Delft University of Technology

Foundation for risk-based asset management for storm surge barriers

Kharoubi, Y.; van den Boomen, M.; Hertogh, M.J.C.M.; van den Bogaard, J.

DOI
10.1201/9781003323020-392

Publication date
2023

Document Version
Final published version

Published in
Life-Cycle of Structures and Infrastructure Systems - Proceedings of the 8th International Symposium on Life-Cycle Civil Engineering, IALCCE 2023

Citation (APA)
Kharoubi, Y., van den Boomen, M., Hertogh, M. J. C. M., & van den Bogaard, J. (2023). Foundation for risk-based asset management for storm surge barriers. In F. Biondini, & D. M. Frangopol (Eds.), *Life-Cycle of Structures and Infrastructure Systems - Proceedings of the 8th International Symposium on Life-Cycle Civil Engineering, IALCCE 2023: PROCEEDINGS OF THE EIGHTH INTERNATIONAL SYMPOSIUM ON LIFE-CYCLE CIVIL ENGINEERING (IALCCE 2023), 2-6 JULY, 2023, POLITECNICO DI MILANO, MILAN, ITALY* (pp. 3214-3221). Taylor & Francis. https://doi.org/10.1201/9781003323020-392

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)
© 2023 The Author(s), ISBN 978-1-003-32302-0
Open Access: www.taylorfrancis.com, CC BY-NC-ND 4.0 license

Foundation for risk-based asset management for storm surge barriers

Y. Kharoubi, M. van den Boomen & M.J.C.M. Hertogh
Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

J. van den Bogaard
Rijkswaterstaat Ministry of Infrastructure and the Environment, Utrecht, The Netherlands

ABSTRACT: Due to climate change, the risk of flooding is increasing with potentially severe consequences on highly populated and economically developed coastal zones. Storm surge barriers protect against such events with the critical task of closing during extreme weather conditions to prohibit the propagation of water. This highlights the importance of maintaining the high reliability of these structures and the challenge to reach this goal for rarely operated and unique infrastructures. To deal with this challenge, the study creates a foundation to set an asset management approach for storm surge barriers or assets with similar characteristics. This is done by studying the case of The Netherlands with the aim to [1] describe the asset management approach, [2] identify key features of the approach, [3] investigate the connection between these features and the characteristics of the barriers, and [4] conclude the influence of the characteristics on the establishment of an asset management approach.

1 INTRODUCTION

The climate is changing with increasing global sea levels, surface temperatures, and precipitation among others. Despite the efforts to reduce emissions and global warming, the effects of climate change will continue to have an influence. The risk of flooding is unavoidable and measures to deal with it are crucial. Hard (infrastructures) and soft (nature-based) protective measures against sea level rise will support the continuity of coastal cities (Pörtner et al. 2022). However, the soft measures are not sufficient to reduce 2100 risks. Hard flood protection measures such as Storm Surge Barriers (SSBs) are required (Du et al. 2020).

SSBs are crucial for flood management especially in responding to climate change effects and complying with strict safety requirements (Jonkman et al. 2013). They are flood defences that are operated during extreme events to avoid catastrophic consequences. This requires high reliability of SSBs during extreme and rare events (Jordan et al. 2019). However, climate change challenges operation and maintenance (O&M) and imposes increasing expenses to sustain the current safety levels of protection measures (Pörtner et al. 2022). High sea level rise scenarios diminish the flood safety provided by SSBs and lead to more frequent closures of SSBs. Furthermore, SSBs deteriorate faster when design water levels are surpassed (Haasnoot et al. 2020). Therefore, O&M of SSBs are intrinsically challenged with strict requirements and are additionally confronted with climate change complications.

