Numerical analysis of the influence of desiccation cracks on the stability of Dutch river dykes

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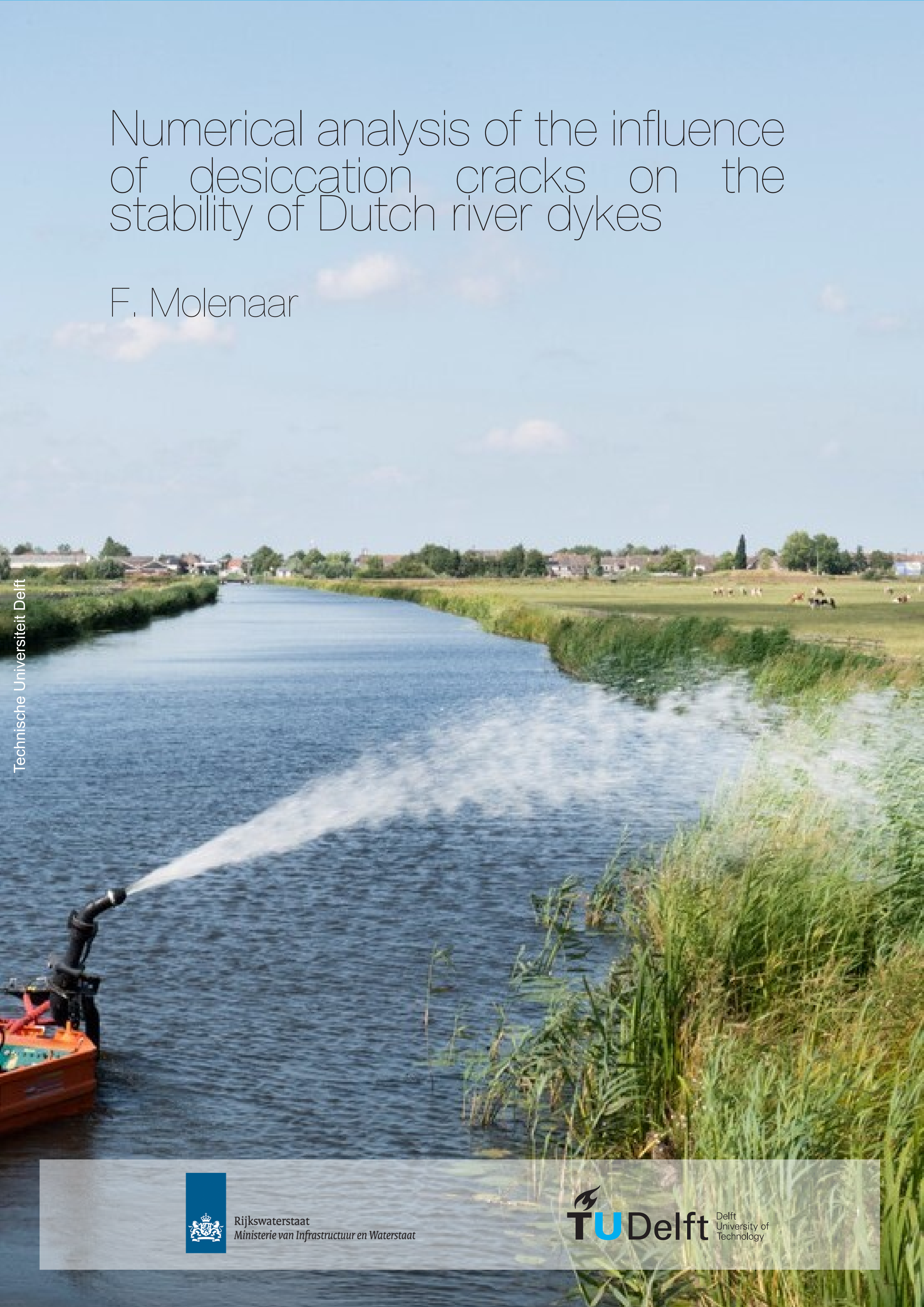

Technische Universiteit Delft

Rijkswaterstaat
Ministerie van Infrastructuur en Waterstaat

TU Delft Delft University of Technology

Numerical analysis of the influence of desiccation cracks on the stability of Dutch river dykes

by

F. Molenaar

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Cover photo by Bram Petraeus: wetting of dykes near Nieuwerbrug to prevent cracks due to droughts.

TU Delft
Rijkswaterstaat
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Preface

This thesis concludes my master's degree in Civil Engineering at the Delft University of Technology. The research is conducted in collaboration with Rijkswaterstaat.

I would like to thank the members of the committee for their guidance during this process. Cristina Jommi, thank you for your clear explanations on the topic. Anne-Catherine Dieudonné, thank you for your constructive feedback on my draft-reports. Robert Lanzafame, thank you for your different views on the topic which really helped me to improve my work. This interesting topic is initiated by Henk van Hemert from Rijkswaterstaat. I want to thank you for all your time, your enthusiasm on the topic and for giving me the opportunity to work at Rijkswaterstaat.

Furthermore, I want to thank my family for their support and my friends for making my time in Delft such a great time. In particular, thanks to Yoram for all the nice coffee breaks. Last, but not least, I want to thank Chris; thank you for your endless patience, your trust and support!

Despite having some tough moments during my research, I am proud of my perseverance and the result. Although my time in Delft did not end as expected due to the coronavirus pandemic, I'm more than happy to be able to graduate in the presence of my family.

Floor Molenaar
Delft, September 2020

Abstract

With changing climatic conditions, droughts are expected to increase in duration and intensity. Under drying conditions, desiccation cracks can form in clay soil, which is often used as dyke cover and in some cases also for the core of the dyke. These desiccation cracks have a potential impact on the stability of dykes. There are several ways in which cracks can have an influence on dyke stability: cracks can provide a preferential path to water flow into the core of the dyke and larger cracks can be part of the failure surface providing little or no shear strength. However, desiccation cracks are currently not explicitly taken into account in the dyke safety assessments. Increasing attention is paid to the formation of cracks in Dutch dykes as regular inspections during dry periods are performed.

The main objective of this study is to gain a better insight into the potential influence of desiccation cracks on the macro-stability of Dutch river dykes. The main research question is formulated as follows: ‘To what extent can desiccation cracking have an influence on the macro-stability of Dutch river clay dykes?’

With the help of PLAXIS 2D software, a numerical model is used to study the hydraulic response and stability of a dyke with desiccation cracks. The difficulty to incorporate desiccation cracks in the numerical model is twofold: the development of cracks is a complex phenomenon that is difficult to predict and adding individual cracks with the help of interfaces can lead to numerical instabilities. Therefore, it is chosen to simulate the effect of cracks by adjusting soil parameters of the cracked layer. From literature review it is concluded that the hydraulic conductivity increases and the strength parameters, cohesion and friction angle, reduce due to cracks. The properties of the top layer of the dyke, with a depth up to 2 meters, are altered to simulate a cracked layer of 2 meters.

Steady-state scenarios, with a low and a high outside (river) water level, as well as time-dependent scenarios, where high water events are simulated, are studied. The influence of precipitation is also taken into account. Both theory and the modelling results show that desiccation cracks can have a negative impact on the macro-stability of Dutch clay dykes. For the steady-state case, a maximum decrease of the factor of safety of 5.6% is found. In the time-dependent scenarios, the factor of safety decreases up to 10.8% if a cracked zone with a depth of 2 meters is present. The magnitude of this decrease is mainly depending on the hydraulic conditions and the crack parameters chosen to simulate the effect of cracks. Both inner and outers slope failure is observed. The largest difference between the factor of safety of the cracked and the uncracked dyke occurs when the dyke fails due to outer slope instability as the factor of safety decreased most in the case of a rapid drawdown.

From these results it follows that cracks can have a negative impact on the macro-stability of a dyke, but the difference is not unambiguous. Important to realise is that there is always an significant uncertainty and variation of results based purely on the differences in approach and methods that are used. Furthermore, the results are based on one type of dyke, consisting entirely of the same clay material. Precaution is advised if significant cracks develop at dykes, but smaller cracks are not likely to lead to failure immediately. The most important recommendations are therefore to focus on maintenance of the clay cover and vegetation and on validation of the modelling results. This can be done by laboratory tests to make more accurate predictions on how soil parameters change due to desiccation cracks and large-scale tests to study failure of a dyke with cracks. Furthermore, dykes with different stratification and geometries should be studied.

Contents

List of Figures

List of Tables

1

Introduction

In this introduction, the context of the research topic is explained. This is followed by the problem statement, the research objective and the methodology of this study.

Photo by: *https://beeldbank.rws.nl, Rijkswaterstaat / Harry van Reeken*

1.1. Context

For ages, dykes are an important part of the flood defence system in the Netherlands. A dyke (or levee, embankment) is a water-retaining structure consisting of soil with sufficient elevation and strength to be able to retain water even under extreme circumstances. In addition, it is essential for the dyke to be impermeable enough in order to retain water. Failure of a dyke can occur due to different failure mechanisms, such as overtopping, macro-instability, micro-instability and piping. To assess the dyke safety, guidelines are composed in which dyke schematization and assessment criteria are described. In the Netherlands, this is defined in the 'Statutory Assessment Instruments' (WBI) (Ministerie van Infrastructuur en Milieu, 2017a).

For the design and safety assessment of dykes, the dyke and underlying soil layers are schematized. This schematization is, in reality, a simplification of a complex and dynamic system. The soil properties and boundary conditions vary over time due to external (climatic) factors, see Figure 1.1. Especially the unsaturated zone, in which soil is not fully saturated as the pores contain both air and water, of a dyke has a dynamic character. Different phenomena play a role in this unsaturated dyke zone and can have a potential impact on the dyke stability. These phenomena are shortly explained below.

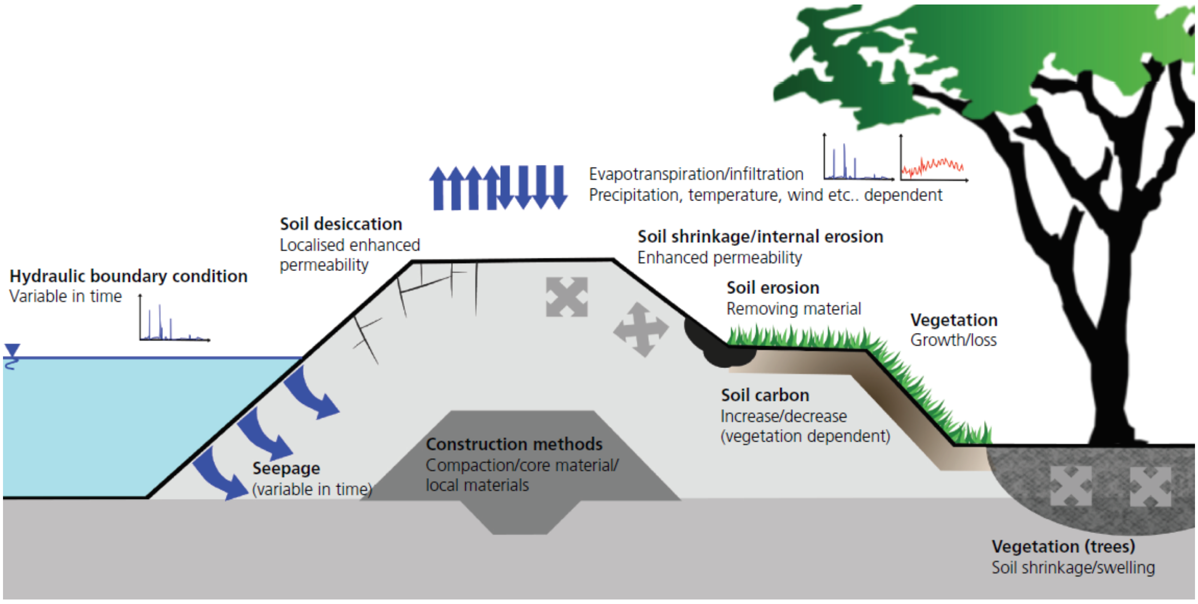

Figure 1.1: Potential climatic interactions influencing a dyke (Bashir et al., 2015)

Soil suction: Inextricably linked to unsaturated conditions are the development of negative pore pressures, referred to as soil suction. It leads to an increase in shear strength. Because of the varying hydraulic boundary conditions as evaporation, precipitation and outside water levels, suction levels will fluctuate over time. Consequently, the shear strength of the soil will vary over time.

Biological processes: In the top layer of a dyke, biological activity occurs. Roots from vegetation penetrate through the soil and animals like worms, insects and moles burrow holes. These holes or tunnels can be for habitation or temporary shelter. Burrows may vary in form from short, single tunnels to larger tunnel complexes consisting of both vertical and horizontal burrows. This can encourage the flow of water through the dyke, which can lead to internal erosion. These holes can also cause instability of the dyke either directly or as a result of the internally eroded material (CIRIA, 2013).

Desiccation cracking: Desiccation cracks are cracks formed due to drying soil. As is illustrated in Figure 1.1, desiccation cracks form under climatic influences as evaporation. Clay will tend to shrink due to a reduction in the moisture content, subsequently, constrained shrinkage will result in cracking. This can occur in the cohesive clay that is used in the dyke top layer as well as in the dyke core. The amount and severity of the cracks is, among other things, dependent on the type of material and the hydraulic conditions, as evaporation and infiltration rates.

Desiccation cracks and biological processes are not constant and not predictable. Often, these kind of phenomena are therefore disregarded in dyke schematization regarding safety assessment. The same applies to the increased shear strength as a result of suction, as suction levels are not constant but subject to change due to external factors.

With predicted climatic changes as increasing droughts, phenomena as desiccation cracks can increase in occurrence and severity. This thesis will focus on desiccation cracking.

1.2. Problem statement

The saturation profile of a dyke changes constantly due to infiltration, evaporation and changing outside water levels. Within the dyke body, a varying unsaturated zone is present where the soil is not saturated. Therefore, dyke strength and stability are not constant and can change due to these climatic changes. There are different phenomena, as introduced before, occurring within this unsaturated zone.

The effect of these phenomena on dyke stability can both positive or negative. Even a positive effect can be a hazard if this is unknown, because an unknown phenomenon that contributes to the dyke safety can lead to an overestimation of dyke safety. This occurs if the positive (with respect to dyke safety) contributing factor dissipates, due to, for example, changing climate and is therefore not longer contributing to the dyke strength. This is, as well, related to the ‘Proven Strength’ (Bewezen Sterkte) of dykes, where the dyke stability factor is adjusted following historic ‘survived’ loads. Also, in this case, unknown positively contributing phenomena can lead to overestimation of dyke safety.

This research will focus on the impact of desiccation cracks on dyke stability. Currently, there are a lot of uncertainties regarding the influence of desiccation cracks. Cracks can influence the stability of dykes in multiple ways: by providing a preferential path for water to flow into the core of the dyke and larger cracks can form part of the failure surface providing little or no shear strength. A lot depends on the crack pattern, crack depth and the interconnection between cracks. With the changing climatic conditions in the Netherlands and the rest of the world, drying-wetting cycles of dykes can increase in intensity. This implies an increasing importance of insight in the influence of desiccation cracking occurring in the unsaturated dyke zone.

Strength of the unsaturated zone and desiccation cracks may be relevant for every type of dyke. However, the hydraulic conditions, geometry and soil differs per dyke type, making certain dykes more prone to desiccation cracking. This thesis focusses on Dutch river dykes consisting of clay.

1.3. Research objective

The main objective of this study is to gain a better insight into the potential influence of desiccation cracks on the stability of Dutch river dykes. The main research question is formulated as follows:

> To what extent can desiccation cracking have an influence on the macro-stability of Dutch river clay dykes?

In order to be able to answer this main question, knowledge on desiccation cracking in the Netherlands is required. Subsequently, the soil properties that are influenced by the cracks is essential. Furthermore, an approach for implementing cracks in a numerical model is needed. This leads to the formulation of a number of sub-questions:

1. What typical cracking pattern and crack depth is expected in Dutch clay dykes?
2. Which soil properties that are influenced by desiccation cracks are important to consider when assessing dyke safety and to what extent?

3. How can desiccation cracks be implemented in a numerical model to study the stability of Dutch dykes?
4. In what way is the hydraulic response of dykes affected by desiccation cracks?
5. Is it necessary to take desiccation cracks into account in the Dutch dyke safety assessment and in what way should this be done?

1.4. Research scope

- The focus of this research is on the impact of desiccation cracks on dyke stability, rather than the processes of the cracking itself.
- Only dykes consisting of cohesive soil (clay) are taken into account.
- In this research only the impact on macro-stability of the inner slope and outer slope will be assessed. Other failure mechanisms are not included.

1.5. Methodology

This study consists of both a literature review and a numerical analysis using the FEM software PLAXIS 2D. A more detailed description of these two parts is given below.

1.5.1. Literature review

The literature review gives relevant background information. First, a description of flood defences system in the Netherlands is given. This includes the typical geometry of dykes, possible failure mechanisms and the current guidelines for the Dutch safety assessment regarding macro-instability. Second, the definition of clay, its properties and the typical clay used for Dutch dykes are introduced. Next, an introduction to unsaturated soil mechanics is given, with emphasis on soil suction and how this influences the shear strength. Last, different aspects of desiccation cracks itself are introduced, including the development and process of desiccation cracking, the potential influence on dyke stability and the typical crack depth and pattern occurring in the field.

1.5.2. 2D numerical analysis

A numerical analysis is carried out. The Finite Element Method (FEM) is preferred over the Limit Equilibrium method (LEM) because no assumptions regarding the shape or location of the critical failure surface has to be made and the hydraulic response can be studied as well. Using the software PLAXIS 2D, the impact of the desiccation cracks on dyke stability is determined, by means of phi/c reduction. PLAXIS 2D is chosen as it is already commonly used in the Netherlands. Numerical simulations are performed considering the linear elastic model with a Mohr Coulomb failure criterion.

Modelling approach
The desiccation cracks are accounted for by implementing a new material in PLAXIS 2D, with different parameters than the initial dyke material. The influence of the cracks is included by using these adjusted material parameters, as cracks can affect multiple parameters: the hydraulic conductivity and strength parameters (cohesion and friction angle). By analysing existing laboratory experiments, the change of these parameters is estimated.

Model scenarios
A reference river dyke, with a typical geometry, is created. Multiple model scenarios are analysed, with different hydraulic boundary conditions, varying crack depths and varying adjusted parameters to simulate the influence of cracks. Both steady-state cases as time-dependent cases, with a fluctuating outside water level, are studied.

Safety analysis
The phi/c or strength reduction method of PLAXIS 2D is used to conduct a safety analysis. With the phi/c reduction method, PLAXIS reduces the friction angle and the cohesion of the soil mass until a failure is identified and PLAXIS determines a factor of safety. The displacements occurring in the final calculation step can be used to indicate the likely failure mechanism.

1.6. Thesis outline

In Figure 1.2, the outline of the thesis is visualised. The main report is followed by two appendices.

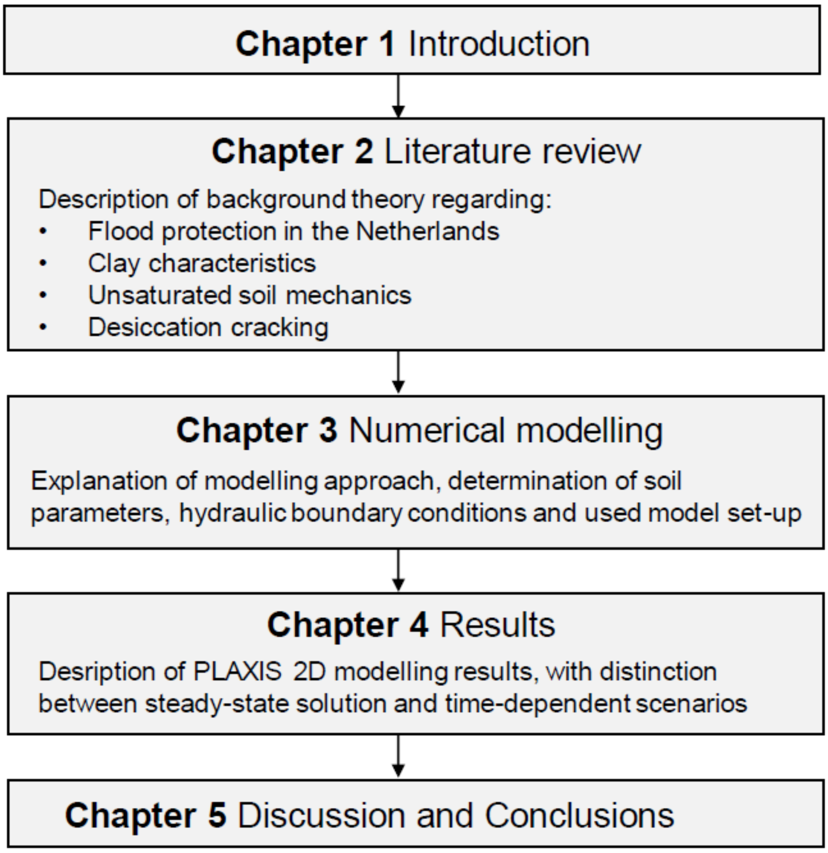

Figure 1.2: Visualisation of report structure

2

Literature review

In this chapter, literature on four relevant topics is discussed. First, a brief introduction on flood defences and potential failure mechanisms is given, and the current guideline for the Dutch safety assessment regarding macro-instability is discussed. Second, a description of the material clay is given, including the typical Dutch clay characteristics. Next, the relevant aspects of unsaturated soil mechanics are explained. Last, a description of current knowledge regarding desiccation cracking is given.

2.1. Flood protection

The Netherlands has an extensive system of flood defences, protecting the land from flooding. Apart from dykes, flood defences can be dams, dunes, storm surge barriers and other hydraulic structures like quay walls or sluices.

2.1.1. Flood defences in the Netherlands

In the Netherlands a distinction is made between primary flood defences and regional flood defences. Primary flood defences protect the land against flooding from the main external sources of water (in Dutch: ”buitenwater”), like the North Sea, the Wadden Sea, the Westerschelde, the Oosterschelde, the IJssel lake and the major rivers. Regional flood defences protect against flooding of lakes, smaller rivers and canals. Local water boards or provinces are responsible for the inspection and maintenance of regional flood defences. The Netherlands has over 3700 km of primary flood defences and about 10000 km of regional flood defences (NKWK, 2019).

Existing primary flood defences are assessed using the rules and methods as stated in the Statutory Assessment Instruments (WBI) (Ministerie van Infrastructuur en Milieu, 2017a). The legal requirements of regional flood defences are determined by the provinces. Generally, the assessment methods of regional dykes are comparable to the assessment of primary dykes (InfoMil (Rijkswaterstaat), 2019).

2.1.2. Dyke structure

The main function of a dyke is to retain water. The dimensions and geometry of a dyke mainly depend on the design loads. For sea dykes, hydraulic loads are generally determined by both waves and high water levels during governing conditions. Thus, as these dykes have to be able to withstand high water levels and wave attack an outer berm or stone revetment can be used. For river dykes wave loads are usually significantly lower but long periods of high water levels can occur. An inner berm can provide sufficient stability for this (Jonkman et al., 2017).

The soil type used for dyke construction depends both on the desired soil characteristics and the availability of the materials. Especially older existing dykes in the Netherlands often fully consist of clay due to the wide availability of clay in nearby surroundings. The more recent constructed dykes usually consist out of a combination of different types of materials, for example sand core with a cover layer of clay. Not one single soil type possesses all the desired characteristics; sand is relatively permeable and clay is very impermeable but deforms more easily upon wetting. Peat is insufficient for dyke construction because of its high compressibility and shrinkage.

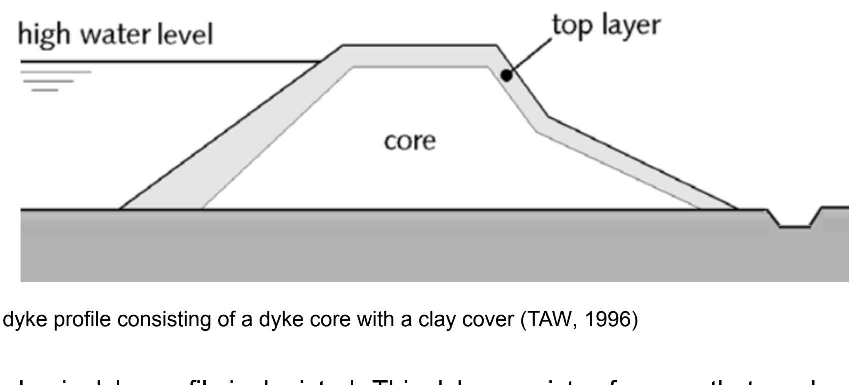

Figure 2.1: Basic dyke profile consisting of a dyke core with a clay cover (TAW, 1996)

In Figure 2.1, a basic dyke profile is depicted. This dyke consists of a core, that can be made of clay or sand and an impermeable clay cover layer. The foundation is an impermeable layer, usually clay. This thesis focusses on a clay dyke core, implying a dyke consisting fully of clay.

2.1.3. Failure of dykes

The main function of a flood defence is to provide safety, i.e. to retain water and prevent flooding. The definition of failure for flood defences is the loss of the water-retaining function. There are various failure mechanisms that need to be considered when assessing or designing dykes or dyke reinforcements. In Figure 2.2, multiple failure mechanisms for dykes are shown. The most common failure mechanisms leading to dyke breaches worldwide are overtopping and the instability of the inner slope (Jonkman et al., 2017). However, not all failure mechanisms are of equal importance for both sea and river dykes. Failure mechanisms relevant for this study are further explained below.

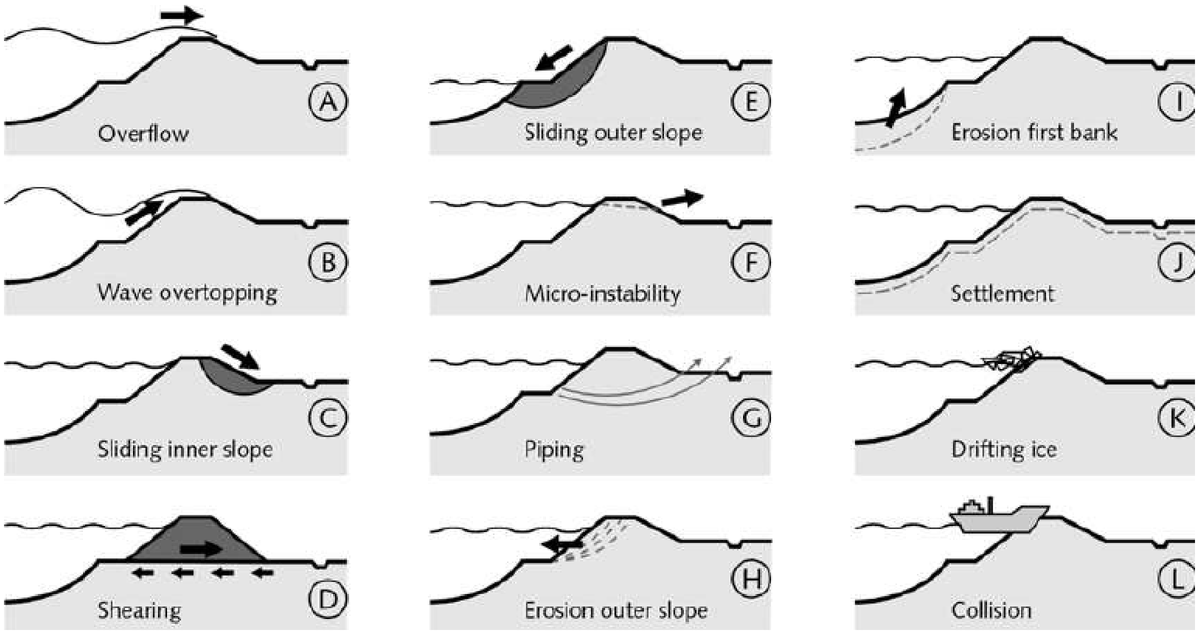

Figure 2.2: Failure mechanisms (Jonkman et al., 2017)

Macro - instability (C + E)

This thesis mainly focusses on the influence of desiccation cracking on macro-stability. Macro-stability is the ability to withstand loads without the loss of its water retaining function due to large deformations. (Jonkman et al., 2017). As can be seen in Figure 2.2 C and E, macro-instability can occur both on the outer and the inner slope of the dyke. The definition according to Rijkswaterstaat WVL (2016) is: “A dyke has failed due to macro-instability when the sliding of a soil plane results in lowering of the crest level and loss of its water retaining function”

Slope instabilities in general are usually triggered by hydrological events or conditions in which the pore water pressures are influenced by an external forcing. The main driver of macro-instability, typically for river dykes, is the infiltration of water into the dyke body and its foundation, leading to an increase of pore pressures resulting in a decrease in effective stress and shear resistance of the soil. During long-lasting floods this situation can lead to a failure of the inner slope (Jonkman et al., 2017). The outer slope can fail due to a rapid drawdown: a fast decrease of the outside (river) water level. This failure can occur due to high pore pressures at the base of the potential slide plane, while at the same time, the horizontal pressure or support from the river water is reduced.

In case of macro-instability, the failure surface concerns of a large part of the dyke body. A shallow sliding plane is considered to be an element of micro-instability or grass cover failure instead of macro-instability.

