Modeling and Improving Dike Durability:

A Robust Reinforcement for The Mastenbroek-IJssel Dike

Bachelor Thesis
Civil Engineering

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6-6-2025

TAUW

HZ UNIVERSITY OF APPLIED SCIENCES

Modeling and Improving Dike Durability

Client	TAUW B.V
Project Title	Modeling and Improving Dike Durability
Subtitle	A Robust Reinforcement for The Mastenbroek-IJssel Dike
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Student Number	00092804
Report Type	Bachelor Thesis
Study Program	Civil Engineering BSc
Place of Study	HZ University of Applied Sciences
Internal Supervisor	Danny Janssen
Company	TAUW B.V
External Supervisor	Barbara Bouman
Date of Completion	06-06-2025
Report Language	English

Pages: 103	Appendices: 11

The cover image displays sub-section De Naters of the Mastenbroek-IJssel dike and was taken during a field visit on March 29th, 2025.

Preface

The content of this thesis covers the topic of water safety through analyzing the effect of utilizing durability to optimize and improve dike reinforcement solutions. The study was carried out during the final five months of my Civil Engineering program at HZ University of Applied Sciences.

I would first of all like to thank TAUW, specifically Margreet Troost and Barbara Bouman, for allowing me the opportunity to work on this research project within their organization. My time at the company has been immensely educational, and it was a pleasure to join the welcoming team of Hydraulic and Geotechnical Engineering.

My sincere appreciation also goes to every colleague at TAUW who helped me throughout my research. Your readiness to answer questions and steer me in the right direction created an open and encouraging atmosphere that made my bachelor thesis process truly enjoyable.

A special word of gratitude is reserved for my in-company supervisor, Barbara Bouman. Your guidance, encouragement and feedback were invaluable throughout my internship. Your expertise in this field and mentorship are admirable. I thank you for all the knowledge you shared with me over the past five months.

Several external experts contributed significantly to this research. I am grateful to the WDOD participants in the variant workshop, whose insights helped assess the feasibility of the preliminary durable reinforcement alternatives. I also thank members from the Sustainable River Management research group at HAN University of Applied Sciences for sharing their expertise on robust dikes and their guidance. I would like to also specifically express my appreciation to Jan-Bert de Hoop for answering all my hydrological questions and supplying crucial datasets for this research. Another special thanks is extended to Nelen & Schuurmans for providing me with a student license for the program 3Di, and to Jonas van Schrojenstein and Sjon van Dijk for their assistance in obtaining and navigating the software.

I am equally indebted to all lecturers at HZ University of Applied Sciences for equipping me with the knowledge and guidance that support this research. Most notably of which I thank Danny Jansen, my mentor from the HZ University of Applied Sciences, whose substantive feedback and encouragement helped elevate this research.

Engineering has interested me for as long as I can remember, but from the first time that I saw the Oosterscheldekering and Afsluitdijk an interest in hydraulic engineering was sparked. At eighteen I moved to the Netherlands to pursue an education in civil engineering, so that one day I could work on projects which improve water safety. This thesis research allowed me to work on an ongoing dike reinforcement project where I learned so much about the field of hydraulic engineering. I hope to continue contributing to the improvement of water safety after my studies.

To everyone who has helped me reach this point today—thank you. Your support brings me one step closer to my dream career. I hope y'all enjoy reading this report and find the results as valuable as I do!

Kerstynn Jones,

02-06-2025

Summary

Throughout this thesis, a competitive durable reinforcement design for the Mastenbroek-IJssel reinforcement project is developed and modeled. In 2024 the Drents Overijsselse Delta Water Board began with the exploration phase of the Mastenbroek-IJssel reinforcement project as 10.8 km of the IJssel dike no longer met the safety standard of 1:3000 years. In order to refine the scope of this research a durable reinforcement alternative was developed for the sub-section of the dike with the lowest overall durability. To identify the least durable dike sub-section a qualitative analysis was made considering durability scores for each section. Dike section De Naters proved to be the most brittle of the sub-sections considering the current cross-section, present failure mechanisms and the previously proposed reinforcement alternatives. For this research an explicitly durable reinforcement design was created for dike section De Naters.

Literature reviews, site visits and expert workshops aided in developing three preliminary durable reinforcement designs. A multi-criteria analysis was made in collaboration with the WDOD, where each preliminary design was evaluated based on spatial impact, technical feasibility, cost-effectiveness and sustainability. As a result from expert meetings, the alternatives were refined into one design for further research. The design combines soil reinforcement of the upper and inner talud, a clay soil improvement on the inner talud, a paved bicycle path on the crest, and a secondary dike built roughly 100 m landward of the primary dike.

Stability calculations performed using D-Stability show that both dikes in the durable reinforcement design meet the required safety factor of 1.24. 3Di was used to model breach simulations of the durable reinforcement design and a brittle design which both meet the design standard of 1:3000 years. The results of the flood simulations were inputted into the SSM-2017 software to determine the overall flood consequences. The overall flood risk of the durable reinforcement design is 5.3 times less than that of the brittle variant. The difference in flood risk is expressed as a robustness index. The robustness index is used to reevaluate the design safety standard, which is used when considering the durable reinforcement alternative. That allows for design optimizations without reducing the overall safety. When construction costs and residual risks are considered, the durable variant proves to be roughly 0.63 million euros more cost-effective than the brittle reinforcement alternative. It should be considered that this cost estimate does not include the land acquisition required for either alternative.

This thesis presents a transferable method for considering durability as an optimization in dike design in addition to the specific results of this case study. By distinguishing brittle from ductile failure behaviors and analyzing the effects, dike reinforcement solutions can be developed; maximizing social benefit and ultimately improving flood-risk management in polders.

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Acronyms:

3Di: 3-Dimensional integrated hydrodynamic modelling software

AHN: Actueel Hoogtebestand Nederland (Elevation data map for the Netherlands)

CPT: Cone Penetration Test

MCA: Multi-Criteria Analysis

NAP: Normaal Amsterdams Peil (elevation reference line in the Netherlands)

QGIS: Quantum Geographic Information System

RWS: Rijkswaterstaat

SSM: Schade-Slachtoffer-Module 2017

TUN: Technische Uitgangspuntennotitie (report for technical starting points)

VKA: Voorkeursalternatief (Preferred Alternatives)

WBN: Waterstand bij Norm (design high-water level)

WDOD: Water board Drents OverIJssel Delta

Key Words:

Berm	Ductile	Phreatic Line
Brittle	Durability	Robust
Cohesion	Foreshore	Schematization
Crest Level (HBN)	Hydrodynamic	Talud

Definitions of Technical Terminology:

Technical Term:	Definition:
Brittle Dike	A brittle dike in the context of this research is a dike which contains no elements that could delay the failure path or reduce the impact of a flood due to a dike breach. This type of dike experiences a rapid failure process.
Durable Dike	A durable dike contains robust elements which create delays in the failure process, in turn reducing the impact of flooding. Durable dikes breach in a slower, more controllable and predictable manner (Waterforum, 2024).
Traditional Dike	A traditional dike is constructed or reinforced using conventional methods. Methods used include heightening and widening the dike using soil, constructing a sheet pile wall in the inner berm and other additional methods. Over the years, these "traditional" approaches have been tried and tested. Traditional

	dikes can be either brittle or durable depending on their durability score.
Durability Score	In this research, a dike's durability score is determined by three main aspects: soil composition, cross-sectional characteristics, and design elements which delay failure processes. The failure process is analyzed in regard to the failure mechanisms present within a cross-section.
Robustness Index	The robustness index is a quantitative value assigned to a dike design depending on the associated risk. This value is based on the durability in relation to flood damage and casualties. The formula used to quantify the robustness index is as follows: $Robustness\ Index = \frac{Risk\ of\ Brittle\ Dike\ Construction\ (euros)}{Risk\ of\ Design\ Construction\ (Euros)}$
Talud	The term talud is Dutch and has no comparable English translation. For this research the term talud is use to describe a section of the dike. The upper talud is the crest region of a dike profile. The inner talud includes the inner slope and inner berm of a dike profile.

Table 1. Technical terminology definitions

1 Introduction

1.1 Motive

In 1825 twenty-two dikes across the north of the Netherlands breached due to an extreme storm event specifically causing 305 deaths and destruction in Overijssel. The IJssel dike was one of the twenty-two dikes breached, which flooded the areas around Kampen (Rijkswaterstaat, 2025). This event is one of the many documented tragedies which reinstate the importance of water safety. Throughout the years water safety in the Netherlands has improved significantly, however there is still room for improvement. Sea level rise, increased storm intensities and excessive river runoff continue to be factors which require water defenses in the Netherlands to be continuously reinforced preventing such flood events.

Figure 1. Flood of 1825 map with impacted areas highlighted in blue (Rijkswaterstaat, 2025)

River dikes traditionally use reinforcement techniques such as heightening, widening and adding hard constructions in order to counteract failure mechanisms and meet water safety standards. In the Netherlands the water safety standards for dikes are based on the approach of preventing an initial collapse. This approach requires dikes to withstand peak hydraulic forces and total failure is expected if a breach occurs. This fast growing brittle failure approach can be observed when analyzing the collapse of sand core dikes. This type of failure is referred to as a brittle breach (den Heijer & Kok, 2022). Not all traditional dikes are brittle, as ductility is defined by the method in which dikes breach. More detailed information on the breaching process can be referenced in section 2.9. This current systematic method of calculating all dikes based on a brittle breaching process is a conservative approach, which falls short. Optimizations to the current method will be analyzed throughout this research.

HAN University of Applied Sciences initiated the study on the robustness of durable dikes, and in 2022, a report was published on the theoretical possibilities of this concept. A new approach to water safety standards is presented by the concept of durable dikes. Durable dikes are defined as dikes which breach in a slower, more controllable and predictable manner (Waterforum, 2024). For further specifications on defining durable dikes, section 2.7 can be referenced. Damage costs and the number of victims are considered when determining flood consequences. By increasing a dike's durability, the consequences of floods can also be reduced, lowering the overall associated risk. Lowering the associated risk has a direct effect on the water safety standard for a dike section. This modification to the safety standards could make durable dikes more attractive in comparison to dikes with a lower durability score. The motive of this research is to apply theoretical and practical knowledge to the case study of the Mastenbroek-IJssel dike reinforcement. Yielding a durable dike reinforcement alternative, which can protect the Mastenbroek polder from future hydraulic conditions. Within this research one sub-trajectory of the Mastenbroek-IJssel dike is examined as a trial for the method of implementing durability into reinforcement strategies. The method utilized and analyzed in this research can be adapted to other dike reinforcement locations, overall influencing water safety and the way in which safety standards are approached.

1.2 Background

Every twelve years, the primary water defenses in the Netherlands are assessed for safety. The water safety standards at which they are assessed are derived from flood risks associated with an area. The probability that a flood could occur and the impact on an area if a flood were to occur are factors considered in determining the flood risk. Current standards assume all dikes experience a brittle and abrupt breaching process. This assumption is a conservative approach, as the standards could be more efficiently met if durability was considered. Due to the method of current regulations, 10.8 km of the 14.6 km-long IJssel dike does not meet water safety standards and requires reinforcement.

Risk= Probability x Impact

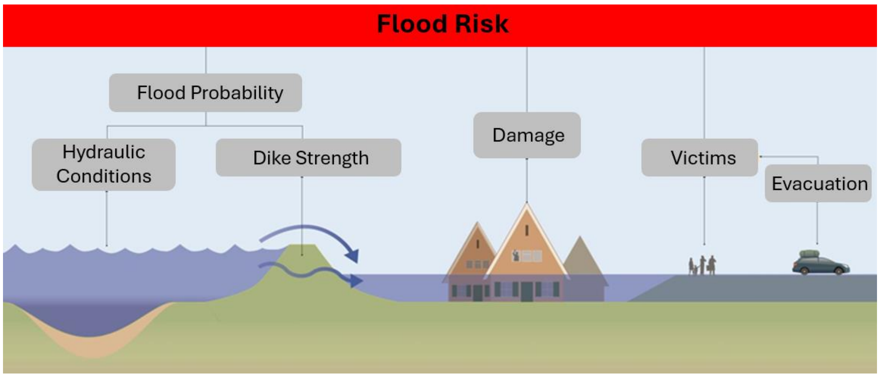

Figure 2. Flood risk visualization (van der Most et al., 2017)

The Water Act of 2017 introduced new water safety standards for primary flood defenses. Each dike was assigned its own safety standard to which it must adhere. These new standards take into account more localized breaches rather than breaches within a whole dike ring system (van der Most & te Nijenhuis, 2019). The WBI 2017 (The Statutory Assessment Instruments 2017) was implemented within the water act of 2017. This system, developed by RWS WVL for the Ministry of Infrastructure and Water Management, outlines the guidelines for evaluating the safety of primary water structures in the Netherlands. The WBI 2017 includes regulations for determining hydraulic loads, structural strength and carry out the overall safety assessment procedure (de Waal, 2018). This change in method has improved the accuracy of flood management and the way in which water safety standards are approached. Considering the durability of a dike in the risk assessment could further improve the approach and accuracy of water safety standards.

Figure 3. Visual of multi-layer safety (van der Most et al., 2017)

The Dutch approach to flood safety is known as "multi-layer safety," consisting of three layers: disaster management, spatial planning, and flood prevention (van der Most et al., 2017). Improving any of these layers can reduce associated risks and in turn water safety standards (van der Most & te Nijenhuis, 2019). Increasing dike durability through the implementation of robust elements can increase the dikes overall strength, reducing the risk of a total collapse, improving layer one. Reducing land usage or using multi-purpose reinforcement design solutions can improve layer two. Delays in the traditional failure path can improve layer three, allowing more evacuation time, ultimately reducing casualties and infrastructure damage. Through improvements in each of the three layers, a reduction is expected to be seen between the robust design standard and the original water safety standard, bringing the cycle back to layer one initial disaster prevention. In addition to proposing a robust reinforcement variant to increase the durability of a section of the Mastenbroek-IJssel dike, this research aims to present an approach for considering a dike's durability when determining the water safety standard.

1.3 Problem Statement

Taking into account the specific project requirements and boundary conditions, this research determines the most optimal durable dike alternative for a specific dike trajectory within the Mastenbroek-IJssel dike reinforcement project. The possibility of reducing the design standard by implementing a risk reduction factor will be evaluated.

The Mastenbroek-IJssel reinforcement project is currently in the investigation phase, which began in 2024 and is expected to continue until 2025. During this phase, a variant study was conducted for all six sections of the 10.8 km-long IJssel dike. The study considered several reinforcement options, including inner slope soil reinforcement, outer slope soil reinforcement, and the use of hard constructions (Wiegink & Rijkeboer, 2024). The alternatives selected from this study are currently undergoing environmental impact assessments. The durability of these previously proposed variants is assessed through assigning durability scores, this process is detailed in Appendix 2.

This research will focus on developing a durable dike alternative for one section of the Mastenbroek-IJssel dike. The proposed durable solution will be compared to both the existing situation and the variants suggested in the previous initial variant study. This comparison will help assess whether durable dikes are attractive and competitive.

1.4 Research Purpose

The purpose of this research is to improve and maintain water safety in the Mastenbroek polder by developing and evaluating a more effective method for flood prevention and management. This research aims to Improve the familiarity of durable dike alternatives and promote their implementation in projects. A detailed benefit analysis of a durable dike variant will assess the practical applicability in the context of the Mastenbroek-IJssel project. This research intends to stimulate further studies on the approaches used to asses water safety standards and durable dike alternatives, inspiring ongoing development.

1.5 Objective and Scope

The goal of this research is to propose a practical, innovative and cost-effective durable reinforcement alternative that meets water safety standards and regulations. The durable alternative selected for further detailing should be extensive enough to be presented alongside previously proposed variants. This study considers the attractiveness of durable dikes in comparison to brittle dikes. Focusing on a durable dikes ability to provide slow growing, controlled, and predictable breaches, minimizes overall flood damage.

1.5.1 Project Scope:

The scope of this project focuses on determining the technical suitability of one detailed durable dike variant for one section of the Mastenbroek-IJssel dike. Multiple possible durable alternatives will be assessed qualitatively through an expert workshop, followed by a multi-criteria-analysis to determine the most feasible variant. Only the winning durable variant will be considered in all research steps subsequent of step four. A robustness index will be identified quantitatively for the winning variant, and a method will be provided for assigning a robust design standard for the durable dike section. The research questions provided in section 1.6 are established through identifying research steps. These main research steps are displayed in figure 4, and the corresponding descriptions of these steps are provided below.

Research Steps Considered:

- **Step 1:** Identify the optimal dike section considering critical durability,
- **Step 2:** Determine probable durable dike variants for the selected dike section,
- **Step 3:** Define the criteria of a feasible design variant,
- **Step 4:** Conduct a multi-criteria analysis to determine the most feasible of the three variants,
- **Step 5:** Determine how the robust elements in the most feasible variant impact the failure path of the selected dike section,
- **Step 6:** Determine the overall stability and flood conditions of the selected dike section in the event of breaching, considering the implementation of the optimal durable variant,
- **Step 7:** Conduct a cost-benefit analysis with the implementation of a robustness index, only considering the most feasible design variant,
- **Step 8:** Identify the suitability of the final detailed durable dike variant, considering the possibility of reducing the design standard of 1:3000, in relation to the robustness index.

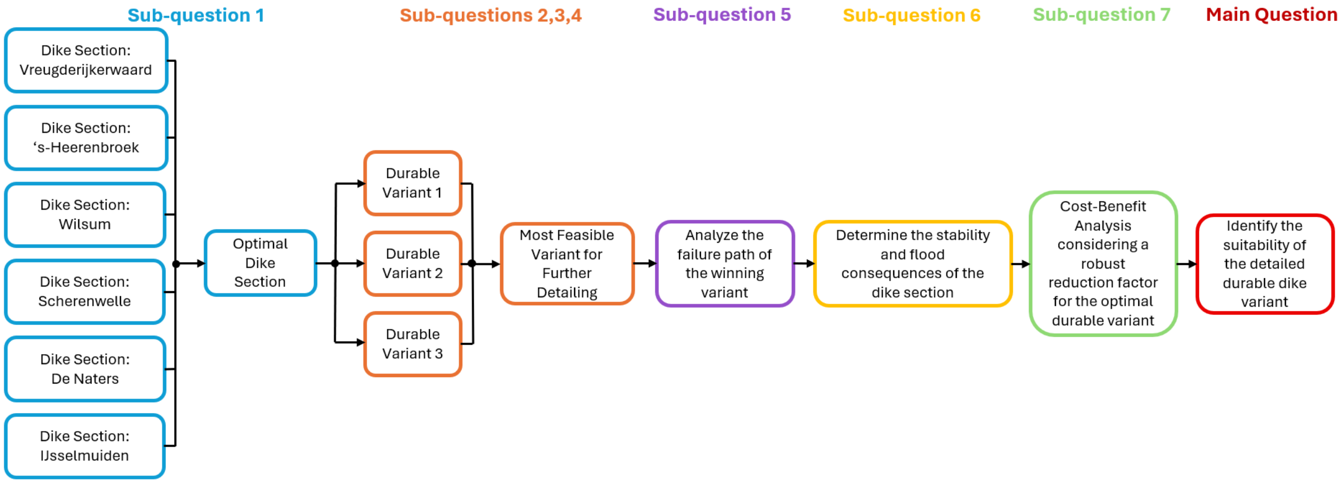

Figure 4. Research pathway approach

1.6 Research Questions

When conducting this research the following sub-questions will be answered, acting as a roadmap to the main question. During the process of answering these questions relative concepts and approaches will be considered to deliver an attractive end product.

1.6.1 Main Question

What is a suitable durable dike design for the Mastenbroek-IJssel dike reinforcement?

1.6.2 Sub-Questions

1. Which dike trajectory of the Mastenbroek-IJssel is the optimal area for a durable dike alternative?
2. What are three reinforcement variants which can be used to increase the durability of the dike section, considering possible robust elements?
3. What set criteria must the durable dike alternative meet?
4. Considering the robust elements, which is the preferred durable variant to detail further based on pre-defined criteria?
5. How can the selected robust reinforcement alternative reduce the impact of the failure mechanisms present within the dike section?
6. How does the preferred robust reinforcement variant limit the consequences of flooding?
7. To what extent is a durable dike design a competitive variant?

1.7 Project Timeline

The Mastenbroek-IJssel dike reinforcement project began in 2024 after failing to meet current water safety standards. The dike reinforcement project will go through three phases and will be completed after 2029. In figure 5 each of the three project phases are displayed with the time allocated. The project is currently in the exploration phase which consists of researching the current situation, determining possible reinforcement alternatives, conducting environmental studies, and providing finalized variant study. Once the reinforcement variants have been decided and detailed, the planning phase can begin. In 2026 the technical aspects of the reinforcement variants chosen will be worked out in detail. Including dimensioning, testing, and practical construction aspects. The construction phases must then also be planned before the execution phase begins in 2029. Once construction of the reinforcements are completed correctly the project will be finished. Due to the constant changing in hydraulic conditions due to sea level rise, excessive river discharge and increased storm intensities, this dike will continue to undergo reinforcement approximately every 50 years.

Figure 5. Project phases of the Mastenbroek-IJssel dike reinforcement project (Wiegink & Rijkeboer, 2024)

The initial variant study of this project has been completed. Currently this project is undergoing step three in phase one, which is the (NRD) environmental assessment reports. The exact steps that need to be taken during the exploration phase are displayed in figure 6. In March of 2026 the Water Board will adopt the preferred reinforcement alternative (Wiegink & Rijkeboer, 2024).

This research adds value to the Mastenbroek-IJssel reinforcement project by offering an additional reinforcement variant, if the results are sufficient and prove successful. Utilizing durable dike reinforcement methods in this project allows theoretical knowledge to be applied to practice in the Mastenbroek-IJssel project.

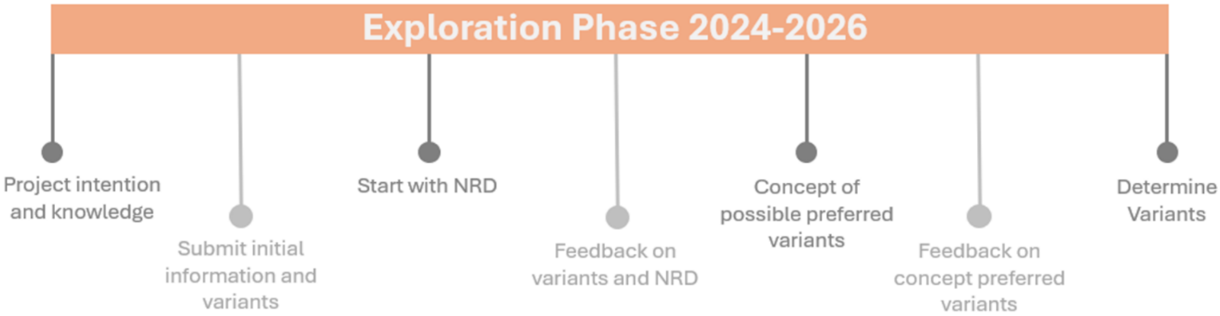

Figure 6. Procedure of current phase of the Mastenbroek-IJssel project (Wiegink & Rijkeboer, 2024)

2 Theoretical Framework

2.1 Current Situation of the Mastenbroek-IJssel Dike

The Mastenbroek-IJssel dike reinforcement project is located between Spooldersluis in Zwolle and the junction of N765 and N760 in IJsselmuiden. This dike trajectory protects the Mastenbroek polder from the IJssel River, which poses risks from upstream river runoff and water surges from the IJsselmeer. Currently, the Mastenbroek-IJssel dike fails to meet the required 1:3000 water safety standard (Wiegink & Rijkeboer, 2024). This dike reinforcement project is part of the High-Water Protection Program (Wiegink & Rijkeboer, 2024).