To preserve the safety levels provided by these structures, maintenance is performed based on intensive work and planning in systematic asset management (AM) approach (Jordan et al. 2019). AM supports organisations to perform O&M with limited budgets and under strict requirements in risky and uncertain conditions (Almeida et al. 2022). However, organisations face challenges such as ageing assets, changing operating conditions, limited resources, and loss of knowledge. AM tries to deal with these challenges through structured decision-making and balanced performance, risk, and resources (Shah et al. 2017). Despite its importance, the needed effort for AM is underrated, knowledge sharing among countries is disrupted, and research on the maintenance of flood defences in relation to their performance is limited

DOI: 10.1201/9781003323020-392

(Jordan et al. 2019). The latter can be supported with information on AM from other assets since AM as an approach is similar in many ways. However, it differs between assets due to the influence of special characteristics of an asset (Herder & Wijnia 2012). Furthermore, standards like the ISO 5500x cover AM requirements but do not cover "how" to fulfil the requirements and provide limited guidance for infrastructure assets. Models from practice can provide a better perspective while fulfilling the ISO requirements (Wijnia & Croon 2015). This is especially important for SSBs since they are relatively new structures, with the first SSB completed in 1958 (Mooyaart & Jonkman 2017), and the importance and complications of their AM is increasing. Therefore, the research aims to create the foundation for setting an AM approach for SSBs or similar assets by studying AM for SSBs from practice and analysing the approach relative to the characteristics of SSBs. This leads to the research question: How do the characteristics of SSBs influence the formation of the AM approach?

2 RESEARCH METHOD

In this paper, the AM for SSBs is investigated with a focus on the influence of SSBs' characteristics on the AM approach. This is done based on literature and case study research. The characteristics of SSBs are derived from literature based on the following iterative process: articles were analysed such that different sections were associated with specific characteristics, the latter were compiled to reach more general characteristics with supporting content, then characteristics with limited evidence were further researched. For the study of the AM approach, the case of The Netherlands was investigated from papers addressing the AM approach, guidelines describing the approach, four interviews with experts who were involved in the development of the AM approach, and supporting documentation from the organisation managing the SSBs. The different sources supported the development of the overview of the AM approach such that general concepts were clarified from papers, detailed topics of the AM approach were explained from guidelines, and connections between topics into processes were concluded based on interviews and documentation from the organisation. Moreover, the data from the different sources were analysed by coding and categorising to identify the key features of the AM approach to reveal the core ideas based on which the overall approach is formed. These key features were then analysed relative to SSBs characteristics based on associations identified from the interviews with experts. Hereafter, the research question is answered and the influence of characteristics on shaping the AM approach is clarified.

3 STORM SURGE BARRIERS AND THEIR CHARACTERISTICS

This section introduces SSBs with clarification of characteristics (in italics) which in turn reveal general and unique properties of SSBs, their functionality, and their history.

A SSB is a *system within a system.* It is part of the flood defence system with the role of controlling water passage, reducing the flood risk, shortening the coastline without closing an estuary (Jonkman et al. 2013), and reducing the disruption of the landscape and environment (Walraven et al. 2022). Under normal conditions, SSBs remain open. They close to protect against flooding in case of storm surges. For SSBs to perform these functions, they consist of sub-systems (structural, mechanical, electrical, software). These sub-systems are studied to assess the sole failure of the SSB system (Mooyaart & Jonkman 2017) which is used for the overall assessment of the flood defence system.

Being part of a national flood defence system, SSBs are *public infrastructures* that are built and operated with national budgets to fulfil national safety requirements. In the USA, the United States Army Corps of Engineers (USACE) built and operated SSBs with different safety levels ranging between 100 and 500-year event (Morang 2016). In The Netherlands, the law specifies the acceptable failure probabilities for sections of the flood defence system with a range of 1:100 to $1{:}10^6$ (Jonkman et al. 2018). These safety levels are reached with *high investment costs* such as the Maeslant barrier with initial costs of $940 million and O&M

expenses reaching $17 million annually (Mendelsohn et al. 2022). Being public and expensive, SSBs are subject to *political processes* and *long-lead times until their construction*. Political reasons, such as funding processes, public support, assessments, and permits, contribute to long-lead times. The lead time for SSBs mentioned in Hill's study spanned between 14 and 37 years with construction time ranging between 8 and 10 years (Hill 2012).