Micro - instability (F)

A dyke can fail due to micro-instability when seepage into the dyke causes the phreatic surface to rise and reach the inner slope of a dyke. In the dyke cover consists of impermeable material such as clay, this leads to an increased pressure inside the dyke body and the dyke cover can be pushed off or erode. (Jonkman et al., 2017). As stated before, the sliding is more shallow than in case of macro - instability. This is illustrated in Figure 2.3.

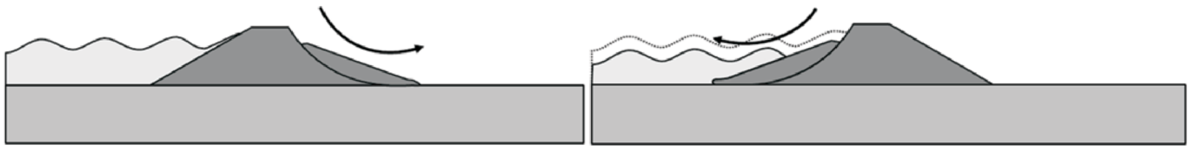

Figure 2.3: Micro-instability (CIRIA, 2013)

2.1.4. Safety assessment macro-instability

The current guidelines for safety assessment in the Netherlands is WBI2017 (Rijkswaterstaat WVL, 2016). According to Rijkswaterstaat WVL (2016), desiccation cracks are not taken into account in the current safety assessments. The fact that the cracks can have an influence on the hydraulic conductivity of the dyke material and therefore the location of the phreatic surface is explained in the guidelines. This can be taken into account when schematizing the pore pressures in the dyke body but there is no standard guideline for this.

Traditionally, safety regarding macro-stability of dykes was assessed based on the Mohr-Coulomb model. In 2017, this approach was abandoned and new guidelines came into effect: WBI 2017. Several changes are implemented, including the introduction of a new material model to describe the soil behaviour. The material model that is used for this macro-stability assessment is based on the Critical State Soil Mechanics (CSSM) framework. In addition, the SHANSEP method (Stress History and Normalised Soil Engineering Properties) is used to the determine the undrained shear strength under critical loading conditions.

In the CSSM framework, a distinction is made between normally consolidated and over-consolidated soils, and between drained and undrained behaviour at failure. The shear strength of the soil is based on the mean effective stress in the soil and the critical state friction angle. Cohesion of the soil is not explicitly taken into account, but is a result of overconsolidation and is therfore incorporated in the over consolidation ratio (OCR). In the normally consolidated state of the soil there is no cohesion.

In addition to the switch to the CSSM framework, a new concept is introduced: SHANSEP (Stress History And Normalized Soil Engineering Properties). This concept takes the effects of stress history and stress path of the soil into account when characterising soil strength.

For assessing dykes on macro-stability in the Netherlands, the Limit Equilibrium Method (LEM) method is used, mainly with the help of the software D-GeoStability (Deltares). This software requires both the subsoil layers, the dyke geometry and the water level as input. The phreatic line can be determined and the corresponding factor of safety is calculated. Different calculation methods exist; Bishop, Spencer, Fellenius or UpliftVan. For each method, a different approach is used in order to determine the critical sliding surface. In D-GeoStability the Uplift-Van method is commonly used.

These methods calculate different possible sliding surfaces. The critial sliding surface can be found by dividing sliding surfaces into slices and iterate the moment equilibrium, the vertical force equilibrium of a slice and the horizontal force equilibrium of a slice (Rijkswaterstaat WVL, 2016).

Load scenarios

In WBI2017, different loading scenarios are recognized that should be considered at the assessment of dykes with respect to macro-stability:

- High water level; height of the water level is dependent on the norms of return period at specific dyke trajectory.
- Average and low water level; mainly relevant for assessing the outside slope stability
- Water level over time (time-dependent water level). The duration of the high water period is dependent on the type of dyke. Longer durations are found along rivers, shorter durations at sea dykes.

Other loadings conditions that may be relevant, depending on local conditions, are waves, wind, traffic and ship collision.

Pore pressure distribution

For the schematization of the pore pressure distributions, the Waternet Creator application available in the RisKeer software (Rijkswaterstaat WVL, 2017) can be used. A distinction is made between four types of dykes:

- Clay dyke on clay
- Sand dyke on clay
- Clay dyke on sand
- Sand dyke on sand

The initial (stationary) location of the phreatic surface is, usually, based on measurements under daily conditions. Waternet Creator gives the location of the phreatic surface as output. In this case, the phreatic surface is a static situation. A time-dependent phreatic surface can also be implemented. As can be seen in figure 2.4, the location of the phreatic surface fluctuates due to external factors such as infiltration and evaporation. During a dry summer, the part of the dyke where unsaturated conditions occur is large and therefore high suction levels are present.

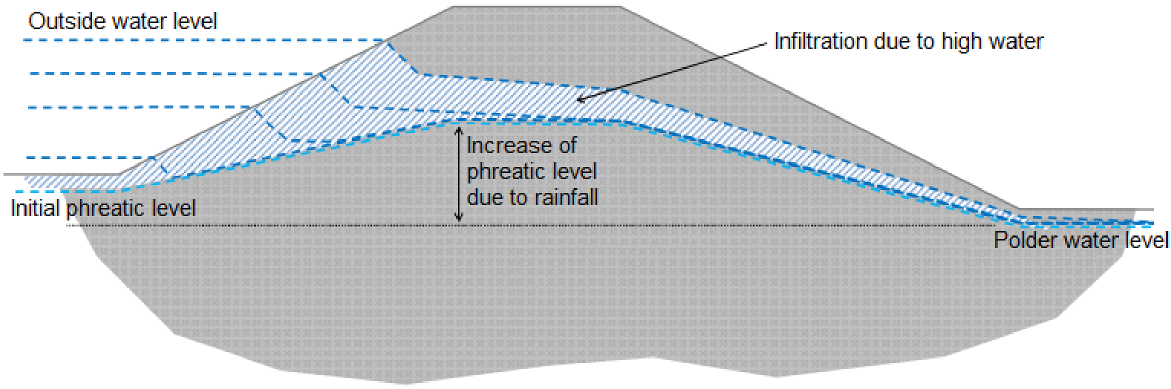

Figure 2.4: Schematization phreatic surface according to Rijkswaterstaat WVL (2016)

Use of Finite Element Method

Apart from LEM methods as D-Geostability, there is a growing demand for the use of Finite Element Methods (FEM) in dyke safety assessments. One explanation for this is the increased interest in structural elements, e.g. sheet piles, in dyke design and LEM is not suitable for this. Another advantage of FEM is that no assumptions regarding the shape or location of the critical failure surface has to be made.

A comparison of the results with a LEM analysis is advised if FEM is used for safety assessment. The shape and location of the critical failure surface should be similar and the differences in the factor of safety must be limited to a maximum of 6%. Small discrepancies are always expected given the differences between the methods. However, significant discrepancies may indicate deviating or incorrect schematizations or numerical inaccuracies (POV Macrostabiliteit, 2020).

2.2. Clay characteristics

Because this thesis focusses on dykes consisting of clay, basic understanding of clay characteristics and the clay used for Dutch dykes is needed.

The term clay can be defined in various ways. Firstly, 'clay' can be used as a general term for the fine mineral soil particles, in the Netherlands often addressed to as lutum. Secondly, clay is, according to the European and Dutch norm NEN-EN-ISO14688, a natural soil that is defined based on a composition of the mass percentages of lutum, silt and sand. These soil particles are classified according to their equivalent grain diameter:

– Sand: an equivalent grain diameter greater than or equal to 63 μm and less than 2 mm;
– Silt: an equivalent grain diameter greater than or equal to 2 μm and less than 63 μm;
– Lutum: an equivalent grain diameter less than 2 μm (in English also referred to as clay particles)

Soils are classified by the fractions of sand, silt and lutum particles. A soil texture triangle for 12 different soil types can be seen in Figure 2.5.

Figure 2.5: USDA Soil texture triangle

The definition for clay as it is used throughout this report, is the second definition as stated above. Clay is a fine-grained, cohesive and natural material, consisting of a combination of various minerals and organic material. Clay is used for the construction of dykes for different reasons. It has a good erosion resistance and relatively low permeability.

2.2.1. Typical Dutch clay

There are a lot of different types of clay occurring at different places in the world, each with a different sand, silt and lutum composition, different organic content and a different mixture of clay minerals. These clays will all have their own properties and behaviour. Because of the clay properties as mentioned before and the availability of clay in the immediate surroundings of the Netherlands, it is often used for dyke constructions.

To be able to make a good comparison between laboratory experiments on certain clay types and the expected behaviour of Dutch clay, a clear understanding of the Dutch clay used for dyke construction is needed. There is, of course, not one exact clay type that is used, so the guidelines and a general description is given. The clays found most in the Netherlands are shown in the soil texture triangle, Figure 2.6.

For the use of clay for dyke construction there are different requirements regarding, for example, the amount of lutum and the organic content. The clay can consist of (a mixture of) different clay minerals

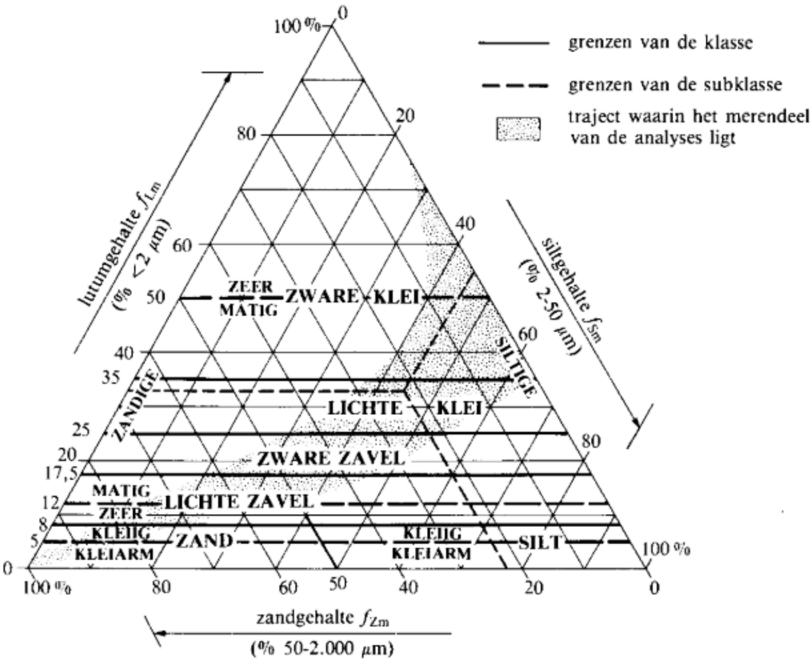

Figure 2.6: Dutch clay classification (Cultuurtechnische Vereniging, 1988)

such as illite, smectite and kaolin. These minerals all have certain characteristics. For example, smectite minerals can adsorb more water than illites. (Albrecht and Benson, 2001).

In the Netherlands, clay is used both for the top layer as for the dyke core. For both applications, there are certain requirements. The basis for the classification of clay for dykes are three categories of erosion resistance, as described by TAW (1996):

1. **Erosion resistant**
   $w_L > 45\%$
   $I_p > 0.73 * (w_L - 20\%)$
   sand content $< 40\%$
2. **Moderately erosion resistant**
   $w_L > 45\%$
   $I_p > 18\%$
   sand content $< 40\%$
3. **Little erosion resistance**
   $w_L > 0.73 * (w_L - 20\%)$
   $I_p > 18\%$
   sand content $< 40\%$

The distinction between the three categories is based on the Atterberg limits (liquid limit w_L and plasticity index I_p) and the sand content, as is visualized in Figure 2.7.

In addition, some extra requirements are added that are valid for all three categories. For all the clay used in Dutch dykes the following requirements apply:

- Organic material content: < 5%
- Water content for working
  - Top layer I_p > 0.75
  - Core: I_p > 0.60
- Salt content: < 4%

Which erosion category the clay should (at least) have is dependent on the type of dyke and the expected hydraulic loads. For dykes experiencing high wave loads, erosion resistant clay is needed.

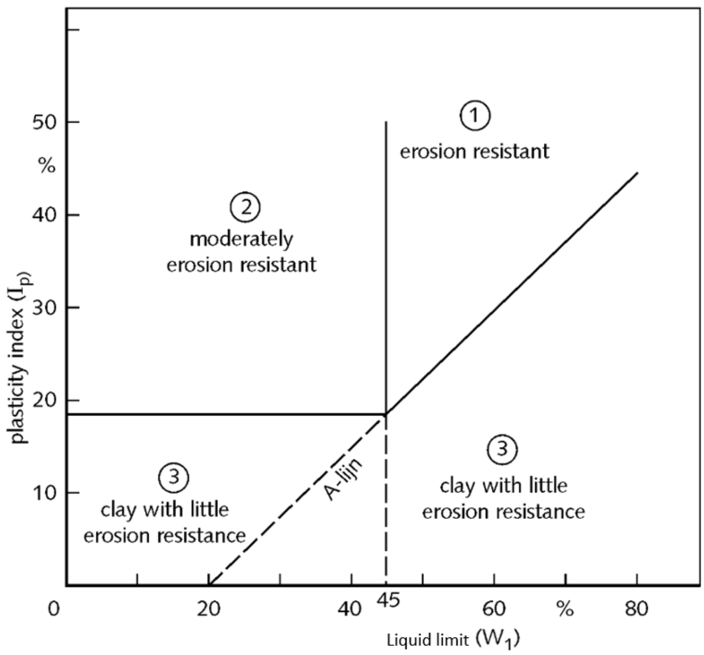

Figure 2.7: Erosion resistance shown as a plasticity diagram (Cultuurtechnische Vereniging, 1988)

2.3. Unsaturated soil

Because desiccation cracks usually occur in the unsaturated zone of a dyke, shown in Figure 2.8, the general characteristics of unsaturated soil are described in this paragraph.

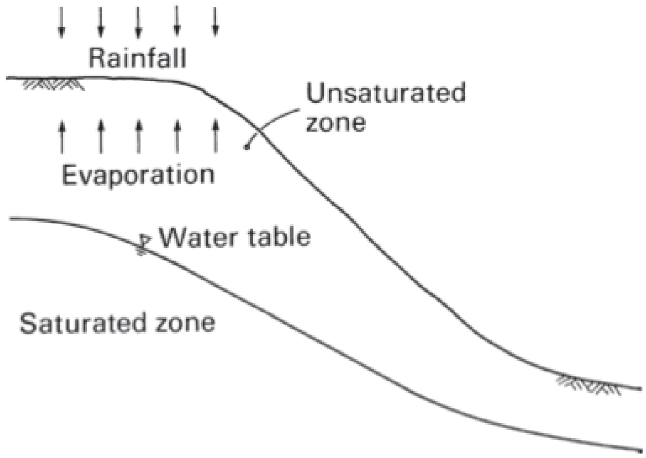

Figure 2.8: Unsaturated zone (Fredlund, 2007)

Traditionally, research focussed mainly on saturated instead of unsaturated soil mechanics. From the 1950's onwards, a growing interest in the mechanical behaviour of unsaturated soils arose and since the 1960's, development of constitutive models for this behaviour started. The unsaturated soil mechanics has lagged behind saturated soil mechanics mainly due to the experimental and theoretical complexities of the subject. The complexity of unsaturated soil behaviour occurs due to the presence of a more-phase system and interdependency of these different phases.

A soil is considered saturated when all the pore space is filled with water and no air is present. Therefore, a saturated soil can be viewed as a two-phase system. An unsaturated soil is commonly defined as a three-phase system consisting of solids, water and air, see Figure 2.9. The soil solids consist of soil particles such as sand, silt, and clay. The relative distribution of the three components is one of the factors that influences the properties of the soil (Fredlund, 2007). In addition, Fredlund (2007), stated that it is more correct to recognize an additional fourth phase: the air-water interface or the contractile skin. This contractile skin forms a fixed barrier between the air and water phases. Stress state changes in the contractile skin can cause an unsaturated soil to change water content, change volume, and change shear strength. This fourth phase is therefore important to consider for the stress state of an unsaturated soil.

The degree of saturation, S, is the ratio of the volume of water to the volume of voids, as depicted in Equation 2.1.

$$S = \frac{V_w}{V_v} \tag{2.1}$$

Where V_w is the volume of water and V_v the volume of voids. With the degree of saturation, soil can be divided into three main groups: saturated, unsaturated and dry soils. Dry soils ($S = 0$) consist of only soil particles and air. In saturated soils ($S = 1$), the voids are filled with water and no air is present. In unsaturated soils ($0 < S < 1$) both air and water occupy the void space of the soil.

2.3.1. Water Retention

Soils are able to retain a certain amount of water and many soil properties are linked to the water content and changes therein. The the soil-water retention curve (SWRC) or soil-water characteristic curve (SWCC) shows the relation between water content and soil suction.

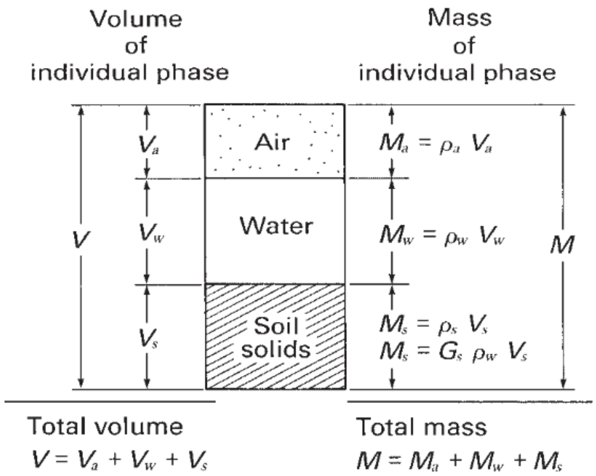

Figure 2.9: Phase diagram unsaturated soil (Fredlund, 2007)

This curve is characteristic for different soil types and their hydraulic properties, as can be seen in Figure 2.10 and is, therefore, widely used in soil mechanics. The shape of the SWCC can provide an indication of the range of suctions that a certain soil can experience (Fredlund, 2007). The SWCC for wetting differs from the drying curve. This dependence on the history of wetting and drying is known as hysteresis, see Figure 2.11.

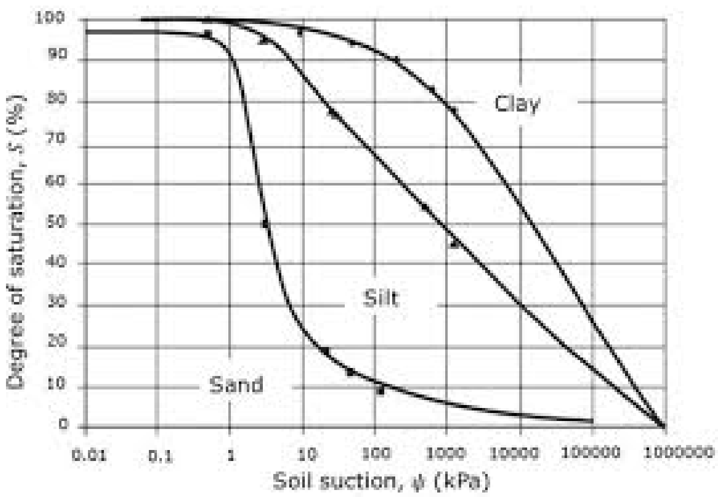

Figure 2.10: Soil water retention curve (Lu and Likos, 2004)

The SWCC can be obtained both by using numerical methods and by laboratory experiments. The most common mathematical representations for the SWCC are the Brooks and Corey Model (1964) and the Van Genuchten Model (1980).

Brooks and Corey (1964) divided the SWCC into two main zones: one zone where the soil suction is less than the so-called air-entry value (AEV) and the other zone where soil suction is greater than the air-entry value, as is depicted in Figure 2.11. The suction level at which air starts to penetrate into the soil is called the air-entry value.

The most common used model for relating water content to matric suction is proposed by Van Genuchten, see Equation 2.2 (van Genuchten, 1980). This equation relates the water content to the matric suction.

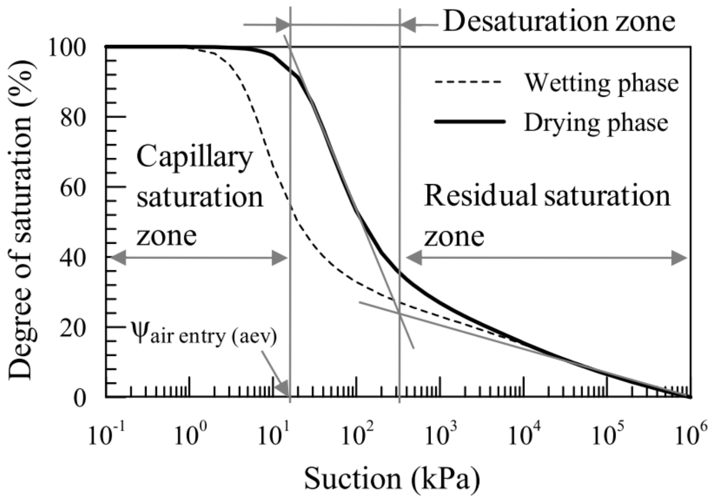

Figure 2.11: Hysteresis(Ravichandran and Krishnapillai, 2011)

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (a|h|^n)}\right]^m \qquad (2.2)$$

Where the normalized water content, Θ, is a dimensionless parameter; $\theta = V_w/V$ is the volumetric water content; θ_r is the residual water content, defined as the water content for which the gradient $d\theta/dh$ becomes zero; θ_s is the saturated water content; h is the matric suction and a,m and n are empirical parameters.

The Van Genuchten model gives a better fit over a wider range of suction levels than the Brooks and Corey model. The Brooks and Corey model is more suitable for undisturbed samples, but if soils approach saturation it tends to have a poor fit. (Eun et al., 2017).

2.3.2. Soil suction

The negative pore pressures present in unsaturated soils are termed soil suction. The total soil suction can be divided in two components: matric suction and osmotic suction. Matric suction is the suction component associated with the capillary action and adsorptive effects. Osmotic suction is the suction component associated with salt content of the pore water. Particularly the matric suction is relevant for this research because it is greatly affected by unsaturated soil processes.

The total soil suction, ψ, is expressed as a positive quantity and is defined as the sum of matric suction, s, and osmotic suction, π. The matric suction can be expressed as the difference of pore air pressure u_a and pore water pressure u_w.

$$s = u_a - u_w \qquad (2.3)$$

The suction influences the shear strength of unsaturated soils, as stated in Fredlund (2007). This will be further discussed in section 2.3.5. The suction will vary over the depth because it is linked to the water content which varies over depth as well. The matric suction at the water table must be equal to zero. The location of the phreatic surface can, therefore, provide valuable information on the likely matric suction profile.

Infiltration (rainfall) and evaporation fluxes have an influence on the suction profile. Rainfall water can reduce the matric suction to zero just below ground surface due to water accumulation. On the other hand, excessive evaporation can lead an increase in suction levels near ground surface. Thus, the matric suction profile is strongly influenced by the location of the phreatic surface and boundary conditions at ground level.

2.3.3. Hydraulic conductivity

Hydraulic conductivity is a quantitative measure of the ability of a soil to transmit fluid. It is not a fixed property of a certain material, but is depending on the suction, water content or degree of saturation. Therefore, the unsaturated hydraulic conductivity differs from the saturated hydraulic conductivity. Generally, the hydraulic conductivity of soil decreases greatly with a reduction in the degree of saturation (Lu and Likos, 2004).

The hydraulic conductivity of unsaturated soil can be described by the hydraulic conductivity function or k-function. As shown in Figure 2.12, this gives a relation between hydraulic conductivity and moisture content or suction.

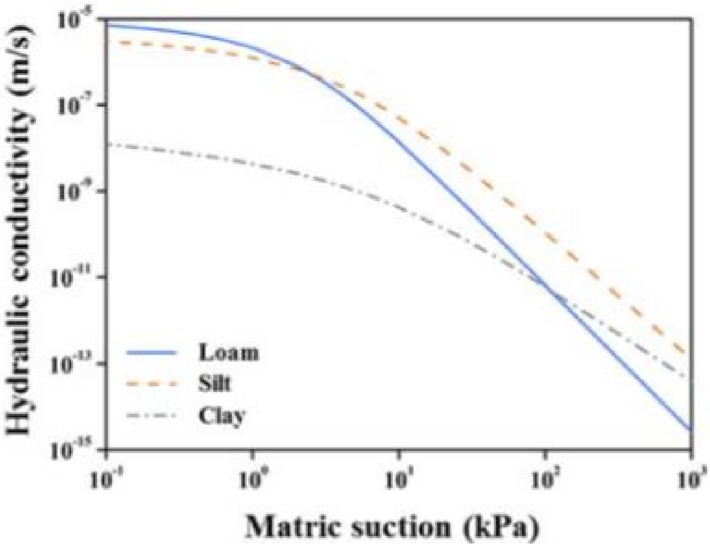

Figure 2.12: Hydraulic conductivity function for different soil types(Yeh and Tsai, 2018)

2.3.4. Phreatic surface

The phreatic surface is defined as the (hypothetical) plane where the pressure in de groundwater is equal to the atmospheric pressure. Soil is saturated with water below the phreatic surface. Above the phreatic surface, groundwater can still be present due to capillary rise. Because of this phenomenon, the groundwater level can be significantly higher than the phreatic surface in case of cohesive soils like clay. Therefore, the soil directly above the phreatic surface can still be saturated. In fine soils, soil suction is caused by the surface tension at the interface of particles, water and air. This leads to negative pore-water pressures, leading to higher effective soil stresses and thus higher soil strength. If there are no capillary rise, the phreatic surface and the groundwater level will coincide.

The unsaturated zone is located between the top of the phreatic surface and the land surface, where the soil is not saturated. As shown in Equation 2.1, this is the case when $S \neq 1$. In reality, a saturated, as well as a capillary zone and an unsaturated zone are present within the dyke. However, the entire zone subjected to suction is referred to as the unsaturated zone, as can be seen in Figure 2.8. In this unsaturated zone negative pore-water pressures are acting (Fredlund, 2007).

As explained above, groundwater is present within the capillary zone. The soil directly above the phreatic surface is usually completely saturated, while the saturation degree decreases in upward direction. A clear boundary of the fully saturated zone above the phreatic surface cannot be designated (TAW, 2004)

The location of the phreatic surface is year-round subjected to change. Due to external factors both an upward flux of water and a downward flux will occur. The difference between these two fluxes determines the pore water pressures in the soil profile. The different external factors that induce changes in the phreatic surface are for example precipitation, wave overtopping and evaporation.

2.3.5. Shear strength

The shear strength of a soil is the magnitude of shear stress that a soil can sustain. In saturated conditions, the shear strength can be expressed by the Mohr-Coulomb failure criterion, as a function of effective normal stress at failure, see equation 2.4 (Terzaghi, 1942).

$$\tau_f = c' + \sigma' \tan \phi' \tag{2.4}$$

With the effective stress principle, as showed in Equation 2.5 (Terzaghi, 1942).

$$\sigma' = \sigma - p_{water} \tag{2.5}$$

Where τ_f is the shear stress on the failure plane at failure, c' is effective cohesion, which is the shear strength intercept when the effective normal stress is equal to zero, σ' the effective normal stress, ϕ' the effective angle of internal friction and p_{water} the pore water pressure.

Suction leads to an increase of shear strength. Based on multiple studies, Sheng et al. (2011) described the general influence of matric suction on the shear strength of unsaturated soils as followed:

1. Under equal vertical pressure, higher suction will result in higher shear strength;
2. Under the same suction level, higher vertical pressure will result in higher shear strength;
3. The relationship between shear strength and the suction is non-linear. At low suction levels, the shear strength increases most rapidly. At high suction levels, the shear strength gradually flattens.

The shear strength of unsaturated soils can be formulated based on two different frameworks: the Bishop stress framework and a framework first proposed by Fredlund et al. (1978).

Bishop and Blight (1963) proposed an effective stress equation for unsaturated soils which relates the net normal stress, which equals the total stress σ minus pore air pressure p_{air}, to matric suction by using a single-valued soil property χ, see Equation 2.6.

$$\tau_f = c' + [\sigma - p_{air} + \chi(p_{air} - p_{water})] \tan \phi' \tag{2.6}$$

Where χ is the effective stress parameter, p_{air} is the pore air pressure, p_{water} the pore water pressure and $(p_{air} - p_{water})$ the matric suction. The parameter χ is depending on the degree of saturation and varies between 0 (dry soils) and 1 (saturated soils). The effective stress parameter χ was introduced to take into account the magnitude of the surface tension effects on the overall unsaturated soil behaviour.The relation between the effective stress parameter χ and the degree of saturation is obtained experimentally.

Fredlund et al. (1978) proposed a linear form of the shear strength equation using $\sigma - p_{air}$ and $p_{air} - p_{water}$ as the independent stress state variables.

$$\tau_f = c' + (\sigma - p_{air}) \tan \Phi' + (p_{air} - p_{water}) \tan \Phi^b \tag{2.7}$$

Where ϕ^b is the angle representing the contribution to the shear strength due to matric suction. This can be a complex function of suction and other variables.