Figure 7. Map of minimal water safety standards for primary dikes. The project location Mastenbroek-IJssel is displayed in black. (Normering, n.d.)

2.1.1 Dike Trajectories

The Mastenbroek-IJssel dike trajectory was divided into 20 sections, as shown in figure 8. The division of the twenty sections is used for technical calculations of the proposed reinforcement alternatives. The 20 sections were then consolidated into six groups based on similar technical characteristics, which can be seen in figure 9. It is possible that all variant studies can efficiently be made based on the consolidated six-dike trajectories. However, the technical calculations should be made to the precision of the 20 individual dike sections (van Meekeren et al., July 2024).

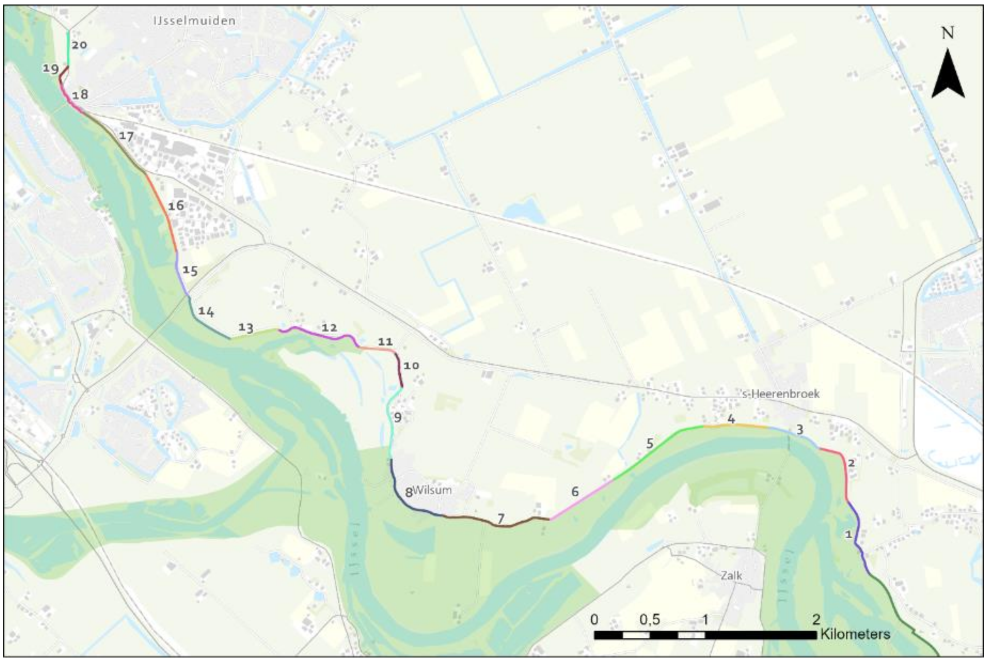

Figure 8. Mastenbroek-IJssel dike trajectories (van Meekeren et al., July 2024)

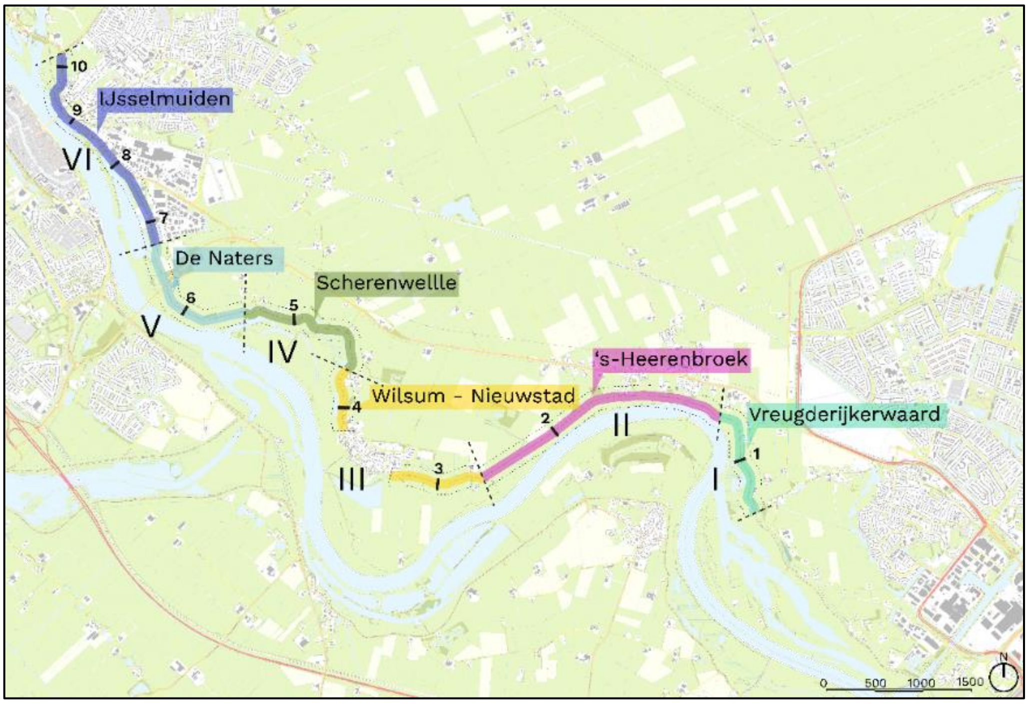

Figure 9. Sub-sections of the Mastenbroek-IJssel dike reinforcement (van Meekeren et al., July 2024)

The selection process and the chosen dike trajectory for further examination in this study are detailed in section 3.2. In the selection process, an analysis of the current cross-sections, soil parameters, and potential failure mechanisms for each of the six trajectories will be conducted to select the most suitable for durable dike reinforcement. Once chosen, an optimal robust reinforcement alternative will be developed for the selected trajectory.

2.1.2 Flood Risk

The required design flood scenario for this project location is an occurrence of 1:3000 years. Discharge from the IJssel River, De Vecht, and the Ketelmeer are all hydraulic influences throughout this dike trajectory. During the VKA phase, hydraulic experts found that storm-dominated high water levels from the IJsselmeer are the decisive weather event to most accurately represent the scenario of 1:3000 years. Figure 10 displays the flood wave, which is a representation of the high water levels in the IJsselmeer for an occurrence of 1:3000 years. As both lakes are directly connected, the hydraulic conditions of the IJsselmeer will also be taken into account for the Ketelmeer in this study. The hydraulic conditions for the IJssel River and De Vecht considered in the research were retrieved from the WDOD and are based on a scenario of 1:1000 years. The probability that a storm-dominated event of 1:3000 years and a river discharge of 1:3000 years occurring simultaneously would be extremely rare. For this research, it was advised to consider the storm-dominated event of the IJsselmeer for a scenario of 1:3000 years and a more frequently occurring river discharge, as this would be a more realistic occurrence. More detailed data on the specific hydraulic parameters considered in this research can be referenced in Appendix 9.

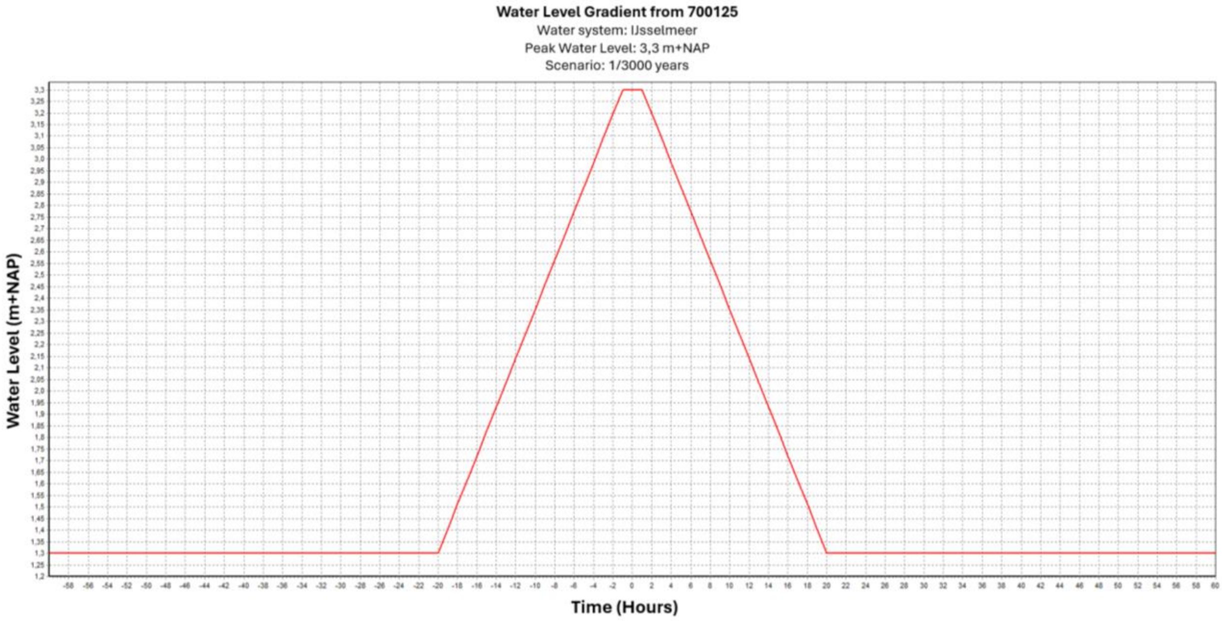

Figure 10. IJsselmeer flood wave for the scenario 1:3000 years (de Hoop, 2025)

2.1.2.1 Elevation and Land Use

Elevation and land use are both variables that influence the flood risk of an area. Elevation is used to determine flood depth, while land use influences the costs of flood impacts. For example, a dike breach in a -1m NAP area would have lower effects than in a -5m area with the same hydraulic speed. Critical flood depths and a flood path can be observed when comparing figures 11 and 12, as water flows to the point of least resistance.

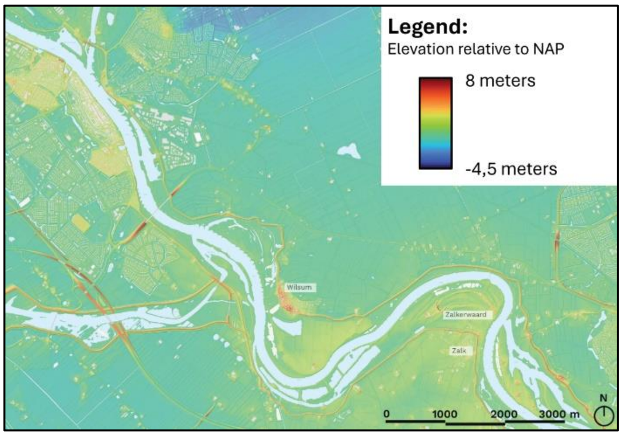

Figure 11: Mastenbroek-IJssel land elevation map (Land id, 2024)

The SSM2017 model, which computes the costs resulting from flood damages, is used in determining the risk value for an area. The risk value then has a direct impact on the water safety standard. The results of the SSM2017 model will also be used for the cost-benefit analysis to determine whether a durable dike alternative is appealing. The findings of this can be found in section 4.6.

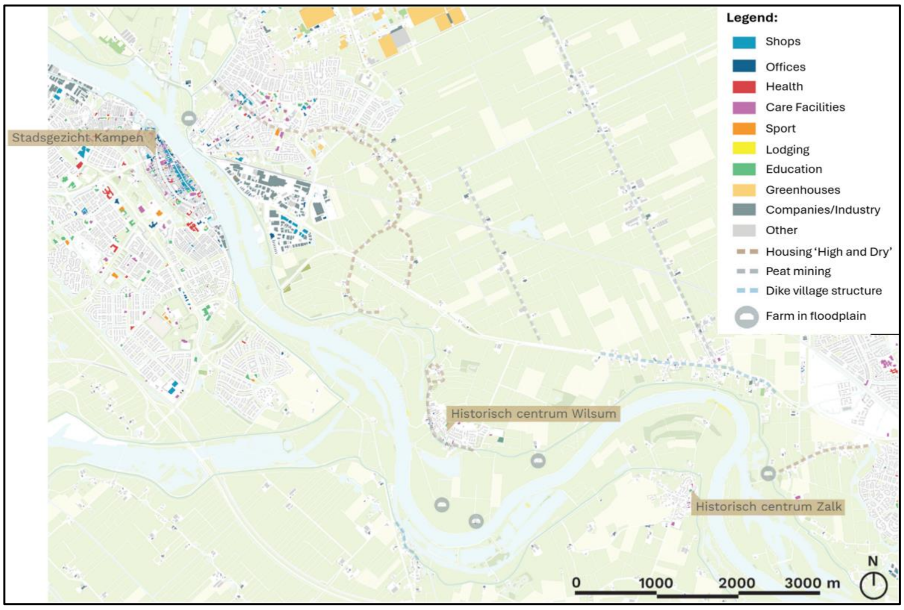

Figure 12. Land use map of Mastenbroek-IJssel project location (Land id, 2024)

2.1.3 Nature 2000 and (NNN)

Nature 2000 areas in the Netherlands are locations with strict restrictions to preserve biodiversity. The Netherlands Nature Network (NNN) of nature reserves throughout the Netherlands focuses on connecting nature reserves to improve biodiversity (CLO, 2018). Although both Nature 2000 and NNN have many similarities, they both have a unique set of regulations. The Mastenbroek-IJssel project location is in both an Nature 2000 and a NNN area. Constructing within these areas comes with challenges; however, it also creates opportunities in which nature forward solutions are more attractive.

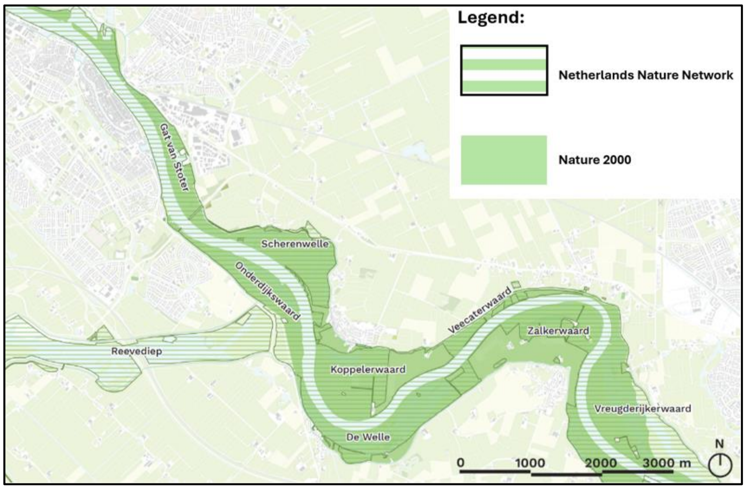

Figure 13. Map displaying that the project location Mastenbroek-IJssel is located in a Nature 2000 and an NNN area (Land id, 2024)

2.2 Project Requirements

The Mastenbroek-IJssel dike reinforcement project requirements have been divided into technical requirements and functional requirements. The technical requirements focus on the design requirements for the dike reinforcement and assumptions made. The Functional requirements focus on what the reinforcement alternative should achieve.

2.2.1 Technical Requirements:

In table 2 below, the technical requirements for durable reinforcement alternatives are provided. These requirements are based on guidelines set forth in the given references for each requirement. Some of the technical requirements apply to all reinforcement designs for the project location. However, some are additional requirements that only apply when considering a durable solution.

Technical Requirement	Source
Hard constructions within a dike reinforcement must have a design life of 100 years. With the realization being in the year 2030, the variant must be designed for the year 2130.	(van Meekeren et al., July 2024)
[BS-00008] The serviceability of the dike reinforcement must be at least 50 years from the moment of completion if only considering natural reinforcement measures. 50 year serviceability does not apply in the case of hard constructions.	(van Meekeren et al., July 2024)
Outer slope of 1:4	(Beoordelingssessies, 2024)
Inner slope of 1:3	(Beoordelingssessies, 2024)
[BS-00018] Maximum slope steepness 1:3	(van Meekeren et al., July 2024)
[BS-00036] Verges should have a slope between 1:20 and 1:40	(van Meekeren et al., July 2024)
The maximum slope length is 17 meters; this requirement was implemented so that the mowing machines can properly maintain the dikes. The mowers are able to cover a maximum length of 17.5 meters.	(Beoordelingssessies, 2024)
The required dike height varies per dike section. Dike sections west of Wilsum fail to meet height requirements. This is due to wind patterns, which cause more intense golf conditions in the western dike sections.	Refer to Figure 9. (Wiegink & Rijkeboer, 2024)
[BS-00037] Minimum verge width of 4 meters	(van Meekeren et al., July 2024)
Maintenance path 4 meters in width	(Beoordelingssessies, 2024)
[BS-00005 & BS-00017] Minimum crest width of 4 meters	(van Meekeren et al., July 2024)
Ditch displacement must be a minimum of 4 meters	(Beoordelingssessies, 2024)
All vertical structures will have a buffer zone of 10m	(Beoordelingssessies, 2024)
Spatial use must be measured from the reference line, which is from the outer crest line to the inner tow and outer toe.	(Beoordelingssessies, 2024)
Temporary work road is not considered in the spatial use	(Beoordelingssessies, 2024)
An overtopping flow rate value of 10 l/s/m is allowable and 1 l/s/m is preferred.	(van Meekeren et al., July 2024)
During the initial design calculations it is not required to factor in subsidence. Subsidence is taken into account afterward as a surcharge on the calculated crown height. The expected subsidence is included in the design height only when the crown is part of the dike reinforcement.	(van Meekeren et al., July 2024)

Table 2. Technical requirements for Mastenbroek-IJssel durable reinforcement variant

2.2.2 Functional Requirements:

Functional Requirement	Source
The proposed reinforcement alternative must solve the water safety issue. The dike currently does not meet the water safety standard of 1:3000	(Wiegink & Rijkeboer, 2024)
The proposed reinforcement alternative must be technically feasible	(Wiegink & Rijkeboer, 2024)
In relation to the cost-benefit analysis, the proposed reinforcement alternative is cost-effective	(Wiegink & Rijkeboer, 2024)
Prevention of any present failure mechanisms such as piping, instability and overtopping due to insufficient dike height is considered in the proposed alternative	(Wiegink & Rijkeboer, 2024)
The proposed reinforcement alternative must make the dike section more durable	Refer to section 1.6.1
It is expected that the reinforced dike can withstand 0.3 meters of water level rise in the Ijsselmeer, considering the reference year of 2080	(van Meekeren et al., July 2024)

Table 3. Functional requirements for Mastenbroek-IJssel durable reinforcement variant

2.3 Boundary Conditions

The Mastenbroek-IJssel dike reinforcement has specific conditions that must be upheld along with additional conditions when considering a durable dike alternative. The following boundary conditions apply;

- The final robust reinforcement alternative must sustain the estimated hydraulic conditions of the IJssel River, De Vecht and IJssel Lake according to data provided by WDOD. In which some of this data was retrieved from Rijkswaterstaat.
- The reinforcement alternative should also sustain a relative water safety standard of 1:3000 for the reference year 2080 (Wiegink & Rijkeboer, 2024).
- The end design product must be achievable considering environmental requirements for Nature 2000 and the Netherlands Nature Network.
- The WDOD would consider the relocation of infrastructure or property markings on or next to the dike if feasible (WDOD, 2024).
- The spatial constraints of the selected dike trajectory must be upheld in the durable dike design.

2.4 Stakeholder Analysis

Stakeholders are vital to a company's or projects success. Only defining said stakeholders is not sufficient; their roles, interests and influence should also be outlined (Mendelow, 1981). In table 4, stakeholders were identified for the Mastenbroek-IJssel project, considering a robust reinforcement variant. The role and positive/negative impacts of each stakeholder were also determined. A Mendelow's power interest matrix was then created, as seen in figure 14, with the determined data from table 4. Stakeholders often influence the design process and variant selection; identifying them and their effects improves the chance of the project's success.

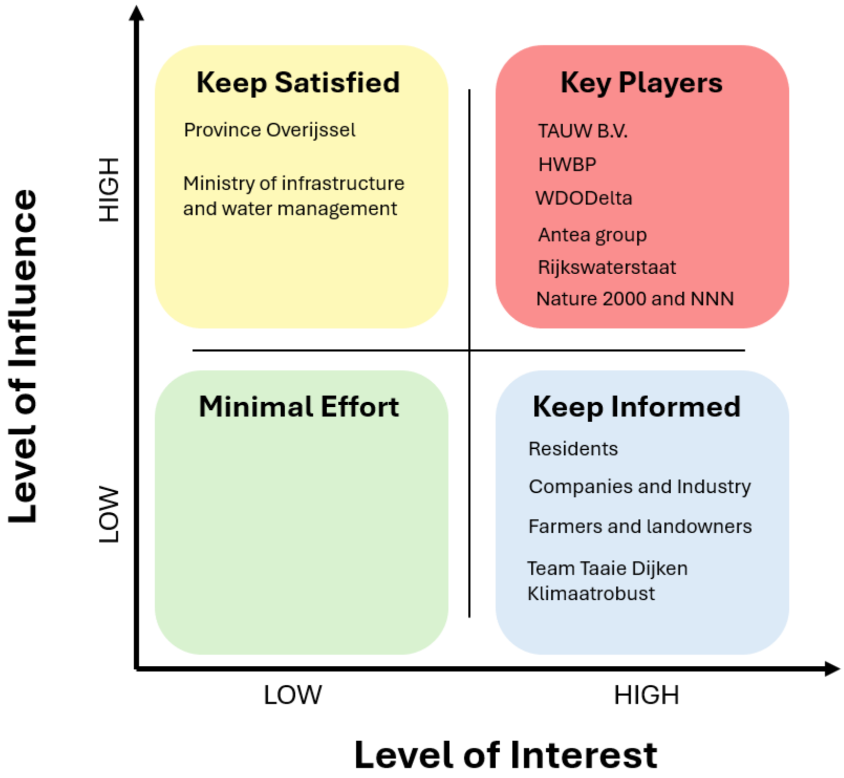

Figure 14. Mendelow's power interest matrix for Mastenbroek-IJssel considering a durable dike variant

2.4.1 Stakeholder Identification

Stakeholder	Role/Responsibility
HWBP (Hoogwater bescherming programma)	The HWBP is an alliance in the Netherlands that aims to have all dikes meet water safety standards by the year 2050. Yearly, the HWBP funds 10 million euros for research for innovative dike solutions (HWBP, 2025).
(WDOD) Waterschap Drents Overijsselse Delta	The water board is responsible for managing the dike reinforcement project. They provide gathered data about the current dike situation, organize research for promising reinforcement alternatives, environmental reports and technical detailing of final alternatives (WDOD, 2025). The water board is also responsible for testing the dikes to make sure they meet water safety standards (D. Janssen, personal communication, February 27, 2025).
TAUW B.V.	TAUW is an engineering consultancy firm that is involved in the exploration phase of the Mastenbroek-IJssel dike reinforcement project, with a focus on the research and detailing of alternatives.
Antea group	Antea is an engineering consultancy firm also assisting with the exploration phase of this project.
Province Overijssel	The province is responsible for zoning plans, maintaining clean groundwater and managing droughts and flooding (Waterbeheer en Klimaatadaptatie, n.d.).
Rijkswaterstaat	Rijkswaterstaat is responsible for maintaining dikes and giving rivers more space within the Netherlands (Waterbeheer in Nederland, 2024).
Residents of the areas along the dike between IJsselmuiden and Zwolle	The residents within the project area must be protected from the IJssel River. A dike reinforcement will reduce flooding risks, which makes the area safer to live in. However, changes to the landscape and temporary inconvenience due to construction could occur as a result of this project. During the exploration phase the residents input on the alternatives is encouraged.
Companies and Industry	Companies and industry areas are responsible for providing their needs and opinions during the exploration phase. This helps ensure that they experience minimal inconvenience.
Farmers and Landowners	The adjustment of property lines is a possibility due to the presence of farmland next to the dike. The landowners are subject to appropriate compensation.
Nature 2000 and NNN organizations	The chosen reinforcement alternative must meet all regulations set forth by the environmental organizations. The organizations are responsible for communicating clear guidelines.
Ministry of Infrastructure and	This ministry is responsible for policy, implementation, and inspection. They oversee (KNMI) the Dutch meteorological institute that advises on weather events and sea-level rise (Ministry of Infrastructure and Water Management, 2024). The Ministry is also responsible for assigning water

Water Management	safety standards to locations based on a detailed risk assessment (D. Janssen, personal communication, February 27, 2025).
Team Taaie Dijken Klimaatrobuust	This team is an alliance of organizations that work together to research and implement durable dikes. This team consists of the following organizations; HAN University of Applied Sciences, TU Delft, Deltares, STOWA, Waterschap Rijn en IJssel, Rijkswaterstaat, HWBP, TAUW, Furgo, HHSK, HHNK, Waterschap rivierenland, H+N+S, Dura Vermeer, Ploegam and Aveco de Bont.