These public structures protect against extreme flood events, thus SSBs are considered *critical infrastructures* as in The Netherlands (NCTV 2017) and the USA (CISA n.d). Critical infrastructures are systems or assets that are vital to a nation because any disturbance in their service can influence national security, economy, health, and safety (Alcaraz & Zeadally 2015). For the case of SSB, the loss in their service leads to flooding from extreme weather events, which in turn results in massive consequences. Such drastic events might occur because SSBs protect high-value economic and urban areas (Aerts 2018) in low-lying coastal zones with increasing populations and growing economies (Jonkman et al. 2013). Besides their primary role, SSBs are *multi-functional* with an impact on the economy, society, and ecology. SSBs reduce the risk of failure and costs of strengthening defences behind them (Nogueira & Walraven 2018) and enable less strict standards in the hinterland which then reduces disruption of the landscape and environment (Walraven et al. 2022). Moreover, SSBs allow navigation to resume especially for port cities and contribute to the economic development of delta regions (Meyer & Nijhuis 2013) SSBs' impact on ecology can be considered by allowing tidal and saltwater exchange (Mooyaart & Jonkman 2017). With these different functions, an *integrated approach* is required to account for the multiple functions of SSBs and their influences (Jonkman et al. 2013). In port cities such as Rotterdam and New Orleans, protection against flooding interacts with urban growth, economic development, and environmental issues (Meyer & Nijhuis 2013).

In practise, an integrated approach leads to *unique* structures that request innovative designs. SSBs are considered prototypes with a unique combination of the physical environment, requirements, and design (Walraven et al. 2022). The location of SSBs in estuaries and deltas with soft soils requires innovations in the design and construction of complicated foundations (Mooyaart & Jonkman 2017). Besides the geological complexity, being in water bodies in socio-economically important regions complicates the design and construction of SSBs. Innovations in science and technology were necessary to reach the design in the USA and The Netherlands (Meyer & Nijhuis 2013). After the challenges in design and construction, a *long life awaits SSBs*. They are designed for long periods such as the Eastern Scheldt barriers with 200 years of lifetime with consideration of 50 cm sea level rise (McRobie et al. 2005). Such design assumptions of the long-life structures might become incompatible as more knowledge is gained. For example, scenarios with accelerated sea level rise (beyond design assumptions) are probable (Haasnoot et al. 2020).

During this long life, SSBs' *operation is limited and dependent* on external conditions and intended use. The closure of SSBs is based on constant water level thresholds or constant annual exceedance probability that is used to update the triggering water level for closure with sea level rise (Chen et al. 2020). Generally, SSBs are designed for irregular storm surges whose occurrences are rare. Most of the barriers in the USA have not yet been operated at or near their peak design height (Morang 2016). In The Netherlands, the frequency of closure ranges from 1 every 10 years to a few times (1-8) a year (Nogueira & Walraven 2018). This dependency on the operation and the long life of SSBs lead to *dynamic operation*. For example, SSBs have to close more frequently and with longer closure duration due to sea-level rise that leads to more recurring water level exceedances (Chen et al. 2020).

4 ASSET MANAGEMENT FOR STORM SURGE BARRIERS: CASE OF THE NETHERLANDS

To investigate the AM for SSBs, the case of The Netherlands is studied based on data collected and analysed from various sources. The low-lying land has a long history of flood protection, strict safety standards, and frequent assessments. To comply with regulations, the so-called "ProBO: Probabilistic Operations and Maintenance" (now known as "Risk-based operations and maintenance") was set and followed by Rijkswaterstaat (Jorissen et al. 2016). ProBO enables demonstrating the fulfilment of performance requirements, provides constant control of the system's performance level, sets O&M processes based on risks that affect performance, and triggers improvement. This is achieved with the different parts of ProBO shown in Figure 1 and elaborated in the following sections.

ProBO covers three main aspects technical, organisational, and contracting. Technical aspects focus on analyses to describe the system, assess risks, and determine performance levels. Organisational aspects cover operations, maintenance, and control and supporting processes. And contracting aspects focus on performance in relation to external parties performing maintenance activities. To sustain and optimise performance levels, the Deming cycle with Plan-Do-Check-Act phases is set as a framework (Bogaard & Akkeren 2011). Accordingly, ProBO is explained by distinguishing between the preparation of the three aspects of the PDCA cycle and the execution of the PDCA cycle.