Bishop's equation has as difficulty that the physical meaning and value of the effective stress parameter χ is not clear. The parameter can only be obtained experimentally. A limitation of the linear form of equation 2.7 is that there is that the parameter ϕ^b is a highly non-linear function of matric suction.

2.4. Desiccation cracking

Desiccation cracks can potentially have an influence on the macro-stability of dykes due to multiple reasons. The cracks can provide a preferential path to water flow into the core of the dyke leading to an increase of infiltration. Larger cracks can be part of the failure surface providing little or no shear strength. In this paragraph, the desiccation crack initiation and development, the factors that influence the occurrence of cracks, Dutch field observations and the typical expected crack depth and pattern are described.

2.4.1. Influence of cracks on slope stability

This thesis focusses on the impact of cracks on the stability of Dutch dykes. Therefore, it is important to look at the aspects of cracks that can play a role in this. Multiple studies as by Wang et al. (2012) and Zhang et al. (2011), address the different factors can play a role at slopes with cracks. Firstly, cracks provide a preferential path to water flow which increase the permeability of the soil. Secondly, cracks can be part of the critical failure surface by providing little to no shear strength. Finally, cracks can be filled with water and lead to an additional driving force on the slope.

2.4.2. Process of desiccation cracking

During droughts, drying cohesive soils can be subjected to desiccation cracking. Cohesive soils, like clay, tend to shrink due to a reduction in the moisture content induced by evaporation. Constrained shrinkage will result in cracking. This restraints can be external, internal or a combination. External constraints can be displacement boundary conditions and interface frictions. Internal constraints are present due to changes in soil structure, such as different soil fabrics and moisture gradient. The driving force behind this shrinking is the development of soil suction during drying. Soil exposed to climatic fluctuations undergoes repeated cycles of drying and wetting during dry seasons and rainy seasons. This leads to constant fluctuations in water content with, as a consequence, crack initiation. Cracks can possibly close as well due to swelling of soils in times of wetting.

A lot of laboratory experiments have been conducted on the process of desiccation cracking. Already in 1917 research focussed on cracks in clay started. Although this thesis is not focussed on the initiation and development of cracks, some of the experiments and relevant conclusions are addressed here to get more insight in the phenomenon of desiccation cracking. Kindle (1917) performed experiments on two clay types from Canada and concluded that spacing of cracks increased with an increasing rate of desiccation and the proportion of clay.

Konrad and Ayad (1997a) proposed a framework for the prediction of the spacing between primary shrinkage cracks in cohesive soils undergoing desiccation. The various steps of the model are presented in Figure 2.13. The key model elements are:

1. The crack initiation occurs when the total principal stress (minor horizontal stress) equals the tensile strength of the soil.
2. Crack propagation is analysed using trapezoidal distribution of total stresses as governed by the material constitutive equations
3. The prediction of primary crack spacing is related to two soil parameters: the tensile strength and the fracture roughness.

Tollenaar (2017) performed several small scale laboratory experiments, studying the effects of boundary conditions and material properties on the propagation of cracks, the relationship between water content, strain rate and tensile strength of the soil and the influence of the drying rate on suction development in the soil. Tollenaar (2017) indicated that the tensile strength is dependent on the water content and concludes that there is a direct association between the tensile strength and the water retention properties of the soil. “As suction arises, tensile stresses are produced in the soil, with fracturing occurring once the tensile stresses reach the tensile strength of the material” (Tollenaar, 2017).

A lot of studies (Tang et al. (2008), Li and Zhang (2011)) focus on the common hypothesis that desiccation cracks initiate at the surface and then propagates downwards. This can be explained by the assumption that the dryer section in the soil profile is located at the surface, and therefore the largest

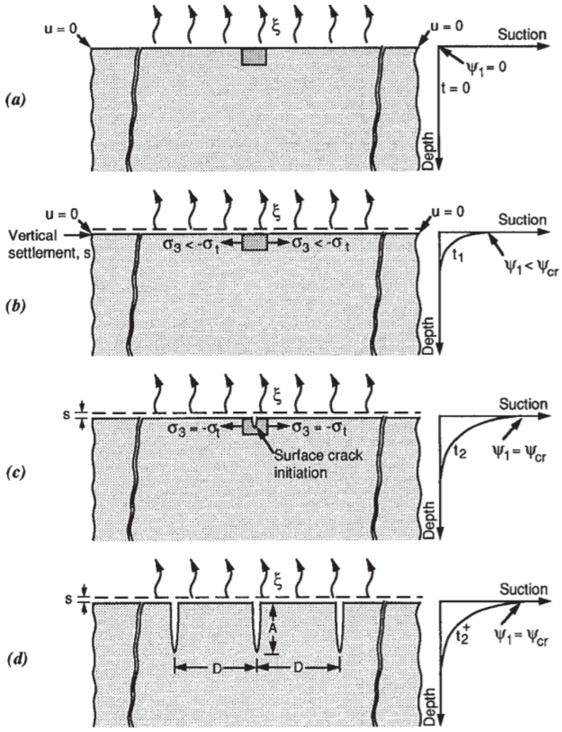

Figure 2.13: Schematic illustration of cracking (Konrad and Ayad, 1997a)

amount of suction, potentially developed at that location.

However, this is not always the case as seen by Jommi et al. (2016) studying the location of the crack initiation. It is concluded from field observations and experiments on Dutch river clay that fractures can initiate below the surface as well. A reasonable explanation for this observations is a dependence of the SWCC on the drying rate. This factor is not considered in previous models.

2.4.3. Field observations

The conclusions described above are all based on laboratory experiments. Important to note is that in field conditions the initiation, development and pattern of desiccation cracks is not as regular as in small scale laboratory experiments. On larger scale, the cracking development will be by local soil structure and weaknesses. From laboratory experiments it is stated that an increasing number of wetting-drying cycles leads to more irregular cracks. In field conditions, on a real dyke, the clay has experienced numerous cycles over the years and a more irregular and heterogeneous type of cracking pattern is expected. Therefore, field observations are of major importance to get insight in crack patterns and development. (Tang et al., 2010)

Dyer et al. (2009) performed a field study to investigate desiccation fissuring of both a historic and a new flood embankment at Thorngumbald near the city of Hull, England. Multiple trial trenches were excavated both on the crest and the landward slope. The trenches of 2003 showed extensive desiccation cracks to a depth of 0.6 meter below the crest height. The upper part of the trench showed fissures both parallel and perpendicular to the surface. In the lower part, mainly vertical fissures occurred. This suggests that there is a distinction between an upper and lower zone with different cracking characteristics. The upper surface zone turned into a two-dimensional network of fissures that allows for lateral flow beneath the surface of the embankment slope and an increased mass permeability.

In 2006, new trenches were excavated and deep cracks with a depth of 1.0 meter were observed. However, the network of cracks was different from the trenches in 2003. In this case, no two-dimensional network of cracks but single deep cracks were found, that could allow flow of water into the core of the dyke. In the 2006 field survey, fissures with a polygonal pattern were found. The width of the polygonal desiccation cracks varied from 5 to 25mm and they were mainly found in areas where a poor grass cover was present. Figure 2.14 shows some of the cracks with their dimensions.

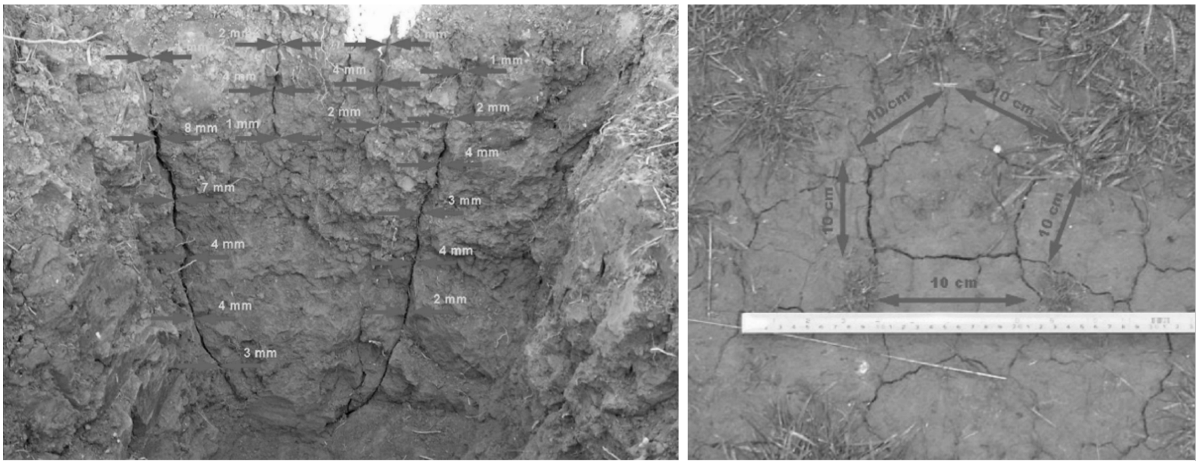

Figure 2.14: Desiccation fissures observed in a trial trench of depth 1m in the historic embankment at Thorngumbald in 2006 (Dyer et al., 2009)

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In addition to the field surveys, laboratory experiments were performed to determine the shrinkage limit, plastic limit and liquid limit of the soil. They concluded the moisture content of the soil in the upper layer is close to the shrinkage limit. In the deeper part of the dyke, it varies between the shrinkage limit and the plastic limit (Dyer et al., 2009).

Alterra (2013) performed several field observations in the Netherlands, as can be see in Figure 2.15. Multiple peat and clay dykes were checked and trenches were excavated at locations where cracks were observed. Cracks with depths larger than 1 m were observed. In California, USA, desiccation cracks with a depth up to 1.22 m are observed in clay dykes. Unfortunately, further details or figures are not given (Jalali et al., 2006).

Figure 2.15: Cracks in Dutch clay dykes, observed in 2013 (Alterra, 2013)

Drought of 2018 in the Netherlands

The drought in the summer of 2018 was almost as severe as the record-breaking drought of 1976, in terms of precipitation deficit. The precipitation deficit is a suitable parameter to describe droughts because it is a reasonable measure of soil desiccation. It is described as the sum of daily potential reference and daily precipitation, starting from April 1st of each year. In Figure 2.16 the cumulative precipitation deficit for different years is shown. The total precipitation deficit of 2018, based on 13 weather stations in the Netherlands, was 296 mm.

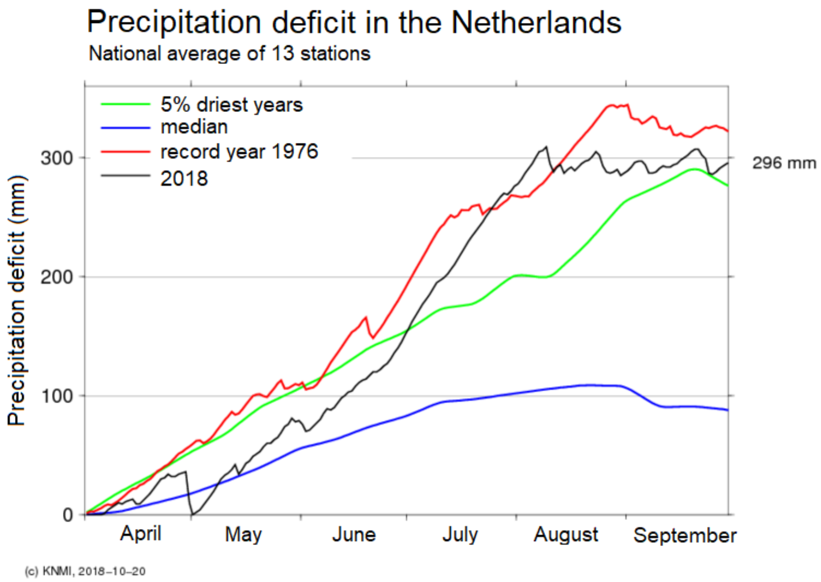


Figure 2.16: Precipitation deficit in 2018

The lack of precipitation, high temperatures and extreme evaporation rates of 2018, raised attention for desiccation cracks in Dutch clay dykes. The deterioration of grass revetments and the occurrence of cracks in clay were observed on multiple primary and secondary dykes. Large differences occurred, with some dykes being strongly affected and other dykes only little affected.

Below, different examples of cracks in clay dykes observed in 2018 are shown. On the Oostvaardersdijk (Figure 2.17, left), a primary dyke, burrowing mice were already causing problems for some years, and the combination of drought and burrows led to severe cracks.

Figure 2.17: Field observations from 2018 drought. Left: Oostvaardersdijk, right: Van Ommen polder

Figure 2.17 (right) shows large cracks in a small regional clay dyke on a peat underground, located in the Van Ommen polder. There were multiple cracks present, some of which had a length of over 10 meters, at least 1 meter in depth and a width up to 0.1 meter. According to Bottema et al. (2019) a combination of factors led to this large crack development. First of all, the clay type is sensitive to shrinkage and was possibly too wet during the dyke construction. In addition, overgrazing of sheep led to exposing of the soil. The presence of a large amount of mice and their burrows contributed to the desiccation of the clay as well. Part of these cracks are likely to close to some extent after wetting, but how fast and to which extent cracks recover is mostly unknown. Moreover, closed cracks remain prone to reopening, so the soil strength will not entirely be comparable to the initial situation.

2.4.4. Factors influencing desiccation cracking

There are multiple factors that have an influence on the crack pattern, amount of cracks and the rate at which cracks occur. A description of the different factors is given in this paragraph.

Vegetation

Typically, dykes in the Netherlands are covered with grass. This vegetation has, in general, a beneficial effect on dyke stability since it increases the resistance against erosion. Also, the grass roots have a positive influence on soil strength and can restrict cracking, as shown by Li et al. (2016). Their laboratory experiments indicated that vegetation roots are capable of minimising the development of cracks, especially in the early stages of the drying–wetting cycles. However, it turned out that roots hindered the sealing or partly closure of cracks during the wetting process.

It is not just the grass itself, but rather the interplay between the grass and the underlying clay layer that determines the strength of the cover. Clay can itself be erosion resistant as long as it is consistent and continuous, but natural clay tends to break up into smaller lumps under the influence of biological and physical processes. This soil structure occurs when clay dries out and shrinks. This process is mitigated by the root structure of the grass cover which holds the lumps together; also, a grass cover keeps the clay moist and minimises the drying process. The cracking of the clay layer is most severe at the surface and decreases from the surface downwards (Jonkman et al., 2017).

The fine segments in the top layer are reinforced by the finer and shorter roots, while the bigger lumps in de deeper layers are reinforced by the bigger and longer roots. This reinforcement is relatively strong. Single roots cannot provide considerable strength, but the intertwined root system does. In one cubic meter of clay cover at the top of a dyke slope the total root length can exceed a million meters (Jonkman et al., 2017).

From the above, it is clear that quality of the grass cover has an influence on desiccation cracking. Clay with a bad grass cover is more prone to desiccation cracking (Stirling, 2014). This is underlined by the field observations discussed above. The cracks are more severe on locations with no grass cover or a grass cover in bad condition.

Cyclic wetting / drying

Omidi et al. (1996) investigated the effect of multiple drying cycles. During the first cycle some cracks are formed which increased in size during the second drying cycle.

Fines content

Yesiller et al. (2000) studied desiccation cracking behaviour of compacted landfill liners. They observed that the content of fines in the clay affected the cracking behaviour significantly. Soils with a larger amount of fines fraction showed the greatest amount of cracking and the least amount of cracking was observed in the soil with lowest fraction of fines.

This findings are supported by the observations of Tang et al. (2008). The experiments showed that soils with a higher fines content and plasticity index I_p have a higher average crack width and a higher CIF (Crack Intensity Factor). In some cases, the fines fraction is recognized to be the most important factor.

Temperature

Tang et al. (2010) investigated the relation between temperature and desiccation cracking. They concluded that desiccation cracks in the surface layer initiate faster at higher temperatures. The surface crack ratio, the ratio of the surface cracks area to the total surface area, increases with increasing temperature (Tang et al., 2010).

Self-healing of existing cracks

In the multiple cycle tests performed by Yesiller et al. (2000), wetting provided some healing to the cracks that developed in the first cycle. However, complete healing of cracks is not possible as cracks remained weak zones. The cracks re-opened and cracking progressed easily when the soil was placed in drying conditions again (Yesiller et al., 2000).

These conclusions are in line with the findings of Boynton and Daniel (1985), who tested the effect of different factors, including desiccation cracks, on the hydraulic conductivity of compacted clay samples. They concluded that the cracks tend to close if soil is wetted, but the hydraulic conductivity is not as low as for undesiccated specimens. A higher confining pressure increases the closure of cracks (Boynton and Daniel, 1985). It can be concluded that desiccation cracks remained weak zones in this case as well.

2.4.5. Typical crack depth

An estimation of the typical crack depth and the maximum expected crack depth in the Netherlands forms a crucial part of the dyke stability analysis. From the small-scale laboratory experiments discussed before, no conclusions can be drawn on the maximum depth of cracks in field conditions. In the field, the depth to which desiccation cracks reach is difficult to determine, as it is not visible from the surface but only by digging trenches. As mentioned in section 2.4.3, Dyer et al. (2009) and Alterra (2013) observed desiccation cracks in clay dykes at depths larger than 1.0 meter.

Apart from field experiments on dykes, field experiments related to clay-liner such as clay-lined waste lagoons can be useful as well. In the latter, a clay layer is used to minimize leakage of waste into the groundwater because of the low hydraulic conductivity characteristics of clay. Because the influence of (desiccation) cracks on the hydraulic conductivity is very important in this case, field experiments are performed, i.e. by (Baram et al., 2012). The objective of this study was to assess the infiltration through clayey vadose zones, with experiments performed in Israel. One of the key observations is that wetting fronts crossed an entire layer (12 or 6 m) within hours, suggesting that the cracks cross the entire unsaturated clay layer. They also observed that desiccation cracks start to form from the minute the soil becomes unsaturated, and that there is high connectivity between the formed cracks, even at high water contents. Repeated measurements during two more winter seasons, showed that the cracks were never fully closed during rainy periods.

Elias et al. (2001) performed field experiments on cracking patterns in different vertisols (soils with a high content of clay) in Sudan. They studied the crack depth, width and length, distances between cracks and calculated the crack volume. Three different vertisols, with a clay content ranging from 40% to 65% are compared. Interesting to see is that crack depth increased with increasing clay content and cracks with a depth of 0.8 m to more than 1.0 m were observed. However, these cracks were only studied from surface level, no trenches were dug, so crack depths can be even larger. In addition, the volume of cracks [m3/ha] increased with increasing clay content, as can be seen in Figure 2.18.
Of course, these results cannot be translated to the clay of dykes one-to-one. Clay used for waste lagoons is selected predominantly on a very low hydraulic conductivity. In case of dykes, other properties like the workability and erosion resistance are important as well. However, it gives an indication of the depth at which desiccation cracks can be expected if droughts intensify.

The crack depth and with that the maximum crack depth is, apart from clay characteristics and the evaporation circumstances at surface level, also dependent on the location of the phreatic surface inside the dyke. If the phreatic surface is located at a large depth due to a low outside water level, the unsaturated zone is larger and therefore the cracks can extent to larger depths than in cases where the phreatic surface is located high inside the dyke. This is dependent on the location and type of dyke, as hydraulic loads are generally different.

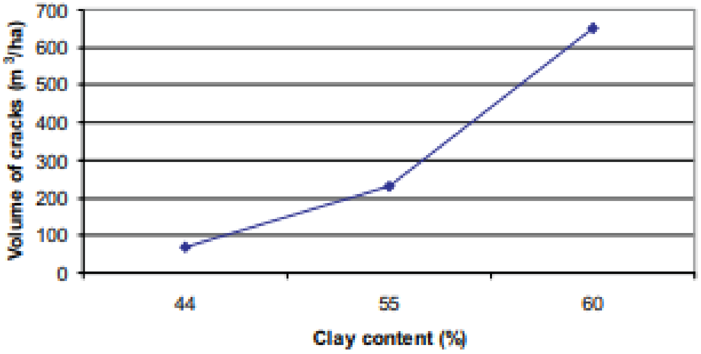


Figure 2.18: Relation between clay content and volume of cracks in vertisols (Elias et al., 2001)

2.4.6. Typical crack pattern

Naturally, the crack intensity, depth and pattern is dependent on multiple factors, like the clay characteristics and hydraulic conditions. The observed crack patterns are generally polygonal shapes, with three to six sides, as can be seen in Figure 2.19. This is also concluded in the studies of Konrad and Ayad (1997a) and Dyer et al. (2009).

Figure 2.19: Observed desiccation crack pattern (Li and Zhang, 2011)

Summary of chapter: Literature

The aim of this chapter was to lay the theoretical foundation for this research by discussing relevant papers on flood protection in the Netherlands, characteristics of the clay used for dykes, unsaturated soil mechanics and desiccation cracking.

Flood protection in the Netherlands
Different mechanisms can lead to the failure of dykes, such as macro-instability, piping and erosion. In the Dutch safety assessments, the increased strength of unsaturated soil is not incorporated. Desiccation cracks can potentially have an influence on the macro-stability of dykes due to multiple reasons. The cracks can provide a preferential path to water flow into the core of the dyke leading to an increase of infiltration. Larger cracks can be part of the failure surface providing little or no shear strength.

Clay characteristics
In the Netherlands, clay is already used for centuries as both the dyke top layer as for the dyke core. A subdivision is made into three categories of erosion resistance. This distinction is based on Atterberg limits and sand content. Clay used for dykes has a sand content below 40% and an organic material content below 5%.

Unsaturated soil
In unsaturated cohesive soils, suction or negative pressures exist. The relation between water content and soil suction is shown by the soil-water retention curve. Hydraulic conductivity will generally decrease with increasing suction, as can be described by the hydraulic conductivity function. Suction leads to an increase of shear strength. The shear strength of unsaturated soils can be formulated based on different basic frameworks: the Bishop stress framework and the independent stress variables framework proposed by Fredlund.

Desiccation cracking
There are multiple factors that have an influence on the crack pattern, amount of cracks and the rate at which cracks occur. The most important factors are: vegetation, fines content, cyclic wetting/drying and temperature. Desiccation cracks can show self-healing upon wetting to some extent. However, during the next drying cycle the chance for cracks initiating at the same location is relatively high: a weak spot is still present.

In the Netherlands, desiccation cracks of depths over 1.0 meter are already observed. With droughts increasing in both intensity and duration, this depth may even increase in the future. Cracks can be interconnected by horizontal cracks joining vertical cracks.

3

Numerical model

In this chapter, all relevant aspects of the PLAXIS 2D model and the model set-up are described. First, the modelling approach is presented. Second, general information on the PLAXIS 2D model and the chosen constitutive model is given. Next, the adjusted soil parameters to simulate the effect of the desiccation cracks are determined. In the last two paragraphs, the model set-up and the PLAXIS 2D calculation phases are discussed.

3.1. Modelling approach

To determine the impact of desiccation cracks on dyke stability a numerical model using the software PLAXIS 2D is used. This software is commonly used in the Netherlands. Further details on PLAXIS 2D are discussed in Section 3.2. There are various methods to implement desiccation cracks in numerical models. As for this thesis, the aim is to study the influence of cracks on macro-stability. The initiation and development of individual cracks is a very complex phenomenon that is difficult to predict. Thus, implementing individual cracks directly into a numerical model is undesirable and can, also, lead to numerical instabilities. Therefore, it is chosen to use an alternative method of including the effects of desiccation cracks: modifying the material properties of the cracked soil. In this way, the impact of cracks is quantified without the need to predict complex cracks patterns. From literature review, it is clear that desiccation cracks can have a influence on both the strength and the hydraulic properties of the soil. It is, therefore, chosen to adjust the cohesion, friction angle and hydraulic conductivity so simulate the effect of cracks. The expected change of the parameters is determined in Section 3.3.

Based on the literature review in Chapter 2, the following key assumptions are included in the model set-up:

- The hydraulic conductivity and shear strength are expected to be affected by desiccation cracks.
- Desiccation cracks in Dutch clay dykes have already reached depths larger than 1 meter.
- Cracks can be observed both at the crest and the slope of a dyke as these parts can be unsaturated and therefore undergo drying.
- Cracks can initiate on surface level but also below surface level. For the stability of Dutch dykes cracks present at the surface level are expected to occur the most often and to have the largest influence. With the chosen modelling approach, cracks are always present at surface level.

For this thesis, a typical geometry for a Dutch river dyke is chosen. The geometry can be seen in Figure 3.1. The clay dyke is founded on a clay layer on top of a sand layer. The used soil parameters are given in the next section. The toe ditch is typical for the Dutch river dykes and will have an influence on the shape and location of the failure plane.

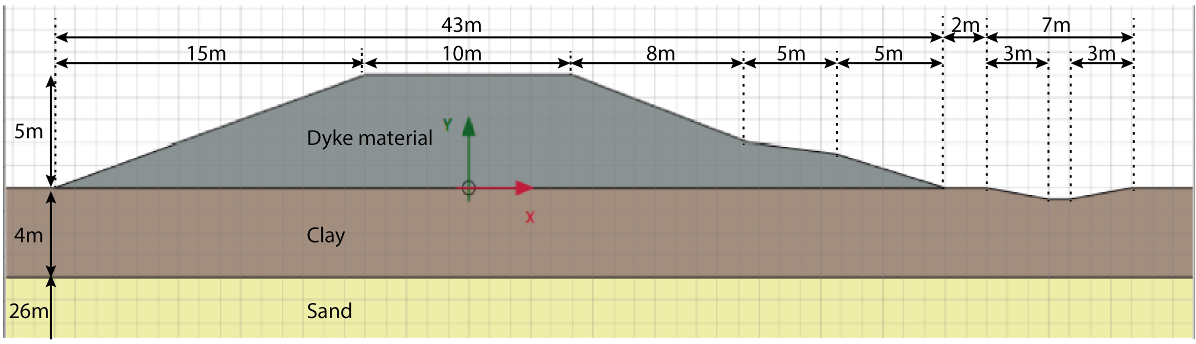


Figure 3.1: Used geometry of typical Dutch dyke

Depth and shape of cracked zone

As discussed in Section 2.4.5, the maximum depth the crack can reach is dependent on multiple factors: the clay characteristics but also on the hydraulic boundary conditions as water level and evaporation rates. For the chosen dyke geometry the unsaturated zone can become large in case of low outside water level. For this dyke, the maximum crack depth is therefore chosen at 2m. The impact of cracks on the factor of safety will of course be dependent on this depth. In this analysis, the upper two meter of the dyke is affected by cracks. The Figure 3.2b, the shape of the cracked zone is shown.

At the crest of the dyke, the cracks extent to a depth of 2 meter. At the slopes of the dyke, however, the depth of the cracks is gradually decreased. The reason for this shape is that the upper part of the dyke will experience more and longer droughts than the lower parts of the slope and will therefore develop deeper cracks. This shape is kept equal for all scenarios, even if the water level is high. This means that, in some model scenarios, cracks will exist in saturated conditions. This is conservative with respect to the safety analysis, as cracks can partly close under high hydraulic load.

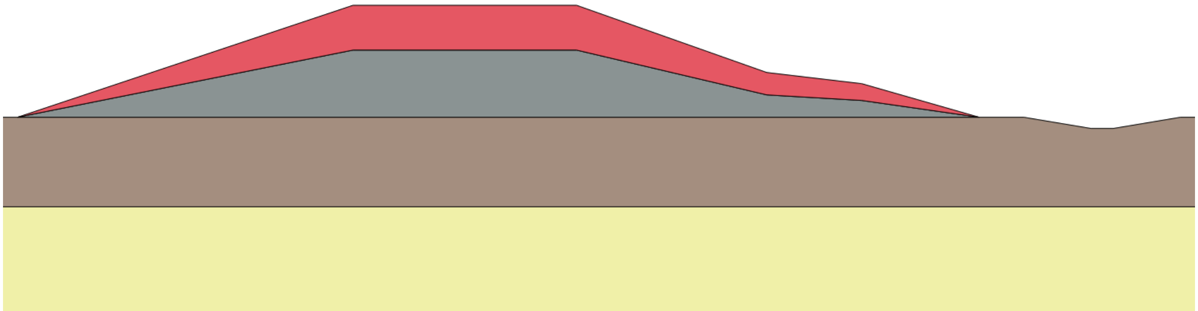


Figure 3.2: Shape the cracked zone, depicted in red

Model scenarios
As described in Chapter 2.1, different hydraulic load scenarios, both steady-state and time-dependent, are considered for safety assessments. To determine the most critical case for a dyke affected by desiccation cracks, these different scenarios are studied. In addition, other aspects like crack depth and initial suction levels are studied to get more insight in the influence of cracks under different conditions.

The following hydraulic conditions are considered:

- **Steady-state:** With respect to steady-state conditions, time is not considered as a constant water level is used. A relatively high water level is used as starting point, as this will lead to the lowest factor of safety. To study the effect of cracks at different water levels, a relatively low water level is considered as well.
- **Time-dependent:** Aim of the time-dependent scenario is to simulate a more realistic situation and determine the influence of cracks on the hydraulic response and dyke stability in this case. In these scenarios, the external water level is fluctuating in time, leading to a non-stationary ground water flow and pore water pressures. This causes the slope stability to be time dependent.
- **Time-dependent including precipitation:** Due to precipitation, the water level inside the dyke will rise. To study the influence of this on the stability and hydraulic response of the cracked dyke, precipitation is included in part of the PLAXIS 2D calculations.