Table 4. Impact analysis of stakeholders for the Mastenbroek-IJssel reinforcement project considering a durable variant

2.5 Soil Properties Analysis

An analysis of soil types present in the Mastenbroek-IJssel project location ensures accurate models for this research. Considering a robust reinforcement measure, this data is used for simulating a dike breach and a slip of the inner sliding plane caused by macro-instability. The areas between Zwolle and IJsselmuiden mainly consist of sand, clay and peat. As there are many varieties of soil, each type of soil within the project area is identified in figure 15.

Figure 16 displays the soil cross-section following the full dike trajectory, which was obtained using Dinoloket's BRO REGIS II v2.2.2 feature. The overview of the soil cross-section is shown from a depth of 5 m to -100 m N.A.P.

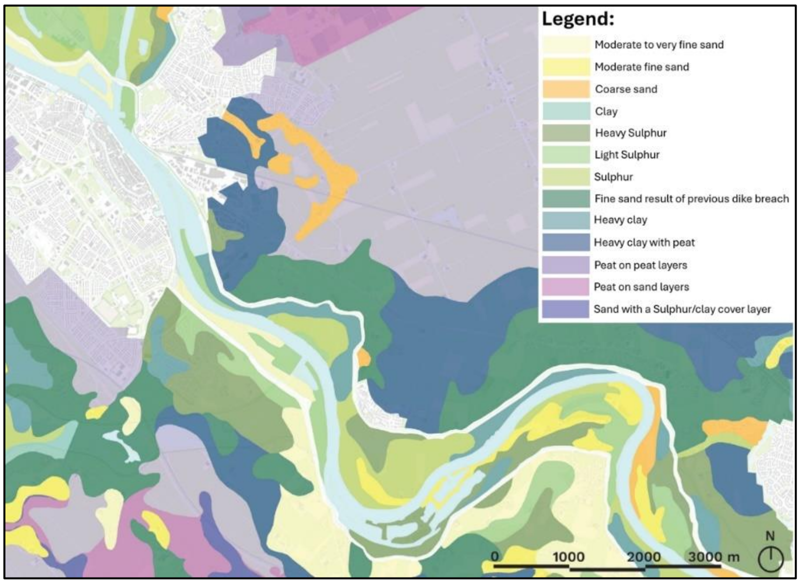

Figure 15. Soil type overview of the Mastenbroek-IJssel project location (Land id, 2024)

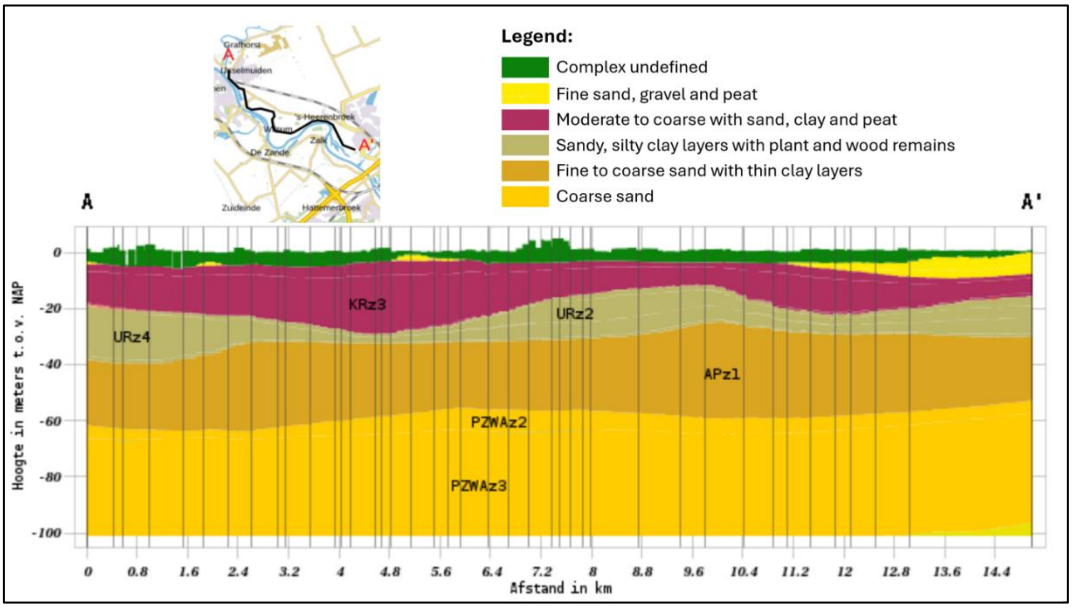

Figure 16. Hydraulic-geomorphic cross-sectional overview of dike trajectory using REGIS II v2.2.2 (Ondergrondmodellen, n.d.)

More specifically, CPTs, mechanical borings, and hand drillings were conducted along the entire dike trajectory in order to obtain precise soil characteristic values for the materials within and surrounding the dike. To classify the soil types and determine their strength, laboratory tests were conducted on the soil samples, including triaxial, compression, sieve analysis, water content, organic matter content and Atterberg limits. The characteristics properties of each type of soil found in the study area are shown in figure 17. The clay used for the dike material starts after +0.5 NAP, and all clay below this limit is Holocene clay, whether homogenous or not (Straver & Bisschop, 2024).

The material characteristics shown in figure 17 are also used to define the soil parameters for the macro-stability calculations. The implementation of these characteristics can be referred to in section 4.2.

Material Characteristics:	$\gamma_{nat;gem}$ [kN/m³]	$\gamma_{dr;gem}$ [kN/m³]	S_{kar} [-]	m_{kar} [-]	POP_{kar} [kPa]	ϕ_{kar} [°]
Dike Material; Sand	17,9	15,4	n.v.t.	n.v.t.	n.v.t.	
Dike Material; Clay	18,3	18,3	0,33	0,92	31,9	29,7
Peat (under the dike)	10,5	10,5	0,38	0,52	22,2	
Peat (next to the dike)	10,5	10,5	0,38	0,52	10	
Clay, silty (Homogenous)	14,4	14,4	0,28	0,93	22,2	
Clay, silty	17,5	17,5	0,31	0,70	27	
Sand (Holocene/Pleistocene)	19,5	17,5	n.v.t.	n.v.t.	n.v.t.	

$\gamma_{nat;gem}$	*natural/field moisture volumetric weight of soil type*
$\gamma_{dr;gem}$	*dry volumetric weight of soil type*
S_{kar}	*characteristic value of undrained shear strength ratio of soil type*
m_{kar}	*strength-increase coefficient*
POP_{kar}	*characteristic value of the Pre-Overburden-Pressure*
φ_{kar}	*characteristic value of the effective angle of internal friction*

Figure 17. Lab tested and analyzed soil characteristics for the Mastenbroek-IJssel dike trajectory (Straver & Bisschop, 2024)

2.6 Dike Failure Mechanisms

During the process of determining the promising alternatives (VKA) for this project the failure mechanisms were identified. As dikes age and weather they can break in many different ways, known as failure mechanisms (Wiegink & Rijkeboer, 2024). Figure 18 displays a map created during the VKA phase of this project, which outlines the areas and failure mechanisms that are present or could be expected. Instability, piping and overtopping are the anticipated methods in which the IJssel dike could fail. Each of these failures will be explained. However, it is important to note that these are only the dike failure mechanisms that apply to this project; there are in general many more.

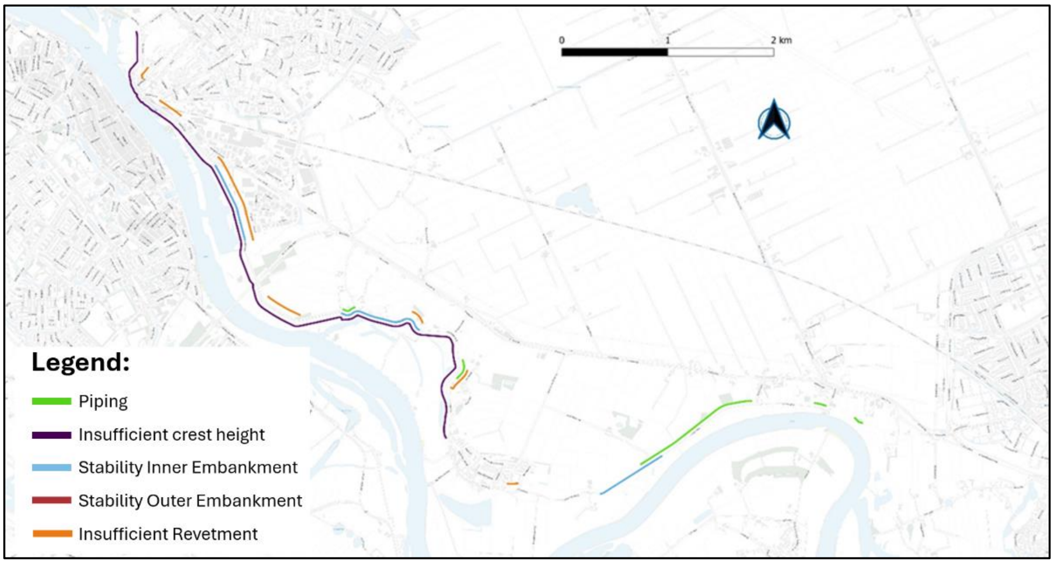

Figure 18. Failure mechanism assessment map for Mastenbroek-IJssel (Wiegink & Rijkeboer, 2024)

2.6.1 Overtopping and Wave Impact

Insufficient dike height implies that overtopping or wave impact would in this case occur during peak conditions of a hydraulic event, which occurs once every 3,000 years. Erosion of the dike occurs in the event of overtopping and wave impact, often in the event of high tide or peak conditions. Traditional dikes often use stone revetment or a grass cover, and because they are not built to withstand such large volumes of water, they frequently collapse (Wiegink & Rijkeboer, 2024). Whereas, a durable dike does not fully collapse under extreme overtopping or wave impact circumstances and remains able to retain normal water conditions. Figure 19 and 20 depict the impact of overtopping a wave impact in a modeled scheme.

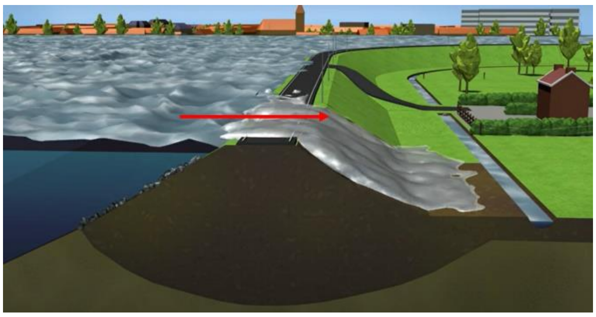

Figure 19. Overtopping
(Unie van Waterschappen, 2014)

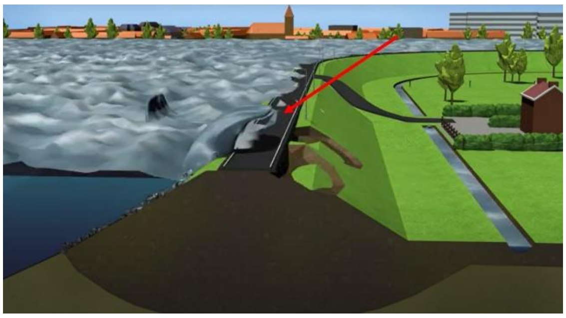

Figure 20. Wave Impact
(Unie van Waterschappen, 2014)

2.6.2 Piping

Piping typically occurs when water levels are excessively high or during extreme weather events. As water travels toward the point of least resistance, the increased water pressure may cause the water to create a channel under the dike, allowing the pressure and water to escape. Sand and other soil particles are also carried by the water. The displacement of water and soil gradually increases; this loss of sediment makes the dike unstable and can cause a collapse (Wiegink & Rijkeboer, 2024). The increasing water pressure in the overburdened soil package can lead to a situation where the weight of the overburdened soil is lower than the water pressure. When the soil package and water pressure fall out of equilibrium, floating or erosion can occur. A pipe under the dike is formed due to this backward water pressure. The piping effect normally forms between two soil layers of different properties and begins to form on the polder side of the dike.

Figure 22 shows the water and soil discharge from a ‘piping’ output point. This potential channel was discovered on November 23, 2023, within the Mastenbroek-IJssel project trajectory. Two more smaller output piping points were found after tests were conducted. This is just one example of the evidence that piping is a present failure mechanism within this project location (TAUW et al., 2024).

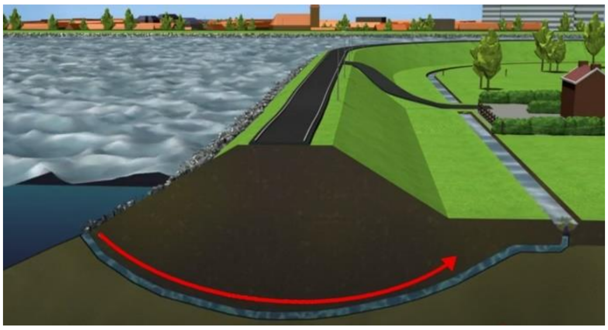

Figure 21. Piping (Unie van Waterschappen, 2014)

Figure 22. Piping Mastenbroek-IJssel (TAUW et al., 2024)

2.6.3 Instability

Both the inner and outer slopes of a dike can experience instability. High water levels can cause dikes to become oversaturated, and once the water levels have subsided, the saturated parts of the dike collapse due to the offset of forces (Wiegink & Rijkeboer, 2024). Once large parts of the dike disconnect or the clay cover is breached, the speed at which erosion occurs increases, and a total collapse of the dike can be expected.

Inner dike instability occurs during extremely high water levels and events. If the dike is unable to withstand the additional load acting on it, a slip in the failure plane due to excess pressure may occur, which leads to the dike collapsing (Wiegink & Rijkeboer, 2024). Compared to solid clay dikes or dikes with additional clay covers, berms, or hard structures, sand core dikes experience both inner and outer instability at an accelerated pace.

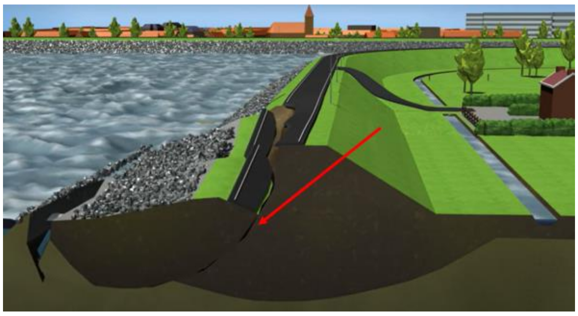

Figure 23. Outer slope instability (Unie van Waterschappen, 2014)

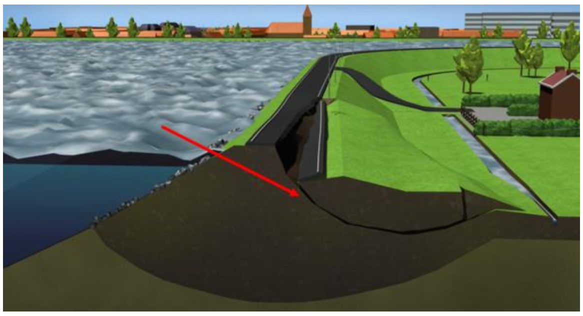

Figure 24. Inner slope instability (Unie van Waterschappen, 2014)

2.7 Defining a Durable Dike

Durable dikes have a slower, more controlled and predictable breach process (Waterforum, 2024). This can be obtained through increased ductility of soil, the implementation of hard constructions, elongated foreshores and golf reduction. Additional possibilities will be researched in this durable dike variant study for the Mastenbroel-IJssel dike.

During an expert workshop on October 26th, 2023, the fundamental characteristics of a durable dike were determined. In the event of a breach durable dikes are primarily designed to reduce the impact of flooding. The cross-section of a breach is reduced in dikes with robust reinforcement measures, such as sheet piles and clay, as researched in the case study of the Pleij dike. These insights were the concluding ideas of the experts during a 'taai dijk workshop' (Podt, 2023). According to the expert responses, a robust reinforcement alternative should meet the twelve identified criteria, which are shown in order of importance in figure 25.

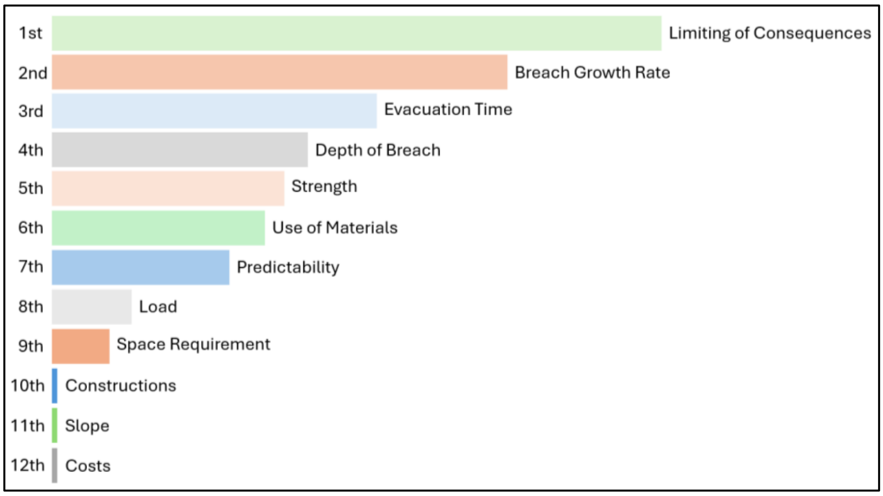

Figure 25. Expert responses of the fundamental criteria of a durable dike (Podt, 2023)

2.8 Failure Path

The visualization of a failure path allows for the assessment of how constructions may fail and how the process can be prevented or delayed. A failure path also outlines the connection between certain failure mechanisms and how they may strengthen each other, leading to an accelerated breaching process (Meindert Van et al., 2022). To properly determine a proactive robust reinforcement alternative for the Mastenbroek-IJssel dike, the possible failures and processes should be identified. A fault tree of potential failure paths for the Mastenbroek-IJssel dike is provided in Appendix 1. Failure paths developed by Deltares for individual failure mechanisms were analyzed to form this cumulative failure path, which includes all of the failures present in the Mastenbroek-IJssel dike trajectory. Piping, macro-instability, overtopping and wave impact are all failure processes displayed in the failure path in appendix one for the Mastenbroek-IJssel dike. The failure path also takes into account how the failure processes could be affected, considering the influence of durability, such as delays in the breaching process. In section 4.1, a failure path for a sub-section of the Mastenbroek-IJssel dike is provided, considering a durable reinforcement alternative and the specific effects the robust elements have on the failure processes present.

A failure path can be defined in phases: initiation, continuation, progression, detection, corrective measures if possible, and ultimately breaching (Meindert Van et al., 2022). The acceleration of the breaching process is influenced by factors such as material composition, hydraulic conditions and breaching path based on the active failure mechanism. Dike failure processes and flood impacts for this research do not consider the interception of corrective measures to prevent breaching. In the design process only an un-intercepted failure process will be considered.

2.9 Dike Breaching Process

The initial breach size is an estimate, and the results of the breaching process will vary depending on the dike material and hydraulic conditions. The size of a breach influences the volume of water that enters the polder. There are three stages to a dike breach: phase zero, breach initiation which can vary depending on the active failure mechanism; the deepening phase, when the breach gets deeper while remaining the same in width; and the widening phase, when the breach stops getting deeper and widens. Phase zero is primarily dependent on the dike's composition; the deepening phase is a rapid process that starts after phase zero. Phase zero for sand occurs within minutes, whereas clay may take up to an hour (Verheij et al., 2003). It is therefore reasonable to anticipate a delay in the breaching phases when considering a durable dike section with a more ductile breaching process. A visualization of the three breaching stages can be seen in figure 26.

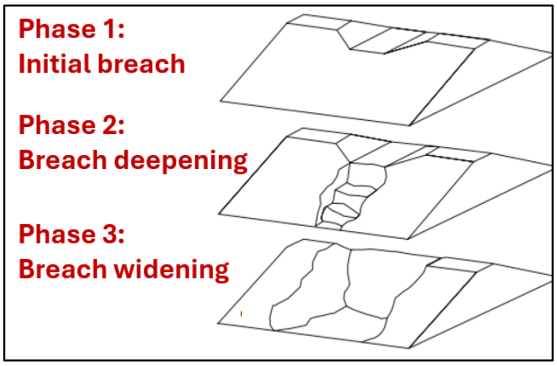

Figure 26. Clay dike breaching stages (Zhu, 2006)

Based on the process by which they break, dikes can be classified as either brittle or durable. Brittle dikes undergo an abrupt breaching process with minimal delay throughout the failure path processes. Whereas ductile breaches are able to absorb more force and energy, delaying the breaching process. Any component in the makeup of a dike structure that creates an obstruction delaying the breaching and flooding process increases the dike's durability.

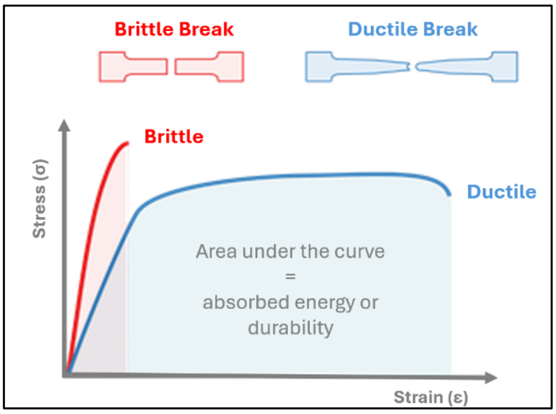

Figure 27. Deformation curve of materials (den Heijer, 2023)

Formula 1 is used to determine breach width and the discharge rate at which flood waters will enter the polder (Visser, 1998). The method of Verheij and van de Knaap is implemented in the 3Di software, which is used in this research for flood modeling. Breach and discharge rate are influenced by soil composition, dike dimensions, and hydraulic conditions. Soil composition plays a direct role in the speed at which phase three in the breaching process occurs. Phase three is represented by factor B in formula 1. The outcome of breach width B in 3Di is modeled based on a pre-defined initial breach width and the erosion speed factor of the identified soil type. Further specifications on breach modeling within 3Di, as well as flood results of the modeled breach, are provided in section 4.3.

$$Q = m * B * H * \sqrt{2 * g * (H)} \qquad (1)$$

Where;

Q = water discharge through the breach $[m^3/s]$
m = discharge coefficient [-]
B = breach width [m]
H = height difference (outer water level - max. breach depth) [m]
g = gravity $[m^2/s]$

2.10 Failure Probability Requirements at Cross-Sectional Level

Each possible failure mechanism has specific failure probability requirements based on the corresponding failure probability factor. For this research, the calculations needed are relative to the failure mechanisms' insufficient crest height and inner macro-instability. This section provides relevant data and knowledge needed for calculations made in the report sections 4.2 and 4.4.2.