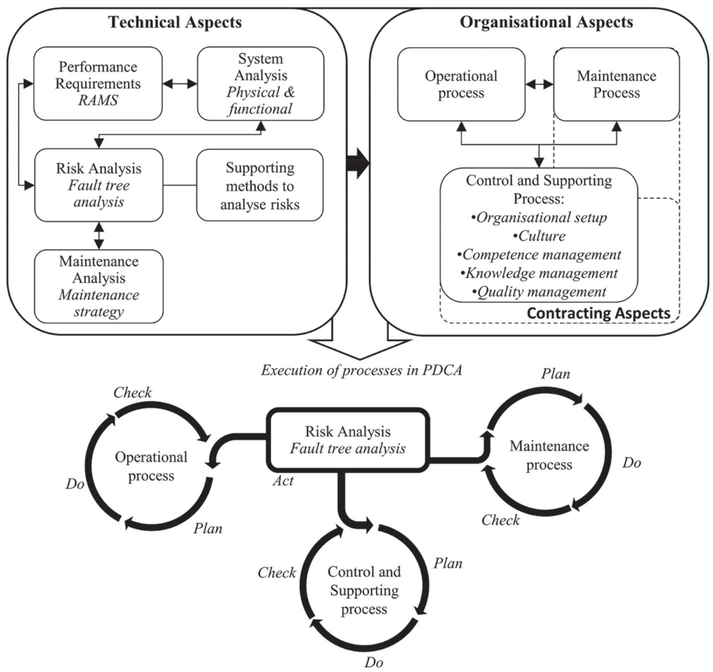

Figure 1. Illustration of ProBO – AM approach for SSBs.

4.1 *Preparation*

4.1.1 *Technical aspect*

The starting point of ProBO is the technical aspects. First, the performance requirements are derived from legislations and policies and translated in terms of quantitative reliability and availability requirements and other qualitative requirements of RAMS (Reliability, Availability, Maintainability, Safety). Afterward, the system is analysed and decomposed into physical and functional breakdown structures. A System Breakdown Structure (SBS) based on design information is performed and functions of elements and components and their interrelations to operate as a whole are determined and quantified in relation to performance requirements. These analyses are used for the risk analysis to reveal the risks that influence performance levels and guide towards actions that deal with these risks. Various methods are used and developed to support the risk analysis as shown in Figure 1. The results of the latter support the development of the fault tree that leads to quantifying the unreliability or unavailability and comparing them with requirements. The comparison leads to an iterative process as shown in Figure 1 with the double arrows. The iterative process aims to eventually meet performance requirements and optimise when possible. Based on the risk analysis, the O&M is studied to sustain performance at acceptable levels and minimise lifecycle costs. The maintenance analysis looks into maintenance strategies using the concept of Reliability Centred Maintenance (RCM) and is based on information from the risk analysis. The aim is to select suitable maintenance to reduce the likelihood of a failure or its consequences. Then, maintenance and inspection activities are determined. The results of the maintenance analysis can be prioritised from a risk perspective such that components contributing most to the performance levels are given more attention in improving maintenance. Furthermore, the analysis can optimise the maintenance and minimise lifecycle costs as long as performance requirements are met (Bogaard & Akkeren 2011).

4.1.2 *Organisational aspects*

The results of the technical aspects are used to set up the organisational aspects of ProBO: operational, maintenance, and control and supporting processes. The operational process focuses on operating the system while ensuring functionality in accordance with performance requirements. So, operational scenarios, activities, procedures, instructions, preconditions, and resources are determined while considering performance requirements, human errors, and repair work during operations. Similarly, preparations for the maintenance process are performed based on the maintenance analysis previously described. The maintenance activities are derived from the analysis and described with the necessary procedures. These procedures are described while considering ways to facilitate repairs and reduce human errors and common cause failures. For both processes, the organisational setup, culture, and knowledge management are clarified with the help of the control and supporting process. Tasks, processes, responsibilities, and roles are linked to the activities to be performed in the O&M processes. The roles are specified in RASCI-method (Responsible, Accountable, Supportive, Consulted, and Informed) to clarify the distribution of roles and the communication between them. Furthermore, knowledge levels, competencies, and skills for the different positions within the department are identified along with development plans and training. To preserve the knowledge, ProBO includes Human Resource Management (HRM) plan. This plan clarifies the distribution of knowledge within the organisation and with external parties. The different features of control and supporting process are clarified in Figure 1 (Bogaard & Akkeren 2011).

