Favourable	2.5 E-07	Meets	Favourable	2.5 E-07
3.9.6.a	Partially Meets	Neutral	2.5 E-07	Partially Meets	Neutral	2.5 E-07
3.8.1.c	Partially Meets	Neutral	2.4 E-07	Partially Meets	Neutral	2.4 E-07
3.4.2.b	Meets	Favourable	2.4 E-07	Meets	Favourable	2.4 E-07
3.4.7.a	Partially Meets	Neutral	2.4 E-07	Partially Meets	Neutral	2.4 E-07
3.4.7.b	Partially Meets	Neutral	2.4 E-07	Partially Meets	Neutral	2.4 E-07
3.4.7.c	Partially Meets	Neutral	2.4 E-07	Partially Meets	Neutral	2.4 E-07
1.30.e	Unknown	Unknown	2.4 E-07	Unknown	Unknown	2.4 E-07
3.7.1.b	Does Not Meet	Adverse	2.3 E-07	Meets	Favourable	1.5 E-08
1.16	No	Favourable	2.3 E-07	No	Favourable	2.3 E-07
3.5.5.b	Does Not Meet	Adverse	2.2 E-07	Does Not Meet	Adverse	2.2 E-07
3.5.5.e	Does Not Meet	Adverse	2.2 E-07	Does Not Meet	Adverse	2.2 E-07
3.5.5.f	Does Not Meet	Adverse	2.2 E-07	Does Not Meet	Adverse	2.2 E-07
3.9.7.a	Partially Meets	Neutral	2.2 E-07	Meets	Favourable	4.5 E-08
3.3.4	Meets	Favourable	2.2 E-07	Meets	Favourable	2.2 E-07
3.6.5.a	Meets	Favourable	2.1 E-07	Meets	Favourable	2.1 E-07
3.6.5.b	Meets	Favourable	2.1 E-07	Meets	Favourable	2.1 E-07
2.33	Yes	Favourable	2.0 E-07	Yes	Favourable	2.0 E-07
3.7.3.a	Unknown	Unknown	2.0 E-07	Unknown	Unknown	2.0 E-07
2.29.b	No	Favourable	1.8 E-07	No	Favourable	1.8 E-07
2.48.a	No	Adverse	1.8 E-07	No	Adverse	1.8 E-07
2.3.d	Yes	Favourable	1.7 E-07	Yes	Favourable	1.7 E-07
2.3.e	Yes	Favourable	1.7 E-07	Yes	Favourable	1.7 E-07
2.3.b	Yes	Favourable	1.6 E-07	Yes	Favourable	1.6 E-07
2.28	Partly	Neutral	1.6 E-07	Partly	Neutral	1.6 E-07
3.6.4.e	Meets	Favourable	1.6 E-07	Meets	Favourable	1.6 E-07
3.7.2.a	Unknown	Unknown	1.5 E-07	Unknown	Unknown	1.5 E-07
3.7.2.b	Unknown	Unknown	1.5 E-07	Unknown	Unknown	1.5 E-07
3.7.2.c	Unknown	Unknown	1.5 E-07	Unknown	Unknown	1.5 E-07
3.7.2.d	Unknown	Unknown	1.5 E-07	Unknown	Unknown	1.5 E-07
1.20.a	No	Favourable	1.5 E-07	No	Favourable	1.5 E-07
3.9.3	Meets	Favourable	1.5 E-07	Meets	Favourable	1.5 E-07
3.9.7.d	Unknown	Unknown	1.5 E-07	Unknown	Unknown	1.5 E-07
3.8.1.a	Meets	Favourable	1.4 E-07	Meets	Favourable	1.4 E-07
3.8.1.b	Meets	Favourable	1.4 E-07	Meets	Favourable	1.4 E-07
1.12	Yes	Favourable	1.4 E-07	Yes	Favourable	1.4 E-07
3.8.2.c	Does Not Meet	Adverse	1.3 E-07	Does Not Meet	Adverse	1.3 E-07
2.1	Yes	Favourable	1.3 E-07	Yes	Favourable	1.3 E-07
2.12	Yes	Favourable	1.3 E-07	Yes	Favourable	1.3 E-07
3.5.1.b	Unknown	Unknown	1.2 E-07	Unknown	Unknown	1.2 E-07
3.7.7.b	Partially Meets	Neutral	1.1 E-07	Partially Meets	Neutral	1.1 E-07
3.7.4.d	Unknown	Unknown	1.1 E-07	Unknown	Unknown	1.1 E-07
3.8.3.c	Partially Meets	Neutral	1.1 E-07	Partially Meets	Neutral	1.1 E-07