Insufficient crest height has a failure probability factor of 0.24 [ω], as set forth in the guidelines of the WBI 2017 (RWS, 2019). Within this research, the required HBN is determined to verify the reinforcement variants' satisfaction with the requirements for insufficient crest height at a cross-sectional level.

The stability of the dike design is quantitatively determined through the required design safety factor. The inner macro-stability safety factor is needed for the processes of this research. Formula 4 is used to determine this safety factor and the safety factor results can be found in table 6. The safety factors per failure mechanisms differ, as each one has a different failure probability factor. It was set forth in the WBI 2017 that the failure probability factor for inner micro-instability is 0.04 [ω] (WBI, 2021). This factor is used for determining the failure probability requirement per cross-section for a failure mechanism per year [ρ eis,dsn]. The length effect factor [N] must also be obtained as an input for finding ρ eis,dsn. Formulas 2 and 3 below are used to find the values of N and ρ eis,dsn. The results of the failure probability requirements for inner macro-stability can be found in table 5. The calculation processes and results below can all be referenced from the TUN document from the VKA phase of this project (van Meekeren et al., July 2024). The application of this safety factor can be found in section 4.2.

$$\text{Peis, dsn} = \frac{\text{Pmax.}\omega}{N} \tag{2}$$

Where;
Peis,dsn= failure probability requirement per cross-section for a failure mechanism per year
Pmax= Maximum allowable flood chance for the dike trajectory (per year); 1:3000
ω= failure probability factor for inner micro-stability (-); 0.04
N= Length effect factor (-); formula 3

$$\text{N} = 1 + \frac{a*L}{b} \tag{3}$$

Where;
a= 0.033 [constant]
b= Length of trajectory with presence of failure mechanism [m]; 50
L= Full length of dike trajectory [m]; 1,4620

Failure Mechanism	N-factor [-]	ρ eis,dsn (cross-section requirement) [chance/year]	β eis,dsn [-]	Years [1/cross-section requirement]
Inner macro-stability	10.6	1.25E-06	4.71	800,000

Table 5. Failure probability requirements results for the scenario 1:3000 years (van Meekeren et al., July 2024)

$$\gamma r = \gamma b * \gamma d * \gamma n \tag{4}$$

Where;
γr = Safety factor required for strength
γb = schematization factor; (this value ranges between 1.0-1.3; due to sufficient data on dike geometry, soil composition, and hydraulic conditions, it was determined that this factor be 1.05)
γd = Model factor; (constant for the method of Uplift-Van; 1.06)
γn = Damage factor; (0.15 x β eis,dsn + 0.41)

Failure Mechanism	Model Factor $[\gamma d]$	Schematization Factor $[\gamma b]$	Damage Factor $[\gamma n]$	Required Safety Factor $[\gamma r]$
Inner macro-stability	1.06	1.05	1.12	1.24

Table 6. Required safety factor results for inner macro-stability (van Meekeren et al., July 2024)

3 Methodology

3.1 Methods of Research

A pathway approach will be used for this variant study's research procedures. The results of each of the sub-questions will determine the main research question's outcome. The primary research question, which is discussed in section 1.6.1, will result in recommendations for improving the durability of a portion of the Mastenbroek-IJssel dike. The durable reinforcement alternative can serve as a brand-new reinforcement variant or as an addition to one of the previously proposed variants in the (VKA). The instruments and methods used in this variant study will be discussed below in chronological order.

Research Tool:	Description:
3Di	3Di is used to model the flood depth and speed of flooding in the polder due to a dike breach. Considering the multiple situations. Original models for this dike trajectory are provided by the water board.
AutoCAD	AutoCAD is a design software in which technical drawings can be made. For this research, AutoCAD is used to create a technical visualization of the final durable dike design.
D-Stability	D-Stability is used to examine the structural stability of the dike considering the current cross-section, proposed reinforcement variants and the robust reinforcement variant.
Microsoft Excel	Microsoft Excel is used for creating the project planning and the viewing of technical data.
Microsoft PowerPoint	Microsoft PowerPoint is used to create figures, flowcharts and the brainstorming of variants.
Microsoft Word	Microsoft Word is used to document the research process and findings.
QGIS	Used to adjust raster data from the flood model results so that it can be used as input in the SMM-2017 model. This program is also used to present information in an organized way.
Riskeer Version 23	The software Riskeer is used in this research to determine the needed crest level in regard to the reduced flood risk of the durable dike design.
SSM2017 model	The SSM-2017 model is used to determine flood damage and casualties.
TAUW Archive	Technical project-related documents provided by TAUW.
World Wide Web	Research documents for the literature review are retrieved via the WWW from digital archives: Research Gate, TU Delft, HZ Study Materials, and other websites listed in this document's references section.

Table 7. Research tools used during this variant study

3.1.1 Sub-question 1:

Which dike trajectory of the Mastenbroek-IJssel is the optimal area for a durable dike alternative?

A selection is made to determine which of the six dike sections is best suited for robust reinforcement. The method for this sub-question uses a qualitative approach. Technical documents from the VKA phase of the project were supplied by TAUW and will be used for this analysis. The current dike cross-section, present failure mechanisms, proposed reinforcement measures, and the durability of the dike (already taking into account the new proposed reinforcement measures) will be considered when selecting the dike trajectory to further detail. Appendix 2 contains the analysis and selection procedure; the following technical documents will be used: D-Stability model files for current and proposed scenarios, (DODelta, et al., 2025), (van Meekeren, et al., August 2024) and any additional documents used will also be sourced in appendix 2.

3.1.2 Sub-question 2:

What are three reinforcement variants which can increase the durability of the dike section, considering possible robust elements?

A completely qualitative literature review will be conducted to inform on potential robust reinforcement elements. The final conclusions and the three most suitable robust reinforcement alternatives based on the pre-selected dike section will be covered in section 3.3. The complete literature review, including non-selected variants, is available in Appendix 3. These variants will be selected based on their compatibility with the failure mechanisms present, project requirements, boundary conditions, the technical characteristics of the cross-section, and the functional aspects of land use.

3.1.3 Sub-question 3:

What set criteria must the durable dike alternative meet?

By identifying the criteria by which the promising robust alternatives will be evaluated, sub-question three will be addressed. Section 3.4.1 will include the criteria selected and a justification for their selection. The five criteria will be chosen based on significant factors relevant to the current circumstance, particularly for robust reinforcement elements. This qualitative method of selecting criteria is then quantified in response to the fourth sub-question.

3.1.4 Sub-question 4:

Considering the robust elements, which is the preferred durable variant to detail further based on the pre-defined criteria?

Sub-question four is addressed by evaluating the proposed reinforcement variants quantitatively using the qualitative pre-established criteria from sub-question three. A percentage will be assigned to each criteria according to its significance to the stakeholders; the sum of all criteria will be 100%. Based on a ranking system of 1 to 3, the alternatives will then be assigned a color/score for each of these criteria. A score of 1/red indicates that the alternative does not satisfy the criteria, while a score of 3/green indicates that it does. Additionally, all decisions will be justified, and where appropriate, references will be cited. The variant with the highest score from the multi-criteria analysis is the most suitable variant. This process, which is described in section 3.4, can be used to identify the preferred robust reinforcement variant in more detail.

3.1.5 Sub-question 5:

How can the chosen robust reinforcement alternative reduce the impact of the failure mechanisms present within the dike section?

The outcome of sub-question four will be carried over into the method for answering sub-question five. The Mastenbroek-IJssel dike's failure path and the failure mechanisms that the particular dike section must resist are determined by referring to section 4.1. The elements of robust reinforcement will be qualitatively analyzed to determine how they might affect the failure mechanisms within the failure path. How the robust reinforcement might affect any possible delays in the breaching process will also be considered. A fault tree visualization made with PowerPoint is used to present the analysis results.

3.1.6 Sub-question 6:

How does the preferred robust reinforcement variant limit the consequences of flooding?

Sub-question six is approached using a combination of quantitative and qualitative methods. The hydraulic speed at which flood water enters the polder and flood depths as a result of the breaching process will be obtained using the program 3Di. Values such as dike material, hard constructions, initial breach width, and maximum breach depth can be altered to obtain flood data in 3Di. The dike's structural aspects, cross-sectional dimensions, and macro-stability can be modeled using D-Stability. Conclusions are then drawn by combining model results with theoretical information from experts and literature. The required crest height and the macro-instability of a dike section are directly influenced by the required design norm. A higher design norm leads to the need for higher and, in turn, wider dike cross-sections. A dike model of the durable design and brittle design cross-section are compared, and as a result, sub-question six is answered.

The existing results of calculations made during the VKA phase in compliance with standard literature such as the 'schematiseringshandleiding macrostabiliteit,' will be used as the input values for the D-Stability models. The pre-existing D-Stability models for Mastenbroek-IJssel and the TUN document will be used to create a D-Stability model for the durable dike variant. Henk Verheij's mathematical theory is used in simulating a breach in the 3Di model. The speed of flood occurrence will be taken into account due to its direct relation with flood damage and casualties. A delay in the breaching/flooding process allows more time for evacuation, and the lower hydraulic speed reduces the damage to infrastructure. These possible reductions will be considered in the following sub-question and the results of the main question.

3.1.7 Sub-question 7:

To what extent is a durable dike design a competitive variant?

The outcome of a cost-benefit analysis will be used to determine the result of sub-question seven. This cost-benefit analysis takes into account a number of factors, including material costs, construction processes, flood damage and dike breach casualties. The SSM-2017 model is used to retrieve the last two values; for accurate results, the outputs of the flood data from 3Di are entered into the model. The data will be organized using QGIS. A quantitative reduction for the durable dike is considered in the benefit analysis. This reduction is based on the flood risk results and the robustness index of the final durable dike design. A qualitative explanation of whether a durable dike is more competitive/attractive than a brittle variant will be supported using the quantitative results of the cost-benefit analysis.

3.1.8 Main Research Question:

What is a suitable durable dike design for the Mastenbroek-IJssel dike reinforcement?

The main question will be answered by the concluding results of the earlier sub-questions. A visual model of the final dike cross-section of the design solution will be supplied, along with a qualitative explanation of the final durable dike design. These results can be found in the report section 4.5.

3.2 Dike Section for Further Examination

A durable dike variant will be determined for dike section De Naters. The results of the dike section selection can be seen in table 8 below. A detailed justification of the entire selection process can be found in Appendix 2. This selection process considered durability scores for each dike section based on expected failure mechanisms, the current situation and previously proposed variants from the

VKA phase of this project. The durability scores of each dike segment were determined by analyzing how certain dike elements might, in theory, cause a delay in the failure path.

It is important to mention that in the current situation of the Mastenbroek-IJssel dike, only dike sub-sections ‘s-Heerenbroek, Scherenwelle, and IJsselmuiden-Tasveld experience the presence of inner macro-instability. However, sections that experience a current insufficient crest height will require a heightening reinforcement to reduce the failure of overtopping. Once the height of the dike is increased, it can be assumed that, for most instances, an inner macro-instability failure will become present due to the alteration of cross-section dimensions. In this analysis, the durability score considering the previously proposed reinforcement variants from the VKA phase was also considered. Therefore, the failure mechanism of inner macro-instability was added as a consideration for all sub-sections that currently experience overtopping.

Section De Naters was the only trajectory out of the six dike sections and sub-sections that was critical for every criteria in Table 7. De Naters obtained the lowest durability scores and was one of the sections with the most failure mechanisms. This section offers the optimal situation for structural analysis for a durable dike variant as macro-instability and overtopping are present. Dike section De Naters is the most suitable dike trajectory for carrying out a thorough, durable dike reinforcement study.

Durability Score:

1= Not durable, 2= Slightly Durable, 3= Partly Durable, 4= Sufficient and 5= Very Durable

Dike Section:	**Failure Mechanisms:**	**Durability Current Situation:**	**Durability Considering Proposed Variant:**
1: Vreugderijkerwaard	N/A until 2050	Data not available	Data not available
2: ‘s-Heerenbroek	Macro-instability inner slope and Piping	1	3
3.1: Wilsum-Oost	Insufficient Revetment	Data not available	Data not available
3.2 A: Wilsum- West	Overtopping	1	4
3.2 B: Wilsum- West	Overtopping	2	5
4: Scherenwelle	Overtopping, Piping and Macro-instability inner slope	1	3
5: De Naters	Overtopping, Macro-instability inner slope and Insufficient Revetment	1	2
6.1: IJsselmuiden- Tasveld	Overtopping and Macro-instability inner slope	2	4
6.2: IJsselmuiden-Spoorlanden	Overtopping and Macro-instability inner slope	1	4
6.3: IJsselmuiden- Station	Overtopping and Macro-instability inner slope	1	5
6.4 A: IJsselmuiden-Frieseweg	Overtopping and Macro-instability inner slope	1	2

6.4 B: IJsselmuiden-Frieseweg	Overtopping and Macro-instability inner slope	2	4

Table 8. Dike section selection

3.2.1 Dike Section De Naters

Dike trajectory De Naters is 1.45km in length for this project, according to the QGIS shape file provided by the WDOD. This dike section consists of three sub-sections, identified as sections 13, 14, and 15. More detailed information for each of the sub-sections can be found in appendix 7. For all calculation purposes for this research, the optimization was made to only consider sub-section 14, with the reference point of D115. This optimization was made as section 14 has the most available and complete data. The information available for section 14 includes research on golf reduction through vegetation in the foreshore, a detailed d-stability model, and a fully modeled breach in 3Di. Section 14, along with section 15, also requires the largest height improvement, which is 140cm.

Figure 28. Dike section 14 of trajectory De Naters

Overtopping and insufficient revetment on the inner talud are failure mechanisms present in dike section De Naters. It is also important to mention that in the presence of soil reinforcement an additional failure mechanism of macro-instability arises. The current dike composition is mostly clay within the outer talud and sand within the inner talud, with a thin clay and grass cover. The current situation's durability score is 1, a result of no delay in the potential failure paths. Considering the suggested VKA reinforcement variants, the dike section De Naters has a durability score of 2, which indicates that it is slightly durable. Dike section De Naters could be made more durable by incorporating more robust reinforcement elements.

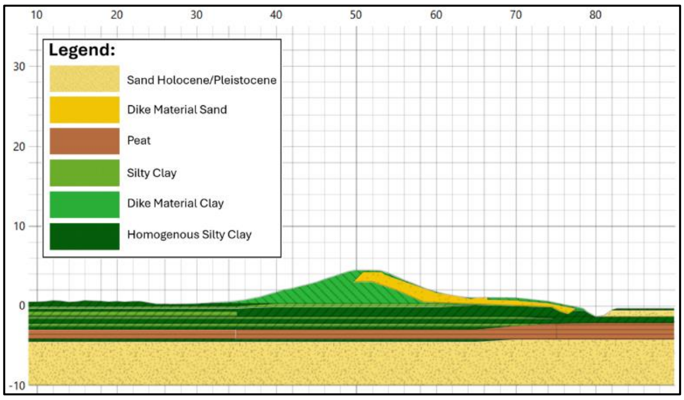

Figure 29. Soil composition and cross-section of dike section De Naters

A technically precise, scaled model of the dike cross-section, including the composition of the soil, is shown in figure 29. The cross-section visualization was made using models from TAUW's D-Stability archives. The previously proposed variants created during the VKA phase of this dike reinforcement project for dike section De Naters are shown in figure 30.

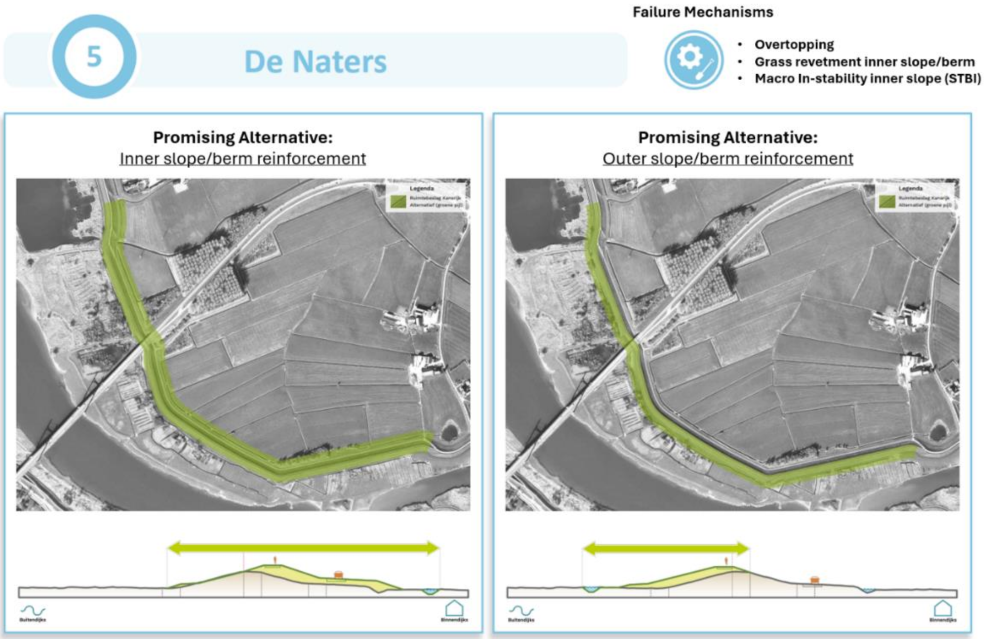

Figure 30. Proposed variants De Naters (DODelta, et al., 2025)

Additionally, this dike section is located west of Wilsum and experiences more severe hydraulic conditions due to wind and current patterns. The spatial factors that should be considered in the robust reinforcement design for this dike section are electrical poles, roadways, an overpass for highway N764, and all of the previously stated boundary conditions and regulations.

3.3 Reinforcement Design Alternatives

The three possible reinforcement variants provided in the following sub-sections were created based on the literature review in appendix 3 and personal ideas based on theoretical knowledge. It is also important to note that these durable dike variants are designed to sustain peak conditions and create delays in the failure path.

These initial design alternatives were presented to experts from the WDOD during a workshop. In the following section, relevant feedback from this expert workshop will be mentioned. For further specifications on the details of this workshop refer to appendix 5.

3.3.1 Durable Dike Reinforcement Variant 1:

This variant implements four durable elements: vegetation on the foreshore, a soil reinforcement to decrease the outer slope, an anchored sheet-pile wall, and an improved revetment. The vegetated foreshore creates a golf reduction, dampening the hydraulic conditions acting on the dike and reducing wave impact. Adding additional soil to create a more gradual outer slope reduces the effect of wave water run-up, creating a delay in overtopping. This improvement also allows the dike to meet height requirements. The installation of a sheet-pile wall in the dike increases the overall stability. In this case, crest height is then considered as the minimum breach depth in a flood model. The anchor of the sheet-pile wall is not load bearing in normal conditions and becomes active when deformation occurs. This occurs when the inner talud erodes due to overtopping, reducing the leverage on the wall due to reduced passive soil pressure. A sheet-pile wall creates a large delay in the failure path and also largely reduces the maximum quantity of water in the polder. Improved revetment helps to counteract the speed at which erosion of the inner slope occurs. Each of the robust elements work together to majorly reduce the impact of flooding in the polder, making this dike design very durable.

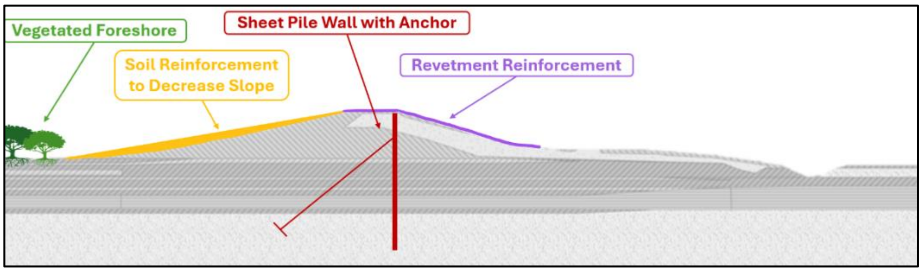

Figure 31. Durable dike reinforcement variant 1

3.3.2 Durable Dike Reinforcement Variant 2:

By implementing a cofferdam inspired hard construction and improving the revetment, the durability of the dike is improved. The cofferdam construction is two sheet pile walls that are interconnected with an anchor. The taller sheet-pile, in this case, is placed in the crown, and the shorter sheet-pile wall is then placed in the outer berm of the dike. This cofferdam construction is very structurally sound as erosion, which occurs to the inner talud during overtopping, does not affect the sheet pile wall. Once erosion of the inner talud has occurred, the hard construction functions as a dam. This is a very expensive construction with a difficult installation process, as the soil of the outer talud must be removed to install the anchor. However, in the event of breaching and overtopping, more of the outer side of the dike remains intact. This decreases the dike reconstruction operations and increases water safety. This system creates a delay or completely stops some steps within the failure path processes. The revetment reinforcement on the crest and inner slope reduces the rate at which erosion occurs, creating an additional delay in the failure path of overtopping. This variant is very durable. However, the cost and construction restraints remain an influencing factor in the implementation of this concept.

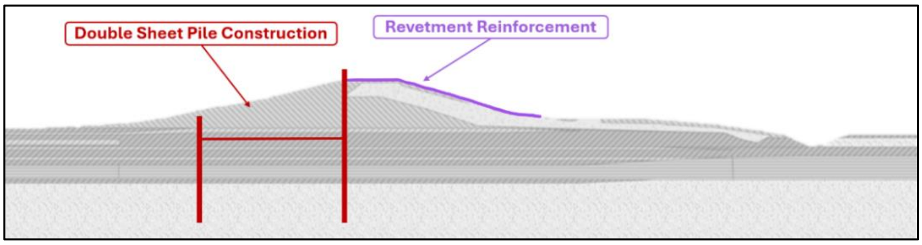

Figure 32. Durable dike reinforcement variant 2

It was advised by the waterboard that the cofferdam construction be relocated. By relocating the taller sheet-pile wall into the inner part of the crest and the shorter sheet-pile wall into the outer slope, the design is made more realistic. This provides a more realistic representation of how a cofferdam construction would be applied in practice. The improved placement of the sheet-pile walls also reduces the amount of excavation needed to place the anchor.

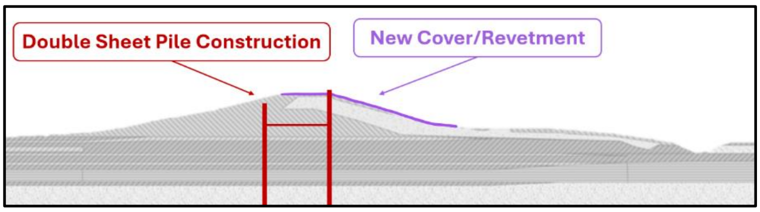

Figure 33. Revised version of durable dike reinforcement variant 2

3.3.3 Durable Dike Reinforcement Variant 3:

The implementation of mix-in-place lime as a soil improvement and a stepped water system with a filter construction is considered in this durable reinforcement alternative. In this scenario, overtopping should not occur during normal hydraulic conditions. However, it is considered to be allowed in the event of extreme weather scenarios -up to the event of 1:3000-. As overtopping can occur, mix-in-place lime is used to counteract the erosion of the crest and inner slope. Implementing lime in the soil reduces the presence of bentonite and increases the soil's erosive strength. Once water flows over the dike it will first be collected in the initial water basin and once full in the second water basin. This allows flood waters to be stored until peak conditions have resided. This design would typically require immense land use; however, in this case, the pre-existing land is given multi-functional uses. The road would be reconstructed inside the first basin, and in normal conditions, it is fully functional; however, during emergency situations, the basin is used for flood water storage. Other road routes are then used for evacuation procedures. Implementing the road below ground level also reduces the effect of noise pollution. The secondary water basin is constructed by widening and deepening the pre-existing canal, working with the concept of 'room for the rivers'. The only additional use of space in this reinforcement is the soil needed to elevate the space between the two water basins. A filter construction is added beneath the secondary water basin to reduce the risk of piping during overtopping. A filter is not needed in the initial basin as the road offers resistance against piping as well as the additional counteracting water pressure in the basin in the event of overtopping. Overall, this is a very durable variant and implements resourceful spatial planning aspects.