4.1.3 *Contracting*

Since external parties are involved in the regular and major maintenance activities, contracting becomes an essential part that requires analysis and preparation in line with the objectives of ProBO. Accordingly, the decision to outsource and the degree of outsourcing are analysed by considering different stages of the PDCA of the maintenance process in relation to failure probabilities. Furthermore, the decision to outsource considers criteria in line with the objectives of ProBO such as: the organisation remains in control and meets performance requirements, risks are small or manageable, and the market situation permits outsourcing. To decide on the degree of outsourcing, the following are evaluated: integration of regular and major maintenance, combining disciplines, and responsibilities of the contractor. In the case of outsourcing, plans and processes are arranged to prepare contractors for applying ProBO. Furthermore, contracts clarify various points (such as contracted activities, performance requirements of the outsourced activities, maintenance mode, procedures, training levels, and documentation requirements) to ensure performance levels are met. In addition, the organisation has to prepare itself with the competencies and necessary knowledge to be able to control the processes and activities of the contractor (Bogaard & Akkeren 2011). Based on the above description, the contracting aspect can be seen in the maintenance process and control and supporting process.

4.2 *Execution of PDCA*

After the preparations are complete, continuous PDCA cycles are performed to preserve performance levels as required. The PDCA cycle is divided such that plan-do-check phases are applied to each of the three processes: operations, maintenance, control and support. Then, the information from the check phases of the processes is combined in a single act phase that evaluates the risk analysis to assess actual performance and compare it with the requirements.

The PDCA cycle starts with creating explicit plans for the processes by covering activities, methods for execution, organisation, and contracting. O&M activities covered in the previous analyses are scheduled and clustered to account for periods during which maintenance cannot be performed. The different details of the organisational and contracting aspects are planned such as work procedures to be followed are clarified, the tasks to be executed are set and allocated, staff training is scheduled, requirements for contracts are defined, and the quality system is set. Then, the plans are executed in the Do stage. The O&M activities are performed while complying with preparations done earlier. It is necessary to follow procedures in order to validate the risk analysis and demonstrate performance. During the do stage, the work is tracked with documentation on deviations, quality, and time. Furthermore, records are kept on actual data on processes, activities, detected anomalies, operational problems, and impractical work procedures among others. These records have to be linked to corresponding activities for assessments and future improvements. In the check phase, the processes are monitored and assessed based on collected data. For technical aspects, the data is used to identify trends and deviations in technical conditions and assumptions used in the risk analysis. For organisational and contracting aspects, the checks include: the quality of performed work of internal and external parties, deviations in the process and schedule, workability of procedures, and training level to further reduce errors. To support the act phase, the check phase also evaluates plans, the impact of proposed improvements, and unexpected behaviours. Accordingly, the check phase leads to a further understanding of all aspects, follow-up actions for improvements, and up-to-date data to be used in the risk analysis. At that time, the act phase proceeds to update the risk analysis and determine actual performance levels that are then compared to requirements. In case the requirements are not met, performance killers are identified and analyses are performed to suggest actions that improve performance to acceptable levels. The analyses look into the data and proposals from the Check phase in relation to performance, organisational maturity, and working methods. When the requirements are met, the influence of the follow-up actions is evaluated, changes to preconditions are analysed, improvement proposals are generated and approved, and clarifications on updates to plans are submitted. At the end of this phase, the input for the following PCDA cycles is set in a report including the new performance levels and follow-up actions. Finally, the plan stage restarts with information from the act stage (Bogaard & Akkeren 2011).

5 ANALYSIS AND DISCUSSION

By analysing the AM approach for SSBs followed in The Netherlands with coding collected data and categorising, the key features of the AM approach are identified as follows:

- Holistic Approach: Covers and connects technical, organisational, and contracting aspects via a risk analysis with the aim to meet performance requirements
- Comprehensive approach: Detailed preparation (analyses, procedures, instructions, process descriptions) and guidance for execution
- Strict approach: Requires following procedures and preparations to validate the risk analysis
- Risk-based: Risk analysis is the core based on which all three processes (Operation, Maintenance, Control and support) are set to manage risks that influence performance
- Quantitative approach: Provides evidence of compliance with performance requirements by assessing reliability and availability performance levels
- Execution that provides constant control: Constant control of the system's performance with regular assessment and checks with PDCA-based execution
- Continuous improvement: Continuous improvement at different levels (PDCA cycles, development plans and training for personnel, quality control, and audits)
- Connection between risks and people: Internal and external parties connected to risks by covering human errors, knowledge, competencies, and culture in relation to risks in the control and supporting process and linking the contracting aspect to the risk analysis