In Table 3.1 the different aspects that are varied are described for both the steady-state scenarios as the time-dependent scenarios. By changing this aspects independently the influence of each aspect is shown.

Constitutive material model
The chosen modelling approach leads to the choice for the Mohr-Coulomb constitutive model: a linear elastic perfectly plastic model with a Mohr-Coulomb failure criterion. To simulate the effect of cracks, different soil parameters are adjusted. From the literature review is decided that the strength parameters, cohesion and friction angle, and the hydraulic conductivity are affected by the cracks. In the more advanced material models, alternative parameters may be used, which makes it more complicated to adjust parameters to simulate the cracked layer. Therefore, the use of the Mohr-Coulomb model is preferred for this study.

Table 3.1: Different aspects that are varied for modelling scenarios

	Aspect	Description
Steady-state	Water level	High water level and low water level
	Initial suction conditions	No suction, linear suction and suction level of 100 kPa
	Initial soil parameters	Different combinations of strength parameter
	Crack depth	Crack depth of 1 meter and 2 meter
	Cracked soil parameters	Different combinations decreasing strength parameters
Time-dependent	Water level	Design water level and measured high water event
	Precipitation	Adding precipitation

3.2. General information PLAXIS 2D

PLAXIS 2D is a software program based on the Finite Element Method to perform two-dimensional deformation, stability and flow analysis for different types of geotechnical applications (PLAXIS, 2019b). PLAXIS 2D is widely used in the Netherlands.

3.2.1. Constitutive material model

PLAXIS 2D calculations can be done using different advanced constitutive material models. As discussed above, the Mohr-Coulomb model is used as a result of the chosen modelling approach to incorporate the effect of cracks. Because the focus is on dyke stability and, therefore, the strength-reduction method is used. A more advanced model will actually behave as a standard Mohr-Coulomb model, since stress-dependent stiffness behaviour and hardening effects are excluded from the safety analysis (PLAXIS, 2019b).

The Mohr-Coulomb model is a simple and common-used linear elastic perfectly plastic model. It is generally used as a first approximation of soil behaviour and uses parameters with a clear physical meaning. The model uses a fixed yield surface, not affected by plastic strains.

In the Mohr-Coulomb material model stress-dependency, strain dependency of stiffness and anisotropic stiffness are not included. According to PLAXIS (2019a), the effective stress states at failure are generally well described using the effective strength parameters ϕ' and c'.

3.2.2. Hydraulic model and relation to effective stress

Groundwater flow in PLAXIS 2D is based on Darcy's law and the principle of flow continuity. A complete description of the models will not be given here but can be found in the scientific manual of PLAXIS (PLAXIS, 2011). The Soil Water Characteristic Curve (SWCC) is introduced to describe hydraulic parameters of the groundwater flow in the unsaturated zones. As described in Section 2.3.5, there are multiple models to describe the hydraulic behaviour of unsaturated soils. As discusses in Section 2.3.1, the most common model in the groundwater literature is the model proposed by van van Genuchten (1980) and this is used in PLAXIS 2D. Several data sets related to the soil-water retention curve are provided. The options are: standard, hypres, USDA, staring and user defined.

PLAXIS 2D uses the Van Genuchten equation in terms of the degree of saturation S, see Equation 3.1. As already discussed in Section 2.3.5, the degree of saturation can be related to the effective stress.

$$S(\psi) = S_{res} + (S_{sat} - S_{res})[1 + (g_a|\psi|)^{g_n}]^{g_c} \tag{3.1}$$

Where $g_c = (1 - g_n)/g_n$ and $\psi = -\frac{\text{suction}}{\text{unit weight of water}}$. The parameters g_a, g_l and g_n are fitting parameters.

In PLAXIS 2D, an alternative formulation of Bishop's framework as shown in Equation 2.6 is used. For the effective stress parameter χ PLAXIS 2D uses the effective degree of saturation S_{eff}, which is equal to $S_{eff} = (S - S_{res})/(S_{sat} - S_{res})$. This leads to the formulation of effective stress as is shown in Equation 3.2.

$$\sigma' = \sigma - S_{eff} * (p_{steady} + p_{excess}) \tag{3.2}$$

Where the sum of p_{steady} and p_{excess} gives p_{water}. PLAXIS 2D uses the term of active pore pressure p_{active} for the effective saturation S_{eff} times the pore water pressure p_{water}. As the effective saturation is 1 below the phreatic surface, the active pore pressures equals the pore water pressures below the phreatic surface.

In PLAXIS 2D there are two options regarding suction: ignore suction or allow suction. In the latter case, PLAXIS 2D considers Bishop's definition of effective stress and it will include suction (negative pore stress) and the degree of saturation in the calculation. In this case, the selection of appropriate hydraulic models for the relationship between suction and saturation as well as the relationship between suction and relative permeability becomes essential (PLAXIS, 2019b). This relationship depends on the selected soil-water retention curve parameters for every soil type. The assumptions made regarding soil parameters are described in Section 3.4.2.

3.2.3. Factor of Safety

PLAXIS 2D is able to perform a safety analysis based on the strength reduction method, also called phi/c reduction method. The shear strength parameters $\tan\phi$ and c of the soil are successively reduced until failure of the structure occurs and a factor of safety is computed. In principe, the dilatancy angle ψ is not affected by strength reduction method, but if the friction angle ϕ has reduced so much that it becomes equal to the (given) dilatancy angle, any further reduction of the friction angle will lead to the same reduction of the dilatancy angle (PLAXIS, 2019b). During the safety analysis performed in PLAXIS 2D, out-of-balance forces are introduced. These out-of-balance forces will result in additional deformations that does not have a physical meaning. Therefore, the magnitude of the deformations occurring during the safety analysis have to be ignored.

With the strength reduction method, a factor of safety can be computed. This factor of safety FoS is the ratio between the initial strength and the strength parameter under limit state after reduction, see Equation 3.3. In PLAXIS the multiplier ΣMsf is used to define the value of the soil strength parameters at a given stage in the analysis. The value of ΣMsf at failure gives the factor of safety of the structure. This gives one factor of safety for the entire dyke.

$$\mathrm{FoS} = \frac{\text{available strength}}{\text{strength at failure}} = \text{value of } \Sigma\text{Msf at failure} \tag{3.3}$$

A large advantage of the strength reduction method is that no assumptions need to be made about the location or shape of the failure surface, which is the case for limit equilibrium methods.

3.3. Soil parameters influenced by desiccation cracks

To determine the influence of the cracks on dyke stability, the change of soil parameters due to cracks is estimated. The parameters described in this section are the hydraulic conductivity and the strength parameters. These parameters are expected to be significantly affected by desiccation cracking and are important for the stability of the dyke.

3.3.1. Change of parameters in time

As discussed, desiccation cracks can have an impact on the hydraulic conductivity and the soil strength. The degree of change of these parameters is dependent on the crack characteristics, like crack depth, width and the amount of cracks. These aspects are not constant in time, but may change due to fluctuating hydraulic conditions. Under dry conditions, new cracks can initiate or existing cracks can develop leading to an increase of the total cracked volume. Thus, the hydraulic conductivity increases and the strength decreases. As cracked clay is unable to heal completely, these soil properties will not recover to their initial value. However, cracks can (partly) close or seal upon wetting, for example during heavy rainfall as the clay will swell. In that event, the hydraulic conductivity can start to decrease again. Summarized, the crack volume will fluctuate as is the case for the associated strength and hydraulic soil parameters, due to the dynamic character of the hydraulic conditions.

For this study, one fixed value for each of the adjusted soil properties, to simulate the cracked layer, is chosen. This implies that the crack characteristics are assumed to be constant over time, even in the transient scenarios.

3.3.2. Hydraulic conductivity

Different laboratory experiments regarding the hydraulic conductivity of clay with desiccation cracks have already been performed in the past, by Rayhani et al. (2007), Omidi et al. (1996), Albrecht and Benson (2001) and Lu et al. (2015). In these experiments, a comparison is given between the initial hydraulic conductivity and the hydraulic conductivity of desiccated clay of the different clays, as is summarised in Table 3.2. In this table, the initial hydraulic conductivity is given by k_0 and the hydraulic conductivity with desiccation cracks is given by k_1.

As can be seen, for each experiment an increase in hydraulic conductivity between the uncracked sample and the cracked sample is noticed. The magnitude of this increase varies, and is most likely depending on both the experimental set-up, the severity of cracks and the type of clay. The experiments have a different set-up and the desiccation cracks are created with different methods, so the amount of cracking and the cracking rate may be different. There is little to no information on the dimensions of the cracks in all four papers. In Figure 3.3, some of the cracked samples are shown. The left sample depicts soil nr. 3, from the experiment of Rayhani et al. (2007). The right samples are soil nr. 9 and nr. 11 respectively from the experiment of Albrecht and Benson (2001). In addition, the hydraulic conductivity can be measured in a different way.

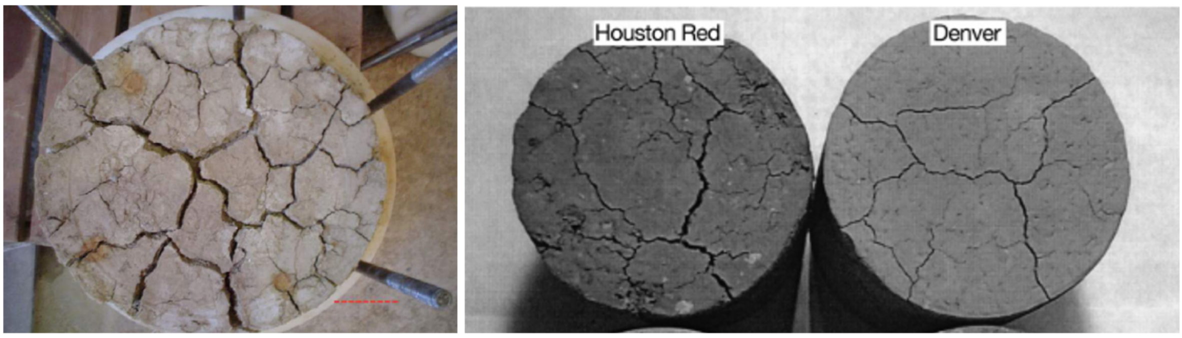


Figure 3.3: Cracked clay samples used for the experiments listed in Table 3.2. Left sample: soil nr. 3 (Rayhani et al., 2007). Middle sample: soil nr. 9. Right sample: soil nr. 11 (Albrecht and Benson, 2001).

Paper	Soil nr.	Soil type	k_0 [cm/s]	k_1 [cm/s]	Factor (k_1/k_0) [-]
Rayhani et al. (2007)	1	CL	3.29*10^{-9}	4.60*10^{-8}	13.92
	2	CL	1.40*10^{-9}	2.70*10^{-8}	19.29
	3	CL	6.88*10^{10}	3.40*10^{-9}	49.42
	4	CH	6.00*10^{10}	9.88*10^{-9}	16.47
Omidi et al. (1996)	5	CH	3.1*10^{-8}	3.5*10^{-7}	11.29
	6	CL	7.7*10^{-8}	2.0*10^{-7}	2.59
	7	n/a	7.5*10^{-8}	9.7*10^{-8}	1.29
	8	n/a	8.0*10^{-8}	1.0*10^{-7}	1.25
Albrecht and Benson (2001)	9	CH	n/a	n/a	400
	10	CH	n/a	n/a	10
	11	CL	n/a	n/a	120
	12	CL	n/a	n/a	5
Lu et al. (2015)	13	n/a	3.6*10^{-8}	1.5*10^{-5}	416.67
	14	n/a	2.5*10^{-8}	8.3*10^{-7}	33.2

Table 3.2: Overview of research into the influence of cracks on hydraulic conductivity of clay, with the initial hydraulic conductivity k_0 and the hydraulic conductivity with desiccation cracks k_1

The results of these four papers are used to make a reasonable assumption on the expected increase of hydraulic conductivity of the clay used for Dutch river dykes. For all papers, details of the sample size and the clay properties are given in table 3.3. In Section 2.2.1 a description of the characteristics of typical Dutch clay used for dykes is given. With these characteristics and the details given in Table 3.3, the results of Omidi et al. (1996) are chosen as most representative for the determination of a reasonable ratio of hydraulic conductivity for the typical Dutch river dyke. The main reason for this is that the experiments of Omidi et al. (1996) are performed on larger samples. Therefore, the results from this experiment are more relevant regarding the field conditions where this thesis is focussing on.

Omidi et al. (1996) uses 4 different soils. Details of the liquid limit and plastic limit are known only for two soil types: soil nr. 4 and soil nr. 5. From the requirements described in section 2.2.1, soil nr. 5 is preferred over soil nr. 4. The ratio k_1/k_0 of soil nr. 5 is 11.3. The following remarks regarding a comparison of soil nr. 5 and the typical clay from the Netherlands are made:

- Clay content; the clay content of soil nr. 5 is 51%. This is slightly higher than the clay content used for Dutch dykes. A higher clay content will lead to a higher surface crack ratio, according to experiments performed by Tang et al. (2008).
- Sand content; the sand content of soil nr. 5 is 16%. However, the sand content of the clay used in the Netherlands has to be between 20 and 40%.
- Liquid limit; soil nr. 5 has a liquid limit of 51%. This is in accordance with the requirements for clay used for Dutch dykes.
- Plasticity index; soil nr. 5 has a plasticity index of 36%. This is higher than the required plasticity index for dykes in the Netherlands.
- In all experiments discussed in this section, the samples are first compacted. On a real dyke, the clay will be of lower compaction than in case of the experiments. Clay with higher compaction will have a lower hydraulic conductivity.

Because this thesis is focussed on the potential influence of cracks on dyke stability and, therefore, on severe cracks, conservative assumptions are made.

It is chosen to use a ratio k_1/k_0 of 15 in this study.

Paper	Soil nr.	USCS class.	Sample size	Predominant mineral	Measurement method	LL	PL	PI	% Clay	W (opt.)
Rayhani et al. (2007)	1	CL	100 mm diameter, height 116 mm	-	Falling head method (ASTM)	32.2	20.8	11.4	18	17
	2	CL		-		36.0	21.3	14.7	43	18
	3	CL		-		42.8	21.6	21.2	50	20.5
	4	CH		-		62.2	24.9	37.3	68	22
Omidi et al. (1996)	5	CH	43 cm diameter, height 3.8 cm	Smectite	Fixed wall permeameters	51.18	14.61	36.57	52.4	18.5
	6	CL		Illite		43.1	23.36	19.74	45.3	18
	7			-						
	8			-						
Albrecht and Benson (2001)	9	CH	100 mm diameter, height 116 mm	Illite/smectite	Flexible wall permeameters	67		46	53	19
	10	CH		Illite/smectite		67		32	40	21
	11	CL		Smectite		49		26	40	18
	12	CL		Quartz		29		16	16	12
Lu et al. (2015)	13				Flexible wall permeameter					19
	14									

Table 3.3: Overview of research into the influence of cracks on hydraulic conductivity of clay

3.3.3. Strength parameters

In addition to the hydraulic conductivity, the shear strength of the soil will change due to desiccation cracks. From theory and experiments it is clear that the strength parameters are expected to decrease with increasing desiccation cracks, as described in section 2.4. Therefore, the strength parameters (effective) cohesion and (effective) friction angle will be adjusted to account for the effect of the desiccation cracks.

The magnitude of the cohesion and friction angle of soil samples with cracks are difficult to measure. In the numerical model, the cracked soil is treated as one homogeneous layer instead of intact soil with discontinuities in the form of cracks. Consequently, it is difficult to give a reasonable prediction of the change of the cohesion and friction angle. It is decided to use a 50% reduction for both the cohesion and the friction angle as a starting point to simulate the effect of cracks. Furthermore, different combinations of the two parameters are used to study the effect of the decreasing shear strength.

As can be seen in table 3.4, the effective cohesion and friction angle are varied both independently and dependently of each other, ranging from a 25% to a 75% decrease. The changes are given as a percentage of the initial parameters that are given in section 3.4.2. These percentages are chosen because it is expected that cracks can have a substantial effect on the strength parameters. This wide range of parameters will give a clear insight in the effect of decreasing shear strength on the dyke stability.

Table 3.4: Adjustment (in percentage) of strength parameters cohesion and friction angle

Parameter combination	1	2	3	4	5	6	7	8
Cohesion c'	-25%	-50%	-75%	0	0	0	-25%	-50%
Friction angle ϕ'	0	0	0	-25%	-50%	-75%	-25%	-50%

3.3.4. Correlation

What is neglected in section 3.3.2 and 3.3.3 is that the change in hydraulic conductivity and the change in the shear strength are actually not independent. More severe desiccation cracks will lead to a higher hydraulic conductivity and simultaneously to a lower strength. If the hydraulic conductivity changes to a large extent due to cracks, the shear strength parameters will, as well, change to a large extent. However, because of the fact that the change in strength parameters is unknown, as described in the previous section, different parameter combinations are chosen.

Thus, the degree of correlation between these combinations and the change of the hydraulic conductivity is hard to estimate. This correlation is therefore not explicitly taken into account.

3.4. PLAXIS 2D model set-up

In this section, the geometry, material properties and calculation phases of the PLAXIS 2D model are described.

3.4.1. Mesh and model dimensions

The following model dimensions are implemented, as can be seen in table 3.5. The dimensions have to be large enough, to make sure that there is the boundaries do not influence the results. The geometry of the dyke is depicted in Section 3.1, Figure 3.1. The dyke has a total width of 43 meters and a height of 5 meters.

Table 3.5: Model dimensions in PLAXIS 2D

Boundary	Value [m]
X_{min}	-250
X_{max}	250
Y_{min}	-30
Y_{max}	10

Regarding the mechanical boundary conditions, the lower boundary is fully fixed, whereas the lateral boundaries are free in the vertical direction and fixed in horizontal direction. The top boundary is free. The lower hydraulic boundary is closed, while the top and lateral boundaries are open.

A relatively fine mesh is generated, as can be seen in Figure 3.4. In total 11381 15-noded triangular elements and 92823 nodes are used. The lower part of the mesh, especially the sand layer, is coarser than the dyke itself. The mesh refines locally closer to surface level, as the infiltration of precipitation requires a finer mesh. Because of the low hydraulic conductivity, a very fine mesh is needed.

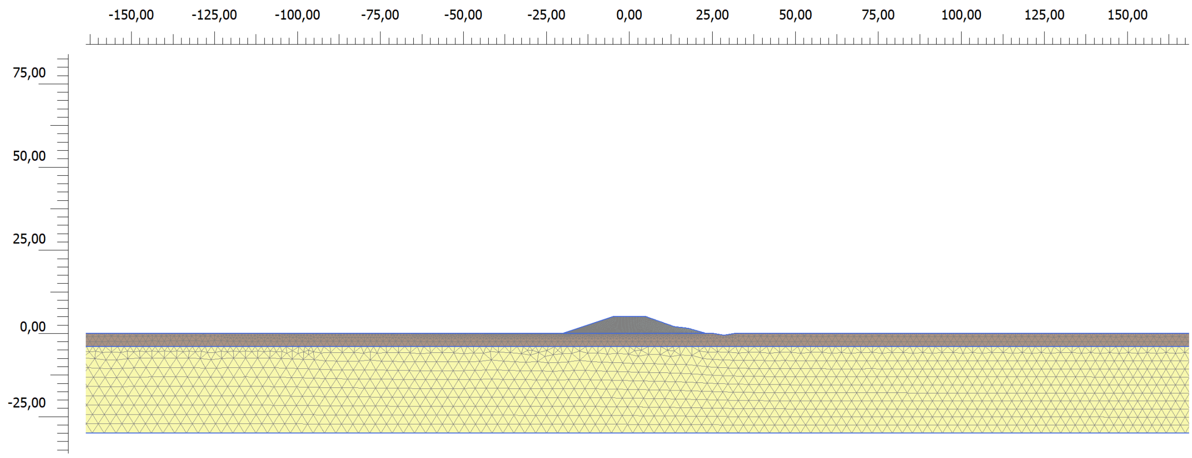


Figure 3.4: Overview of mesh used in PLAXIS 2D

A more detailed view of the mesh is shown in Figure 3.5.

3.4.2. Material properties

In table 3.6, the parameters used for the PLAXIS2D model are presented. A distinction is made between the sand layer, the clay layer and the clay dyke material. For the different parameters choices, an explanation is given below. As explained before, the desiccation cracks are simulated by adjusting the parameters. In table 3.6, the cracked dyke material is, therefore, stated as a new soil type. Most of the parameters are not influenced by the cracks and are, thus, kept the same as in case of the dyke material. The effective cohesion, friction angle and the hydraulic conductivity of the cracked material are varied to account for the effect of the cracks, as is described in Section 3.3.

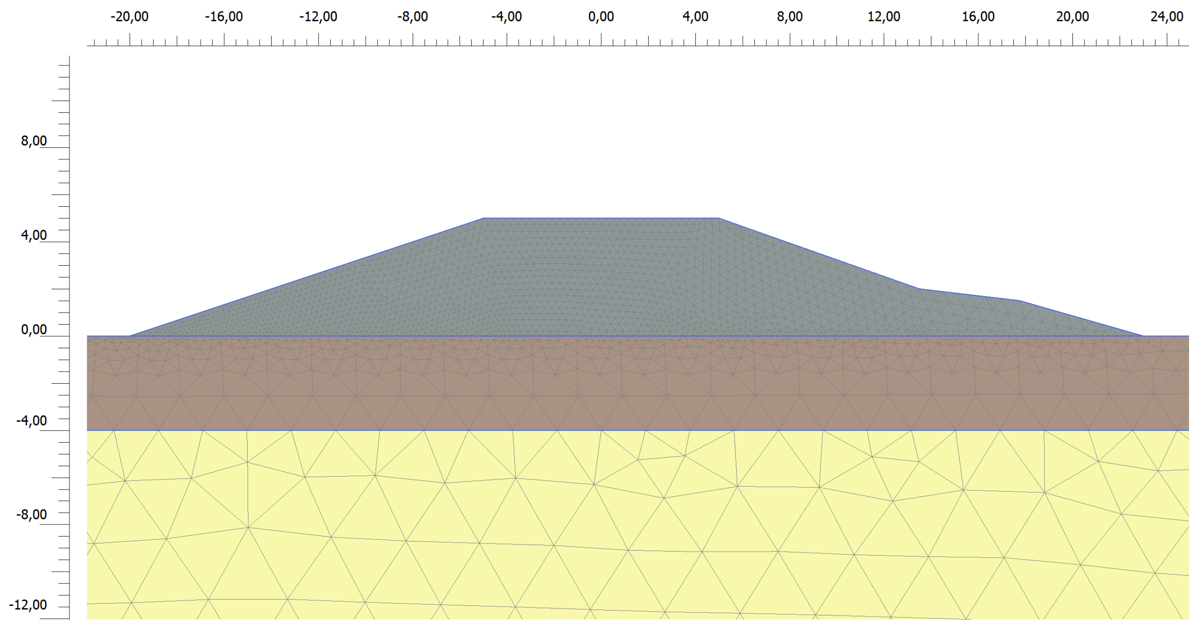


Figure 3.5: Detailed mesh

Table 3.6: Soil parameters used for the PLAXIS 2D model

			Sand	Clay	Dyke material	'Cracked' material
Drainage type			Drained	Undrained A	Undrained A	Undrained A
Unsaturated volumetric weight	γ_{unsat}	$[kN/m^3]$	17	16	16	16
Saturated volumetric weight	γ_{sat}	$[kN/m^3]$	20	17	18	18
Stiffness	E'	$[kN/m^2]$	13000	4000	4000	4000
Poisson's ratio	ν'	-	0.3	0.3	0.3	0.3
Effective cohesion	c'	$[kN/m^2]$	0	2.5	5	*varied*
Effective friction angle	ϕ'	degrees	30	20	22.5	*varied*
Horizontal hydraulic conductivity	k_x	$[m/day]$	25	0.03	0.02	*varied*
Vertical hydraulic conductivity	k_y	$[m/day]$	25	0.03	0.02	*varied*

Drainage type

With the drainage type, a distinction can be made between drained and undrained behaviour. In the case of undrained behaviour, PLAXIS2D offers three types: Undrained A, Undrained B and Undrained C. With Undrained A and Undrained B it is possible to specify undrained behaviour in an effective stress analysis, using effective model parameters. Undrained C can be used for an total stress analysis and is therefore not relevant for this study.

In case of Undrained A, the effective stress parameters (cohesion and friction angle) are used to estimate the undrained shear strength. In case of Undrained B, strength is defined as undrained shear strength s_u, with friction angle ϕ set to zero. For this study, Undrained A will be used because it allows for the adjustment of both the cohesion and the friction angle for the different scenarios. The imposed drainage type is only relevant for initial stress generation and plastic calculation phases. The drainage type is ignored when performing a fully coupled flow-deformation analysis.

Poisson's ratio

As stated in PLAXIS (2019a), the effective Poisson's ratio chosen should be smaller than 0.35 for materials with drainage type 'Undrained A'. The reason for this is to ensure that the soil skeleton is much more compressible than the pore water. Therefore, a poisson's ratio of 0.3 is chosen for both the sand and clay layer as for the dyke material.

Cohesion
Different water boards in the Netherlands have collections of results of soil experiments. Waternet (2015), from Hoogheemraadschap Amstel, Gooi en Vecht, published a collection of results from 127 triaxial tests on clay from dykes. For cohesion, an average value of 5.3 is given for clays with a volumetric weight between 15 and 17 kN/m^3. From data of waterschap Rijnland, a value of 2.3 is given (Stoop, 2010). For this study, a cohesion of 5 is chosen for the dyke material. The reason for assuming a relatively high value, is that this value will be varied, as described in Section 3.3.3, to simulate the cracked layer.

Friction angle
Based on the same dataset as the cohesion, the friction angle is based on triaxial tests on clay dykes done by Waternet (2015).

Saturated hydraulic conductivity
The saturated hydraulic conductivity k_{sat} refers to the hydraulic conductivity under saturated conditions. According to the PLAXIS 2D reference manual PLAXIS (2019b), the ratio between the highest and lowest permeability value should not exceed 10^5 in order to obtain accurate results. For all soil types, the hydraulic conductivity is based on the values mentioned for dyke material in (TAW, 2004). In case of the cracked dyke material, the initial saturated hydraulic conductivity is multiplied by factor 15, as explained in Section 3.3.2.

Soil-water retention curve and hydraulic conductivity function
In PLAXIS 2D, several data sets and models to model flow in the unsaturated zone are available. This is in particular relevant for the dyke material itself as a large part of the dyke can be unsaturated. For this study, it is chosen to base the van Genuchten parameters on the Staring dataset, as it is based on tests on Dutch soils (DLO-Staring Centrum, 1994). The Staring dataset divides the Dutch soils into 18 soils. The dyke material is based on the predefined parameters of 'Heavy Clay'.

The SWRC for the cracked material needs to be altered in order to account for the desiccation cracks. Only few researchers have attempted to directly measure the soil-water retention curve for cracked soil. Abbaszadeh et al. (2015) conducted a total of six tests on artificially cracked clay samples to determine the SWRC. When comparing this to the SWRC of the intact soil, it can be concluded that a significant difference between the SWRC for cracked an intact clay is present in the lower suction range. The air-entry value of the cracked soil is lower, even for the relatively small crack widths considered in this laboratory study. At suction levels higher than 100 kPa, the SWRC of the cracked soil converges to the SWRC of the intact soil.

An approach as discussed by Fredlund et al. (2010), is to consider the SWRC curve of cracked material as a bimodal SWRC with a matrix phase and a facture phase. However, PLAXIS does not offer the possibility of inserting bimodal retention curves. Fredlund et al. (2010) also concludes that the air-entry value reduces as the crack width is increased.

PLAXIS 2D uses the Van Genuchten equation in terms of the degree of saturation S, see Equation 3.4.

$$S(\psi) = S_{res} + (S_{sat} - S_{res})[1 + (g_a|\psi|)^{g_n}]^{g_c} \tag{3.4}$$

Where $g_c = (1 - g_n)/g_n$ and $\psi = -\frac{\text{suction}}{\text{unit weight of water}}$. The parameters g_a, g_l and g_n are fitting parameters. Caution is needed because the predefined data sets as the Staring dataset are given in terms of water content θ, while the user defined model requires the degree of saturation S instead. As stated in the reference manual PLAXIS (2019b), the saturated degree of saturation S_s is assumed to be equal to 1, and therefore $S_r = \theta_r/\theta_s$.

The soil-water retention curves used for the model are shown in Figure 3.6. The AEV of the cracked dyke material is one order of magnitude smaller than the intact dyke material.