The water board advised that it would be more feasible in this case to implement a clay soil improvement instead of the use of lime. It was also mentioned that the water storage gained by this design is minimal in the occurrence of extreme weather events. Therefore, a double dike placed approximately 100m away from the primary dike would be more efficient for storing flood waters.

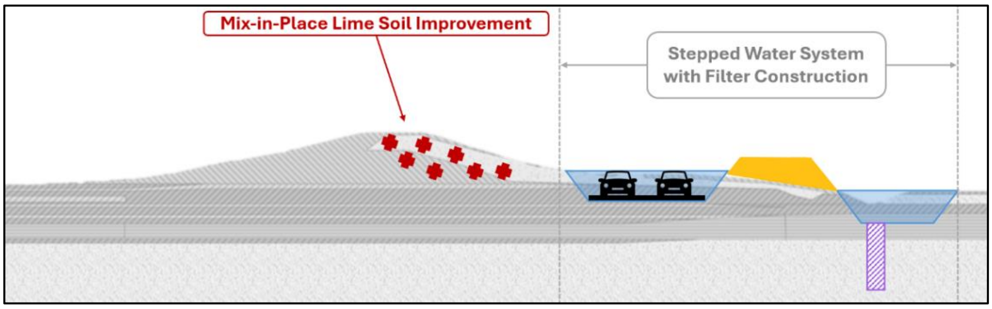

Figure 34. Durable dike reinforcement variant 3

3.4 Multi-Criteria Analysis of Alternatives

The multi-criteria analysis is used to determine which of the three proposed durable dike variants is the most feasible in terms of execution potential. Criteria for this analysis were retrieved from the (Notite Kansrijk Alternative) document from the WDOD. During the VKA phase of the Mastenbroek-IJssel dike reinforcement project, area impact, technical feasibility, cost-effectiveness and sustainability were four criteria used to identify the feasibility of a variant. This same criteria is used for determining which durable dike variant is the most suitable for further study. Using the same criteria as in the VKA phase of this project allows for the durable variant to be easily compared next to the existing variants.

Each of the pre-defined criteria are weighted of equal importance, as each of these criteria are of the most importance to varying stakeholders. Each of the four criteria are worth 25% of the final feasibility of a variant. This weighting of criteria was also advised by the waterboard during an expert workshop, which can be referenced in appendix 5. The ranking system for the criteria is as follows: red indicates that the alternative does not satisfy the criteria, yellow indicates that the alternative partly satisfies the criteria and green indicates that the criteria is fully satisfied.

3.4.1 Criteria Definitions:

Area impact: The area impact considers land use, nature and affected infrastructure.

Technical feasibility: The technical feasibility focuses on structural soundness, constructability and maintainability of a dike reinforcement variant based on theoretical and practical knowledge.

Cost-effectiveness: The cost-effectiveness of a variant considers expected overall investment costs, life-cycle costs and repair costs due to failure based on qualitative values. A cost estimate will be completed for the final design variant of this research.

Sustainability: The criteria for sustainability is based on how future proof the variant is. This includes the ability for future further reinforcement, its ability to withstand future water conditions, the impact on biodiversity and the use of repurposed and renewable resources.

3.4.2 MCA Results:

The following MCA was conducted during an expert workshop with the WDOD, which can be referenced in Appendix 5. During this workshop the experts were presented with sufficient background information about the reinforcement project, the research goal, each of the three durable reinforcement alternatives and the pre-defined criteria. Each of the experts was asked to evaluate the three variants based on the criteria. The results of this MCA process are provided in figure 35 below. The final conclusion of the experts was that a fourth alternative should be made consisting of elements from proposed alternatives one and two. For further specifications and references on the content of this workshop, refer to appendix 5.

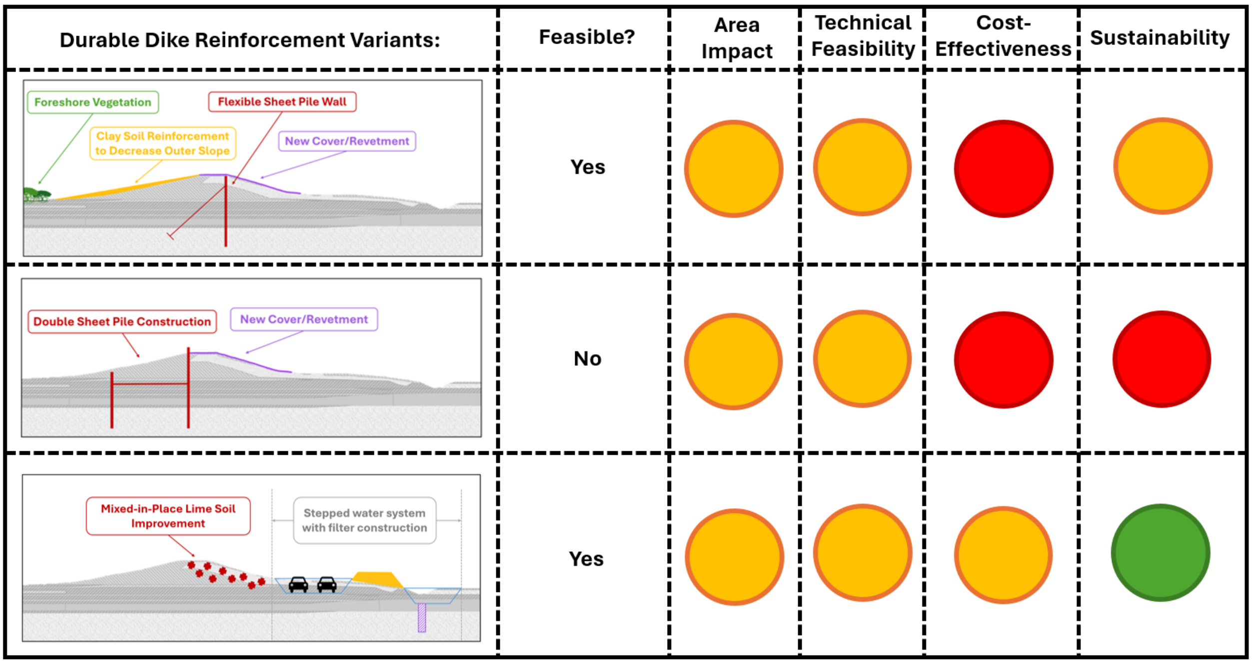

Figure 35. Multi-criteria analysis results

3.4.3 Durable Dike Design for Further Research:

During the expert workshop, the durable dike design for further study was not determined. To finalize the durable dike design, an expert meeting with researcher and lecturer Frank den Heijer from HAN University of Applied Sciences was organized; for the details of this meeting, refer to Appendix 5.

The durable dike design for further study consists of a vegetated foreshore for golf reduction, an erosion resistant bike path at the crest, a clay soil improvement, a clay soil reinforcement on the inner talud and the implantation of a double dike system. During a study for dike section De Naters, it was found that at reference point D115, a 50% golf reduction can be considered if 125m of heavy vegetation is located on the foreshore. The 50% golf reduction resulted in the conclusion that the needed design height could be reduced by 35cm (de Hoop, 2024). A 50% golf reduction through vegetation will be applied in this design. Therefore, the height considered in the clay soil reinforcement is 1.05 meters. The clay soil improvement will be executed by excavating the sand dike material from the previous reinforcement in 1989 and replacing it with clay while also adding the additional clay heightening reinforcement. The double dike system will be placed at a maximum distance of 100m away from the primary dike and will be constructed of clay. The distance between the primary dike and double dike varies throughout the full trajectory, as near the points of connection to the primary dike this distance between the two dikes is shorter. Additional technical details of this reinforcement design can be found in section 4.5.

This durable dike design functions by first reducing the golf and initial hydraulic conditions acting on the dike before the critical water level is reached. Then, in the event of overtopping the paved bike path and improved revetment, reduce the rate of cover breach. The clay soil improvement and additional clay reinforcement reduce the rate of breaching through material cohesion properties and increased soil volume. When flood water surpasses the primary dike, it first enters the double dike system and once full it begins to enter the polder at a reduce velocity. Appendix 3 can be referenced for additional information on the functioning of a double dike system. The durability of this reinforcement design will be quantified in section 4.4.1.

The robust elements in this design function by creating delays in the failure path and in turn reducing the risk of a flood scenario. In section 4.1, the failure path of dike section De Naters and delays created by each of the robust elements can be found. This design will be further studied to determine its influence on the failure path, structural stability, flood consequences, and overall attractiveness as a reinforcement design solution.

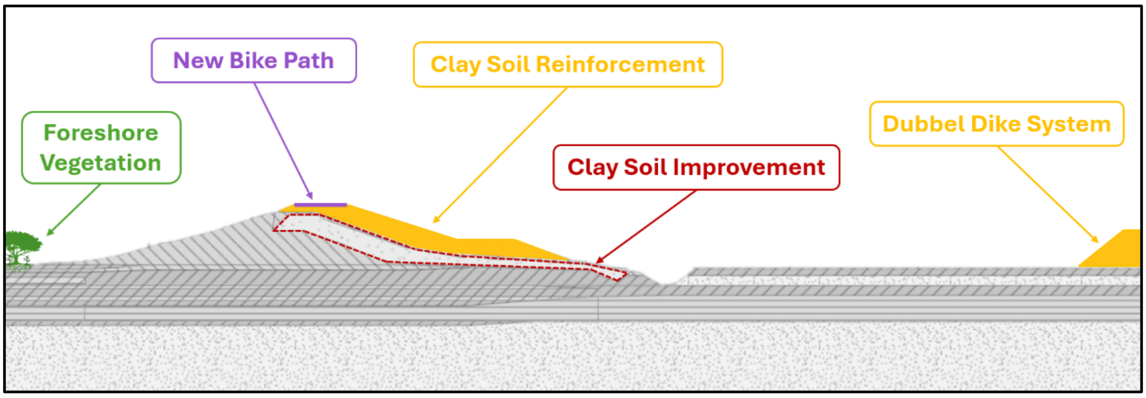

Figure 36. Durable dike design for further research

4 Results

4.1 Failure Path Considering the Durable Dike Reinforcement

If dike section De Naters were to fail, the expected failure mechanisms would include overtopping, wave impact, macro-instability of the inner talud, and insufficient revetment. The processes of each of these failure paths have been included in figure 37 below. This failure path also analyzes delays created by robust elements considering the implementation of the durable dike reinforcement, as discussed in section 3.4.3.

Represented by the gray squares in figure 37 are the expected failure processes for dike section De Naters with no included delays. Yellow squares provide which robust element would cause a delay in a specific stage of a failure process. The green squares display a resolution and end to the failure path processes. Light red squares provide the ways in which robust elements could create delays, and the dark red square displays that the maximum water depths in the polder have been reached.

By increasing the durability of the dike, it is expected that the time in which peak flood levels are reached is delayed, reduced, or avoided entirely. This section provides a qualitative analysis of how the failure path could be affected through robust elements individually. In section 4.4, the results of the failure path processes and delays as a whole are quantitatively analyzed. This is done by obtaining the cost of flood consequences due to a breach considering a brittle dike design and the durable dike design; the breach is modeled to occur during the peak of a 1:3000 year high water weather event.

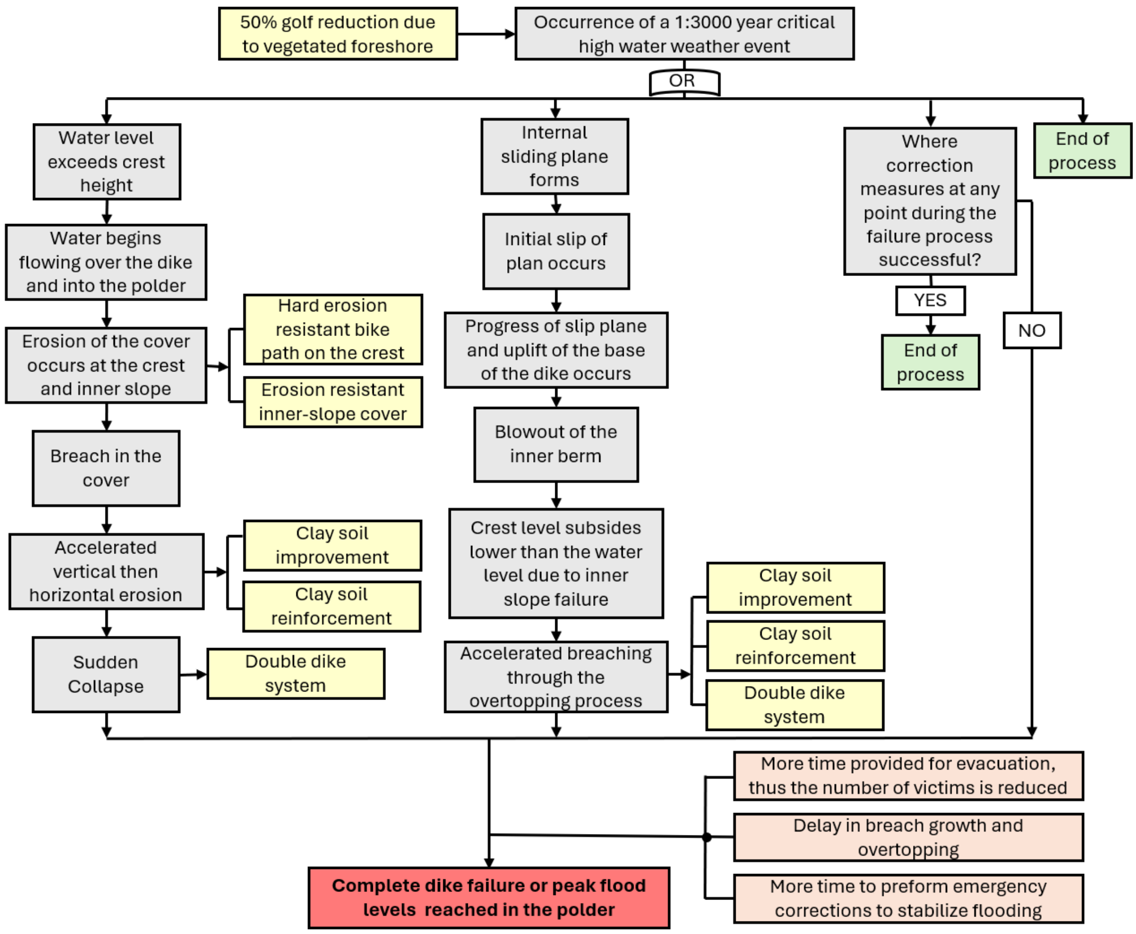

Figure 37. Failure path dike section De Naters with robust reinforcements

4.2 Dike Stability Analysis

In the current situation dike section De Naters experiences no macro-instability issue. However, during the VKA phase of this project, it was identified that in the event of inner soil reinforcement, the dike no longer meets the required safety factor for inner macro-stability. As the durable dike design includes a land side soil reinforcement the inner macro-stability must be verified. The modeling software D-Stability was used to determine if the durable dike design sustains the required design safety factor for inner macro-stability. Further explanation about the failure mechanism of macro-instability can be found in section 2.6.3.

The final results of the inner macro-stability calculations will be provided in this section. However, additional details on the processes and formulas used to obtain these results are provided in Appendix 8. The required design safety factor for inner macro-stability for the Mastenbroek-IJssel dike trajectory is 1.24. The process of how this required safety factor was determined can be found in section 2.10. The macro-stability calculations consider a standard of 1:3000 years and a high water level (WBN) for the design year 2080, which for section 14 is +3.24m NAP (van Meekeren et al., July 2024). For the double dike, the WBN was considered as +2.5m NAP, which is the total height of the double dike. This assumed WBN is relevant as the double dike functions as a water reservoir connected to the primary dike and would become entirely full in the case of extreme flooding. The stability of both dikes was analyzed for the scenario of the pre-mention high water levels.

As a result of the D-stability models displayed in figures 38 and 39, both the primary dike with additional robust reinforcement elements and the double dike meet the required safety factor. The durable reinforced primary dike has an actual design safety factor of 1.268, and the double dike has an actual design safety factor of 1.256. In order for a dike design to be considered safe, the actual design safety factor must be larger than that of the required design safety factor. The original crest width of the double dike was 1.5m, however the required safety factor was not met. The crest width was then increased to 2m, which allows for a sufficient actual design safety factor.

The inner macro-stability calculations abided by the methods available from (RWS, 2017d), (RWS, 2021a) and (RWS, 2021b).

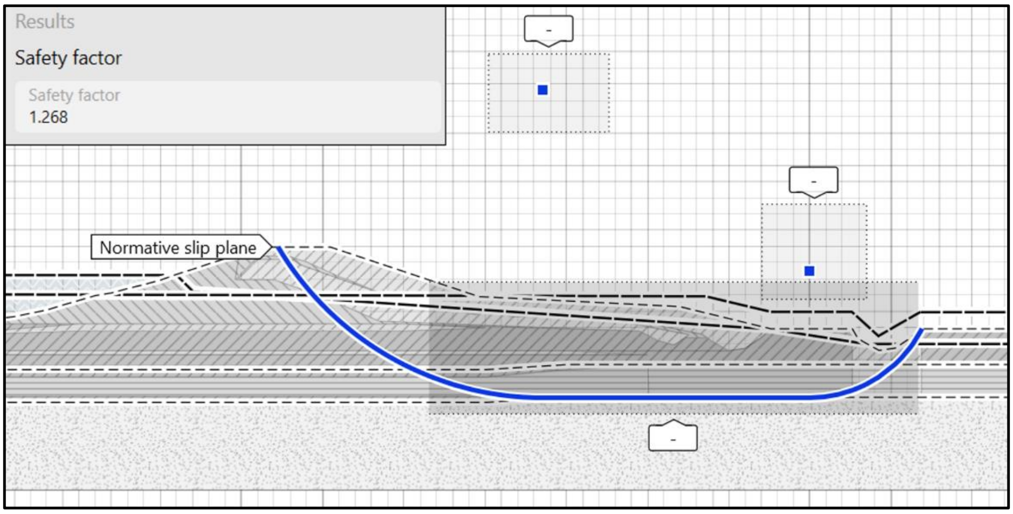

Figure 38. D-stability results for the primary dike considering the durable dike design

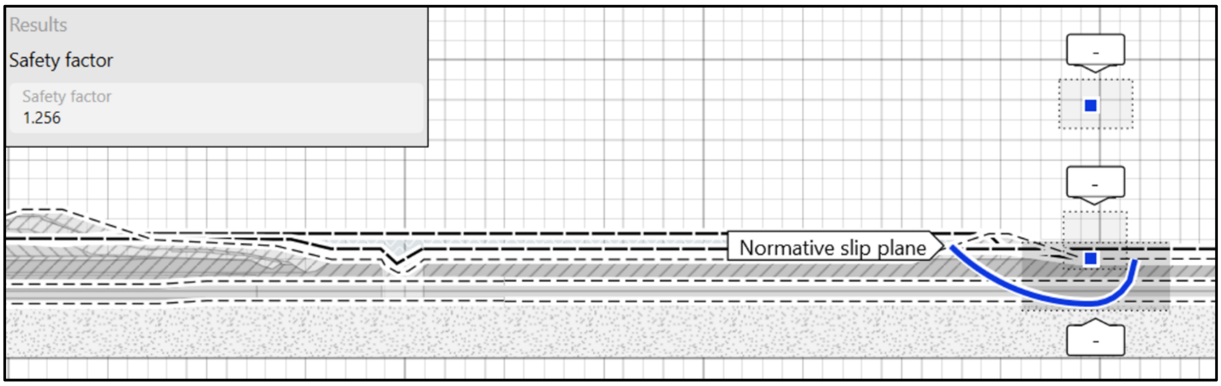

Figure 39. D-stability results for the double dike considering full reservoir

4.3 Flood Model Analysis

3di is a modeling software that uses QGIS as a foundation for its additional functions. For this research, 3Di was used to model a dike breach in order to analyze the flood effects on the Mastenbroek-IJssel polder. An overview of the full 3Di model can be seen in figure 40; the green hatched refinement grids in this model represent the area of the project scope. The WDOD provided a copy of their 3Di model for the province of Overijssel to be used as the base model for this research. All alterations made to the base model to create the revisions needed for this research are detailed in Appendix 9. It is important to consider that the original model is still being developed by the WDOD and the results in the research are built off of revision 26 from the original model.

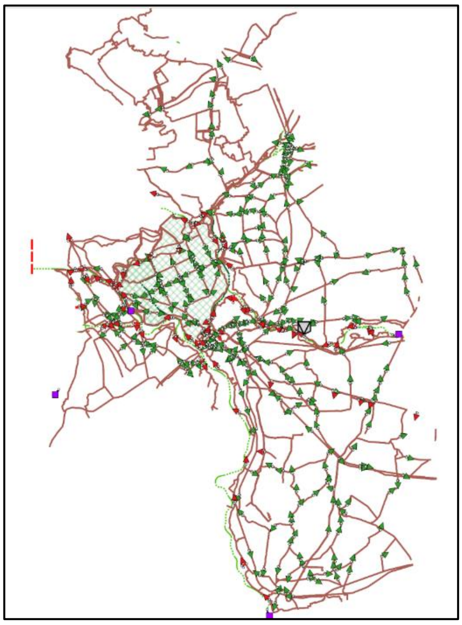

Figure 40. Overview of the full 3Di model

Figure 41 displays the model location where the different variants for dike section De Naters were modeled. The durable dike variant for further research and a brittle dike variant considering the current HBN requirement is modeled and compared in this analysis. To recreate the durable dike design, an obstacle was added to represent the double dike with the corresponding crest height of +2.5m NAP. During a breach simulation, once flood waters in the area between the primary dike and the double dike reach 2.5m NAP, the water begins to enter the polder. The obstacle representing the primary dike was given a crest height of +4.95m NAP; this is the same height considered in the design. The vegetation element was not additionally added to this model as it is already considered in the design crest height reduction of the primary dike. The material of the primary dike for the durable design was considered by making the material property in the breach 24 clay. The brittle dike was modeled by removing the obstacle for the double dike, changing the primary dike height to +5.3mNAP, and making the breach material property sand. The required dike height for dike section De Naters in order to meet the norm of 1:3000 years without a golf reduction

Figure 41. Focus area for breach modeling

is +5.3mNAP. The crest height used for the durable dike design also meets the required norm, considering a 50% golf reduction. It is important to note that revetment is not considered in either of the revisions. For more details on hydraulic conditions used in this model and for the processes on how the breaches were modeled, refer to Appendix 9.

The results of the flood model for the Mastenbroek-IJssel polder are provided in figure 42 in the form of maximum water depth maps. Through this visualization, it can be observed that the durable dike design results in significantly lower maximum flood depths than that of the brittle dike design.