3.7.3.c	Unknown	Unknown	1.1 E-07	Unknown	Unknown	1.1 E-07
3.8.4.b	Unknown	Unknown	1.1 E-07	Unknown	Unknown	1.1 E-07
3.8.4.c	Unknown	Unknown	1.1 E-07	Unknown	Unknown	1.1 E-07
3.7.5.b	Unknown	Unknown	1.0 E-07	Unknown	Unknown	1.0 E-07
2.44	No	Favourable	9.2 E-08	No	Favourable	9.2 E-08
3.3.5.b	Meets	Favourable	9.1 E-08	Meets	Favourable	9.1 E-08
3.8.2.b	Partially Meets	Neutral	8.1 E-08	Partially Meets	Neutral	8.1 E-08
3.9.5.a	Meets	Favourable	6.8 E-08	Meets	Favourable	6.8 E-08

3.9.5.b	Meets	Favourable	6.8 E-08	Meets	Favourable	6.8 E-08
3.9.5.c	Meets	Favourable	6.8 E-08	Meets	Favourable	6.8 E-08
3.9.5.d	Meets	Favourable	6.8 E-08	Meets	Favourable	6.8 E-08
1.30.b	No	Favourable	6.5 E-08	No	Favourable	6.5 E-08
1.30.d	No	Favourable	6.5 E-08	No	Favourable	6.5 E-08
3.7.3.b	Unknown	Unknown	6.1 E-08	Unknown	Unknown	6.1 E-08
3.4.3.b	Meets	Favourable	5.9 E-08	Meets	Favourable	5.9 E-08
2.48.c	No	Adverse	5.4 E-08	No	Adverse	5.4 E-08
3.9.6.b	Meets	Favourable	5.0 E-08	Meets	Favourable	5.0 E-08
3.9.6.c	Meets	Favourable	5.0 E-08	Meets	Favourable	5.0 E-08
3.5.5.a	Meets	Favourable	4.5 E-08	Meets	Favourable	4.5 E-08
1.29	No	Favourable	3.9 E-08	No	Favourable	3.9 E-08
3.7.5.a	Meets	Favourable	3.1 E-08	Meets	Favourable	3.1 E-08
3.7.5.e	Meets	Favourable	3.1 E-08	Meets	Favourable	3.1 E-08
3.8.2.a	Meets	Favourable	3.0 E-08	Meets	Favourable	3.0 E-08
2.32	No	Favourable	2.9 E-08	No	Favourable	2.9 E-08
3.7.7.a	Meets	Favourable	2.3 E-08	Meets	Favourable	2.3 E-08
3.7.7.c	Meets	Favourable	2.3 E-08	Meets	Favourable	2.3 E-08
3.7.7.d	Meets	Favourable	2.3 E-08	Meets	Favourable	2.3 E-08
2.48.e	No	Adverse	2.0 E-08	No	Adverse	2.0 E-08
3.5.5.c	Meets	Favourable	1.5 E-08	Meets	Favourable	1.5 E-08
3.7.5.d	Meets	Favourable	1.0 E-08	Meets	Favourable	1.0 E-08
2.49	N/A	x	x	Yes	Favourable	2.2 E-07
2.1	N/A	x	x	N/A	x	x
2.5	N/A	x	x	N/A	x	x
2.7	N/A	x	x	N/A	x	x
2.19.b	N/A	x	x	N/A	x	x
2.47	N/A	x	x	N/A	x	x
2.48.b	N/A	x	x	N/A	x	x
2.48.d	N/A	x	x	N/A	x	x
2.48.f	N/A	x	x	N/A	x	x
		Total	*8.1 E-04*		*Total*	*6.4 E-04*

Table C.4: Inputs, Effects and Contribution to the Probability of Failure (PoF) (for 2017 and 2022) Case 2: Example Improvement Case (Author) – *Colour Scale: Favourable (Green), Neutral (Yellow), Adverse (Red), Unknown (Orange), Highest Contribution (Red) - Lowest Contribution (Green))*

ID	2017			2022		
	Selected Input	Effect	PoF	Selected Input	Effect	PoF
1.15	Yes	Adverse	6.4 E-05	Yes	Adverse	6.4 E-05
1.13	Yes	Adverse	4.0 E-05	Yes	Adverse	4.0 E-05
2.31	Moderately, 25-100 m	Adverse	3.8 E-05	Moderately, 25-100 m	Adverse	3.8 E-05
2.3.a	No	Adverse	3.6 E-05	Yes	Favourable	6.1 E-07