The key features noted above emerged during the development of ProBO which was initially designed for the Maeslant barrier to demonstrate the reliability of the barrier. Various requirements, challenges, and drivers shaped ProBO into how it is now. The fact that the barrier is a public and critical infrastructure with strict safety requirements triggered the quantitative approach to demonstrate and control performance levels and improve maintenance to reach acceptable performance levels. A comprehensive, quantitative, and risk-based approach was needed to deal with the barrier's limited operation that hinders the direct understanding of performance. The limited operation challenged the maintenance of the components with information from suppliers that were assessed as insufficient due to operating conditions different from prescribed. This required an analysis (in this case fault tree) that is detailed to a level that can guide activities and support the calculation of performance from inspection and testing information. The fault tree analysis was inspired by [1] the design and construction phases that used this analysis to prove the requirements are met and [2] the nuclear power plants that have similar safety demands. This shows the influence of having strict requirements and being a critical infrastructure with safety-related regulations on the choice of approach. Furthermore, being a system within a system is another characteristic that had a role in choosing a quantitative and risk-based approach. The barrier protects the dike ring in the hinterland and supports the dikes in meeting their requirements, so the reliability of the barrier during O&M is needed to calculate the dike's probability to hold a certain water level.

As ProBO developed with more analyses, it became a holistic approach covering more than just maintenance. Initially, the design for operating the Maeslant barrier was fully automated to avoid human failure risks. However, human interaction was introduced to correct technical failures and improve the performance of the barrier. With the addition of human interaction, procedures, instructions, and training were added to reduce failure rates due to human errors. This is especially important for the closure of the barrier where the team follows strict procedures and instructions for certain failures or incidents that are analysed and detailed in the fault tree. Furthermore, human resource management was introduced to prepare the teams with the necessary knowledge and skills. Knowledge is managed since SSBs have a long life and are unique, so the learning possibilities from other similar assets are limited and it is necessary to learn from the specific asset.

Since the approach covers various details, its application is not unified for all SSBs. The details of the comprehensive approach are directly influenced by the uniqueness of SSBs, their multi-functionality, and their frequency of operation. For instance, the location and design of the SSB influence the O&M in different ways such as frequency, level of flexibility, and difficulty. Similarly, the multiple functions of SSBs (such as the discharge of rivers and navigation) influence the maintenance planning and the operation frequency controls the amount of asset information used in the analysis. Multi-functionality is also related to the risk-based and quantitative features of ProBO since they enable studying the influence on safety from other functions and demands of stakeholders. Safety remains the primary function of SSBs and other demands are considered after attaining the required safety levels with the risk analysis. Furthermore, the results of the risk analysis can be used to provide evidence of the performance level and the request for certain budgets for improvement from the government. Since the maintenance relies on budgets granted by the government, political processes can impact the ability to continuously improve and be in control of performance.

6 CONCLUSIONS

The current research investigated the unique characteristics of SSBs and how these shaped the AM approach for SSBs in the Netherlands. The derived characteristics provided background information on SSBs and helped in realising the challenges or requirements that certain characteristics create for the AM approach. This was further analysed in the case study that showed the development and implementation of an AM approach in practice. The results showed that certain characteristics of SSBs (such as limited operation and strict requirements) have a clear and direct connection to key features of the AM approach which has matured over time. Therefore, the study connects general characteristics, that apply to SSBs and other assets, to key features of an AM approach that can be considered for the AM of SSBs and assets with similar characteristics. Furthermore, future considerations for AM as noted by experts include [1] benefiting from advances in maintenance and data management, [2] starting early with innovations and solutions for maintenance complications due to climate change, and [3] considering O&M in the design phase since the design might over-complicate the situation. These results are preliminary, and this case is part of a wider study on AM for SSBs.

REFERENCES

Aerts, J. C. 2018. A review of cost estimates for flood adaptation. *Water*, 10, 1646.

Alcaraz, C. & Zeadally, S. 2015. Critical infrastructure protection: Requirements and challenges for the 21st century. *International journal of critical infrastructure protection*, 8, 53–66.