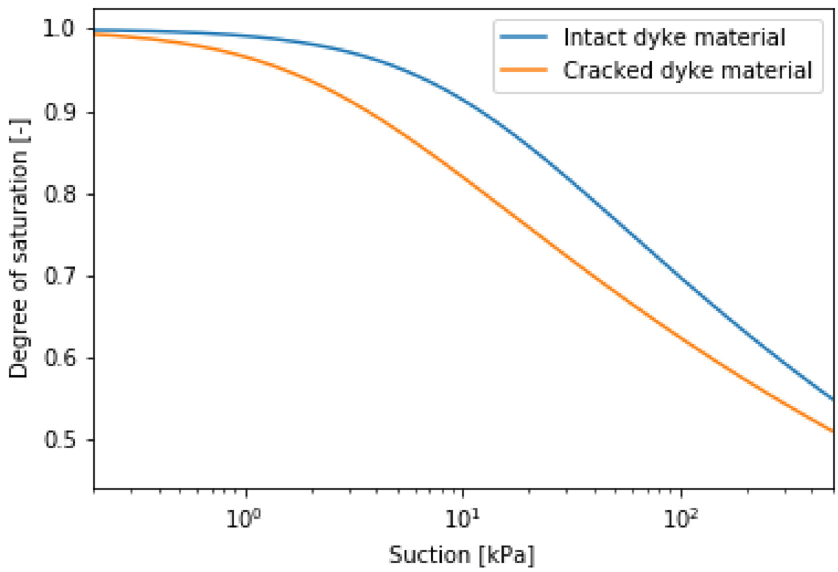


Figure 3.6: Soil-water retention curves used for PLAXIS 2D calculations

The input parameters to define the shape of the curves in PLAXIS 2D are given in Table 3.7.

Table 3.7: Van Genuchten parameters used in PLAXIS 2D model

	S_{sat}	S_{res}	θ_s	θ_r	g_a	g_l	g_n
Dyke material	1.0	0.0179	0.56	0.01	0.95	-4.295	1.158
Cracked material	1.0	0.0170	0.59	0.01	3.95	-5.901	1.120

In addition, the hydraulic conductivity function (HCF) is needed to account for the effect of suction on the hydraulic conductivity. The actual permeability is the relative permeability times the saturated permeability. The relative permeabilty is bounded by a minimum of 10^{-4}, as can also be seen in Equation 3.5 and depends on the effective saturation.

$$k_r(S_{eff}) = \max\left[(S_{eff})^{g_l}\left(1-\left[1-S_{eff}^{\frac{(g_n}{g_n-1}}\right]^{\frac{(g_n-1)}{g_n}}\right), 10^{-4}\right] \quad (3.5)$$

Figure 3.7 shows the relative permeability function for both materials.

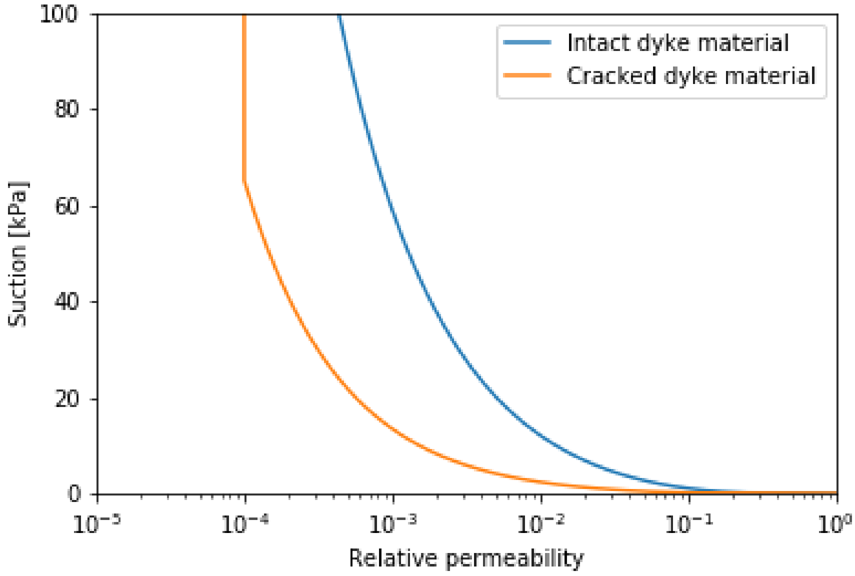


Figure 3.7: Hydraulic conductivity functions used for PLAXIS 2D calculations. The relative permeabilty is bounded by a minimum of 10^{-4}

3.4.3. Calculation phases

In this section, the different calculation phases implemented in PLAXIS2D are briefly described. Both a steady-state solution and a situation with fluctuating water level is considered. The calculation phases are shown in table 3.8 and table 3.9. Regarding the safety analysis it is important to check whether a stable safety factor is obtained at the end of the calculation phase.

Table 3.8: Plaxis 2D calculation phases for the steady-state scenarios

Steady state solution	
Initial phase:	gravity loading
The initial stresses are generated based on the volumetric weight of the soil. Pore pressures are calculated using 'steady-state groundwater flow'.	
Phase 1:	plastic calculation
Plastic nil-step to ensure that the stress field is in equilibrium.	
Phase 2:	safety analysis
Determination of safety factor using strength reduction method	

In the time-dependent scenarios, the water level is fluctuating. The design water level and the measured high water event are divided into different time steps which are each followed by a safety analysis. Consequently, the variation of the factor of safety in time is obtained.

Table 3.9: Plaxis 2D calculation phases for the time-dependent scenarios

Time-dependent solution	
Initial phase:	gravity loading
The initial stresses are generated based on the volumetric weight of the soil. Pore pressures are calculated using 'steady-state groundwater flow'.	
Phase 1:	plastic calculation
Plastic nil-step to ensure that the stress field is in equilibrium	
Phase 2:	fully coupled flow-deformation
Both pore pressures and deformations change in time according to time dependent hydraulic boundary conditions. Varying water level is applied for a certain amount of time.	
Phase 3:	safety analysis
Determination of safety factor using strength reduction method	
Phase 4 - 12:	
Alternately repeating phase 2 and 3, with varying water level.	

Summary of chapter: Numerical model

An alternative method of including the effects of desiccation cracks is used: adjusting the soil properties of the cracked material. From the literature review, it is clear that desiccation cracks can have a influence on the hydraulic conductivity, cohesion and friction angle. In case of the hydraulic conductivity, an estimation of the increase can be made. For the strength parameters this is more difficult, so different combinations are used.

Various scenarios with respect to the hydraulic conditions and crack conditions are created. These scenarios will be compared to the main analysis. Steady-state scenarios with a low and a high water level are studied. Time-dependent water conditions are imposed as well to study the impact of cracks in time-dependent conditions. Both a design water level and a measured high water event are used.

4

Results

In this chapter, the results of the PLAXIS 2D analyses are presented. Different scenarios are analysed, with both steady-state and time-dependent boundary conditions. For every case, a comparison is made between the 'uncracked' dyke and the dyke that is affected by desiccation cracks to quantify the influence of the cracks.

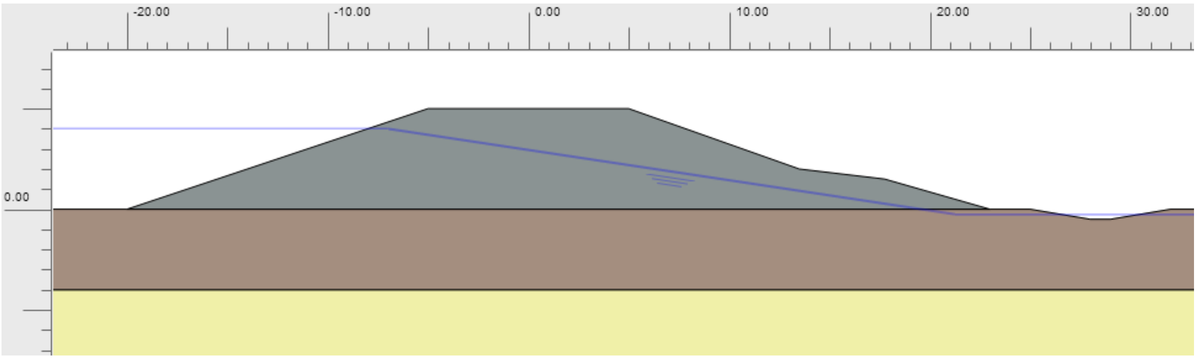
First, the results of the steady-state solution are presented. Different aspects are varied, such as suction level, crack depth and crack parameters. Subsequently, results of the time-dependent scenarios are shown, using fully-coupled flow-deformation calculations. Precipitation is both included and excluded in the time-dependent calculations.

4.1. Steady-state conditions

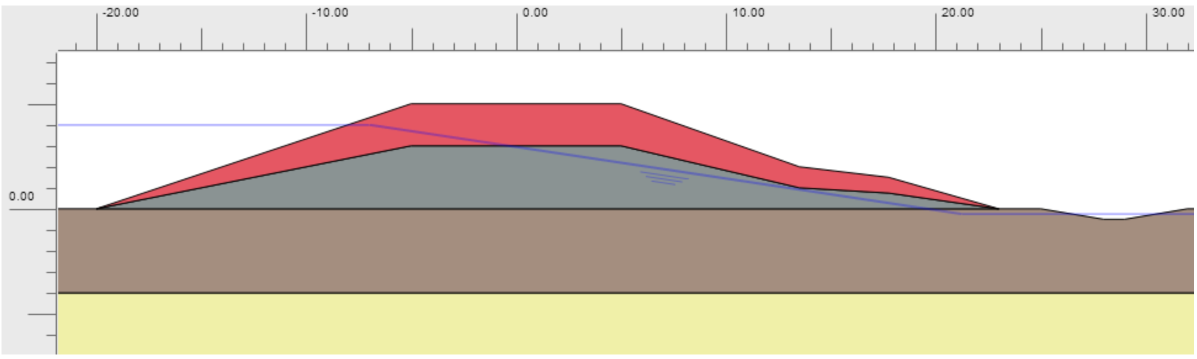
Time is not considered in case of the steady-state solution as the water level is kept constant. The influence of different factors, such as crack depth, parameters and water level, are studied by implementing different scenarios. First, the main analysis is discussed, in which the initial uncracked dyke is compared to a dyke with cracks of 2 meter depth. Thereafter, the different scenarios are described.

4.1.1. Main analysis

Two main cases are compared: the initial uncracked dyke and a dyke with the upper two meters affected by cracks. The cracked layer is simulated by reducing both the friction angle and the cohesion by 50%, and increasing the hydraulic conductivity by a factor of 15. Thus, the cohesion is 2.5 kPa instead of 5 kPa and the friction angle changes from 22.5 degrees to 11.25 degrees. For these steady-state cases, a relatively high outside water level at 4 m (above the reference level of 0) is imposed. This is 1 meter below the crest level, as can be seen in Figure 4.1. The effect of suction in the unsaturated zone is taken into account. From 4.1b follows that part of the cracked layer is located in the saturated zone. It is chosen to use the same shape of the cracked zone for all the analyses, despite the unrealistic situation that follows from this in case of a high outside water level. Although it is unclear if cracks fully close upon wetting, cracks in the saturated zone in steady-state condition will usually not occur in reality. However, this is not expected to have a significant effect on the results. The failure surface will not cross this zone.



(a) Uniform dyke without cracks



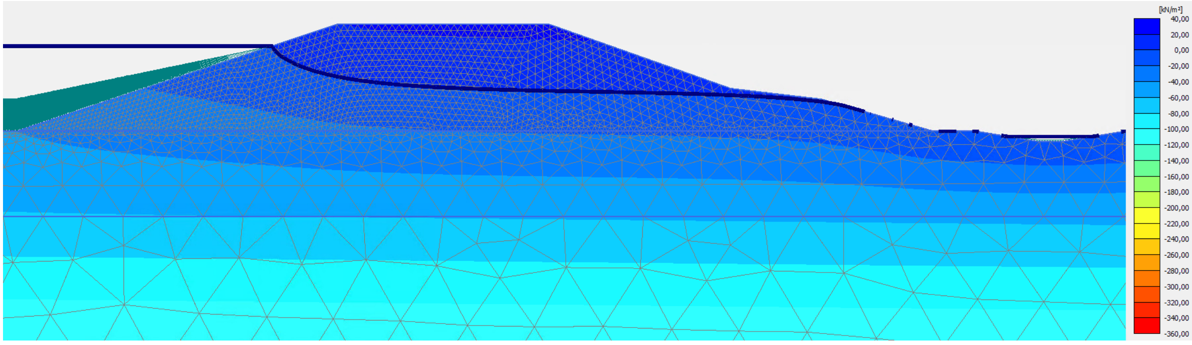
(b) Dyke with 2 meter cracks: cracked zone is shown in red

Figure 4.1: Overview of imposed outside water level and cracked layer for the main analysis

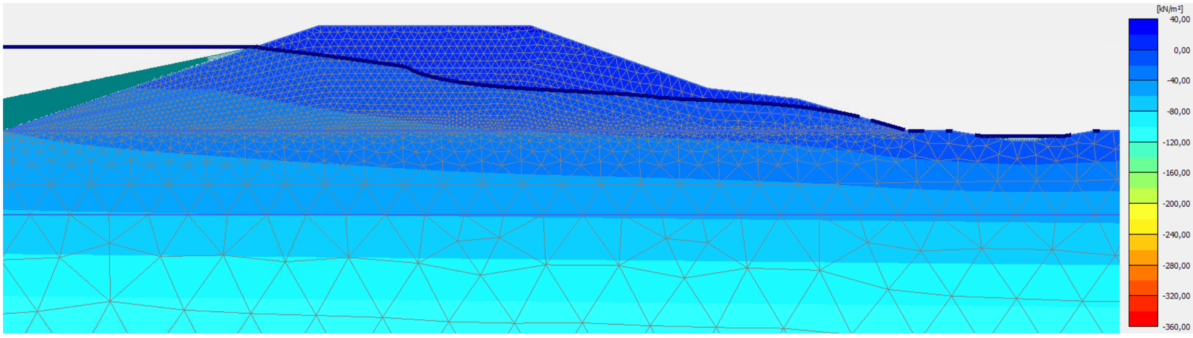
Hydraulic Response

The steady-state water pressure calculation is done by using the 'steady-state groundwater flow' setting of PLAXIS 2D. By studying the pore pressures, degree of saturation and suction levels of the dyke in different cases, insight in the hydraulic behaviour of the dyke under cracked conditions is gained.

In Figure 4.2, the pore pressures are depicted. The blue line represents the phreatic level. Important to notice is that in PLAXIS 2D positive values represent negative pore pressures and thus suction.



(a) Dyke without cracks: pore pressures ranging from -340 at a depth of -30 m to 25.2 kN/m^2 at crest level



(b) Dyke with 2 meter cracks: pore pressure ranging from -340 at a depth of -30 m to 21.9 kN/m^2 at crest level

Figure 4.2: Active pore pressures (pressure is negative) for intact dyke and cracked dyke. The blue line is the phreatic level.

When looking at the phreatic level it is clear that at the side where the outside water enters the dyke, the water reaches further into the dyke body in the cracked case. This is due to the increased hydraulic conductivity. In the middle of the dyke body, the pore pressures are therefore slightly higher in case of the cracked dyke. However, it is visible that the exit point on the inner side of the dyke (right side in the figure) is located lower in case of the cracked dyke. This is also due to the higher hydraulic conductivity. The cracked dyke also has a lower minimum level of the degree of saturation, as it ranges 100% to 73.97% at crest level. For the dyke without cracks the degree of saturation at crest level is 81.47%. The maximum suction level for the cracked dyke is 25.23 kPa and located at crest level.

Safety analysis

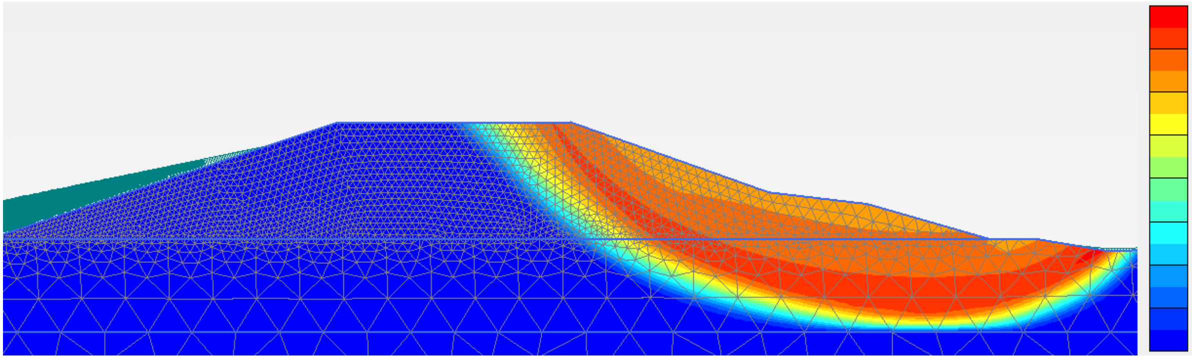
A safety analysis is performed on both the initial dyke and the cracked dyke. From the analysis of the hydraulic response, it is shown that the cracked dyke has a smaller unsaturated zone, and lower suction levels. In addition, the cracked layer has reduced strength parameters. It is therefore expected that the factor of safety is lower in case of the cracked dyke.

The factor of safety is determined for both cases, see Table 4.1. The dyke with cracks up to 2 meter depth has a 5.2% lower factor of safety compared to the intact dyke.

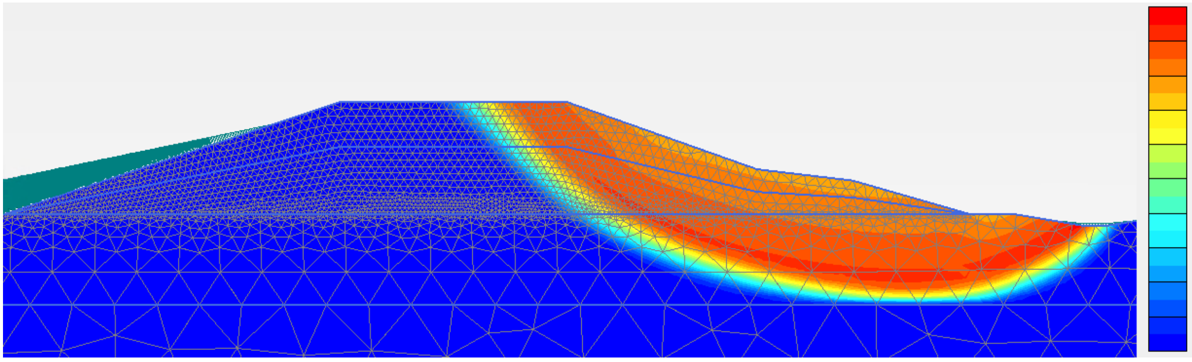
Table 4.1: Factor of safety for intact and cracked case, where cracks are modelled by 50% strength reduction

FOS - No cracks	FOS - 2 meter cracks	Change of FOS
1.15	1.09	-5.2%

Due to the 'artificial' strength reduction used in the safety analysis, out-of-balance forces are introduced leading to displacements. The magnitude of these displacements do not have a physical meaning, although it gives an indication of the failure mechanism. By observing the displacements plot of the safety analysis, an indication of the failure mechanism is given. In Figure 4.3, the displacement plot of the initial uncracked dyke and the cracked dyke are shown. In both cases, the sliding plane has a similar shape. The occurred failure mechanism is macro-instability as the failure surface reaches a large depth. When looking at this plot, it can be seen that apart from the dyke body, a lot of the mobilized resistance is coming from the clay layer underneath the dyke itself as the failure surface crosses the entire clay layer.



(a) Uniform dyke without cracks



(b) Dyke with 2 meter cracks

Figure 4.3: Displacements for intact dyke and cracked dyke

4.1.2. Influence of initial conditions

In the main analysis, the suction automatically calculated by PLAXIS 2D is used, which implies a linear gradient of suction. In this section, the influence of this choice is studied. Three types of initial conditions regarding suction are considered to see the influence of increasing strength and decreasing hydraulic conductivity with different suction levels.

Especially in the upper layers of the dyke , a great variation of suction pressures can occur. In PLAXIS 2D, the pore pressures are assumed to be linear both below and above the phreatic surface. In reality, this value can be both lower and higher, depending on external climatic conditions such as evaporation and precipitation. According to TAW (1996), a suction pressure of 100 kPa at surface level is a representative value for clay dykes with a grass cover in the Netherlands in very dry conditions.

The case where suction is ignored, is a more hypothetical case as in reality there will always be suction to some extent in clay above the phreatic surface. However, it is interesting to see the influence of the suction on the factor of safety, as suction will contribute to the shear strength and therefore to the dyke safety.

Therefore, the hydraulic response and factor of safety for three different initial conditions are compared:

- No suction
- Linear gradient of suction (as used in the previous analyses)
- Suction pressure of 100 kPa at surface level

This is visualised in Figure 4.4, where the pore pressure profile is shown for the three different cases.

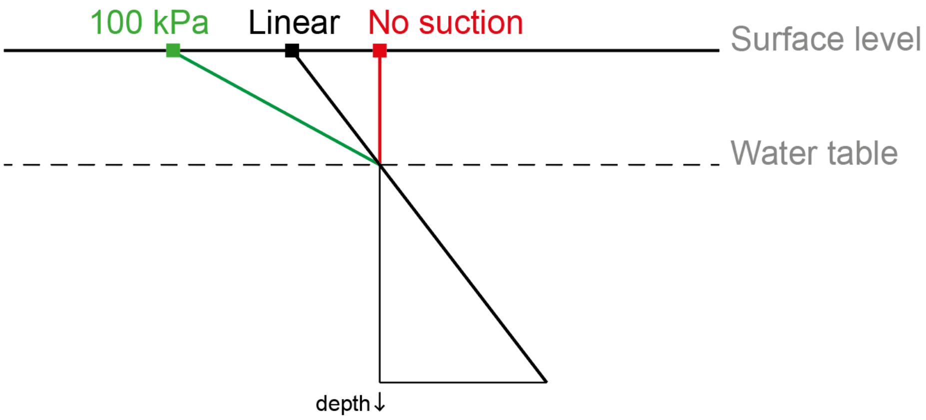
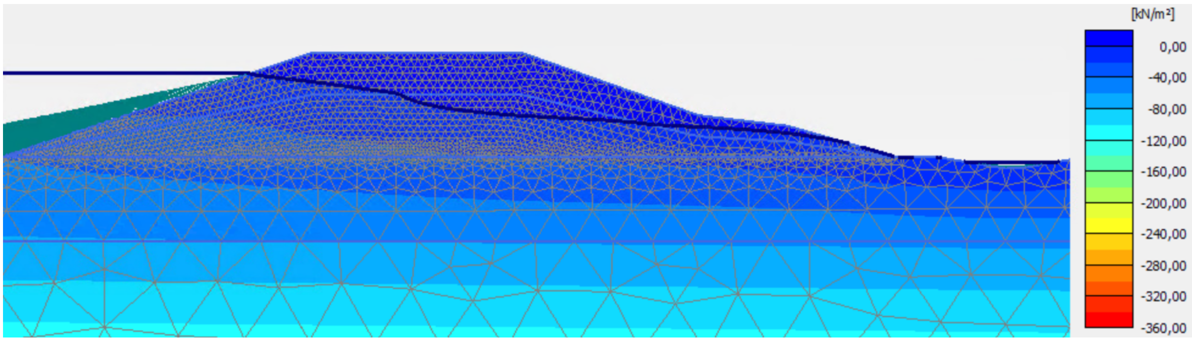


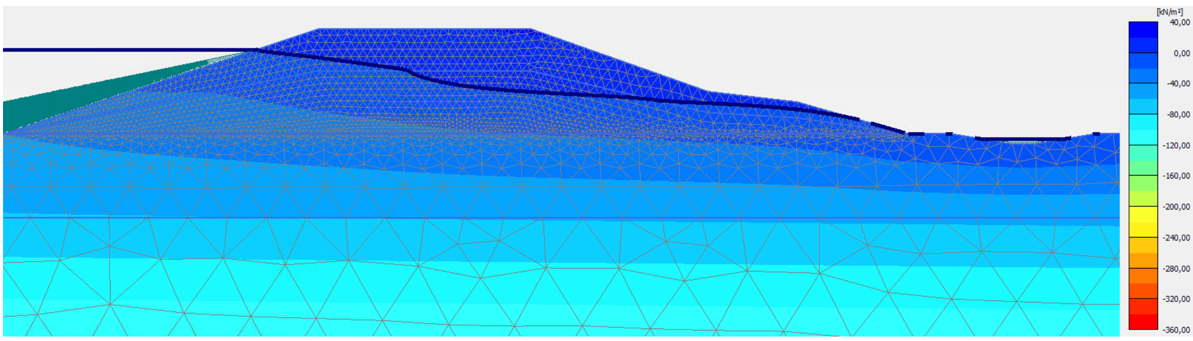
Figure 4.4: Pore pressure profile for the different inital conditions

Hydraulic Response

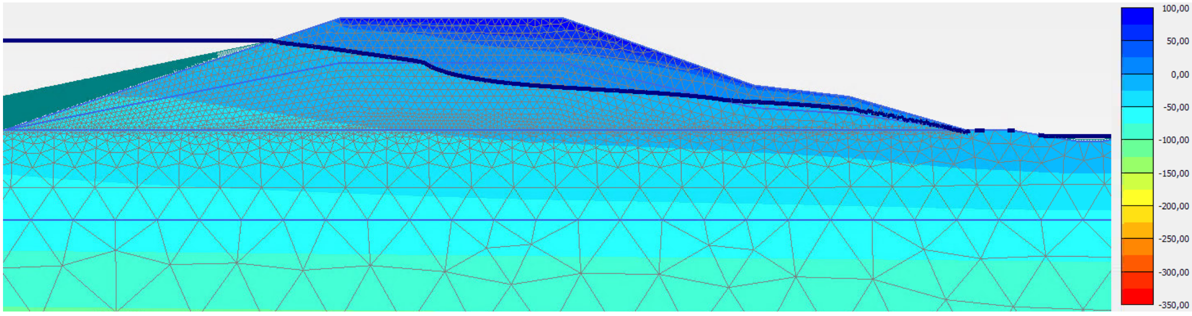
In Figure 4.4 the pore pressures of the three different suction conditions are shown, for the dyke with 2 meter cracks. This analysis is also performed for the dyke without cracks. The location of the phreatic surface is not changed for the different suction cases as the outer water level is kept the same.



(a) No suction: pore pressures ranging from -340 at -30 m to 0 kN/m^2 at crest level



(b) Linear suction: pore pressure ranging from -340 at -30 m to 21.9 kN/m^2 at crest level



(c) Suction level of 100 kPa at crest imposed: pore pressure ranging from -340 at -30 m to 100 kN/m^2 at crest level

Figure 4.4: Pore pressures (pressure is negative) for intact dyke and cracked dyke. Blue line is phreatic level.

Safety analysis

In Figure 4.5, the factors of safety for the different suction conditions are shown. As expected, a higher suction level at surface level leads to a higher factor of safety as suction increases the shear strength of the soil. This effect is both seen in the case without cracks as in the case with cracks of 2 meters depth. In table 4.2 the factor of safety is given for each case.

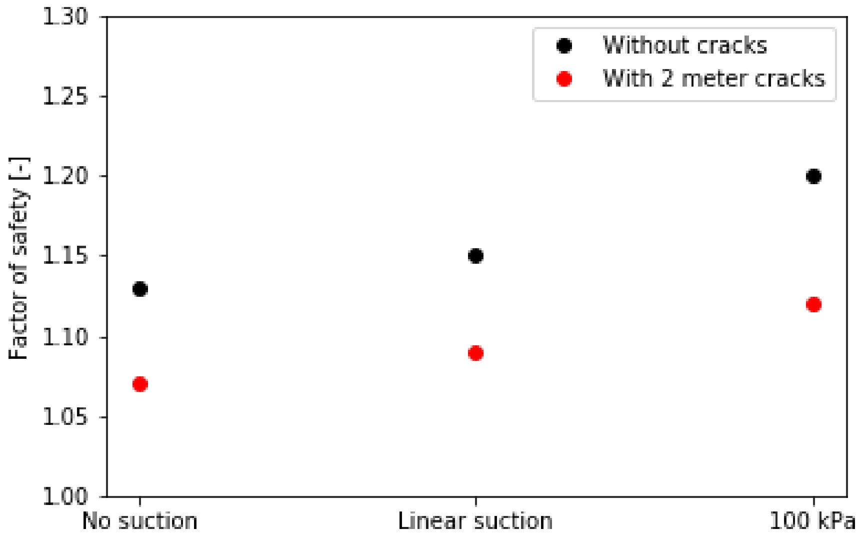


Figure 4.5: Change of factor of safety with different initial conditions regarding suction level

Table 4.2: Factor of safety for different initial suction levels, where cracks are modelled by 50% strength reduction

	No suction	Linear suction	100 kPa
Without cracks	1.13	1.15	1.20
With 2m cracks	1.07	1.09	1.13
Change of FOS	-5.3%	-5.2%	-5.8%

4.1.3. Influence of initial strength parameters

The values for cohesion and friction angle are based on collections of laboratory tests on Dutch clay. The same soil test results can be represented by different combinations of cohesion and friction angle. Therefore, an alternative combination of cohesion and friction angle is implemented in PLAXIS 2D to see if the influence of cracks on dyke safety is different with lower cohesion and higher friction angle.

In this case the uncracked cohesion c' = 3 kPa and friction angle ϕ' = 26°. All other parameters are kept the same as in the main analysis.

Safety analysis

In table 4.3 the factor of safety is shown for the uncracked dyke and the dyke with a cracked zone of 2 meter depth for the adjusted initial strength parameters. In case of the cracked dyke, the cracked material is simulated the same way as in the main analysis: by a 50% reduction of both cohesion and friction angle.