The breach width and discharge through the breach for both designs are displayed in figure 43. While the brittle dike design has a larger and longer total breach discharge rate, the clay dike has a far smaller breach width, and phase zero of the breaching process occurs less rapidly. After peak flood conditions, the breach discharge rate of the durable dike design returns to zero due to the double dike. The water level accumulated in the double dike reservoir is higher than the river's after-peak conditions, causing a backflow in which the discharge slightly falls below zero. The flood results of both designs are quantified in terms of risk in section 4.4.

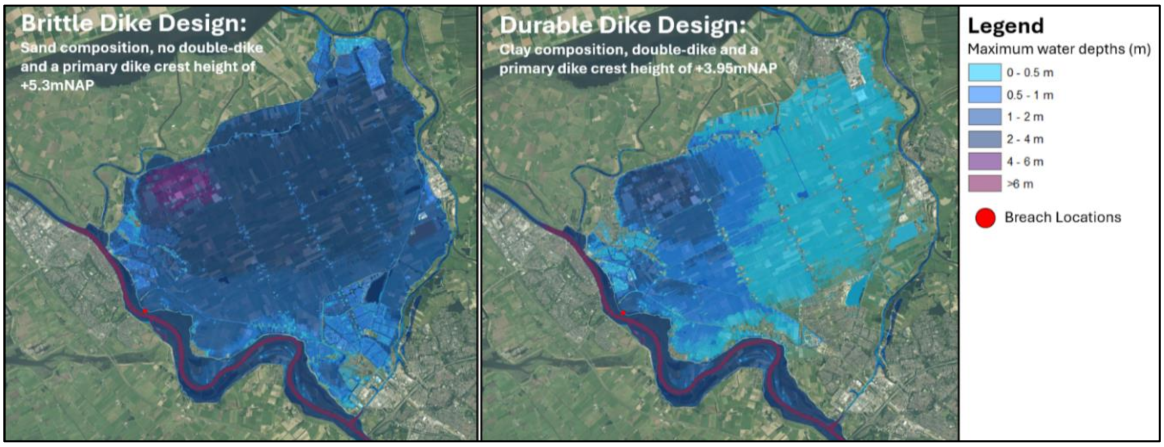

Figure 42. Flood water depth maps from breach modeling simulations

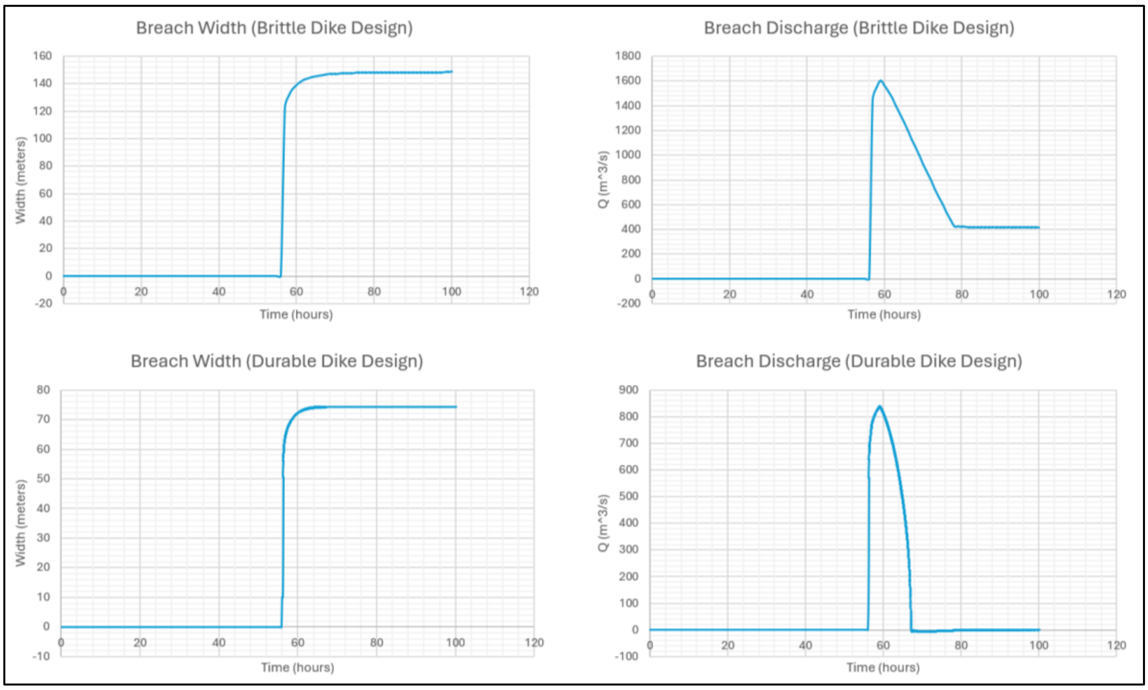

Figure 43. Breach width and discharge for the durable dike and brittle dike designs

4.3.1 Sensitivity Analysis

The brittle dike design and the durable dike design contain multiple varying elements, such as material type, crest height, and the presence of the double dike structure. Sensitivity variants were modeled to analyze the effect of different elements within the two previous designs. The revisions used to complete the sensitivity analysis are the same as the ones used for the durable dike design, except slight adjustments were made. For the sensitivity analysis design 1, sand was chosen as the material for the primary dike instead of clay. To model the sensitivity analysis design 2, the double dike obstacles were omitted and the material property of the primary dike breach was set to clay. The maximum water depth maps of both sensitivity analysis design results can be seen in figure 44. Although the sensitivity design 2 has a material composition of clay, the total flood depths are overall larger due to the absence of the double dike. The double dike is able to retain the discharge through the breach at normal conditions. These results are justified in the breach width and discharge graphs provided for both sensitivity analysis designs in figure 45 below.

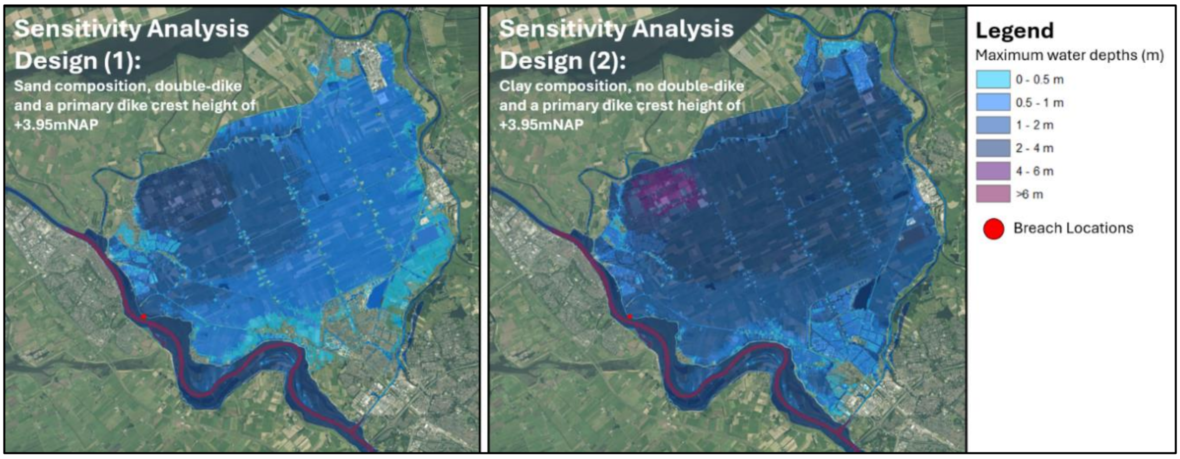

Figure 44. Flood water depth maps for sensitivity analysis designs

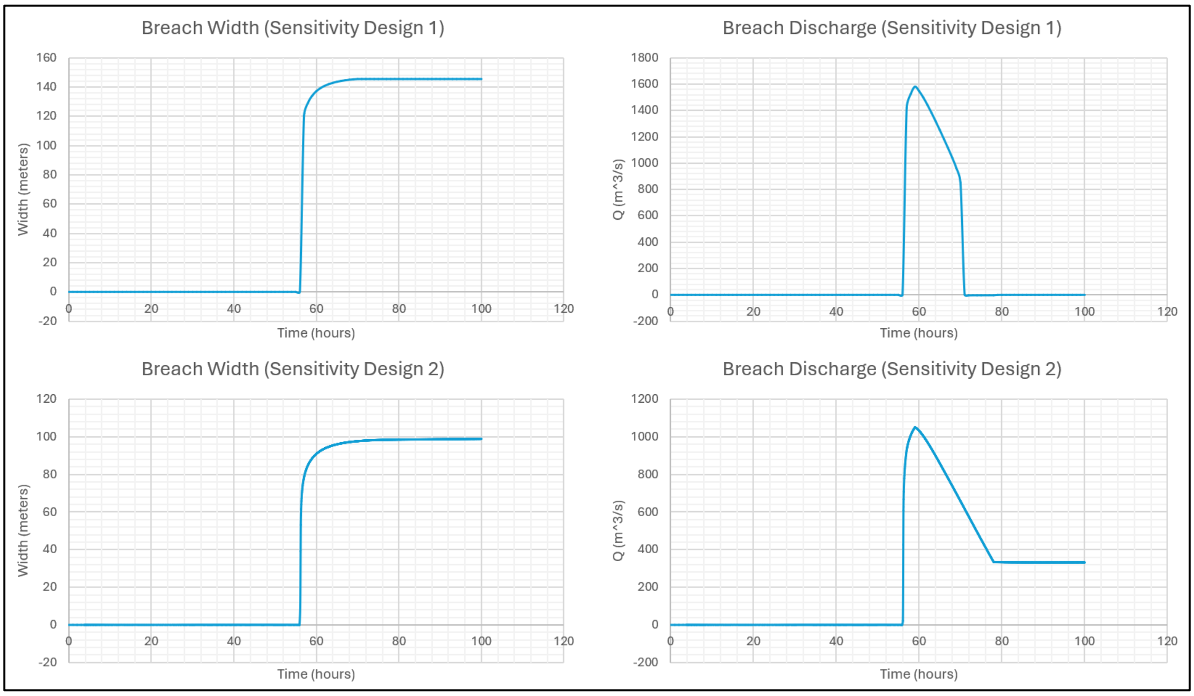

Figure 45. Breach width and discharge for the sensitivity analysis designs

To observe the effect of different soil types throughout the flooding process, the durable dike design can be compared to sensitivity analysis design 1, as seen in figures 46 and 47. The effect of incorporating a double dike can be observed when comparing the durable dike design with sensitivity analysis design 2, as provided in figures 48 and 49 below. By comparing the results of both combinations, it can be observed that the double dike element of the durable dike design makes the largest impact on the overall flood depths. The soil type of the primary dike also proves to be significant. However, it has less overall effect than the double dike in this scenario.

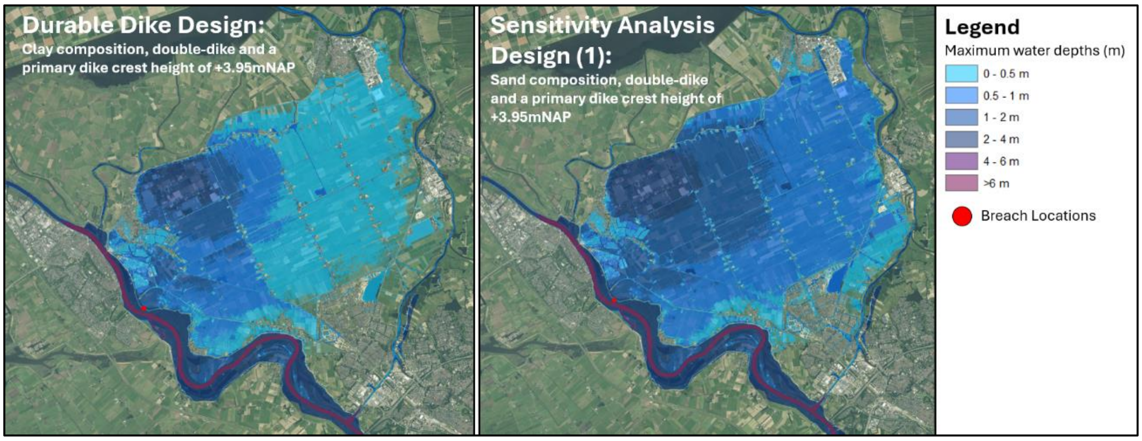

Figure 46. Flood water depth maps for the durable dike design and sensitivity analysis design 1

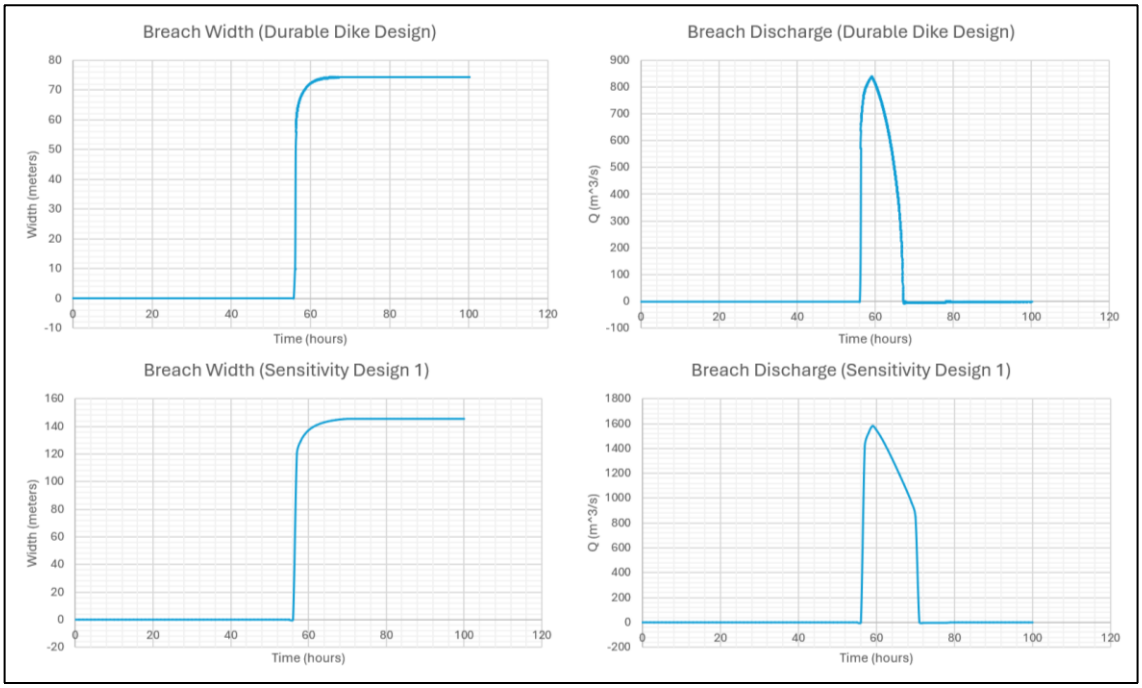

Figure 47. Breach width and discharge for the durable dike design and sensitivity analysis design 1

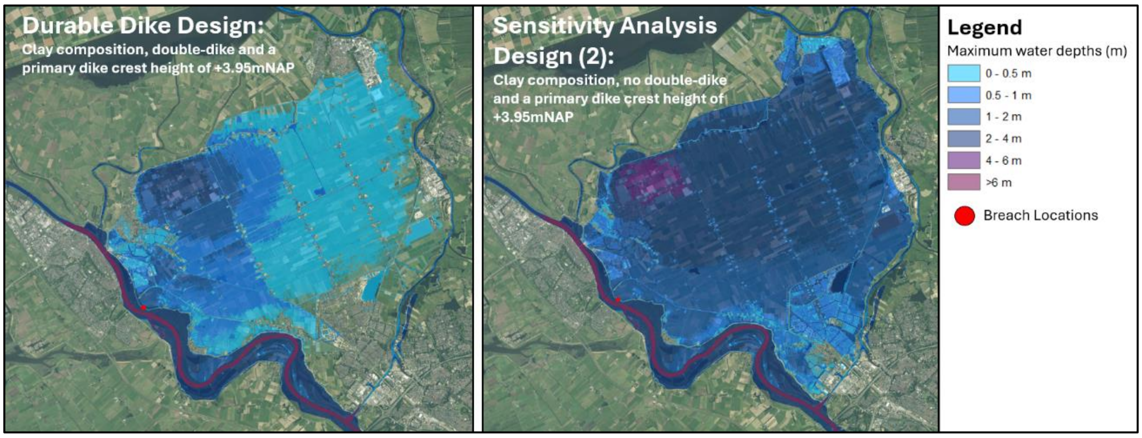

Figure 48. Flood water depth maps for the durable dike design and sensitivity analysis design 2

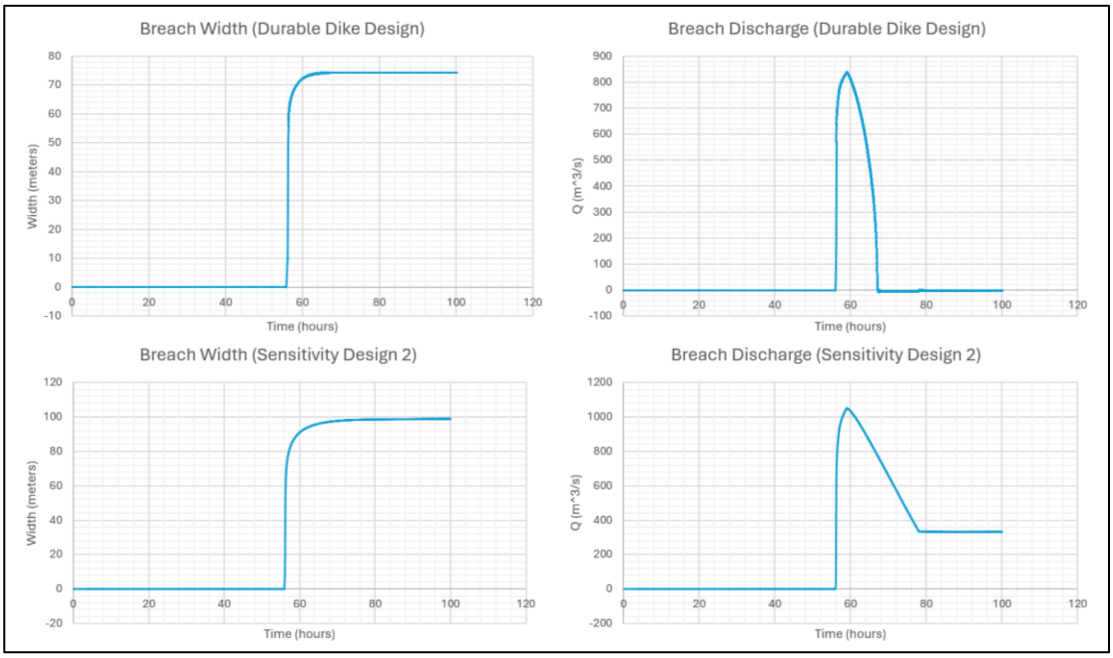

Figure 49. Breach width and discharge for the durable dike design and sensitivity analysis design 2

4.4 Flood Consequences

The SMM model allows for the damages and victims of a flood to be determined for a given dike trajectory within the Netherlands. This is done by inputting a variety of raster sets from flood model results into the SSM model. The 3Di flood model results are detailed in the previous section 4.3. For this research, the maximum water depth raster set was used as input for the SSM model. Additional raster sets such as velocity, arrival time, and rise rate improve the accuracy of the SSM model results but are not required (Heymen, 2024). In order to retrieve these additional data sets, the software Lizard can be used; however, this software was not available for this research. As only maximum water depth raster sets were used for all of the scenarios, the results remain comparable. QGIS was used to clip each of the raster sets down to the area of the project scope using the clip raster to mask layer function. This was done to ensure that the rasters for each of the scenarios compute the results for the same area once inserted into the SSM model. In order for the raster sets to be compatible with the SSM model, the pixel size was changed from 1 to 5 using the resampling tool from the SAGA Next Gen plugin in QGIS. The results retrieved from the SSM model for all design scenarios are provided in table 9 below.

Model Scenario	Damages (euros)	Victims; without evacuation (people)
Brittle Dike Design	3,100,000,000	98
Durable Dike Design	660,000,000	6
Sensitivity Design (1)	1,000,000,000	14
Sensitivity Design (2)	3,100,000,000	96

Table 9. SSM model results

In order to calculate the risk in euros that a flood scenario would cause, the consequences need to be determined in terms of euros. From the SSM results, the data for damages in euros and the number of victims associated with each scenario are provided. Consequences are determined by a sum of total damages and victims from a given flood event (van der Most & te Nijenhuis, 2019). In order to determine the victims in euros, a cost needs to be associated with each person. For this research, it is assumed that each victim costs 6.5 million euros. This factor can be changed and would not affect the end result of this research, as the victims for all scenarios are multiplied by the same cost per victim. The results of the cost in euros for flood consequences per model scenario can be found in table 10. The risk of a flood can be calculated by multiplying the consequences of the flood by the chance of the flood occurring (van der Most & te Nijenhuis, 2019). The flood chance for the Mastenbroek-IJssel dike trajectory is 1:3000 years. The results of the risk in euros for each flood scenario can be found in table 11. The flood risk results are used to determine a robustness index for the design alternatives, which is explained in section 4.4.1.

Consequences= Damages + Victims

Model Scenario	Damages (euros)	Victims (euros)	Consequences (euros)
Brittle Dike Design	3,100,000,000	637,000,000	3,737,000,000
Durable Dike Design	660,000,000	39,000,000	699,000,000
Sensitivity Design (1)	1,000,000,000	91,000,000	1,091,000,000
Sensitivity Design (2)	3,100,000,000	624,000,000	3,724,000,000

Table 10. Flood consequence results

Risk= Consequences x Chance

Model Scenario	Consequences (euros)	Chance (norm)	Risk (euros)
Brittle Dike	3,737,000,000	1/3000	1,245,666.67
Durable Dike	699,000,000	1/3000	233,000.00
Sensitivity Design (1)	1,091,000,000	1/3000	363,666.67
Sensitivity Design (2)	3,724,000,000	1/3000	1,241,333.33

Table 11. Flood risk in euros

4.4.1 Robustness Index

Considering each of the design scenarios, the durable dike design offers a much lower total risk. The difference between the risk of the brittle construction and that of another design construction is the robustness index (den Heijer, et al., 2025, np). This index allows the robustness of a design construction to be quantified. The robustness index for the durable dike design for this research can be found in table 12. A robustness index for the brittle design being compared is always 1. The robustness index indicates how much more frequent the chance of flood can be based on the reduction in the total risks for the design. A new design standard can be calculated by multiplying the robustness index of the design construction by the current standard (den Heijer, et al., 2025, np).

The design constructions, in this case, are the durable dike and sensitivity analysis designs. In table 15, the process and results of the robust design standards for each design can be found.

Establishing a new design standard does not change the required water safety standard for a dike trajectory. The brittle dike design was modeled to meet the required height for dike section De Naters in the environmental event of 1:3000 years. However, the risks associated with this dike design are much higher. The durable dike design was also made to meet the original standard of 1:3000 years and results in significantly lower total risks when compared to that of the brittle dike and sensitivity analysis designs. After establishing the reduced risk experienced by the design constructions, the dike crest height and stability requirement are lowered by considering a robust design standard. The reduced robust norm is only used to justify or optimize the design construction for which the reduction was made. The original safety standard for the dike trajectory will remain the same when determining any other dike design in which a robust index and new design standard have not been determined.