2.38	Yes ('regular tailings")	Adverse	3.0 E-05	Yes ('regular tailings")	Adverse	3.0 E-05
2.26	Yes	Adverse	2.5 E-05	Yes	Adverse	2.5 E-05
2.51	No/Limited measures in place	Adverse	2.1 E-05	Measures in place meet design	Favourable	8.3 E-07
3.1.1.a	Does Not Meet	Adverse	2.0 E-05	Does Not Meet	Adverse	2.0 E-05
2.24	No	Adverse	2.0 E-05	No	Adverse	2.0 E-05
1.26	Yes	Adverse	2.0 E-05	Yes	Adverse	2.0 E-05
1.17	Yes	Adverse	2.0 E-05	Yes	Adverse	2.0 E-05
2.13	No	Adverse	1.7 E-05	No	Adverse	1.7 E-05
2.4.a	No	Adverse	1.5 E-05	No	Adverse	1.5 E-05
2.30	Yes, close to or exceeding natural angle of	Adverse	1.3 E-05	Slightly, but < natural angle of repose	Neutral	2.6 E-06
3.2.1	Does Not Meet	Adverse	1.3 E-05	Does Not Meet	Adverse	1.3 E-05
1.27	Yes	Adverse	1.3 E-05	Yes	Adverse	1.3 E-05
2.16	No	Adverse	1.3 E-05	Yes	Favourable	5.1 E-07
2.21.b	No	Adverse	1.2 E-05	No	Adverse	1.2 E-05
1.14	Yes	Adverse	9.0 E-06	Yes	Adverse	9.0 E-06
1.4	Dfc (continental; no dry season; cold	Neutral	8.6 E-06	Dfc (continental; no dry season; cold	Neutral	8.6 E-06
2.34	Yes	Adverse	8.2 E-06	Yes	Adverse	8.2 E-06
3.3.2.b	Does Not Meet	Adverse	7.4 E-06	Meets	Favourable	2.9 E-07
1.2	Yes, inactive faults which may potentially	Neutral	7.2 E-06	Yes, inactive faults which may potentially	Neutral	7.2 E-06
3.3.3.a	Does Not Meet	Adverse	6.5 E-06	Partially Meets	Neutral	1.3 E-06
3.3.3.b	Does Not Meet	Adverse	6.5 E-06	Meets	Favourable	2.6 E-07
3.6.2.b	Does Not Meet	Adverse	6.3 E-06	Meets	Favourable	2.5 E-07
3.6.2.c	Does Not Meet	Adverse	6.3 E-06	Meets	Favourable	2.5 E-07
3.3.6.a	Does Not Meet	Adverse	6.1 E-06	Partially Meets	Neutral	1.2 E-06
3.3.6.b	Does Not Meet	Adverse	6.1 E-06	Meets	Favourable	2.5 E-07
3.3.6.c	Does Not Meet	Adverse	6.1 E-06	Meets	Favourable	2.5 E-07
3.4.4.a	Does Not Meet	Adverse	6.0 E-06	Does Not Meet	Adverse	6.0 E-06
3.4.4.b	Does Not Meet	Adverse	6.0 E-06	Does Not Meet	Adverse	6.0 E-06
2.2	No	Adverse	5.9 E-06	No	Adverse	5.9 E-06
1.5	Dfc (continental; no dry season; cold	Neutral	5.6 E-06	Dfc (continental; no dry season; cold	Neutral	5.6 E-06
1.1	PGA ≤ 0.2 g (return period 475 years/10%	Favourable	5.5 E-06	PGA ≤ 0.2 g (return period 475 years/10%	Favourable	5.5 E-06
1.11	Yes, embankments between 25 and 100 m	Neutral	5.5 E-06	Yes, embankments between 25 and 100 m	Neutral	5.5 E-06

3.1.1.b	Unknown	Unknown	5.5 E-06	Unknown	Unknown	5.5 E-06
2.49	No	Adverse	5.4 E-06	Yes	Favourable	2.2 E-07
3.11.1	Unknown	Unknown	5.2 E-06	Unknown	Unknown	5.2 E-06
2.46	Yes	Adverse	4.8 E-06	Yes	Adverse	4.8 E-06
1.7	Yes, with potential thawing in the next	Adverse	4.6 E-06	Yes, with potential thawing in the next	Adverse	4.6 E-06