Almeida, N., Trindade, M., Komljenovic, D. & Finger, M. 2022. A conceptual construct on value for infrastructure asset management. *Utilities Policy*, 75, 101354.

Bogaard, J. V. D. & Akkeren, K. V. 2011. Leidraad risicogestuurd beheer en onderhoud conform de ProBO werkwijze. IN RIJKSWATERSTAAT (Ed. The Netherlands.

Chen, Z., Orton, P. & Wahl, T. 2020. Storm Surge Barrier Protection in an Era of Accelerating Sea-Level Rise: Quantifying Closure Frequency, Duration and Trapped River Flooding. *Journal of Marine Science and Engineering*, 8, 725.

Cisa, C. a. I. S. A. n.d.. Dams Sector.

Du, S., Scussolini, P., Ward, P. J., Zhang, M., Wen, J., Wang, L., Koks, E., Diaz-Loaiza, A., Gao, J. & Ke, Q. 2020. Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai. *Global Environmental Change*, 61, 102037.

Haasnoot, M., Kwadijk, J., Van Alphen, J., Le Bars, D., Van Den Hurk, B., Diermanse, F., Van Der Spek, A., Essink, G. O., Delsman, J. & Mens, M. 2020. Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands. *Environmental Research Letters*, 15, 034007.

Herder, P. & Wijnia, Y. 2012. A systems view on infrastructure asset management. *Asset Management*. Springer.

Hill, D. 2012. The lessons of Katrina, learned and unlearned. *Journal of Coastal Research*, 28, 324–331.

Jonkman, S. N., Hillen, M. M., Nicholls, R. J., Kanning, W. & Van Ledden, M. 2013. Costs of adapting coastal defences to sea-level rise—new estimates and their implications. *Journal of Coastal Research*, 29, 1212–1226.

Jonkman, S. N., Voortman, H. G., Klerk, W. J. & Van Vuren, S. 2018. Developments in the management of flood defences and hydraulic infrastructure in the Netherlands. *Structure and Infrastructure Engineering*, 14, 895–910.

Jordan, P., Manojlovic, N. & Fröhle, P. 2019. Maintenance of Flood Protection Infrastructure in the North Sea Region–An Analysis of Existing Maintenance Strategies. *Coastal Structures 2019*, 654–662.

Jorissen, R., Kraaij, E. & Tromp, E. 2016. Dutch flood protection policy and measures based on risk assessment. *E3S Web of Conferences*. EDP Sciences.

Mcrobie, A., Spencer, T. & Gerritsen, H. 2005. The big flood: North Sea storm surge. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 363, 1263–1270.

Mendelsohn, R., Fairbank, A. & Rajaoberison, A. 2022. The Economics of Storm Gates. *Coastal Management*, 1–14.

Meyer, H. & Nijhuis, S. 2013. Delta urbanism: planning and design in urbanized deltas–comparing the Dutch delta with the Mississippi River delta. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, 6, 160–191.

Mooyaart, L. & Jonkman, S. N. 2017. Overview and design considerations of storm surge barriers. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 143, 06017001.

Morang, A. 2016. Hurricane barriers in New England and New Jersey: History and status after five decades. *Journal of Coastal Research*, 32, 181–205.

Nctv 2017. Weerbare vitale infrastructuur. IN VEILIGHEID, N. C. T. E. (Ed. Den Haag, the Netherlands.

Nogueira, H. I. S. & Walraven, M. 2018. Overview storm surge barriers. Rijkswaterstaat, Deltares, I-Storm.

Pörtner, H.-O., Roberts, D. C., Poloczanska, E. S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V. & Okem, A. 2022. IPCC, 2022: Summary for Policymakers. *Climate Change*.

Shah, R., Mcmann, O. & Borthwick, F. 2017. Challenges and prospects of applying asset management principles to highway maintenance: A case study of the UK. *Transportation Research Part A: Policy and Practice*, 97, 231–243.

Walraven, M., Vrolijk, K. & Kothuis, B. B. 2022. Design, maintain and operate movable storm surge barriers for flood risk reduction. *Coastal Flood Risk Reduction*. Elsevier.

Wijnia, Y. & Croon, J. D. 2015. The asset management process reference model for infrastructures. *9th WCEAM Research Papers*. Springer.