The design standard for the durable dike design considering durability is approximately 1:570. This value was then rounded up to 1:600, which is the result displayed in table 15. Standards if rounded must be rounded up.

$$\boldsymbol{Robustness\ Index} = \frac{\boldsymbol{Risk\ of\ Brittle\ Dike\ Construction\ (euros)}}{\boldsymbol{Risk\ of\ Design\ Construction\ (Euros)}}$$

Risk of Brittle Dike Design (Euros)	Risk of Durable Dike Design (Euros)	Robustness Index [-]
1,245,666.67	233,000.00	5.3

Table 12. Robustness index result for durable dike design

Risk of Brittle Dike Design (Euros)	Risk of Sensitivity Design (1) (Euros)	Robustness Index [-]
1,245,666.67	363,666.67	3.4

Table 13. Robustness index result for sensitivity design (1)

Risk of Brittle Dike Design (Euros)	Risk of Sensitivity Design (2) (Euros)	Robustness Index [-]
1,245,666.67	1,241,333.33	1

Table 14. Robustness index result for sensitivity design (2)

Robust Design Standard= Robustness Index of Design Construction x Current Standard

Model Scenario	Robustness Index [-]	Current Standard [chance/year]	Robust Design Standard [chance/year]
Durable Dike Design	5.3	1/3000	1/600
Sensitivity Design (1)	3.4	1/3000	1/900
Sensitivity Design (2)	1	1/3000	1/3000

Table 15. Robust design standard for each model scenario

4.4.2 Required Crest Height

For the current situation, the required crest height of the primary dike for section 14 is 5.3m NAP. This requirement was determined during the VKA phase of the Mastenbroek-IJssel reinforcement project. A standard of 1:25000 must be sustained, considering an overtopping rate of 10 l/s/m (van Meekeren et al., July 2024). This design standard for insufficient crest height is influenced by the overtopping rate and the failure probability factor from the WBI 2017, as previously mentioned in section 2.10. Crest height required (HBN) is determined based on this standard of 1:25000. The water safety norm in general for the entire dike trajectory remains 1:3000 years.

A value of 0.24m for expected settlement is added to all required HBN values calculated. The required crest level for each design scenario, as well as the reduced robust target probability, can be found in table 16. The target probability for each design scenario considered a robust index reduction in regards to the standard 1:25000 for HBN. For further details on the calculation process, refer to Appendix 10.

Design Scenario	Robust Design Standard [chance/year]	Required Crest Height HBN [m NAP]
Durable Dike Design	1/600	4.1
Sensitivity Design (1)	1/900	4.2
Sensitivity Design (2)	1/3000	5.3

Table 16. Required crest height for each design scenario considering robustness

4.5 Technically Detailed Final Design

The final durable dike design is adapted from an optimized version of the durable dike design for further research, as provided in section 3.4.3. This final design considers a 38,390.67m^3 clay soil improvement, a 130,236.22m^3 clay soil reinforcement on the upper and inner talud, a paved bike path on the crest of the dike, a relocated road on the berm of the dike, and a double dike construction at approximately 100m away from the primary dike. Vegetation of 125m on the foreshore is no longer needed as the required design height is +4.1m NAP, considering the robust design reduction. This design, therefore, sustains the height requirements without an additional 50% golf reduction. The double dike meets the design requirements of a regional hydraulic structure (STOWA, 2017). Data from the project's VKA phase (TAW, 1996) and educated approximations were used to establish the subsoil composition, clay categories, cover dimensions, and hard construction dimensions. AutoCAD was used to create detailed technical drawings, which include design dimensions and material specifications. These technical drawings can be found in Appendix 11.

A more detailed explanation of how the robust elements within this design function can be found in section 3.4.3. Design optimizations could improve the attractiveness of this alternative; however, they are not considered in this research. The replacement of the double dike could offer a promising optimization to this durable dike design. As the largest impact of the double dike is retaining the river water after peak conditions, therefore the double dike could potently be placed closer to the primary dike, reducing the amount of required land acquisition. The crest level, as seen in table 16, could also be optimized. In order to find the robustness index considering the altered height, a new flood analysis would have to be performed. Then, the HBN would have to be revised to take the new robustness index into account. This optimization would require an iterative approach, which was not considered in this study yet may yield promising results for design optimization.

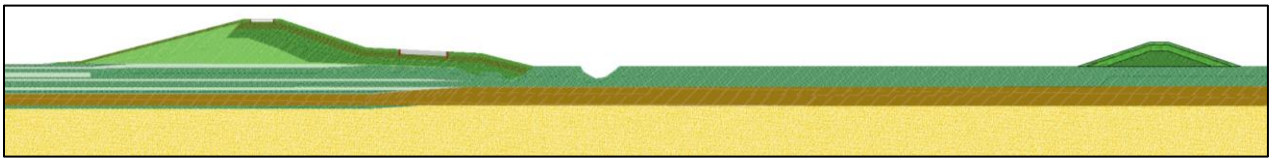

Figure 50. Cross-sectional view of the final durable dike design for dike section De Naters

4.6 Cost-benefit analysis

The cost-benefit comparison between the durable and the brittle dike variants focuses quantitatively on the costs of soil material, material transportation, sand excavation, and flood risk losses. Material and construction work costs for this analysis include the 21% VAT, which applies to construction in the Netherlands (Rijksoverheid, 2024). This analysis omits components such as the water inlet, bike path, and road components, as they are relatively the same for both variants. The brittle alternative adopts the inner-talud reinforcement geometry previously determined in the VKA phase, which meets the required HBN of +5.30 m NAP. The reinforcement costs for each variant, as displayed in table 19, show that the durable variant is €379,512.03 more expensive than the brittle alternative. However, when the significantly smaller expected flood risk of the durable dike is accredited, the durable alternative becomes, in total, €633,154.64 less expensive. These results do not account for construction costs or land acquisition costs of either alternative. The resale price of sand excavated from the durable design's inner talud is included in the total reinforcement cost estimate of the durable dike design.

It is important to consider that the costs of soil materials also include transportation to the project location, but do not consider construction costs. Due to the phase of the Mastenbroek-IJssel dike reinforcement project, all pricing estimates are confidential at this time. Prices used for this cost-benefit analysis were retrieved from the 2021 cost estimate of the Stad Tiel dike reinforcement project (TAUW Group bv, 2021). The Mastenbroek-IJssel dike reinforcement is expected to be executed in 2030. An inflation percentage estimate for the year 2030 was added to all costs from the year 2021. The inflation estimates were determined using linear interpolation between the years 2021 and 2024 with data retrieved from (CBS, 2025) for hydraulic constructions. This is a method approximation used for the purposes of this research, and it should be considered that inflation prices are typically not linear and can be unpredictable.

Several aspects of this analysis remain, which will be evaluated qualitatively. The spacing currently considered (approximately 100m) for the secondary dike increases the use of land relative to the brittle dike design. Some of this land use is offset by a 4.3 m shorter channel relocation due to the narrower inner-talud soil reinforcement for the durable dike design. A detailed land valuation study is needed to establish whether land acquisition costs would change the current advantage of the durable dike design. The constructability of the two designs differs in several key ways. The durable dike design requires the extra construction of a secondary double dike. By comparison, the brittle dike alternative requires additional excavation as the channel next to the existing dike must be relocated farther landward. Additionally, the vertical constraint imposed by the overcrossing bridge will decrease the feasibility of continued heightening for this dike section in the future. Considering durability the design process therefore offers an advantage by increasing the long-term sustainability of the dike. Sustainability is improved by considering the need for future reinforcement efforts.

By analyzing the flood modeling results, it can be observed that the secondary dike mainly suppresses the post-peak discharge rate into the polder. This suggests that its present durable dike crest of +2.50 m NAP may be conservative; an optimization such as lowering or relocating the secondary dike could further reduce construction efforts, material costs, and land use. In its current form, the durable alternative appears economically attractive, outperforming the brittle variant by roughly € 0.63 million. However, its definitive competitiveness depends on design refinements and land use costs. The WDOD is open to the relocation of infrastructure or property markings on or next to the dike when deemed feasible (WDOD, 2024).

Material	Price per Unit (2021)	Price per Unit (2030) + 82.63%
Sand (25,000 - 50,000m^3; discount -11%)	€11.70 per m^3	€21.37 per m^3
Clay (erosion class 1)	€15 per m^3	€27.39 per m^3
Clay (erosion class 2)	€13.5 per m^3	€24.66 per m^3
Sand excavation from dike construction	€1.44 per m^3	€2.63 per m^3

Table 17. Reinforcement costs per unit

Reinforcement Design	Material	Material Quantity	Cost of Material	Material Cost + BTW
Durable Dike Design	Clay (class 1)	44,068.15 m^3	€ -1,207,026.63	€ -1,460,502.22
	Clay (class 2)	86,168.07 m^3	€ -2,124,909.61	€ -2,571,134.58
	Sand (repurposed)	38,390.67 m^3	€ +730,163.67	€ +883,498.04
	Sand (excavated)	38,390.67 m^3	€ -100,967.46	€ -122,170.63
Brittle Dike Design	Sand	42,736.70 m^3	€ -812,822.12	€ -983,514.77
	Clay (class 1)	41,625.23 m^3	€ -1,140,115.05	€ -1,379,539.21
	Clay (class 2)	17,686.60 m^3	€ -436,151.56	€ -527,743.38

Table 18. Total reinforcement costs considering BTW

Reinforcement Design	Total Material Cost + BTW	Risk €	Total Cost
Durable Dike Design	€ 3,270,309.39	€ 233,000.00	€ 3,503,309.39
Brittle Dike Design	€ 2,890,797.36	€ 1,245,666.67	€ 4,136,464.03

Table 19. Total overall cost considered for each reinforcement design

5 Discussion

This research was focused on developing a suitable durable dike design for a sub-trajectory of the Mastenbroek-IJssel reinforcement project and determining the attractiveness of this design alternative. In the process of determining the attractiveness of the durable dike design for dike section De Naters, a robust design standard was also considered. This robust design standard increases the attractiveness of durable dike alternatives by considering their associated lower flood risk. A robust design standard does not affect the pre-defined water safety standard for this dike trajectory, which is 1:3000 years. This approach to dike design challenges the way in which standards can be approached when also considering the durability of a dike. This research quantified the effects of this approach for the durable dike design studied for dike section De Naters.

A robust design standard, based on the approach and methods used in this research, can only be determined per individual dike sub-section. The underlying robustness index, which is used to determine the robust design standard, varies based on the following factors: cross-section geometry, soil composition, and additional design elements. Consequently, the standard established for sub-section De Naters cannot be applied to the entire Mastenbroek-IJssel dike trajectory, as the robustness index differs per cross-section.

Initially, the sub-section of the Mastenbroek-IJssel dike trajectory with the lowest durability score was chosen as the project scope for this research. Multiple durable dike design,s which are composed of robust elements, were proposed to the WDOD in a workshop. After consultation with many experts, a final durable design alternative was chosen based on feasibility. The durability of this durable design for further detailing was then qualitatively analyzed in a failure path analysis. This analysis showed where and how each of the individual robust elements in the final durable design could positively affect the stages within the failure path. The failure path analyzed contained the stages of the expected failure mechanisms for dike section De Naters. In the analysis of consequences for flood scenarios, the overall combined effects of the robust elements in the durable dike design are quantified.

Quantitatively, this research provided results such as maximum water depth maps for flood modeling and the total cost of flood consequences for dike design scenarios. When comparing the results of the flood depth maps and the cost of consequences, the durable dike design is significantly more efficient than that of a brittle dike design. Both the brittle and durable designs meet the required design dimensions for the water safety standard of 1:3000 years. However, the consequences and, therefore, in turn, the risk of the durable dike design are 5.3 times lower than that of the brittle design. By considering a new design standard that is 5.3 times that of the current standard, the required design dimensions are lowered for the durable dike design. This optimization of 5.3 in the design standard increases the attractiveness of the durable dike alternative. The new design standard for dike section De Naters considering this specific durable dike design is 1:1100 years. It is important to impose that this new standard only applies to optimizing or justifying the durable dike design for which the new design standard was decided. This durable design already previously proved to meet the current safety standard of 1:3000 when comparing the total risk to that of the brittle alternative. This approach towards the standard does not make the durable dike any less safe than that of a brittle dike that, on paper, meets the design dimensions of 1:3000 years.

In determining the attractiveness of the durable dike design, both the costs and benefits are analyzed. This includes the design of soil material costs, construction methods, land use, material use, and sustainability. The quantitative cost estimate of both designs shows that the durable dike design is €0.63 million more cost effective considering construction materials and flood risks. That advantage is provisional as the double dike variant requires the additional acquisition of approximately 100 m of agricultural land. Considering the overall costs and benefits of both designs, it can be determined that the durable dike design is a competitive and attractive reinforcement alternative.

Results from all of the previous steps in this research aided in answering the main research question: What is a suitable durable dike design for the Mastenbroek-IJssel dike reinforcement? The concepts and ideas that this research sparked, as well as the answer to the main research question, are provided in the conclusion.

6 Conclusion and Recommendations

6.1 Conclusion

Throughout this research, the impact of dike durability on flood risks was qualitatively and quantitatively analyzed. The processes of this research helped to define a method by which dike durability can be approached to improve water safety. Water safety is an important topic in the Netherlands, as about 26% percent of the land is located below sea level and is protected by dikes or other hydraulic structures. To conclude this research, each of the findings for the main and sub-research questions are provided below.

Sub-question one, *"Which dike trajectory of the Mastenbroek-IJssel is the optimal area for a durable dike alternative?"*, is answered in this research by determining the durability score of each sub-trajectory of the Mastenbroek-IJssel dike. As a result of this process, sub-section De Naters proves to have the overall lowest durability score. This dike section, considering the current cross-section, receives a durability score of 1. Considering the previously proposed reinforcement alternatives from the VKA phase of this project, the durability score was increased slightly to 2. For further details on this process, refer to section 3.2.

Sub-question two, "What are three reinforcement variants which can be used to increase the durability of the dike section, considering possible robust elements?", is answered by proposing three durable dike designs for dike section De Naters. The robust elements implemented into these designs are the results of knowledge gathered about the project location and from a literature review. Each of the three proposed durable dike designs are detailed in section 3.3.

Sub-question three, *"What set criteria must the durable dike alternative meet?"*, is determined based on the same design criteria for the alternatives in the VKA phase of this project. Area impact, technical feasibility, cost-effectiveness, and sustainability are the four criteria used to define the feasibility of a design alternative.

Sub-question four, *"Considering the robust elements, which is the preferred durable variant to detail further based on pre-defined criteria?"*, is determined by the results of an expert workshop with the WDOD and an expert meeting with Frank den Heijer. The preferred durable dike variant for further detail can be found in section 3.4.3.

Sub-question five, *"How can the selected robust reinforcement alternative reduce the impact of the failure mechanisms present within the dike section?"*, is determined by conducting a failure path analysis for dike section De Naters considering the durable dike design elements. In this analysis, it is depicted where and how each of the robust elements in the design would positively affect the failure path stages. The fault tree of this failure path analysis can be found in section 4.1.

Sub-question six, *"How does the preferred robust reinforcement variant limit the consequences of flooding?"*, is concluded by using the SSM model to retrieve the damages and victim results for the flood scenario of the durable dike design. The design dimensions of the durable dike design are determined during the stability modeling process in the software D-stability. Further details on this model and the results can be found in sections 4.2 and Appendix 8. These design values are then used as input in the flood modeling process in the software 3Di. The details of the flood modeling process and results can be referenced in sections 4.3 and Appendix 9. The raster's retrieved from the results of the flood modeling are used as input in the SSM model to obtain the consequences of a flood scenario. To conclude this sub-question, the durable dike variant reduces the consequences of flooding by 5.3 times more than that of the brittle dike variant. Further detailing on this process can be found in section 4.4.

Sub-question seven, *"To what extent is a durable dike design a competitive variant?"*, is determined through a cost-benefit analysis comparing the final durable dike and brittle dike design. From this analysis, the conclusion can be drawn, based on the factors considered in this research, that the final durable dike design is a competitive reinforcement variant. This variant proves feasible enough to be evaluated beside the two currently proposed reinforcement alternatives for dike section De Naters of the Mastenbroek-IJssel reinforcement project. For more information on the processes and results of this analysis, refer to section 4.6.

To conclude the main research question, *"What is a suitable durable dike design for the Mastenbroek-IJssel dike reinforcement?",* it is made clear through the results of this entire research process that the final durable dike design for dike section De Naters is a suitable reinforcement alternative for the Mastenbroek-IJssel project. The final durable dike design can be found in section 4.5.

The processes and findings of this research could be used as an outline for approaching dike durability. Considering durability when assessing if a dike needs to be reinforced based on its assigned water safety standard could help prioritize dike reinforcement projects. Adapting the methods used in the research process to other polder locations, water safety and the way in which safety standards are approached could be globally improved.

6.2 Recommendations

Within this research, there are several areas where more in-depth study is advised. These changes would improve the accuracy of the research methods and results. Initially, it is recommended that a quantitative approach to the assignment of durability scores for dikes be considered. As qualitative assessments are based mainly on educated judgment, determining a new approach would improve the objectivity, consistency, and accuracy of the evaluations. A quantitative approach to assigning durability scores would make it easier for a standardized application across all primary dikes in the Netherlands.

By assessing dike cross-sections with a standardized and quantified durability score, a robustness index could be assigned to all river dike sub-sections in the Netherlands. In turn, this would increase the feasibility of applying robust design standards to reinforcement designs per sub-section during the design process. Currently, the Sustainable River Management research group at HAN University of Applied Sciences is creating an atlas that maps the robustness of river dike cross-sections in their current state. As previously stated in this research, it is important to consider that not all current dikes have an initial durability score of 1.

Furthermore, it is advised that multiple feasible durable reinforcement variants be fully evaluated by assessing their flood consequences rather than focusing exclusively on the most feasible design. A final durable design variant could then be selected based on a combination of factors such as consequences costs, initial investment, life cycle costs, and end of life costs. This approach allows for a decision to be made on the final design variant based on quantitative values. Due to the time available for this research and the scope of the project, this method was not used but is recommended when feasible.

To manage the scope of this research, all calculations made focused specifically on the characteristics of reference point D115 (sub-section 14) due to its critical importance. Additional research is advised for sub-sections 13 and 15 of dike section De Naters. The design of the proposed double dike system was based on assumed parameters, including approximate placement, height, width, and slope. As such, further research is recommended to evaluate how variations in these parameters affect flood risk outcomes, as well as the consideration of a breach occurring in the double dike.

Additionally, the placement of components such as the inlet, secondary outlets, and electricity poles located within dike sections De Naters should be considered in the execution of reinforcement designs.

Overall, the methods of this research yielded acceptable results. However, the cost-benefit analysis could be refined by accounting for additional expenses such as land acquisition costs and design optimizations. A itemized cost estimate for each design variant is recommended for completeness. The cost estimate in this research considered soil material, material transport, and excavation costs due to the time restraint. Therefore, the consideration of additional factors in the cost-benefit analysis would improve the overall reliability of the research results. The ultimate objective of continuously developing and exploring new strategies to improve water safety is supported through the refining of the methods implemented in this research.

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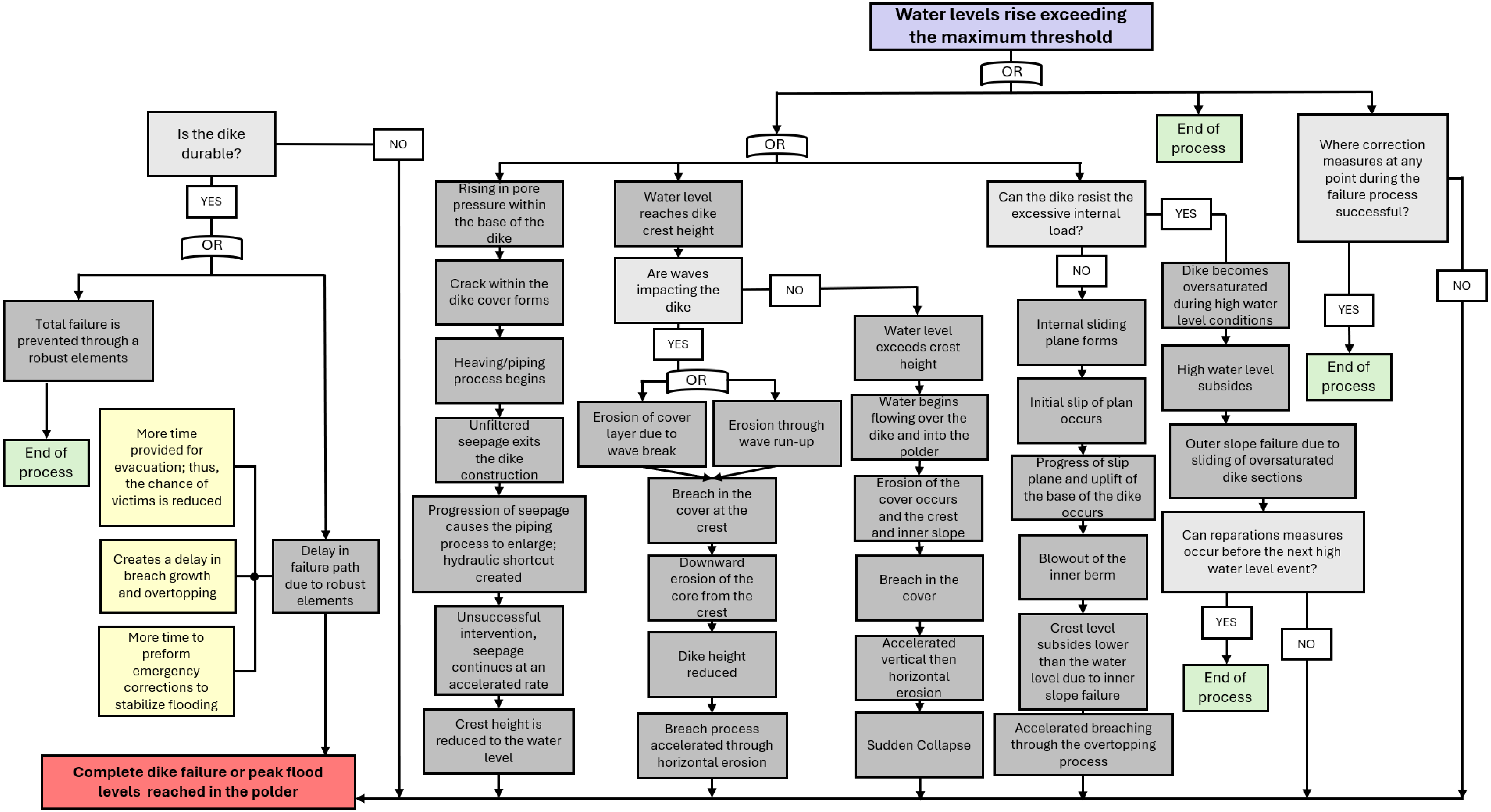
‘The hydrodynamic simulations were performed with 3Di and the computer facilities both were made freely available by Nelen & Schuurmans under their Academic License.’

Appendices

Appendix 1: Fault Tree Mastenbroek-IJssel Dike



Appendix 2: Selecting a Dike Section

The study scope would become broad if a durable dike variant was determined and analyzed for each of the six sections of the Mastenbroek-IJssel dike, which is 14.6 km long. Thus, the most suitable section of the Mastenbroek-IJssel dike for a robust reinforcement will be identified in this appendix. A cross-sectional overview of each of the six dike sections will be presented, along with the previously proposed variants that were developed during the VKA phase of this dike reinforcement project. The dike cross-sections show the composition of the soil beneath and inside the dike and are technically accurate scaled models. The models from TAUW's D-Stability archives were used to create the cross-section visualizations provided in this appendix.

To determine which section of the dike is the most suitable to make more durable, the failure mechanisms and the durability of the dike in its existing state, as well as with the proposed variants, will be analyzed in Table 8. The dike section, which scores the lowest in durability and has the most failure mechanisms, will be the dike section which will be further detailed in this study, as it is the critical dike section. The lowest scores for each section are highlighted so that they are easily visible. Justifications and educated assumptions will be given for each score in the following sub-sections. Appendix 1 can be referred to for the expected failure path of the Mastenbroek-IJssel dike considering each possible failure mechanism. Any soil reinforcement will automatically receive a durability score of two as additional soil creates more material to be eroded before failure creating a slight delay in the failure path (Podt, 2024).