Table 4.3: Factor of safety for intact and cracked case, where cracks are modelled by 50% strength reduction, with two different combinations of initial strength parameters

	FOS - Main analysis	FOS - Adjusted initial strength parameters
No cracks	1.15	1.14
With 2 meter cracks	1.09	1.08
Change of FOS	-5.2%	-4.8%

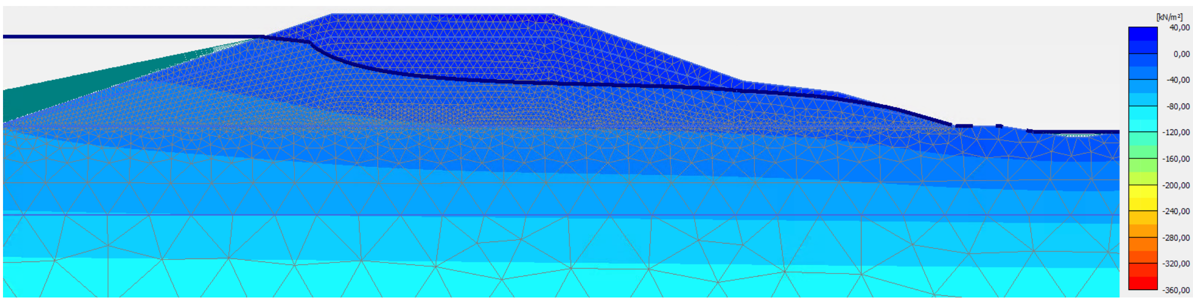
A decrease of the factor of safety is noticeable in both cases, although, it is shown that the decrease of the factor of safety is smaller with the adjusted initial strength parameters. The initial parameters have an slight influence on the magnitude of the decrease.

4.1.4. Influence of crack depth

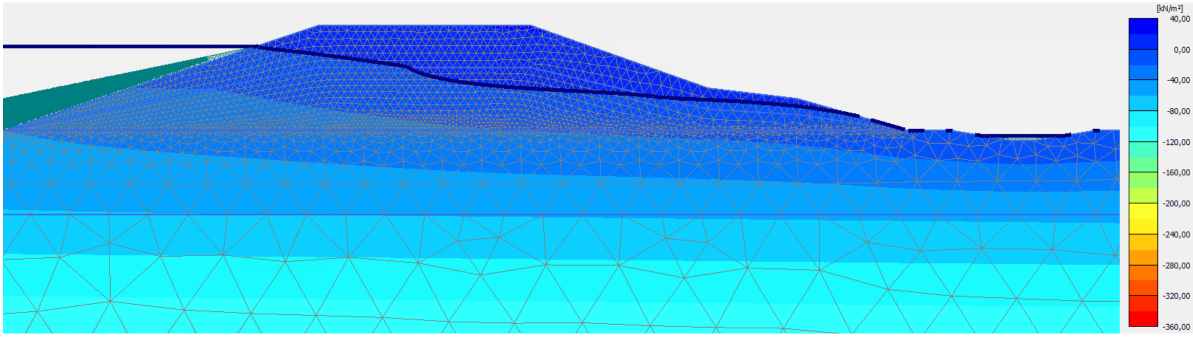
The assumed crack depth in the main analysis is 2 meter. This is seen as a possible but rare scenario. Known cases of desiccation cracks in clay dykes reach to depths around 1 meter. Therefore, the influence of the crack depth is studied by simulating a cracked layer of 1 meter and compare with the results of the main analysis.

Hydraulic Response

Self-evidently, the hydraulic response changes with changing crack depth. In Figure 4.5 the pore pressure distribution is shown. The phreatic surface is located slightly higher if the cracks reach to a depth of 2 meter instead of 1 meter. The location of the exit point at the inner slope is comparable in both cases.



(a) Pore pressure distribution for case with 1m cracks, ranging from -340 kN/m^2 to 22.63 kN/m^2



(b) Pore pressure distribution for case with 2m cracks

Figure 4.5: Pore pressure distribution, comparison between 1 meter en 2 meter cracks

Safety analysis

In Figure 4.6, the factor of safety of the dyke with no cracks, 1 meter cracks and 2 meter cracks are compared. The factor of safety decreases with the crack depth. This has multiple reasons. A smaller cracked zone means a smaller part of the dyke that has a decreased shear strength. Therefore, the overall dyke stability will be less affected if the cracks are less deep. Additionally, the unsaturated zone is larger in the case of the 1 meter cracked dyke than in case of the dyke with 2 meter cracks and therefore contributes more to the strength. This is due to the fact that the hydraulic conductivity is increased in the cracked zone.

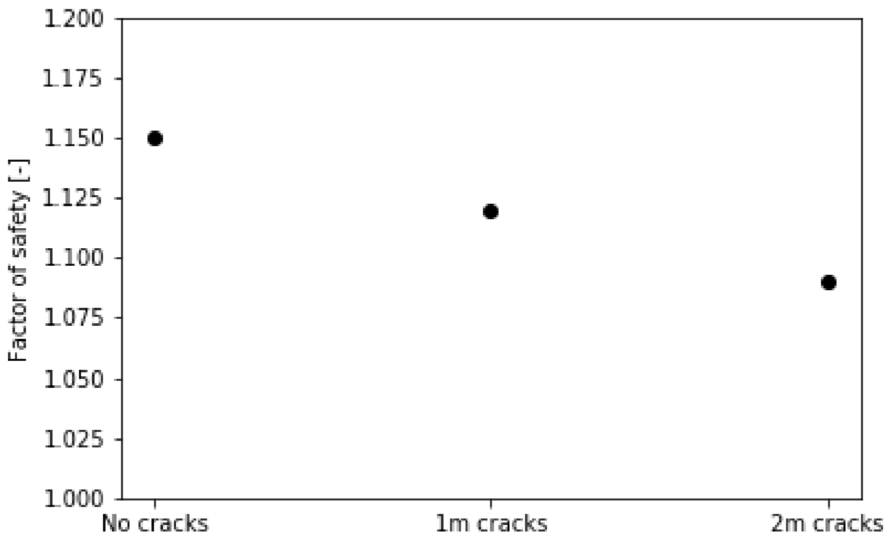


Figure 4.6: Change of factor of safety with different crack depth

As can be seen in table 4.4, the factor of safety decreases with 2.6% in case of a cracked layer of 1 meter and 5.2% in case of a 2 meter cracked layer. The decrease of the factor of safety is practically linearly with the increase of the crack depth.

Table 4.4: Factor of safety for intact and cracked case, where cracks are modelled by 50% strength reduction

FOS - no cracks	FOS - 1 meter cracks	FOS - 2 meter cracks
1.15	1.12	1.09

4.1.5. Influence of cracked soil parameters

As the modelling approach is based on the assumption that the hydraulic conductivity, cohesion and friction angle are changing due to the cracking, the magnitude of these changes is of considerable importance. However, as described in Section 3.3, these estimated parameter changes are not unambiguous. Therefore, a range of parameter combinations is considered. The effective cohesion and friction angle are varied both independently and dependently of each other, ranging from a 25% to a 75% decrease, as shown by table 4.5. This is compared to the base case of 50% decrease of both cohesion and friction angle that is already shown in the main analysis in Section 4.1.1.

Table 4.5: Adjustment (in percentage) of strength parameters cohesion and friction angle

Parameter combination	1	2	3	4	5	6	7	8
Cohesion c'	-25%	-50%	-75%	0	0	0	-25%	-50%
Friction angle ϕ'	0	0	0	-25%	-50%	-75%	-25%	-50%

As in this section only the strength parameters are varied, the hydraulic response is not shown as this is not affected by a change of the strength parameters.

Safety analysis

In figure 4.7 the factor of safety is given for every parameter combination. In combination number 1 to 3 (red in the figure), only the cohesion is adjusted. In number 4 to 6 (blue), only the friction angle is adjusted. In number 7 and 8, both the friction angle and the cohesion are changed. From this plot it is shown that adjusting the value of the friction angle has a greater influence than adjusting the cohesion. Combination 8 is the combination of strength parameters that is used in the main analysis shown in Section 4.1.1. This combination leads to the lowest factor of safety of the 8 different parameter combinations. From these results it is shown that adjusting the friction angle has a larger impact on the factor of safety than the cohesion.

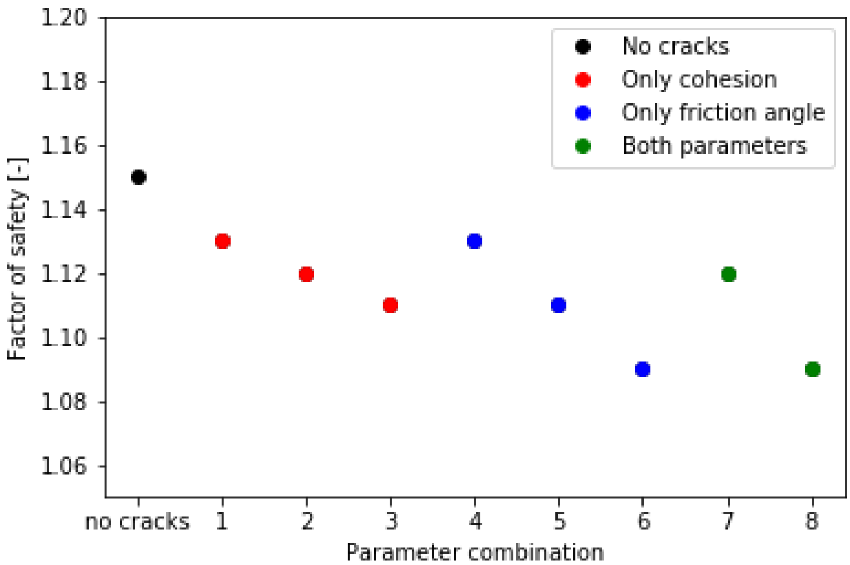


Figure 4.7: Change of factor of safety with different parameter combinations used to simulate the cracked layer. The parameter combination number corresponds to the numbers given in table 4.5.

4.1.6. Influence of outside water level

The high water level considered in the base case is compared to a case with low water level. As depicted in figure 4.8, the outside water level is located at +0.5 m above the base of the dyke.

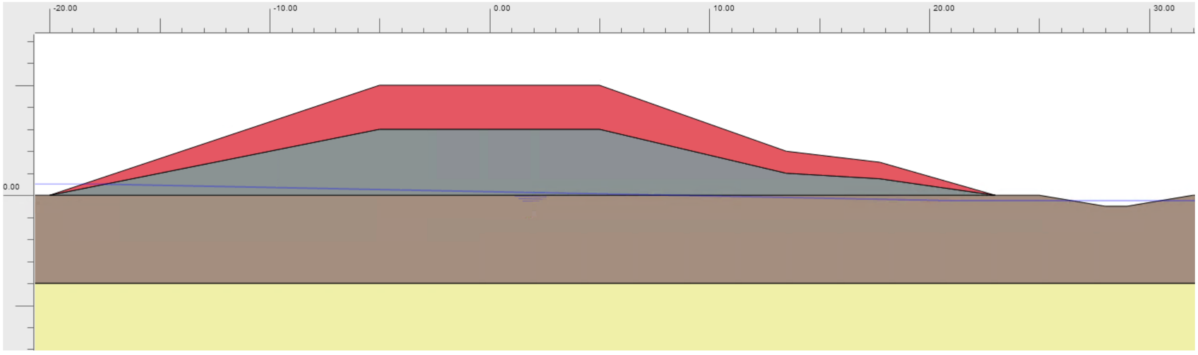


Figure 4.8: Overview of situation with relatively low outside water level, outside water level shown with blue line.

Hydraulic Response

The pore pressure distribution for the cracked dyke with low outside water level is depicted in figure 4.9. In this case, the dyke body is predominantly located above the phreatic level. This is a hypothetical situation, as in reality it is likely that bulging occurs to some extent in the centre of the dyke due to precipitation.

As can be seen in figure 4.9, only a very small part of the cracked zone is located below the phreatic surface. This means that the hydraulic response will not be affected a lot by the cracked zone.

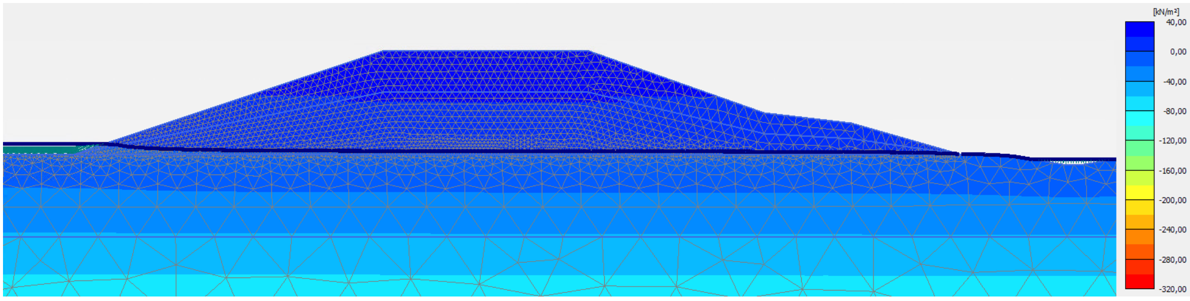


Figure 4.9: Dyke with 2 meter cracks and low water level: pore pressure ranging from -305 at -30 m to 33.95 kN/m^2 at crest level

Safety analysis

In table 4.6 a comparison is made between the safety factors of the high water case and the low water case. As expected, the safety factor is higher for the situation with low water level as the hydraulic load is smaller and there is a larger unsaturated zone which contributes to the overall stability. The difference between the factor of safety of the cracked and the uncracked dykes is smaller in case of a low outside water level. This is presumably due to the fact that the phreatic surface of the dyke is less affected by the cracks when there is a low outside water level: the location of the phreatic level is almost equal for both the cracked and the initial uncracked dyke. In the scenario with the high water level, there is a greater difference between the phreatic level of the cracked dyke and the uncracked dyke.

Nevertheless, there is still a decrease in the factor of safety in case of the dyke with a cracked layer due to the fact that the failure surface intersects the cracked zone and this layer has a lower shear strength.

Table 4.6: Factor of safety for high water case compared to low water case, with cracks modelled by 50% strength reduction

	FOS - high water level	FOS - low water level
No cracks	1.15	1.49
With 2 meter cracks	1.09	1.40
Difference	-5.2%	-4.7%

4.1.7. Summary of steady-state results

In the main analysis, a comparison is made between the hydraulic behaviour and overall stability of a dyke that is not affected by cracks, and a dyke of which the upper two meters are affected by desiccation cracks. In the subsequent sections, different factors are varied independently of each other to study the impact of the choices that are made regarding these factors. The main analysis, where the uncracked dyke is compared to a dyke with a 2 meter cracked zone and 50% reduction of strength parameters, showed a decrease of 5.2% of the factor of safety.

In all simulations, the factor of safety decreased in the case of a cracked dyke. In figure 4.10 an overview of all the results from the different scenarios are shown with respect to change of the factor of safety compared the same scenario without cracks. The magnitude of the decrease of the strenght parameter to simulate the cracks, called 'crack parameters', give the largest spread in the decrease of the factor of safety. At the same time, the change of these parameters due to the cracks is difficult to estimate and will depend on the crack characteristics.

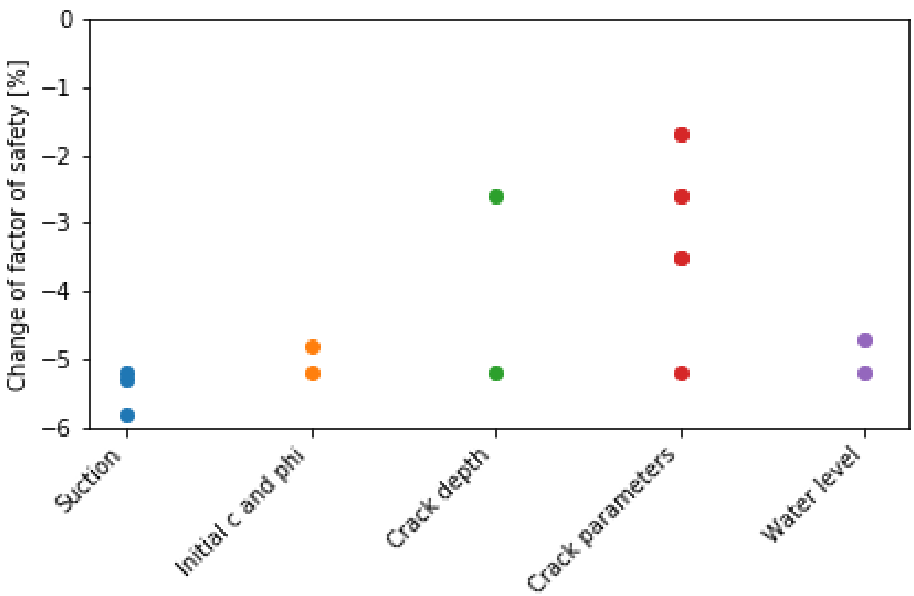


Figure 4.10: Summary of safety analysis of all steady-state scenarios

In Table 4.7, the different scenarios that are illustrated in Figure 4.10 are summarised.

Table 4.7: Different aspects that are varied for modelling scenarios

Aspect	Description
Suction	No suction, linear suction and suction level of 100 kPa
Initial c and phi	Different combinations of initial cohesion and friction angle
Crack depth	Crack depth of 1 meter and 2 meter
Crack parameters	8 different combinations of the change of cohesion and friction angle
Water level	High water level and low water level

It is clear that the crack parameters have the largest influence on the change in factor of safety. As the initial combination of the cohesion and friction angle does not lead to a very large spread in the change of factor of safety, this is not taken into account. A changing water level will of course be implemented in the time-dependent scenarios.

4.2. Time-dependent conditions

In this section, the effect of cracks on the hydraulic response and factor of safety of the dyke under time-dependent conditions are studied. This is done by implementing two different fluctuating water levels: a design water level and a measured high water event. In addition, the influence of precipitation will also be studied by both including and excluding precipitation. The time-dependent cases are a more realistic representation of the conditions that can occur in reality.

For official dyke safety assessments, design water levels corresponding to norms are used. For different return periods the design water level can be computed, in the Netherlands this can be done using software HydraNL and Waterstandsverloop. The design water level is based on the peak water level that can occur during a high water event with a certain return period.

The dyke that is used for the numerical model is an artificial dyke. Therefore, it is decided to choose a location in the Netherlands and to base the time-dependent water levels on the data and measurements of this location. Important for this research is to use a location where water levels during a high water event are not influenced by stormsurges at the Noordzee and IJsselmeer. It is, therefore, decided to use measurement location Dodenwaard, located in the river Waal. This location is suitable as the dyke height nearby is comparable to the geometry used in this study and both the design water levels as water level measurements are available at this location. More detailed information on this exact location is presented in Appendix A.

The duration of a high water event in reality can have a substantial influence on the dyke stability. Therefore, the differences between the design water levels and the actually occurring water levels during periods of high water are studied. To be able to make a good comparison, it is necessary to have a similar peak water level. For this reason, a return period of 100 years is used in the case of the design water level as there are multiple measured high water events that reach a similar peak water level.

In Figure 4.11 the design water level for a return period of 100 years at location Dodewaard is shown. On the x-axis the water level in m +NAP and on the y-axis the time in hours is shown. The duration of the event is around 24 days, the water level starts at 7.997m +NAP with a peak level at 11.497m +NAP. The total water level rise is thus 3.5 meter. The dykes near this location have a similar height as the geometry used in this study.

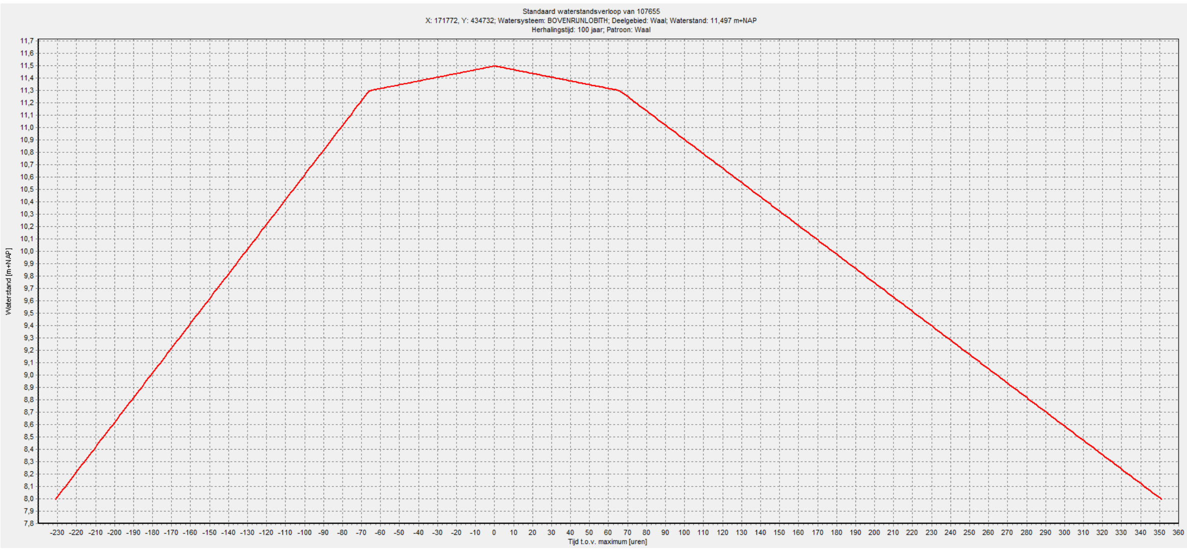


Figure 4.11: Design water level at location Dodewaard, return period of 100 years

The development of the water level over time of five different high water events is compared: from 1993 until 2017. A complete description can be found in appendix A. The event of 1993 is used as PLAXIS 2D input. The main reason for this is that the duration of this water event is significantly longer than the design water level and is, therefore, an interesting comparison. Figure 4.12 shows both water levels, with on the y-axis the water level in m +NAP corresponding to the Dodewaard location. In the next paragraphs, the flow functions used in PLAXIS 2D are shown. The design water level shows a peak water level rise of 3.5 meter. As the peak water level at the dyke in the location of Dodewaard is around 1 meter below crest level and the dyke has a similar height, the reference (zero) level of the chosen geometry is corresponding to 7.5 +NAP in Figure 4.12.

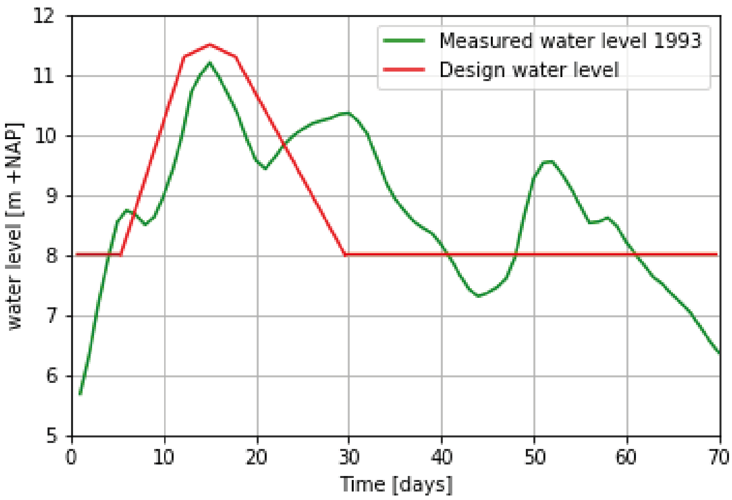


Figure 4.12: Measured water level of high water event in 1993 and design water level with return period of 100 years, at location Dodewaard

Both the 1993 high water event as the design water level with return period of 100 year are used for the numerical analyses. A total time of 70 days is considered in both cases. In PLAXIS 2D a flow function can be used to describe the variation with time of the water level. The calculations are divided in different time-steps to compute output at chosen moments in time. In part of the cases precipitation is included.

4.2.1. Design water level

With PLAXIS 2D, output is generated at six different time steps. These intervals are chosen such that the changes in hydraulic response and factor of safety can be monitored closely. A total time of 70 days is considered. The first 20 days the water level is constant at +0.5 m. After 20 days, water level rise to a maximum of +3.8 m starts. The toe or base of the dyke is used as a zero level in the dyke geometry. In Figure 4.13 the flow function as implemented in PLAXIS 2D is shown. The red dotted lines represent the different time steps.

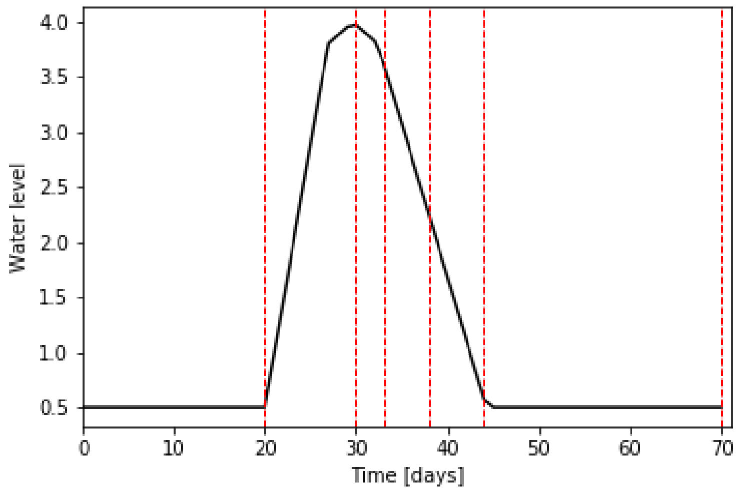


Figure 4.13: Flow function for the design water level, with different time intervals after which the output is computed

Hydraulic response

As there are six time steps at which output is generated, the hydraulic response can be studied at each step. At the first time-step, at t = 20 days, the results are equal to the low water level steady-state scenario as discussed in Section 4.1.6. A large part of the dyke is unsaturated at this moment, leading to a relatively low degree of saturation. At t = 20, the water level is rising, to the maximum level at t = 30 days. During these 10 days, part of the dyke becomes saturated due to the increasing water level. In Figure 4.14, the pore water pressures are shown at different time steps. The blue line indicates the phreatic surface. It can be seen that, due to the low permeability of the dyke material, it takes more time for the water pressures inside the dyke to rise. If this is compared to the steady-state solution, it can be seen that the high water level peak of 24 days in total is too short for the phreatic surface to rise until the level it has in the steady-state situation.

In Figure 4.15, the same plots are shown for the dyke with 2 meter cracks. It is visible that the higher hydraulic conductivity in the cracked zone leads to a faster adjustment of the pore water pressure in the dyke. The delay in the response of the pore water pressures, as discussed before, is smaller.

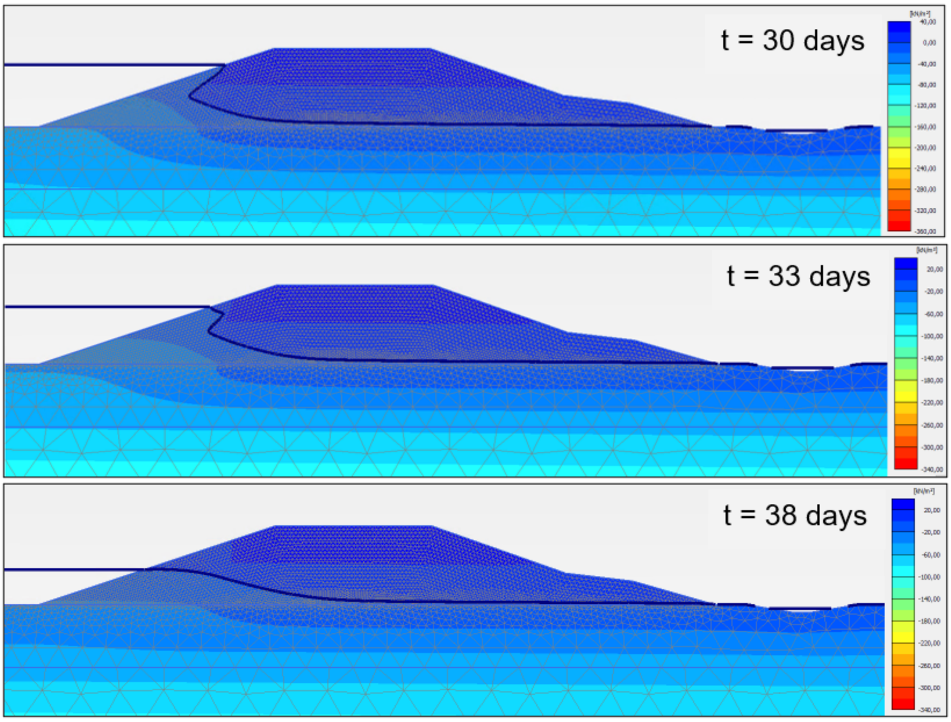


Figure 4.14: Pore water pressure at different moments in time for dyke without cracks, blue line indicates phreatic surface

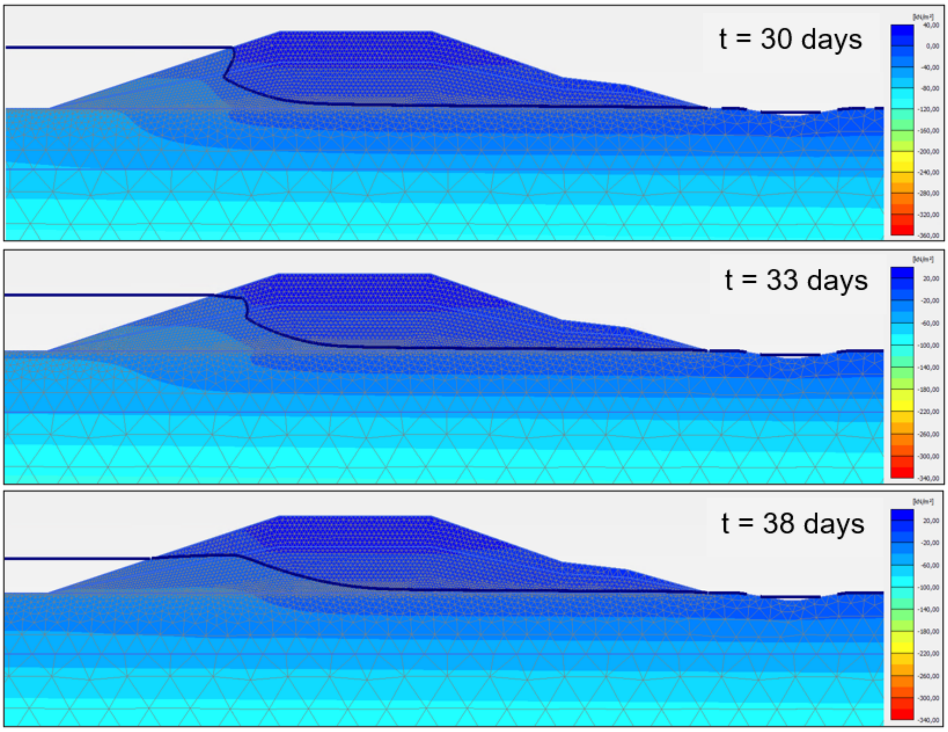


Figure 4.15: Pore water pressure at different moments in time for dyke with 2m cracks, blue line indicates phreatic surface

In Figure 4.16, the degree of saturation at t = 30 days and t = 33 days is depicted for both cases. The minimum degree of saturation for the uncracked dyke is 76.91% at t = 30 days and 77.50% at t = 33 days. For the cracked dyke, the minimum degree of saturation is 69.93% at t = 30 days and 70.41% at t = 33 days. As expected, the minimum degree of saturation is lower for the cracked case as it involves a higher hydraulic conductivity in the upper layer.