3.3.2.a	Partially Meets	Neutral	4.4 E-06	Partially Meets	Neutral	4.4 E-06
2.4	Yes	Adverse	4.3 E-06	Yes	Adverse	4.3 E-06
1.21	Yes	Adverse	4.2 E-06	Yes	Adverse	4.2 E-06
3.10.2	Unknown	Unknown	3.9 E-06	Unknown	Unknown	3.9 E-06
3.10.3	Unknown	Unknown	3.9 E-06	Unknown	Unknown	3.9 E-06
2.8	No	Adverse	3.8 E-06	No	Adverse	3.8 E-06
3.6.2.a	Partially Meets	Neutral	3.8 E-06	Meets	Favourable	7.5 E-07
2.27	Partly	Neutral	3.6 E-06	Partly	Neutral	3.6 E-06
1.25	Yes	Adverse	3.4 E-06	Yes	Adverse	3.4 E-06
2.9	No	Adverse	3.3 E-06	Partially	Neutral	6.5 E-07
3.9.1.a	Does Not Meet	Adverse	3.3 E-06	Does Not Meet	Adverse	3.3 E-06
3.3.1.b	Does Not Meet	Adverse	3.1 E-06	Meets	Favourable	1.2 E-07
2.22	Considered to be	Neutral	3.1 E-06	Considered to be	Neutral	3.1 E-06
3.1.2.b	Partially Meets	Neutral	3.0 E-06	Partially Meets	Neutral	3.0 E-06
1.20.b	Yes, but material only present in minor	Neutral	2.9 E-06	Yes	Adverse	1.5 E-05
3.5.1.d	Does Not Meet	Adverse	2.9 E-06	Meets	Favourable	1.2 E-07
3.5.4.b	Does Not Meet	Adverse	2.9 E-06	Does Not Meet	Adverse	2.9 E-06
3.2.2	Partially Meets	Neutral	2.8 E-06	Partially Meets	Neutral	2.8 E-06
2.2	No	Adverse	2.7 E-06	No	Adverse	2.4 E-06
3.1.2.a	Partially Meets	Neutral	2.7 E-06	Partially Meets	Neutral	2.7 E-06
3.10.1.a	Unknown	Unknown	2.6 E-06	Unknown	Unknown	2.6 E-06
3.10.5.a	Unknown	Unknown	2.6 E-06	Unknown	Unknown	2.6 E-06
3.12.2.a	Unknown	Unknown	2.6 E-06	Unknown	Unknown	2.6 E-06
2.43	Yes	Adverse	2.6 E-06	Yes	Adverse	2.6 E-06
2.17	Partially	Neutral	2.6 E-06	Partially	Neutral	2.6 E-06
2.15	Partially	Neutral	2.6 E-06	Yes	Favourable	5.1 E-07
1.6	Dfc (continental; no dry season; cold	Neutral	2.5 E-06	Dfc (continental; no dry season; cold	Neutral	2.5 E-06
3.6.4.b	Partially Meets	Neutral	2.5 E-06	Meets	Favourable	4.9 E-07
1.18	Yes	Adverse	2.4 E-06	Yes	Adverse	2.4 E-06
3.5.6.a	Partially Meets	Neutral	2.3 E-06	Meets	Favourable	4.6 E-07
3.5.6.a	Partially Meets	Neutral	2.3 E-06	Meets	Favourable	4.6 E-07
3.9.2.a	Does Not Meet	Adverse	2.3 E-06	Does Not Meet	Adverse	2.3 E-06
3.3.5.a	Does Not Meet	Adverse	2.3 E-06	Meets	Favourable	9.1 E-08
3.4.6.a	Does Not Meet	Adverse	2.1 E-06	Does Not Meet	Adverse	2.1 E-06
3.6.3.a	Partially Meets	Neutral	2.1 E-06	Meets	Favourable	4.2 E-07
3.6.3.b	Partially Meets	Neutral	2.1 E-06	Meets	Favourable	4.2 E-07
3.6.3.c	Partially Meets	Neutral	2.1 E-06	Meets	Favourable	4.2 E-07
3.9.1.b	Does Not Meet	Adverse	1.8 E-06	Does Not Meet	Adverse	1.8 E-06
3.9.1.c	Does Not Meet	Adverse	1.8 E-06	Does Not Meet	Adverse	1.8 E-06
3.5.1.a	Partially Meets	Neutral	1.7 E-06	Meets	Favourable	3.5 E-07
3.11.2	Unknown	Unknown	1.7 E-06	Unknown	Unknown	1.7 E-06