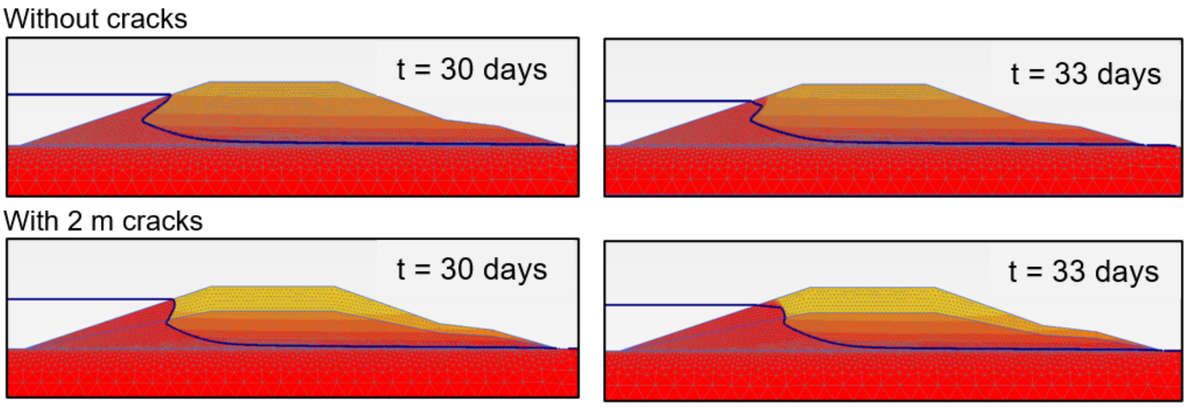


Figure 4.16: Degree of saturation at t = 30 days (left) and t = 33 days (right). Upper figures depict case without cracks, lower figures depict dyke with 2m cracks

Safety analysis

The factor of safety changes over time due to the changing hydraulic conditions. The water level fluctuates between +0.5 m and +3.9 m. The steady-state solutions for these minimum and maximum water level give the extremes in terms of factor of safety.

Figure 4.17 shows the variation of the factor of safety over time. The blue and red lines represent the factor of safety associated with, respectively, the dyke with no cracks and the dyke with 2 meter cracks. The dotted grey line combined with the right y-axis shows the water level variation. The yellow area shows the time-steps for which the failure mechanisms is outer slope instability. At all other time-steps the dyke failed due to inner slope instability.

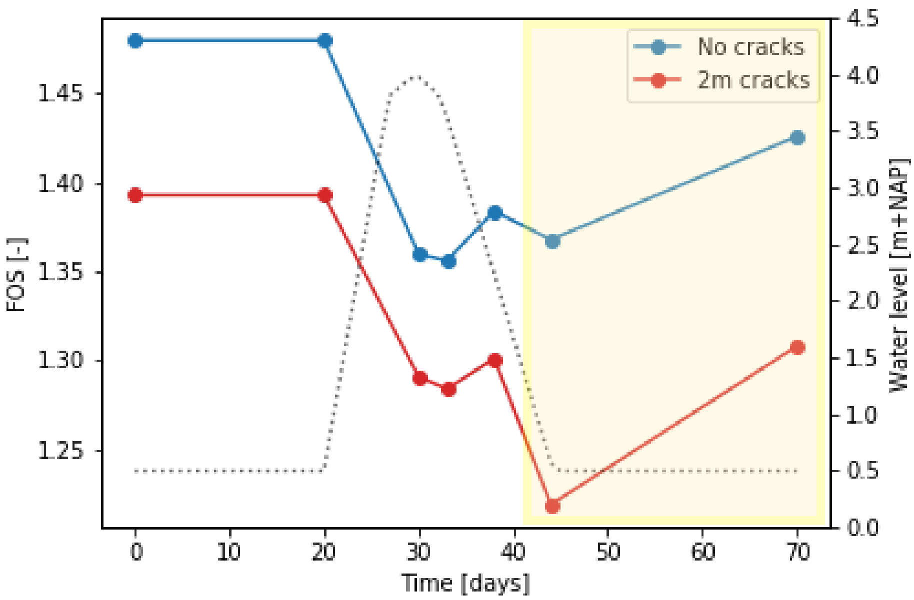


Figure 4.17: Factor over safety over time for design water level. Failure due to both inner and outer slope instability. The yellow area shows the time-steps at which outer slope instability occurred.

The factor of safety at t = 0 days and t = 20 days represents the steady-state solution with a constant low water level at +0.5 m. At this point, the factor of safety is highest due a combination of low hydraulic loads and a large unsaturated zone which increases the shear strength of the soil. With a rising water level, starting at t = 20 days, the factor of safety decreases. This decrease continues until t = 33 days, which is a number of days after the water level peak passed. This delay is caused by the relatively low permeability of the clay, as it takes time for the pore pressures inside the dyke to respond. From this moment, the factor of safety starts to increase in time as the water level decreases.

However, at t = 44 days, the factor of safety decreases again. In addition, a divergence between the two cases is seen at this point as the factor of safety decreases drastically for the dyke with 2 meters, while it decreases just slightly for the uncracked dyke.

A possible explanation for this could be a difference in the failure mechanism that occurred. At every time-step the hydraulic conditions are different, and this can lead to divergences in the failure mechanism to leads to failure. In Figure 4.18, the failure mechanisms are visible by looking at the displacement plots at failure. If the failure mechanism at t = 38 days is compared to the failure mechanism at t = 44 days, it is clear that there is a switch from inner slope instability to outer slope instability. Due to the rapid water level drawdown, the accumulation of excess pore water pressures inside the dyke can lead to failure of the outer slope. The risks of flooding of the hinterland is relativity low in case of instability of the outer slope, because the (outside) water level is usually low at the moment of failure. However, a second high water event occurring before restoring the dyke can lead to flooding.

From Figure 4.18 it is concluded that a change of failure mechanism occurred in both cases and is therefore not an explanation for the divergence between the factor of safety for both cases at t = 44 days. However, it can be seen that the failure surface of the dyke without cracks is smaller than that of the cracked dyke. This could lead to the relatively low factor of safety for the cracked dyke.

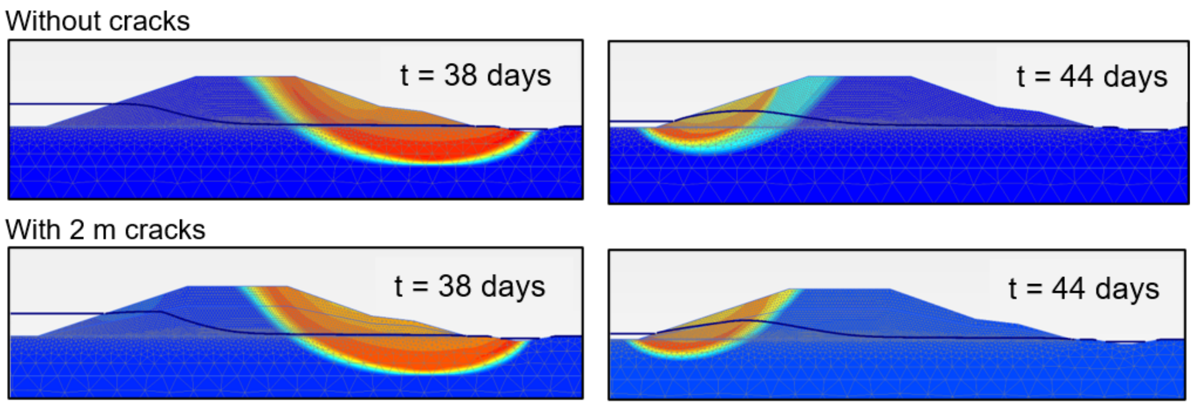


Figure 4.18: Failure surface at t = 38 days (left) and t = 44 days (right). Upper figures depict case without cracks, lower figures depict dyke with 2m cracks

The fact that the decrease in factor of safety is significantly larger in the cracked case is noteworthy. To further study this, two new analyses are performed: one with only the strength parameters adjusted and one with only the hydraulic conductivity adjusted.

In figure 4.19, the factor of safety is shown for these cases. In orange and green, the cases are shown where only one of the factors is adjusted. From this, it is clear that the sudden decrease in the factor of safety at time = 44 days is caused by the higher hydraulic conductivity in the upper 2 meter. However, the largest part of the 4.7% to 9.9% decrease of the factor of safety is caused by the adjusted strength parameters. It appears that the influence of the hydraulic conductivity on the stability of the dyke starts to play a role only when the failure mechanism switches from inner to outer slope instability, as happens at t = 44 days.

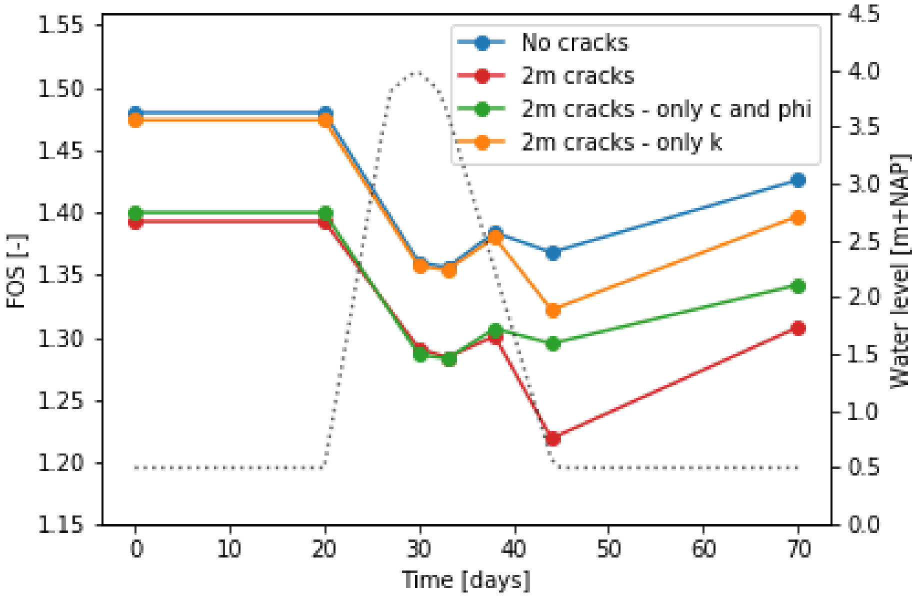


Figure 4.19: Factor over safety over time for design water level, including a case with only the strength parameters and a case with only the hydraulic conductivity adjusted. Failure due to both inner and outer slope instability.

The maximum difference between factor of safety of the cracked and the uncracked dyke is acquired at t = 44 days, when the difference has increased to 10.9%. After 70 days, the factor of safety is 8.3% lower in case of the cracked dyke.

Including precipitation

In the above analysis, precipitation is not taken into account. In reality, there is a large chance that, at least on part of the 70-day time interval, rainfall occurs. When assessing flood defences in the Netherlands, extreme precipitation is not considered explicitly (Rijkswaterstaat WVL, 2016). The reason for this is that the chance of simultaneous occurrence of high water level and extreme rainfall is assumed to be very small. Normal precipitation and evaporation do play a role in the location of the 'daily' phreatic surface.

To get a feeling for the amount of precipitation occurring during high water events, the measured precipitation per day during high water events in the past is compared. Daily (before the year 2000) or hourly (after 2000) measurements are available from 50 different KNMI weather stations spread across the country. If the daily precipitation during the five high water events are compared it can be seen that high water levels do not necessarily correspond to high precipitation values at the same location and there is no direct correlation, see appendix A. During the high water event of 1993, the total amount of precipitation at the location near Dodewaard is 291 mm, which corresponds to average of 4.2 mm per day during the 70 days. There are several days at which a large amount of precipitation occurred, at one day even around 40 mm. With such a large amount of water at a short period of time, it is likely that part of the precipitation is infiltrated into the dyke but also a large part will run-off. It is chosen to implement an average precipitation of 2 mm/day.

Figure 4.20 shows the development of the factor of safety over time for the scenario including precipitation of 2mm/day. As expected, the cracked dyke shows a lower factor of safety at every moment in time. However, if compared to Figure 4.17, it is clear that the difference in factor of safety between the cracked and the uncracked dyke is smaller if precipitation is included.

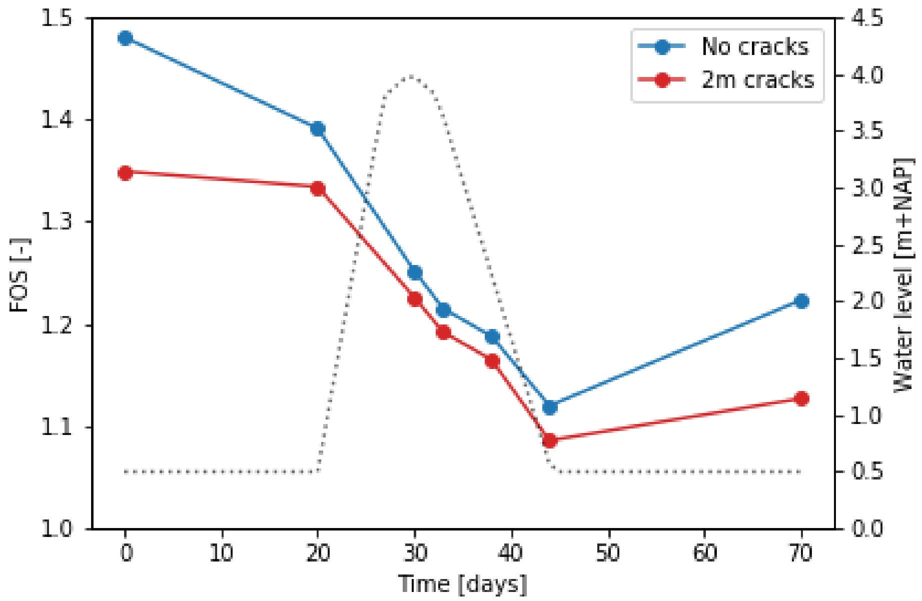


Figure 4.20: Factor over safety over time for design water level, including precipitation of 2mm/day

It can be concluded that precipitation has a negative impact on dyke stability. This is as expected, as the degree of saturation increases due to the infiltration. As suction is included, the suction levels decrease when the dyke saturates and that leads to a lower shear strength.

It should be noticed that the hydraulic conductivity of the cracked layer may be overestimated in this scenario where precipitation is included. Presumably, if the crack volume increases, the hydraulic conductivity increases and the soil strength decreases. If the crack volume decreases, due to partly closure of cracks upon wetting, the hydraulic conductivity can decrease again. This means that, if the adjusted value is used for the hydraulic conductivity simultaneously with a scenario with precipitation, this increased hydraulic conductivity can be overestimated.

4.2.2. Measured high water event

In addition to the design water level, a measured high water event is studied. As introduced in Section 4.2, the high water event of 1993 is chosen. The water levels used are based on measurements from the Dodewaard location as discussed before. A period of 70 days is considered, from 12-12-1993 until 20-02-1994. The flow function is shown in figure 4.21. The highest water level is +3.821 m above the base of the dyke, the lowest water level is +0.5 m. The flow function is divided in 10 different time intervals, after which output regarding hydraulic response and the safety analysis is generated. Precipitation is not included in this scenario.

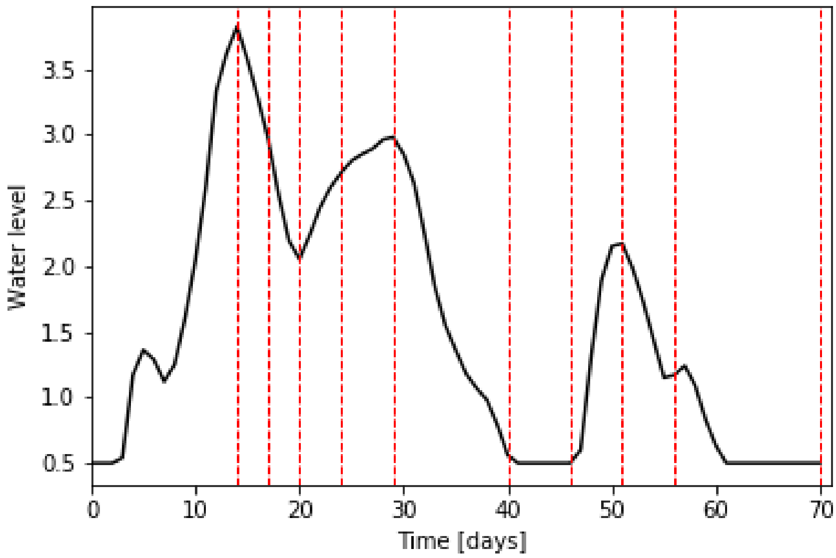


Figure 4.21: Flow function for the measured water level, the high water event of 1993.

Safety analysis

Figure 4.22 shows the variation of the factor of safety over time. The blue and red lines represent the factor of safety associated with, respectively, the dyke with no cracks and the dyke with 2 meter cracks. The grey line combined with the right y-axis shows the water level variation.

The factor of safety at time = 0 represents the steady-state solution with a constant low water level at +0.5 m above zero level. At time = 0, there is a difference of 5.6% between the cracked and the uncracked dyke, as already reported in Section 4.1. After this, the water level rises, which leads to a decrease of the factor of safety in both the cracked and the uncracked case. Between day 14 and day 20, there is a small increase in the factor of safety for both cases, caused by the decreasing water level. At time = 40 days, there is a divergence between the uncracked and the cracked dyke.

To better understand the development of the factor of safety, the corresponding failure mechanisms are inspected. Until t = 29 days, the failure mechanism occurred is instability of the inner slope. In figure 4.23, the failure surface at different time-steps is shown for the dyke with 2m cracks. It is clear that the failure mechanism switches to outer slope instability at t = 40 days and switches back to inner slope instability at t = 51 days. If this is compared to the factor of safety over time as seen in Figure 4.22, the lowest factor of safety at t = 40 days corresponds to instability of the inner slope due to the rapid drawdown of the water level. At t = 70 days the factor of safety suddenly decreases again, which coincides with a new switch from inner to outer slope instability. After 70 days, the factor of safety is expected to increase again.

The same phenomenon as with the design water level is visible here: the factor of safety decreases significantly at t = 40 days due to the switch from inner to outer slope instability.

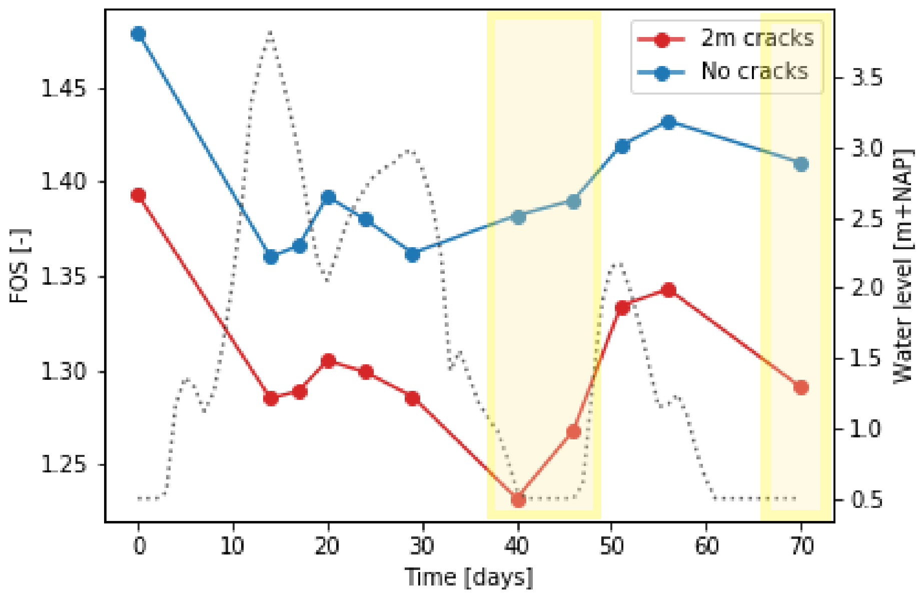


Figure 4.22: Factor over safety over time for high water event in 1993. Failure due to both inner and outer slope instability, the yellow area shows the time-steps at which outer slope instability occurred.

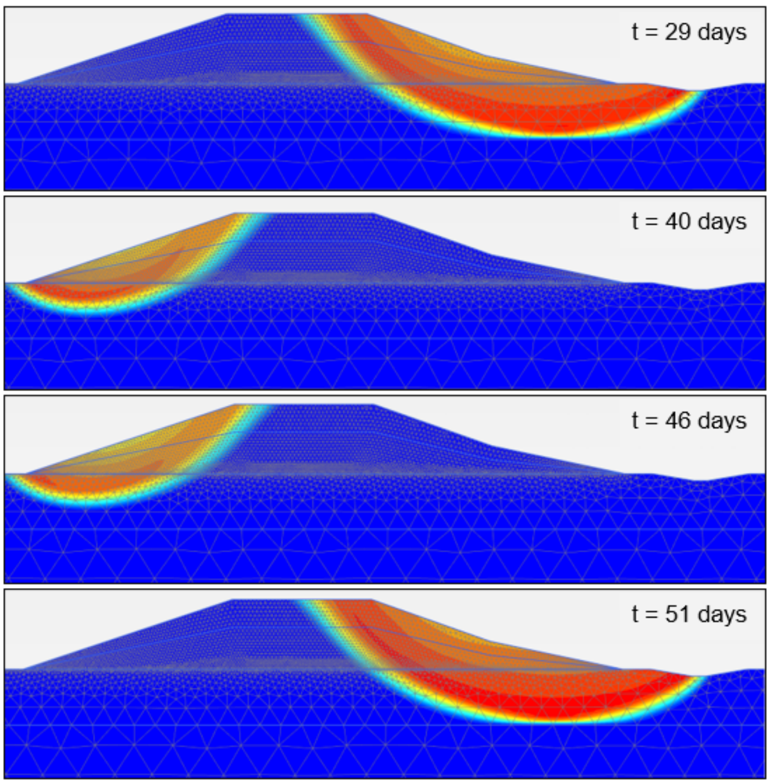


Figure 4.23: Failure mechanism at different timesteps, dyke with 2m cracks

4.2.3. Comparison between design water level and high water event of 1993

In both cases, the dyke fails due to both outer- and inner macro-instability at different time-steps. The drawdown of the water level after the peak level is in both cases relatively rapid, leading to outer slope instability being the governing failure mechanism. The lowest factor of safety in the design water level scenario is 1.22 (at t = 44 days) and the lowest factor of safety in the case of the high water event of 1993 is 1.23 (at t = 40 days). This is remarkable, as the total duration of the high water level is longer in case of the measured high water event and it was therefore expected to lead to the lowest factor of safety. Though, it seems that the rapid drawdown is more critical in the case of the design water level. If only the time-steps where inner slope instability occurred are compared, the lowest factor of safety for the design water level is 1.284 (at t = 33 days) and for measured 1993 water level it is 1.286 (at t = 29 days).

4.2.4. Summary of time-dependent results

The dyke with 2m cracks experiences lower factor of safety at all time-steps than the dyke without cracks. In both cases, the factor of safety decreases due to rising of the water level. Logically, the factor of safety changes over time due to the changing hydraulic boundary conditions. Overall, the development of the factor of safety over time is comparable for the uncracked and the cracked dyke. However, there are some time-steps at which a divergence between the two cases is observed. This divergence is mainly caused by the increased hydraulic conductivity due to the cracks, which leads to a lower factor of safety when failure is a result of outer slope instability. The difference in terms of factor of safety between the uncracked and the cracked dyke ranges from 5.6% to 10.9%. This range can be narrowed down when distinguishing between different failure mechanisms. If inner slope instability occurs, the maximum decrease of the factor of safety due to cracks is 5.7%. If the dyke fails due to outer slope instability, cracks lead to a maximum decrease of the factor of safety of 10.9%.

5 Discussion and conclusions

5.1. Discussion

5.1.1. Interpretation of findings

The main results found in Chapter 4 are regarding a change of the factor of safety between an uncracked dyke and a dyke affected by 2m cracks. According to the model results, the difference in terms of factor of safety between the uncracked and the cracked dyke ranges from 5.6% to 10.8%. This decrease in factor of safety can be seen as a significant change, however, it should be noted that the Dutch guidelines concluded that there may be a change of factor of safety between limit equilibrium and finite element method calculations up to 6% purely because of the differences in approach (POV Macrostabiliteit, 2020). This shows that there is always an significant uncertainty and variation of results based on different existing methods. From a broader perspective, it is important to realise that the computed factors of safety are solely an approximation at one single dyke cross-section and does not necessarily represents the safety of a dyke system. In addition, these calculations are based on a simplification and are therefore only an approximation. In reality, the computed safety factor will also depend on the simplifications and on the calculation method. Generally, calculations done by FEM software like PLAXIS 2D lead to a lower factor of safety compared to LEM calculations. A reason for this can be that in PLAXIS 2D failure occurs consistently according to any failure mechanism with the lowest factor of safety, while LEM only considers a finite number of possible failure surfaces.

The largest difference between the factor of safety of the cracked and the uncracked dyke appears to occur when the dyke fails due to outer slope instability rather than inner slope instability. The outer slope instability is triggered by a relatively fast decrease of the outside water level. From a flood risk point of view, this failure mechanism leads to a lower risk of flooding of the hinterland, as this failure mechanisms occurs not at the peak water level. A breach of the dyke will therefore presumably have a smaller impact if the dyke failure is repaired before a new high water event develops.

This study focussed on only one dyke type: a river dyke consisting entirely of clay. Self-evidently, the results of this study are not directly applicable to all types of dykes. Looking at the failure mechanisms occurring at the safety analysis, it is shown that a large part of the resistance is coming from the clay layer below the dyke. This significant part of the failure surface is not affected by the existence of desiccation cracks. A thinner clay layer underneath the dyke, or a larger dyke can increase the influence of the cracks on the dyke stability. In addition, the hydraulic loads of another dyke type will be different. For example, at lake dykes, the variation in water level is generally smaller and wind set up can play a larger role. For sea dykes, the duration of high water events is relatively short, compared to river dykes. Smaller dykes like a ’boezemkade’, which is a dyke around a polder will generally have a smaller unsaturated zone as the water level is constantly high. The occurrence of very deep cracks is therefore smaller, but the impact can be larger than in case of river dykes, as the dyke is usually smaller.

5.1.2. Modelling approach

The conclusions are drawn based on the PLAXIS 2D model in which different scenarios are simulated. Validation of the model results was not possible during this study, but is definitely needed to determine the reliability of the results. However, these results can be seen as a first step of quantifying the influence of cracks on dyke stability in order to assess if the current guidelines in the Netherlands need to further elaborated on this subject.

In this model, the zone that is affected by desiccation cracks is assumed to be a homogeneous zone with adjusted soil parameters. A number of aspects of this modelling approach need to be considered.

No distinction is made between different crack intensities. In reality, the influence of few minor cracks will be different to a more severely cracked dyke. In this thesis, only a fully cracked zone is considered. To be able to distinguish between this, insight is needed in how parameters as the hydraulic conductivity change under different crack conditions and crack patterns. This does not influence the validity of the results as the parameters are determined based on fully developed cracks and can therefore be seen as ‘worst-case’ scenario.

In order to simulate the effects of the desiccation cracks, the hydraulic conductivity and strength parameters are adjusted. The change of the hydraulic conductivity is based on several laboratory experiments. However, the behaviour of cracks is difficult to measure in laboratory experiments. These experiments are done on small scale samples, which can lead to neglecting the effect of larger interconnected systems of cracks. In addition, the hydraulic conductivity of soil is different in field conditions than in laboratory conditions.

For this study, a fixed value of the cohesion and friction angle is chosen to simulate the cracked layer. This implies that the crack characteristics are assumed to be constant over time, even in the transient scenarios. However in reality, the crack volume will fluctuate as hydraulic conditions have a dynamic character. A solution for this could be to link the (expected) maximum volume of cracks to a minimum value for the cohesion and friction angle. Over time, this volume of cracks fluctuates as is the case for the cohesion and friction angle. However, to be able to do this, more information is needed on the relation between crack intensity and strength of the soil. The same applies to the hydraulic conductivity.

Presumably, if the crack volume increases, the hydraulic conductivity increases and the soil strength decreases. If the crack volume decreases, due to partly closure of cracks upon wetting, the hydraulic conductivity can decrease again. This means that, if the adjusted higher value is used for the hydraulic conductivity simultaneously with a scenario with precipitation, this increased hydraulic conductivity can be overestimated. Though, it is expected that the influence of this on the results is not significantly large as it is shown that the decrease in factor of safety is mainly due to the decreased strength.

5.1.3. Limitations of numerical model

Besides the limitations regarding the modelling approach, the PLAXIS 2D model is based on certain assumptions. The use of a numerical model inevitably has limitations when representing reality. Assumptions have to be made regarding soil parameters, geometry and boundary conditions.

With determining the dyke geometry and soil parameters, a first step has been made to make a representative case for Dutch river dykes. The soil parameters are chosen based on collections of soil samples from Dutch clays and therefore represent the Dutch clay characteristics. However, in reality not only clay dykes exist but also dykes of sand with a clay clover. The hydraulic behaviour of a sand dyke differs largely from a clay dyke as the hydraulic conductivity is much larger.

The dyke geometry chosen is assumed to be a representative simplification of the Dutch river dykes. Below the dyke, a clay layer of 4 meter is present. As is shown in the results, the failure surface crosses this clay layer completely in most cases. This implies that a lot of the resistance is coming from this clay layer. If the clay layer is thinner, the reduction of the factor of safety in case of the cracked dyke can be larger. The height of the dyke itself can also have an influence on the results.

5.2. Conclusions

The main objective of this study was to gain a better insight into the potential influence of desiccation cracks on the stability of Dutch river dykes. The following main research question was formulated: “to what extent can desiccation cracking have an influence on the macro-stability of Dutch river clay dykes?”.

In order to answer this question, numerical modelling is used. With the help of PLAXIS 2D, the hydraulic response and dyke stability are studied. Several model scenarios are considered. To formulate a suitable modelling approach and conditions, multiple sub-questions were formulated. These questions are discussed first, before treating the main question.

What typical cracking pattern and crack depth is expected in Dutch clay dykes?
The crack characteristics as crack depth and pattern vary per situation, due to different clay characteristics, dyke construction and hydraulic boundary conditions. Because hydraulic conditions change over time and crack intensity can increase due to cyclic wetting/drying the crack characteristics can also change over time. Desiccation cracks are already observed on a large scale on Dutch dykes. Due to climate change, droughts are expected to increase in severity and occurrence. Crack characteristics as the crack depth can be difficult to measure as it varies in time and excavation may be needed. In field conditions, cracks of depths over 1.2 meter are already observed. Cracks often have three to six-sided polygon shape and can be interconnected systems.

Which soil properties that are influenced by desiccation cracks are important to consider and to what extent?
Cracks can influence the stability of dykes in multiple ways: by providing a preferential path to water flow into the core of the dyke and cracks can form part of the failure surface providing little or no shear strength. Consequently, cracks can have an influence on the hydraulic conductivity and the shear strength parameters of the soil. From literature, it is concluded that the hydraulic conductivity is expected to increase with a factor 15. The change of the strength parameters, cohesion and friction angle, is difficult to estimate as it is harder to test samples with cracks. However, it is clear that a decrease in shear strength is expected if the failure surface coincides a crack. It is therefore decided to study a range of shear strength parameters. Important to realise that the adjusted values for the friction angle and the cohesion that are used in the model do not necessarily represent values occurring in reality. They are artificially chosen values to reduce the shear strength.

How can desiccation cracking be implemented in Plaxis 2D to study the stability of Dutch dykes?
In this thesis, the influence of desiccation cracking is implemented in the numerical model by simulating a cracked zone with adjusted soil parameters. In this way, the failure surface will always intersects the cracked zone. An alternative method is to directly create cracks in PLAXIS 2D mesh by adding an interface with different soil parameters. However, this will lead to numerical instabilities and forces the modeller to make a decision on the location of the crack.

In what way is the hydraulic response of dykes affected by desiccation cracks?
Due to a higher hydraulic conductivity in the cracked layer, the cracked zone adapts faster to changes in hydraulic boundary conditions. A finite water level peak can therefore lead to a higher location of the phreatic surface.

The main objective of this study is: **“to what extent can desiccation cracking have an influence on the macro-stability of Dutch river clay dykes?”**
From both the theory as from the modelling results, it is shown that desiccation cracks can have an negative impact on the macro-stability of Dutch clay dykes. The factor of safety can decrease up to 10.8% if a cracked zone is present. The magnitude of this decrease depends on the hydraulic conditions as external water level, and the crack parameters. Cracks can have an influence on both the inner and outer slope stability. From the model results it seems that outer slope instability is affected most by the cracks. Regarding safety of the hinterland, outer slope instability is usually induces to a lower flood risk than inner slope instability.

A maximum of 10.8% decrease of factor of safety for the studied dyke is not necessarily significant as the use of soil models and numerical modelling always brings in uncertainties. Moreover, the most critical situation for a cracked dyke is at rapid drawdown, when the dyke fails due to outer slope instability.

From this follows the answer to the last subquestion: **is it necessary to take desiccation cracks into account in the Dutch dyke safety assessment and in what way should this be done?**
Currently, desiccation cracking is not taken into account during the regular dyke safety assessments in the Netherlands. From the results is concluded that cracks can have a negative influence on dyke safety regarding macro-instability, but the difference is not unambiguous. Precaution is needed if significant cracks develop at dykes, but smaller cracks are not likely to lead to failure immediately. However, if a dyke is expected to have a significant unsaturated zone and is therefore more susceptible to desiccation cracks, the effect of cracks may be incorporated to get a more realistic safety assessment. This can be done with the same approach as is used in this thesis: adjusting the parameters of a cracked zone. However, it depends on the adopted material model which parameters are used. In the new Dutch safety guidelines, the Critical State Soil Mechanics (CSSM) model and the SHANSEP (Stress History And Normalized Soil Engineering Properties) method are introduced. This model uses a different approach of shear strength and therefore the shear strength can not be adjusted in the same way as is done in this study. More research is needed before it is feasible to take this into account.

5.3. Prospects regarding Dutch guidelines

Currently, both the additional strength of the unsaturated zone and the decreased strength of a cracked clay layer are not taken into account. It is assumed that if cracks develop, they are observed during the regular checks that are performed in times of droughts. Any crack can then be repaired before a high water event occurs. The additional strength of the unsaturated zone is complex as it varies due to changing hydraulic conditions. In dry times, the strength related suction is more available then in wet periods when suction levels drop due to increasing saturation of the dyke. It is therefore difficult to determine whether it is safe to rely on additional strength due to suction and under which conditions.

The current Dutch guidelines are based on the Critical State Soil Mechanics (CSSM) model and the SHANSEP (Stress History And Normalized Soil Engineering Properties) method. As the approach of shear strength is different than in the case of the traditional Mohr-Coulomb model, the shear strength of the cracked layer can not be adjusted in the same way as is done in this study. The increased hydraulic conductivity can be implemented in the same way. If the SHANSEP NGI-ADP model is used, it is more complex to incorporate the effect of cracks on the strength in the numerical model as the model parameters are different.

From literature is seen that the quality of the grass cover can have a influence on the development of desiccation cracks as clay with a bad grass cover is more prone to desiccation cracking. Therefore, emphasis should be placed on maintenance of vegetation, since it can contribute to minimizing the development of desiccation cracks.

5.4. Recommendations regarding future research

For future research, the recommendations can be divided into two types: the scope of the study and the validation of the results. Regarding the first: the scope of the research should broadened.

- This study focusses only on dykes consisting entirely of clay, while a significant part of the Dutch dykes consists (partly) of a sand core. In addition, the influence of the chosen geometry needs to be studied.
- An 3D analysis should be performed to study the 3D-effects of cracks on flow through the dyke and dyke stability.
- The adjusted parameters that are used to simulate the effect of cracks could be linked to a crack intensity or crack volume. In this way, the time-dependent variation of the effect of cracks can be incorporated. To be able to do this, more information is needed on the change of parameters with changing crack volume.

Secondly, apart from the scope of the research, validation of the results is incredibly important to increase the reliability of the results. Different assumptions that are made regarding the modelling approach and the model itself to need to be validated.

- One of these aspects is the depth that cracks reach in Dutch dykes. This can be studied in the field by digging trenches or by more innovative techniques like radar.
- The results are heavily dependent on the assumptions that are made regarding the adjusted material properties to simulate the influence of cracks: the friction angle and the strength parameters cohesion and hydraulic conductivity. The reduction in strength parameters is difficult to validate as it will be dependent on the orientation and occurrence of individual cracks. In this modelling approach, the cracked layer is seen as a continuum although, in reality, it is a soil layer with discontinuities instead. In addition, cracks are scale-dependent which makes the strength parameters difficult to determine in laboratory experiments, as is also the case for the hydraulic conductivity. Measurements of the pore pressures in time in a real dyke that is affected by cracks would be valuable.
- In addition to the previous point, the hydraulic conductivity of cracked clay should be studied for different crack volumes and also in case of wetting by, for example, precipitation. If cracked clay is wetted, cracks can partly seal due to swelling, which can affect the increased hydraulic conductivity. It would be interesting to see the fluctuation of hydraulic conductivity over time with changing hydraulic boundary conditions.
- The influence of cracks on the overall dyke stability could be validated by scale model tests in the laboratory or via full scale failure tests.

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Appendices

A

Water level and precipitation input

For the time-dependent cases both a design water level and an historical , measured high water event are taken into account. In addition, precipitation is applied to see the influence of precipitation on the dyke stability. In this appendix, a detailed description of the obtained input used for the Plaxis 2D model is given.

A.1. Design water level

Every dyke in the Netherlands is designed and assessed based on a design water level: the water level with a certain return period it has to be able to withstand. The design water level corresponds to a probability of exceedance of this water level. For this thesis, the design water level with a return period of 100 years is chosen. For this return period, the peak water level corresponds to the peak level of the high water event of 1993. In this way, a good comparison can be made between the results of these two model scenarios.

Important for this research is to use a location where water levels during a high water event are not or hardly influenced by stormsurges at the Noordzee and IJsselmeer. It is therefore decided to use measurement location Dodenwaard, located in the river Waal. Both design water levels as water level measurements are available at this location.

For different return periods the design water level plot can be computed using the Dutch software HydraNL and Waterstandsverloop. In figure A.1 the design water level for a return period of 100 years at location Dodewaard is shown. On the x-axis the water level in m +NAP and on the y-axis the time in hours is shown. The duration of the event is around 24 days, the water level starts at 7.997m +NAP with a peak level at 11.497m +NAP. The total water level rise is thus 3.5 meter.

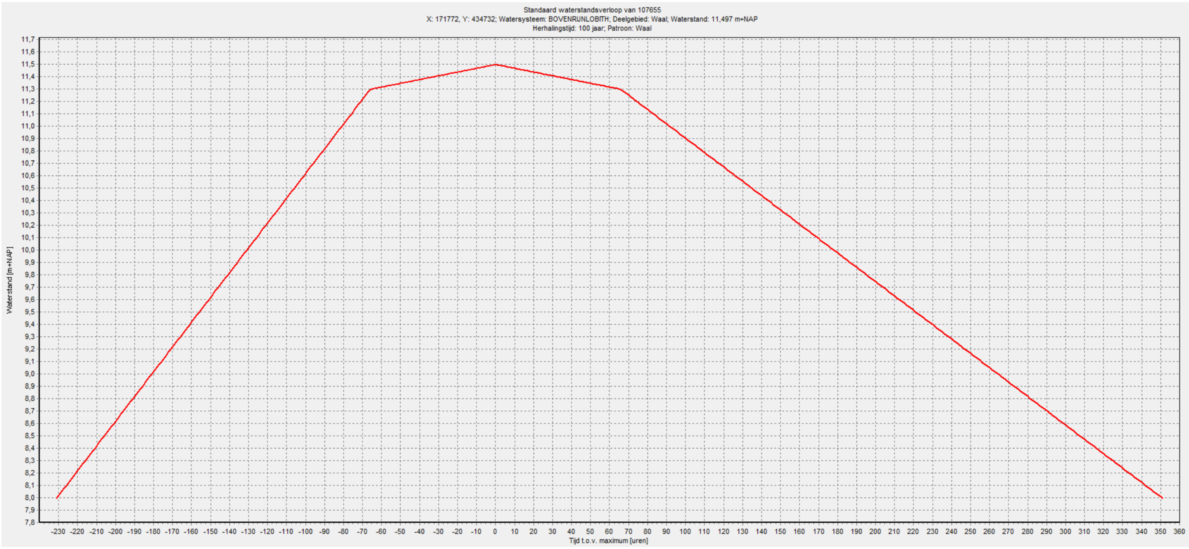


Figure A.1: Design water level at location Dodewaard, return period of 100 years

A.2. Measured high water event

At multiple measurement stations in the Netherlands the water level, among other things, is measured. In figure A.2, the chosen output location near Dodewaard is shown in red. This measurement station is located in the Waal river and is present for a longer period to be able to obtain measurements starting from 1990.

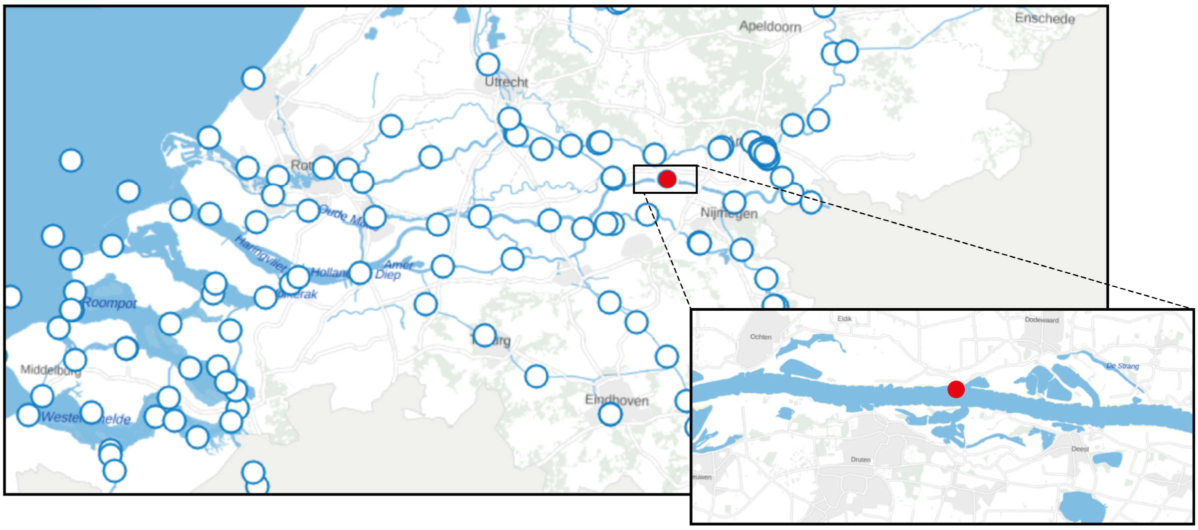


Figure A.2: Location of measured water level in the Waal river near Dodewaard

Different historical high water events that occurred in the last 30 years are compared as described in table A.1. For every high water event, a period of 70 days is selected. Figure A.2 shows the corresponding measured water levels. For this thesis, it is decided to use the high water event of 1993. This event has a considerably longer duration but a slightly lower peak level than the design water level and is therefore an suitable case to compare with. Thus, the effect of the high water level duration on the dyke stability can be assessed.

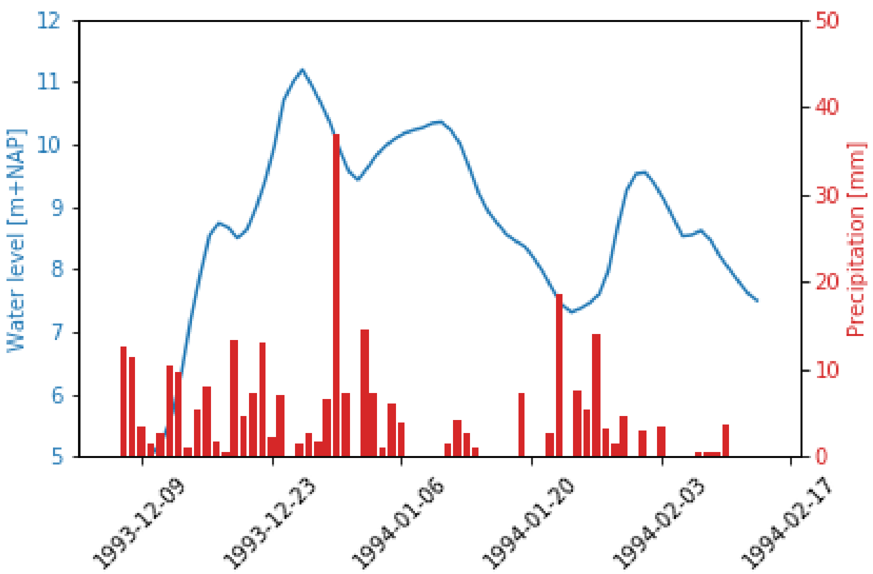
Table A.1: Dates of used high water events

Year	Dates
1993	06/12/1993 - 14/02/1994
1995	08/01/1995 - 19/03/1995
1998	23/10/1998 - 01/01/1999
2002	01/12/2002 - 09/02/2003
2017	08/12/2017 - 16/02/2018

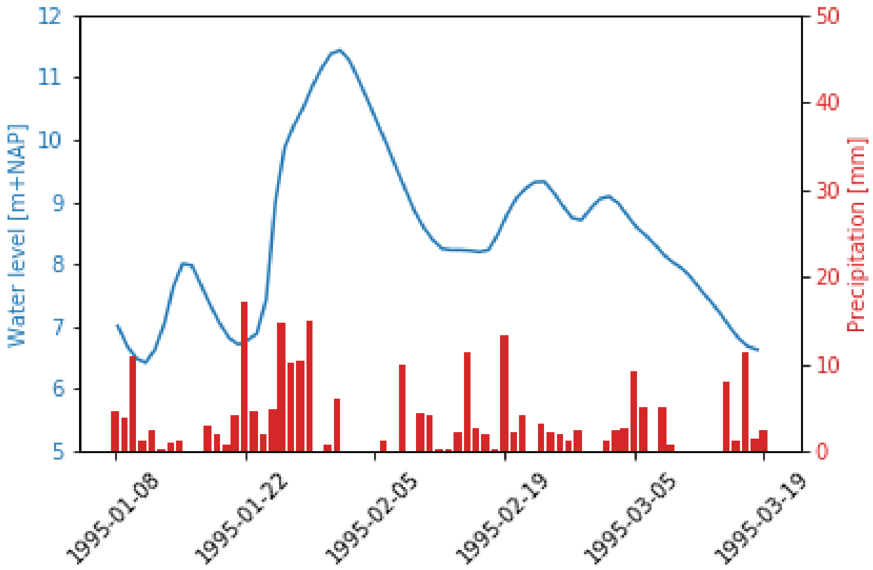
A.3. Precipitation

As for the water level, precipitation for a certain return period can be determined. However, for dyke design and assessment in the Netherlands, precipitation is not explicitly taken into account. Implicitly, the location of the phreatic surface that is used for modelling is influenced by precipitation, but individual precipitation events are usually not included.

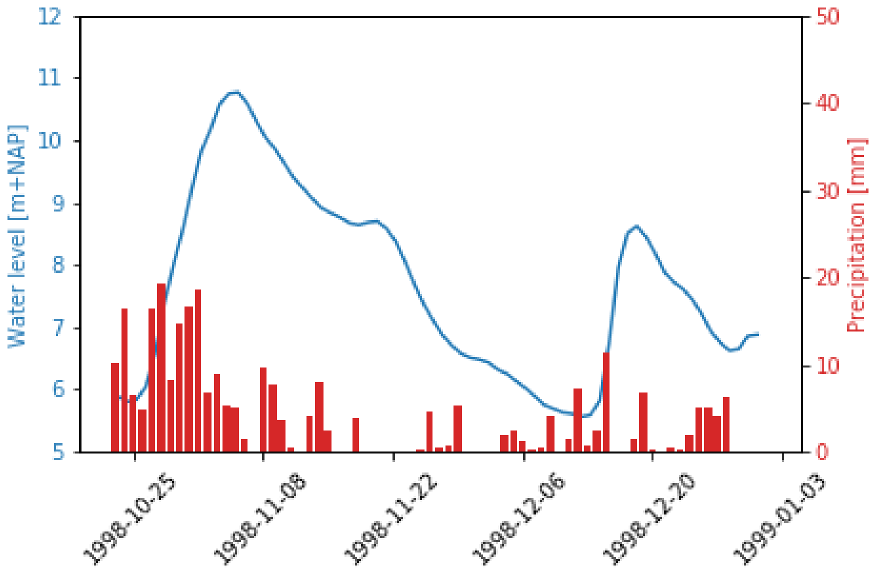
The difficulty with using design precipitation, is that the high water event and the high precipitation event do not necessarily occur simultaneously and the spatial and temporal distribution of precipitation are variable. For this study, it is therefore decided not to use the precipitation with a certain return period but look into the actually occurred precipitation during high water events. Daily (before the year 2000) or hourly (after 2000) measurements are available from 50 different KNMI weather stations spread across the country. Three measurement locations: Volkel, Herwijnen and Deelen, are at an equal distance, around 30km, from the water level measurement location Dodewaard that is used as water level input. Daily precipitation measurements of these three locations are averaged to get reasonable values at location Dodewaard. If the daily precipitation during five high water events are compared, as shown in figure A.2 it is shown that the high water level and high precipitation are not directly correlated: high water levels do not necessarily correspond to high precipitation values at the same location.



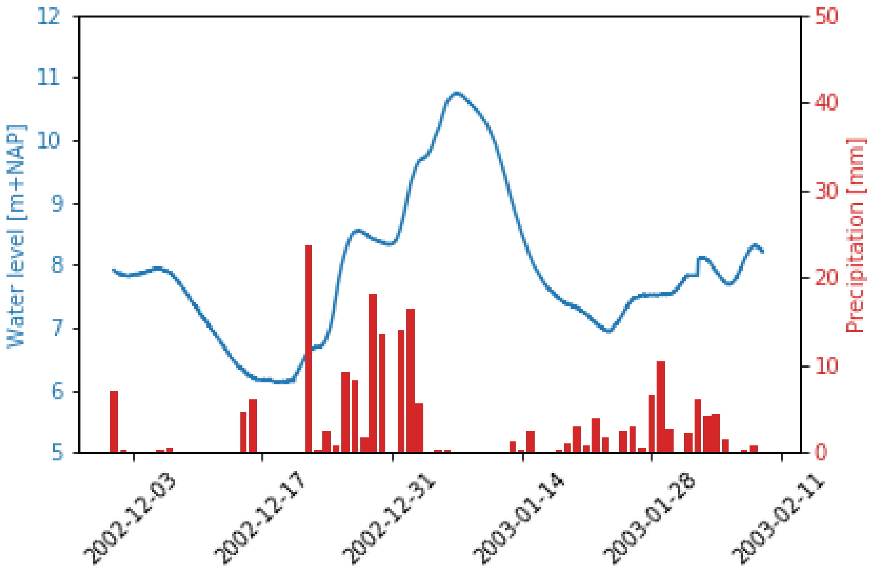
(a) Water level and precipation high water event of 1993



(b) Water level and precipitation high water event of 1995

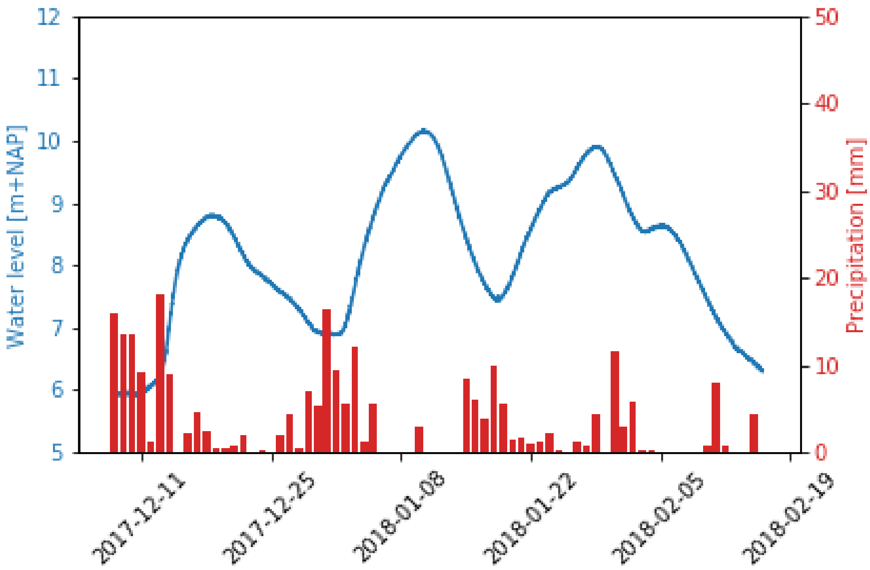


(c) Water level and precipitation high water event of 1998



(d) Water level and precipation high water event of 2002

Figure A.1: Comparison of water level and of precipitation of various high water events



(e) Water level and precipation high water event of 2017

Figure A.2: Comparison of water level and of precipitation of various high water events

In table A.2 the total precipitation and average precipitation per day, for the total period of 70 days, are given for every high water event.

Table A.2: Total precipitation and average precipitation per day occurring during high water event

Year	Total precipitation [mm]	Average precipitation [mm/day]
1993	291.0	4.2
1995	241.5	3.4
1998	276.5	4.0
2002	192.9	2.8
2017	247.0	3.5

As can be seen, the amount of precipitation occurring during the high water event of 1993 is relativity high. Part of this precipitation, especially if a lot of precipitation occurs in a short time, will run-off instead of infiltrate into the dyke. It is chosen to use precipitation of 2 mm/day in the PLAXIS 2D model. In PLAXIS 2D precipitation is implemented as a discharge in m/day. It is applied at all boundaries that represent the ground surface. In addition, a maximum pore pressure head relative to the elevation of the boundary, ψ_{max}, needs to be specified. This variable simulates run-off: when the groundwater head increases above this level, the infiltration discharge changes into the corresponding head (PLAXIS, 2019b).

B

Results time-dependent conditions

A total period of 70 days is considered, subdivided in time intervals varying from 3 to 20 days. After each time step, output regarding the hydraulic response and the safety analysis is obtained. Both scenarios without precipitation and a scenario where an daily precipitation is included are considered. In Table B.1 the factor of safety for every scenario with the design water level is shown. In Table B.2 the factor of safety for the high water event scenarios is given.

For all these scenarios, unless stated otherwise, the hydraulic conductivity is increased with factor 15 and the strength parameters cohesion and friction angle are both reduced with 50%.

Table B.1: Factor of safety for design water level scenarios at the end of each time interval

Time [days]	0	20	30	33	38	44	70
No cracks, no precipitation	1.48	1.48	1.36	1.36	1.38	1.37	1.43
2m cracks, no precipitation	1.39	1.39	1.29	1.28	1.30	1.22	1.31
2m cracks, adjusting only c and ϕ and not k, no precipitation	1.40	1.40	1.29	1.28	1.31	1.30	1.34
2m cracks, adjusting only k and not c and ϕ, no precipitation	1.47	1.47	1.36	1.35	1.38	1.32	1.40
no cracks, including precipitation	1.48	1.39	1.25	1.22	1.19	1.12	1.22
2m cracks, including precipitation	1.35	1.33	1.23	1.19	1.17	1.09	1.13

Table B.2: Factor of safety for high water event scenarios at the end of each time interval

Time [days]	0	14	17	20	24	29	40	46	51	56	70
No cracks	1.48	1.36	1.37	1.39	1.38	1.36	1.38	1.39	1.42	1.43	1.41
2m cracks	1.39	1.29	1.29	1.31	1.30	1.29	1.23	1.27	1.33	1.34	1.29