3.12.1.a	Unknown	Unknown	1.7 E-06	Unknown	Unknown	1.7 E-06
3.12.1.b	Unknown	Unknown	1.7 E-06	Unknown	Unknown	1.7 E-06
2.5	No	Adverse	1.7 E-06	No	Adverse	1.7 E-06
3.8.3.a	Does Not Meet	Adverse	1.7 E-06	Partially Meets	Neutral	3.3 E-07
3.1.2.c	Partially Meets	Neutral	1.6 E-06	Partially Meets	Neutral	1.6 E-06
1.23	No	Neutral	1.5 E-06	No	Neutral	1.5 E-06
2.4.b	Yes	Neutral	1.5 E-06	Yes	Neutral	1.5 E-06
3.6.4.d	Partially Meets	Neutral	1.5 E-06	Partially Meets	Neutral	1.5 E-06
3.4.5	Partially Meets	Neutral	1.4 E-06	Partially Meets	Neutral	1.4 E-06
2.6	Yes	Neutral	1.4 E-06	Yes	Neutral	1.3 E-06
3.10.1.b	Unknown	Unknown	1.3 E-06	Unknown	Unknown	1.3 E-06
3.10.4.a	Unknown	Unknown	1.3 E-06	Unknown	Unknown	1.3 E-06
3.10.4.b	Unknown	Unknown	1.3 E-06	Unknown	Unknown	1.3 E-06
3.10.4.c	Unknown	Unknown	1.3 E-06	Unknown	Unknown	1.3 E-06
3.10.5.b	Unknown	Unknown	1.3 E-06	Unknown	Unknown	1.3 E-06
2.54	Measures in place meet design	Favourable	1.3 E-06	Measures in place meet design	Favourable	1.3 E-06
3.6.1.a	Partially Meets	Neutral	1.3 E-06	Meets	Favourable	2.5 E-07
3.4.2.a	Partially Meets	Neutral	1.2 E-06	Partially Meets	Neutral	1.2 E-06
3.4.7.a	Does Not Meet	Adverse	1.2 E-06	Partially Meets	Neutral	2.4 E-07
3.4.7.b	Does Not Meet	Adverse	1.2 E-06	Partially Meets	Neutral	2.4 E-07
3.4.7.c	Does Not Meet	Adverse	1.2 E-06	Partially Meets	Neutral	2.4 E-07
3.8.5.a	Does Not Meet	Adverse	1.2 E-06	Does Not Meet	Adverse	1.2 E-06
3.8.5.b	Does Not Meet	Adverse	1.2 E-06	Does Not Meet	Adverse	1.2 E-06
2.52	Measures in place meet design	Favourable	1.2 E-06	Measures in place meet design	Favourable	1.2 E-06
3.5.5.d	Does Not Meet	Adverse	1.1 E-06	Does Not Meet	Adverse	1.1 E-06
3.9.7.c	Does Not Meet	Adverse	1.1 E-06	Does Not Meet	Adverse	1.1 E-06
3.3.4	Partially Meets	Neutral	1.1 E-06	Meets	Favourable	2.2 E-07
1.30.a	Yes, in the close vicinity	Neutral	1.1 E-06	Yes, in the close vicinity	Neutral	1.1 E-06
2.42	Yes, a couple	Neutral	1.1 E-06	Yes, a couple	Neutral	1.1 E-06
1.31	Yes	Adverse	1.0 E-06	Yes	Adverse	1.0 E-06
2.25	Yes, Demonstrated	Favourable	1.0 E-06	Considered to be	Neutral	5.0 E-06
3.9.1.e	Does Not Meet	Adverse	9.9 E-07	Does Not Meet	Adverse	9.9 E-07

3.9.1.f	Does Not Meet	Adverse	9.9 E-07	Does Not Meet	Adverse	9.9 E-07
3.7.6.a	Unknown	Unknown	9.8 E-07	Unknown	Unknown	9.8 E-07
3.7.6.b	Unknown	Unknown	9.8 E-07	Unknown	Unknown	9.8 E-07
3.5.4.c	Does Not Meet	Adverse	9.6 E-07	Meets	Favourable	3.8 E-08
1.30.f	Yes	Adverse	9.4 E-07	No	Favourable	3.8 E-08
2.53	Measures in place meet design	Favourable	9.3 E-07	Measures in place meet design	Favourable	9.2 E-07
2.29.a	Yes	Neutral	9.2 E-07	Yes	Neutral	9.2 E-07
3.9.2.c	Unknown	Unknown	9.1 E-07	Unknown	Unknown	9.1 E-07
1.3	Catchment area ≈ TSF footprint	Favourable	8.8 E-07	Catchment area ≈ TSF footprint	Favourable	8.8 E-07
3.12.2.b	Unknown	Unknown	8.7 E-07	Unknown	Unknown	8.7 E-07
1.24	Potentially	Neutral	8.5 E-07	Potentially	Neutral	8.5 E-07
1.9	Possibly	Neutral	8.3 E-07	Possibly	Neutral	8.3 E-07
3.6.4.a	Partially Meets	Neutral	7.8 E-07	Meets	Favourable	1.6 E-07
3.6.4.c	Partially Meets	Neutral	7.8 E-07	Meets	Favourable	1.6 E-07
3.6.4.e	Partially Meets	Neutral	7.8 E-07	Meets	Favourable	1.6 E-07
2.21.a	Yes, >20 m	Favourable	7.6 E-07	Yes, >20 m	Favourable	7.6 E-07
2.45	Potentially	Neutral	7.3 E-07	Potentially	Neutral	7.3 E-07
1.22	Yes, but material only present in minor	Neutral	6.7 E-07	Yes, but material only present in minor quantitie	Neutral	6.7 E-07
2.23	Yes	Favourable	6.5 E-07	Yes	Favourable	6.5 E-07
2.11	Partially	Neutral	6.5 E-07	Yes	Favourable	1.3 E-07
3.9.1.d	Partially Meets	Neutral	6.5 E-07	Partially Meets	Neutral	6.5 E-07
1.8	No	Favourable	6.3 E-07	No	Favourable	6.3 E-07
2.18	Yes	Favourable	6.0 E-07	Partially	Neutral	3.0 E-06
3.3.1.a	Partially Meets	Neutral	5.8 E-07	Meets	Favourable	1.2 E-07
3.5.4.a	Partially Meets	Neutral	5.7 E-07	Meets	Favourable	1.1 E-07
3.7.7.e	Does Not Meet	Adverse	5.6 E-07	Unknown	Unknown	2.3 E-07
3.7.7.a	Does Not Meet	Adverse	5.6 E-07	Meets	Favourable	2.3 E-08
2.14	Yes	Favourable	5.1 E-07	Partially	Neutral	2.6 E-06
3.9.4	Meets	Favourable	4.8 E-07	Meets	Favourable	4.8 E-07
3.9.2.b	Unknown	Unknown	4.6 E-07	Unknown	Unknown	4.6 E-07
3.9.2.d	Unknown	Unknown	4.6 E-07	Unknown	Unknown	4.6 E-07
3.5.3.b	Partially Meets	Neutral	4.3 E-07	Partially Meets	Neutral	4.3 E-07
3.4.6.b	Partially Meets	Neutral	4.3 E-07	Partially Meets	Neutral	4.3 E-07
3.4.6.c	Partially Meets	Neutral	4.3 E-07	Partially Meets	Neutral	4.3 E-07
3.6.1.b	Partially Meets	Neutral	4.2 E-07	Meets	Favourable	8.4 E-08
3.6.1.c	Partially Meets	Neutral	4.2 E-07	Meets	Favourable	8.4 E-08
1.28	No	Favourable	3.9 E-07	Yes	Adverse	9.8 E-06
3.7.1.b	Does Not Meet	Adverse	3.8 E-07	Meets	Favourable	1.5 E-08
3.4.1.a	Partially Meets	Neutral	3.7 E-07	Partially Meets	Neutral	3.7 E-07
3.4.1.b	Partially Meets	Neutral	3.7 E-07	Partially Meets	Neutral	3.7 E-07
3.5.5.b	Does Not Meet	Adverse	3.7 E-07	Does Not Meet	Adverse	3.7 E-07
3.5.5.e	Does Not Meet	Adverse	3.7 E-07	Does Not Meet	Adverse	3.7 E-07
3.5.5.f	Does Not Meet	Adverse	3.7 E-07	Does Not Meet	Adverse	3.7 E-07
3.5.5.c	Does Not Meet	Adverse	3.7 E-07	Meets	Favourable	1.5 E-08
2.35	No	Favourable	3.7 E-07	No	Favourable	3.7 E-07
1.1	No	Favourable	3.7 E-07	No	Favourable	3.7 E-07
3.5.1.c	Meets	Favourable	3.5 E-07	Meets	Favourable	3.5 E-07
2.32	Yes	Unknown	3.5 E-07	No	Favourable	2.8 E-08
3.7.4.a	Unknown	Unknown	3.4 E-07	Unknown	Unknown	3.4 E-07
3.7.4.b	Unknown	Unknown	3.4 E-07	Unknown	Unknown	3.4 E-07
3.7.4.c	Unknown	Unknown	3.4 E-07	Unknown	Unknown	3.4 E-07
3.8.3.b	Partially Meets	Neutral	3.3 E-07	Partially Meets	Neutral	3.3 E-07
3.8.4.a	Unknown	Unknown	3.3 E-07	Unknown	Unknown	3.3 E-07
2.28	Unknown	Unknown	3.2 E-07	Yes	Favourable	3.2 E-08
2.37	No	Favourable	3.2 E-07	No	Favourable	3.2 E-07
2.36	No	Favourable	3.2 E-07	No	Favourable	3.2 E-07
3.7.5.c	Unknown	Unknown	3.1 E-07	Unknown	Unknown	3.1 E-07
2.19.a	No	Neutral	3.0 E-07	Yes	Adverse	9.1 E-07
3.5.2.a	Meets	Favourable	3.0 E-07	Meets	Favourable	3.0 E-07
3.5.2.b	Meets	Favourable	3.0 E-07	Meets	Favourable	3.0 E-07
3.4.3.a	Partially Meets	Neutral	2.9 E-07	Partially Meets	Neutral	2.9 E-07
3.4.3.c	Partially Meets	Neutral	2.9 E-07	Partially Meets	Neutral	2.9 E-07
3.4.3.b	Partially Meets	Neutral	2.9 E-07	Meets	Favourable	5.9 E-08
3.3.5.c	Meets	Favourable	2.7 E-07	Meets	Favourable	2.7 E-07
3.5.3.a	Meets	Favourable	2.6 E-07	Meets	Favourable	2.6 E-07
3.9.6.a	Partially Meets	Neutral	2.5 E-07	Partially Meets	Neutral	2.5 E-07
3.8.1.c	Partially Meets	Neutral	2.4 E-07	Partially Meets	Neutral	2.4 E-07
3.4.2.b	Meets	Favourable	2.4 E-07	Meets	Favourable	2.4 E-07
1.30.e	Unknown	Unknown	2.4 E-07	Unknown	Unknown	2.4 E-07
3.7.1.a	Partially Meets	Neutral	2.3 E-07	Partially Meets	Neutral	2.3 E-07
1.16	No	Favourable	2.3 E-07	No	Favourable	2.3 E-07
3.8.2.c	Does Not Meet	Adverse	2.2 E-07	Does Not Meet	Adverse	2.2 E-07
3.9.7.a	Partially Meets	Neutral	2.2 E-07	Meets	Favourable	4.5 E-08
3.9.7.b	Partially Meets	Neutral	2.2 E-07	Partially Meets	Neutral	2.2 E-07
3.6.5.a	Meets	Favourable	2.1 E-07	Meets	Favourable	2.1 E-07
3.6.5.b	Meets	Favourable	2.1 E-07	Meets	Favourable	2.1 E-07
2.33	Yes	Favourable	2.0 E-07	Yes	Favourable	2.0 E-07
3.7.3.a	Unknown	Unknown	2.0 E-07	Unknown	Unknown	2.0 E-07

1.29	Potentially	Neutral	2.0 E-07	Potentially	Neutral	2.0 E-07
2.29.b	No	Favourable	1.8 E-07	No	Favourable	1.8 E-07
2.48.a	No	Adverse	1.8 E-07	No	Adverse	1.8 E-07
1.19	No	Favourable	1.6 E-07	No	Favourable	1.6 E-07
3.7.2.a	Unknown	Unknown	1.5 E-07	Unknown	Unknown	1.5 E-07
3.7.2.b	Unknown	Unknown	1.5 E-07	Unknown	Unknown	1.5 E-07
3.7.2.c	Unknown	Unknown	1.5 E-07	Unknown	Unknown	1.5 E-07
3.7.2.d	Unknown	Unknown	1.5 E-07	Unknown	Unknown	1.5 E-07
1.20.a	No	Favourable	1.5 E-07	No	Favourable	1.5 E-07
3.9.3	Meets	Favourable	1.5 E-07	Meets	Favourable	1.5 E-07
3.9.7.d	Unknown	Unknown	1.5 E-07	Unknown	Unknown	1.5 E-07
3.8.1.a	Meets	Favourable	1.4 E-07	Meets	Favourable	1.4 E-07
3.8.1.b	Meets	Favourable	1.4 E-07	Meets	Favourable	1.4 E-07
1.12	Yes	Favourable	1.4 E-07	Yes	Favourable	1.4 E-07
2.1	Yes	Favourable	1.3 E-07	Yes	Favourable	1.3 E-07
2.12	Yes	Favourable	1.3 E-07	Yes	Favourable	1.3 E-07
3.5.1.b	Unknown	Unknown	1.2 E-07	Unknown	Unknown	1.2 E-07
3.7.7.b	Partially Meets	Neutral	1.1 E-07	Meets	Favourable	2.3 E-08
3.7.4.d	Unknown	Unknown	1.1 E-07	Unknown	Unknown	1.1 E-07
3.8.3.c	Partially Meets	Neutral	1.1 E-07	Partially Meets	Neutral	1.1 E-07
3.7.3.c	Unknown	Unknown	1.1 E-07	Unknown	Unknown	1.1 E-07
3.8.4.b	Unknown	Unknown	1.1 E-07	Unknown	Unknown	1.1 E-07
3.8.4.c	Unknown	Unknown	1.1 E-07	Unknown	Unknown	1.1 E-07
3.7.5.b	Unknown	Unknown	1.0 E-07	Unknown	Unknown	1.0 E-07
3.3.5.b	Meets	Favourable	9.1 E-08	Meets	Favourable	9.1 E-08
2.41	No	Favourable	9.1 E-08	No	Favourable	9.1 E-08
2.44	No	Favourable	9.1 E-08	Yes	Adverse	2.3 E-06
3.8.2.b	Partially Meets	Neutral	8.1 E-08	Partially Meets	Neutral	8.1 E-08
3.9.5.a	Meets	Favourable	6.8 E-08	Meets	Favourable	6.8 E-08
3.9.5.b	Meets	Favourable	6.8 E-08	Meets	Favourable	6.8 E-08
3.9.5.c	Meets	Favourable	6.8 E-08	Meets	Favourable	6.8 E-08
3.9.5.d	Meets	Favourable	6.8 E-08	Meets	Favourable	6.8 E-08
1.30.b	No	Favourable	6.5 E-08	No	Favourable	6.5 E-08
1.30.c	No	Favourable	6.5 E-08	No	Favourable	6.5 E-08
1.30.d	No	Favourable	6.5 E-08	No	Favourable	6.5 E-08
2.39.a	No	Favourable	6.4 E-08	No	Favourable	6.4 E-08
2.39.b	No	Favourable	6.4 E-08	No	Favourable	6.4 E-08
3.7.3.b	Unknown	Unknown	6.1 E-08	Unknown	Unknown	6.1 E-08
3.7.5.d	Partially Meets	Neutral	5.1 E-08	Meets	Favourable	1.0 E-08
3.9.6.b	Meets	Favourable	5.0 E-08	Meets	Favourable	5.0 E-08
3.9.6.c	Meets	Favourable	5.0 E-08	Meets	Favourable	5.0 E-08
3.5.5.a	Meets	Favourable	4.5 E-08	Meets	Favourable	4.5 E-08
3.5.4.d	Meets	Favourable	3.8 E-08	Meets	Favourable	3.8 E-08
3.5.4.e	Unknown	Unknown	3.8 E-08	Unknown	Unknown	3.8 E-08
3.7.5.a	Meets	Favourable	3.1 E-08	Meets	Favourable	3.1 E-08
3.7.5.e	Meets	Favourable	3.1 E-08	Meets	Favourable	3.1 E-08
3.8.2.a	Meets	Favourable	3.0 E-08	Meets	Favourable	3.0 E-08
3.7.7.c	Meets	Favourable	2.3 E-08	Meets	Favourable	2.3 E-08
3.7.7.d	Meets	Favourable	2.3 E-08	Meets	Favourable	2.3 E-08
2.48.e	No	Adverse	2.0 E-08	No	Adverse	2.0 E-08
2.48.f	No	Adverse	3.1 E-08	N/A	x	x
2.48.b	N/A	x	x	N/A	x	x
2.48.c	N/A	x	x	N/A	x	x
2.48.d	N/A	x	x	N/A	x	x
2.1	N/A	x	x	N/A	x	x
2.5	N/A	x	x	N/A	x	x
2.7	N/A	x	x	N/A	x	x
2.3.c	N/A	x	x	N/A	x	x
2.3.d	N/A	x	x	N/A	x	x
2.3.e	N/A	x	x	N/A	x	x
2.3.b	N/A	x	x	N/A	x	x
2.19.b	N/A	x	x	N/A	x	x
2.47	N/A	x	x	N/A	x	x
		Total	*7.7 E-04*		*Total*	*6.3 E-04*