Durability Score:

1= Not durable, 2= Slightly Durable, 3= Partly Durable, 4= Sufficient and 5= Very Durable

Dike Section:	Failure Mechanisms:	Durability Current Situation:	Durability Considering Proposed Variant:
1: Vreugderijkerwaard	N/A until 2050	Data not available	Data not available
2: ‘s-Heerenbroek	Macro-instability inner slope and Piping	1	3
3.1: Wilsum-Oost	Insufficient Revetment	Data not available	Data not available
3.2 A: Wilsum- West	Overtopping	1	4
3.2 B: Wilsum- West	Overtopping	2	5
4: Scherenwelle	Overtopping, Piping and Macro-instability inner slope	1	3
5: De Naters	Overtopping, Macro-instability inner slope and Insufficient Revetment	1	2
6.1: IJsselmuiden- Tasveld	Overtopping and Macro-instability inner slope	2	4
6.2: IJsselmuiden-Spoorlanden	Overtopping and Macro-instability inner slope	1	4
6.3: IJsselmuiden- Station	Overtopping and Macro-instability inner slope	1	5
6.4 A: IJsselmuiden-Frieseweg	Overtopping and Macro-instability inner slope	1	2
6.4 B: IJsselmuiden-Frieseweg	Overtopping and Macro-instability inner slope	2	4

Table 8. Dike Section Selection

Dike Section 1: Vreugderijkerwaard

Dike section Vreugderijkerwaard is currently undergoing retesting and does not have a reinforcement assignment until 2050 (van Meekeren, et al., August 2024). As a result, no accurate data is available, such as a D-Stability model or a poster illustrating the possible variants. Due to the lack of data it is not optimal to select this dike section for further study.

Dike Section 2: 's-Heerenbroek

The dike section 's-Heerenbroek experiences macro-instability in the inner slope and piping. Overtopping is not a problem due to less intense hydraulic conditions east of Wilsum, a direct influence of the wind direction. The proposed variants from the VKA process include a soil reinforcement or a filter construction in the inner berm. The current dike has a gradual slope, a large width, and a partially sandy core with a clay cover. Without a filter construction, sand would quickly be displaced in the event of piping, causing dike failure. The instability of the inner slope would breach the clay layer, leaving the sand exposed and causing accelerated failure. The durability score of the current dike section is 1 due to the little to no delay in the failure path processes.

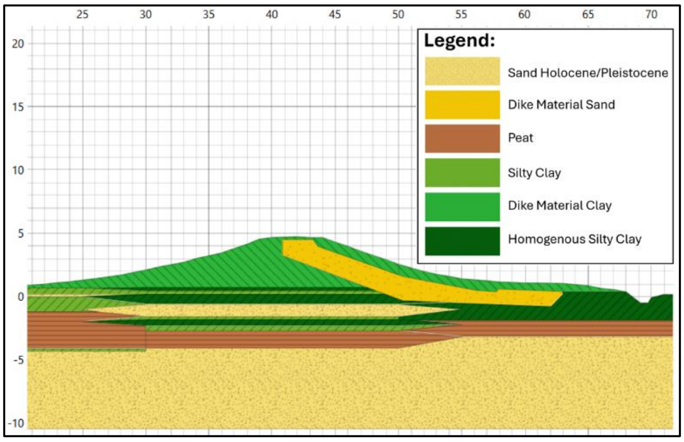


Figure 51. Soil composition and cross-section of dike section 's-Heerenbroek

The durability score considering the proposed variants is 3 due to the possible delays in the failure path. A filter construction will create a delay in the speed at which a piping failure will occur. In the event of a macro-instability failure more of the dike would remain intact; adding additional soil on the inner berm might delay the failure path or alter the location of the failure plane. However, only one of the delays in the failure process would occur as the delays discussed are considered in two separate variants. Overall, the dike section with the proposed variants is already partially durable.

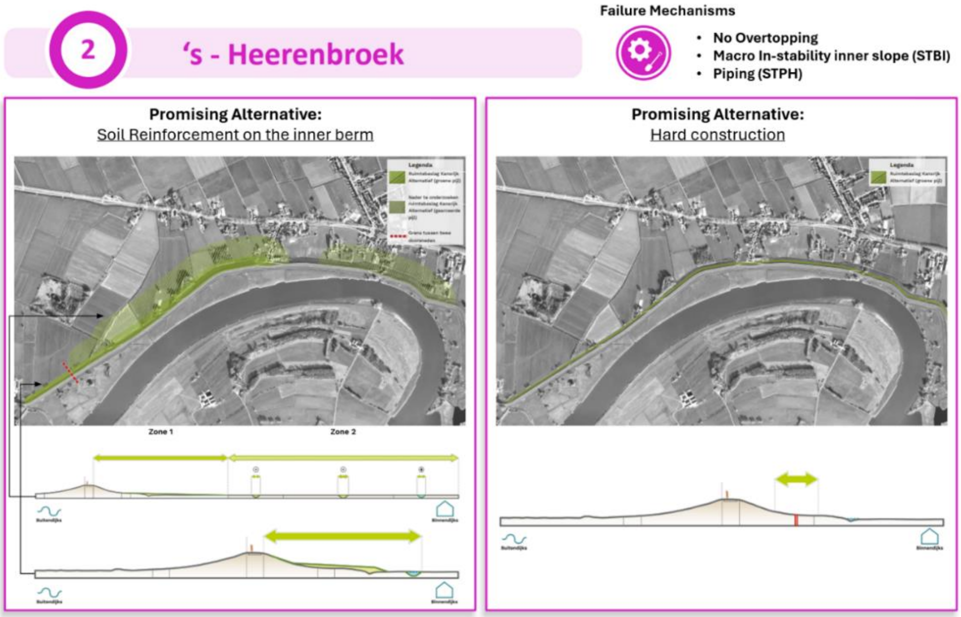


Figure 52. Proposed variants 's-Heerenbroek (DODelta, et al., 2025)

Dike Section 3.1: Wilsum-Oost

The only failure currently present in the dike section Wilsum-Oost is insufficient revetment. The proposed VKA variant already considers a new revetment reinforcement. As there aren't any stability issues, there also aren't any D-Stability models currently available for this section. Sub-questions 5 and 6 focus on durable dike stability and would not be applicable in this case. Due to the lack of data and present failures, this dike section is automatically not an optimal dike section to further detail for this study.

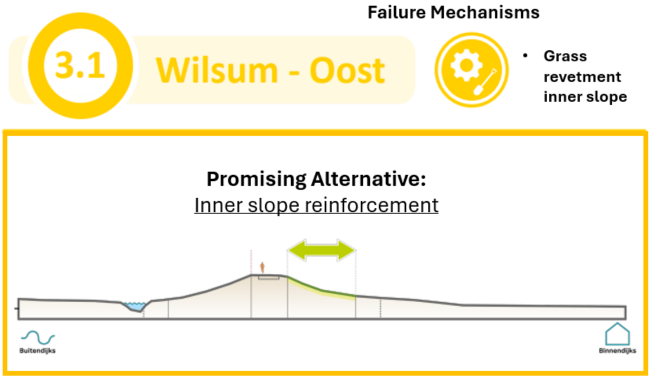


Figure 53. Proposed variant Wilsum-Oost (DODelta, etl., 2025)

Dike Section 3.2: Wilsum- West

Dike section Wilsum-West is divided into two parts, A and B, both of which experience overtopping due to insufficient crest height (van Meekeren, et al., August 2024). Due to differences in cross-section, soil composition and proposed VKA alternatives, sections A and B will be analyzed separately.

Wilsum-West (A) is a sand core dike with a sand base layer, small crest width, and steep slope. Its current state has a durability score of 1 due to its inability to delay the normal overtopping failure path. Once the clay cover is breached, the sand core would be eroded within minutes, causing total failure (Verheij et al., 2003). However, the proposed VKA reinforcement variants can improve its durability to 4. Variant three uses a hard construction from the top of the crest to the base of the dike, ensuring that the minimum crest is the height of the hard construction. This concept is also used when inputting the crest height values for initial breach dimensions. Variants one and two would also delay the failure path of overtopping but will not be discussed as variant three is already sufficient.

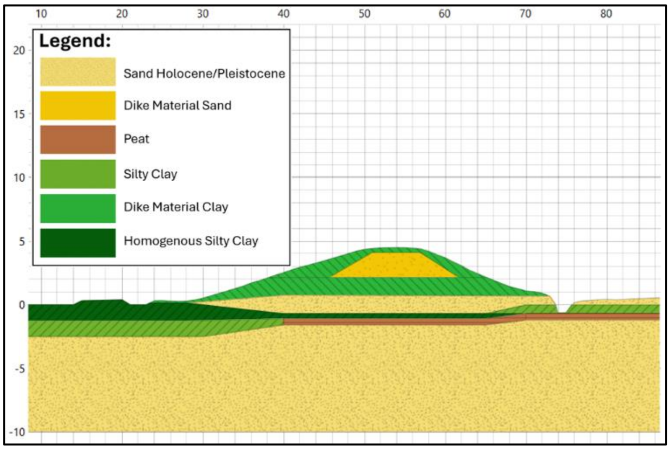


Figure 54. Soil composition and cross-section of dike section Wilsum-West (A)

Wilsum-West (B) is composed mostly of clay within the crest and core with a sand layer at the base and has a gradual slope and large width. A clay core dike in the event of overtopping can take up to one hour to fully breach (Verheij et al., 2003). This factor in itself creates a delay in the failure path. Therefore, it receives a durability score of 2. Considering a hard construction, proposed variant three, section (B) receives a durability score of 5. The justification remains the same as in section (A); however, in addition the presence of clay increases the durability. Overall, Wilsum-West with the implementation of proposed variant three, is durable in regards to failure path delay.

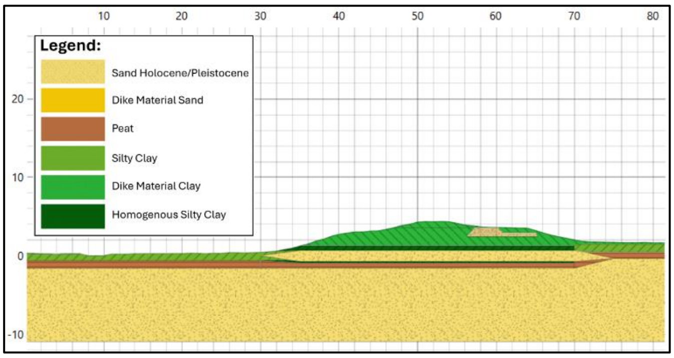


Figure 55. Soil composition and cross-section of dike section Wilsum-West (B)

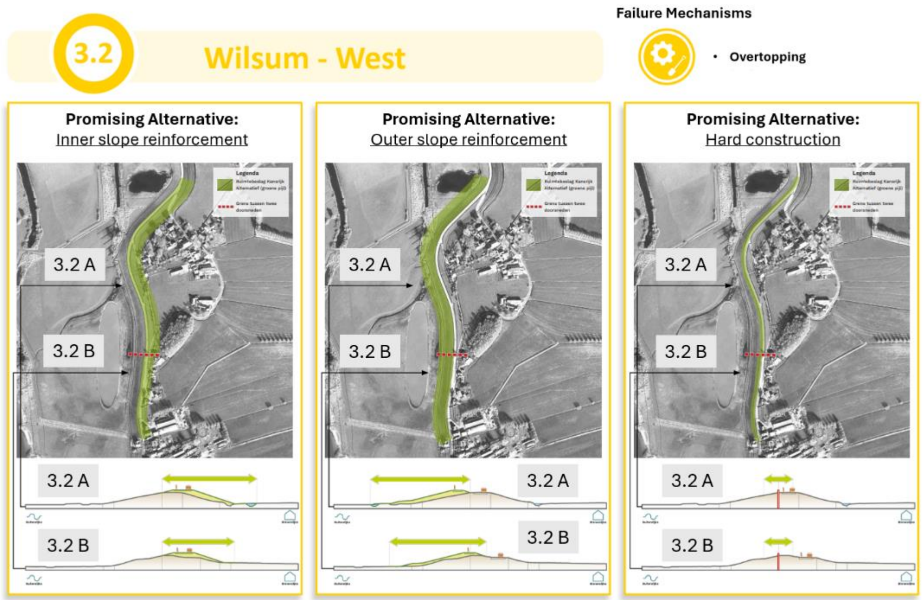


Figure 56. Proposed variants Wilsum-West (DODelta, et al., 2025)

Dike Section 4: Scherenwelle

Without reinforcement, the Scherenwelle dike section will experience overtopping and macro-instability in the inner slope and piping. In this dike trajectory, piping mostly occurs near the locations of earlier breaches (van Meekeren et al., August 2024). These breaches occurred during the flood of 1825. The Scherenwelle dike is wide, has an average slope plane and is mostly composed of a sandy core with a clay cover and base layer. The durability score of this section in its current state is 1. The current dike cross-section offers little to no delay in the failure paths.

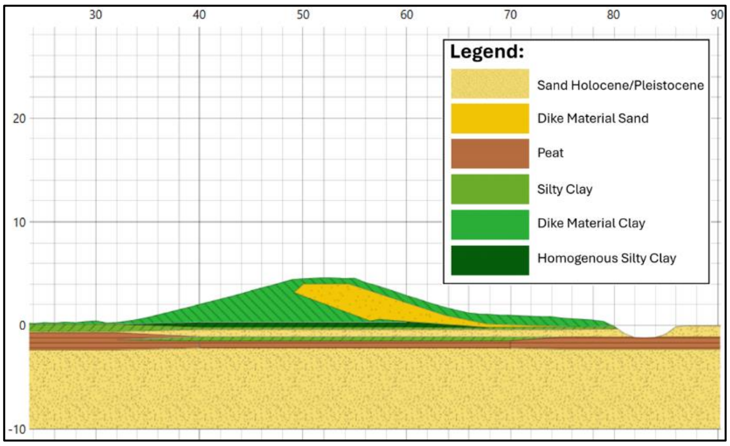


Figure 57. Soil composition and cross-section of dike section Scherenwelle

The durability score for the proposed VKA variants in this section is a 3. Variants one and two, which involve soil reinforcement to the inner or outer talud, could delay failure paths for macro-instability and overtopping. Overtopping can increase the failure path of macro-instability as the inner talud slips and overtopping takes over. The influence of additional soil would most likely relocate the slip plane from the inner slope to the inner berm. Additionally, a wider dike means that more of the dike would remain in the case of a macro-instability failure. Therefore, the assumption that variants one and two would create delays in the failure path is feasible. Variant three involves the implementation of filter construction in the inner berm, which would delay the speed at which soil is displaced under the dike, delaying the failure path for piping. Overall, the durability of this dike section is only partly durable considering the proposed variants, as not all failure paths are delayed for each failure mechanism in every variant.

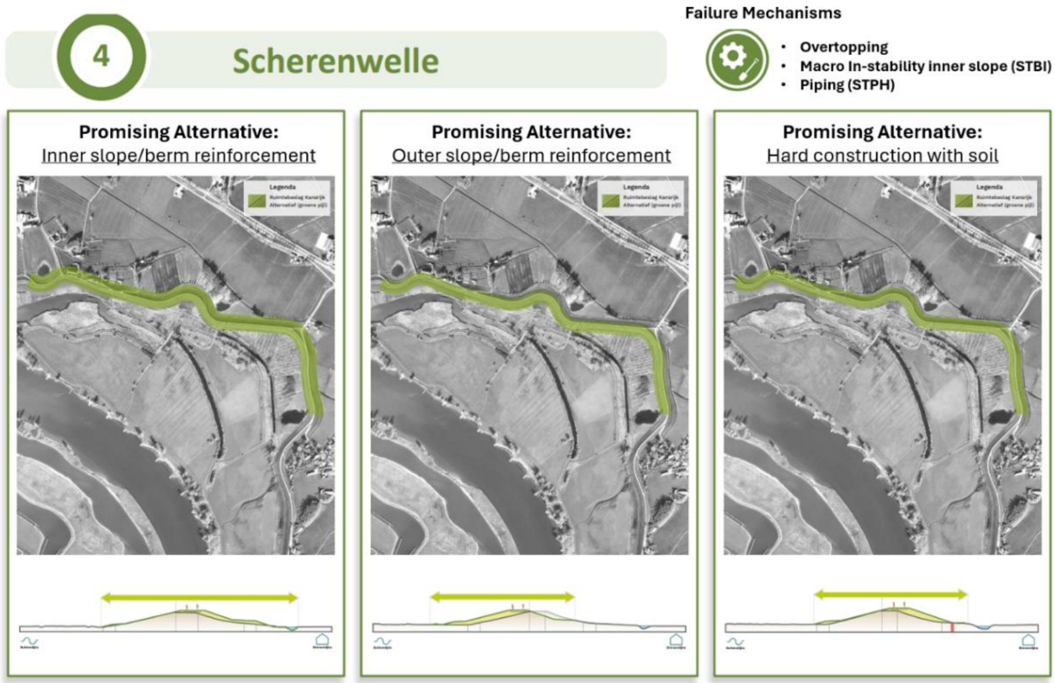


Figure 58. Proposed variants Scherenwelle (DODelta, et al., 2025)

Dike Section 5: De Naters

Overtopping, insufficient revetment on the inner talud, and macro-instability in the inner slope are the failure mechanisms expected in dike section De Naters. The current dike composition is mostly clay within the outer talud and sand within the inner talud, with a thin clay and grass cover. The crest height for this section is insufficient; therefore, overtopping will occur and not be delayed, as the crest and inner talud are primarily composed of sand. Consequently, the current situation's durability score is 1, a result of no delay in the failure paths.

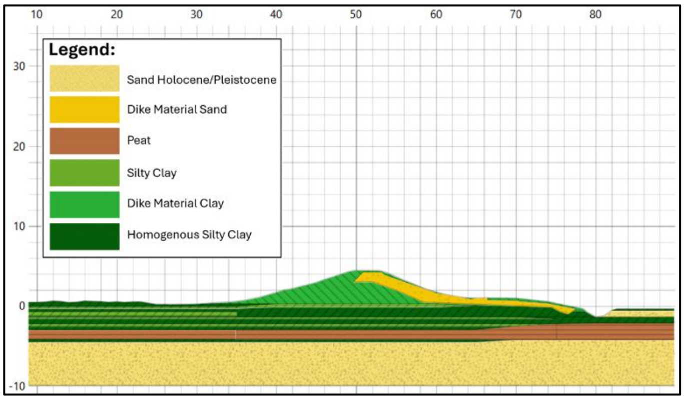


Figure 29. Soil composition and cross-section of dike section De Naters

When taking into account the suggested VKA reinforcement variants, the dike section De Naters has a durability score of 2, which indicates that it is slightly durable. The failure path of all the existing failures would be slightly delayed by variant one, which is a soil reinforcement on the crest and inner talud. As the reinforcement improves the cover and revetment on the inner talud where the sand core is present. Variant two, however, is not durable as it reinforces the outer talud with soil, leaving the thinly covered sand core on the inner talud exposed. Dike section De Naters could overall be made more durable by incorporating more robust reinforcement measures.

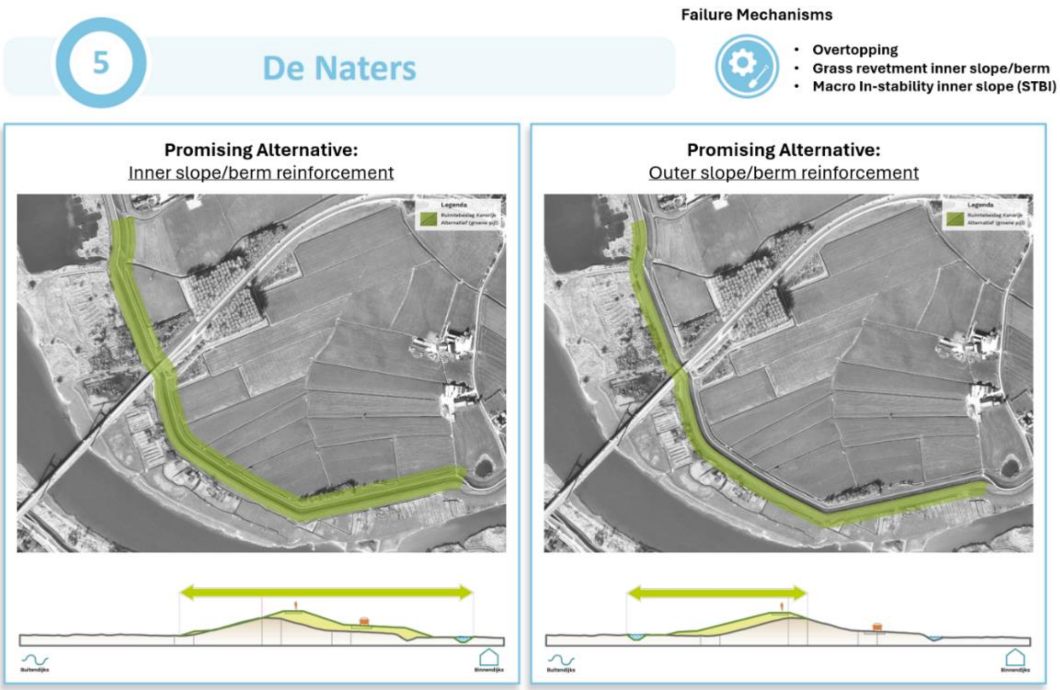


Figure 30. Proposed variants De Naters (DODelta, etl., 2025)

Dike Section 6.1: IJsselmuiden- Tasveld

Dike section IJsselmuiden-Tasveld will experience overtopping and macro-instability in the inner slope. The dike is wide, with a gradual slope, mostly made up of clay with some sand within the crest and inner talud, which have a thick clay cover. This section is slightly durable and receives a durability score of 2. The thick clay layers offer a slight delay in the overtopping failure process and the wide width delays the failure path associated with the macro-instability of the inner slope.

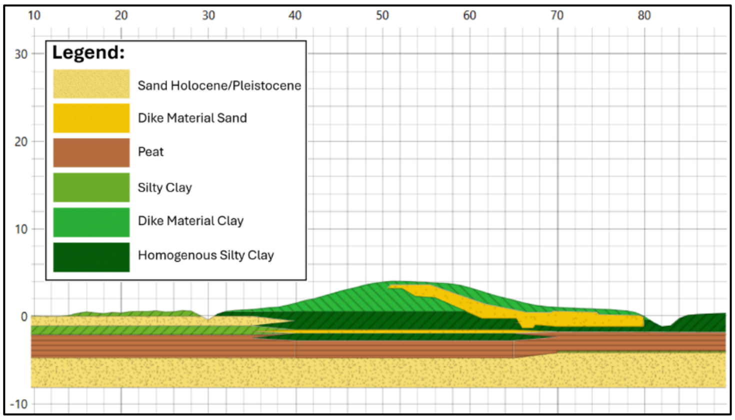


Figure 59. Soil composition and cross-section of dike section IJsselmuiden-Tasveld

Considering the variants proposed during the VKA phase, IJsselmuiden-Tasveld has a durability score of 4. Both of the suggested variants will improve the crest and inner talud cover. The additional soil cover reduces the rate at which erosion of the inner dike from overtopping occurs. The larger width increases the dike stability if the failure plane slips in the occurrence of macro-instability, delaying the failure path. Variant two offers additional durability by incorporating a hard structure in the inner berm as well as a soil reinforcement. This section's overall durability is sufficient considering the reinforcement alternatives. However, additional robust elements could make this dike section more durable.

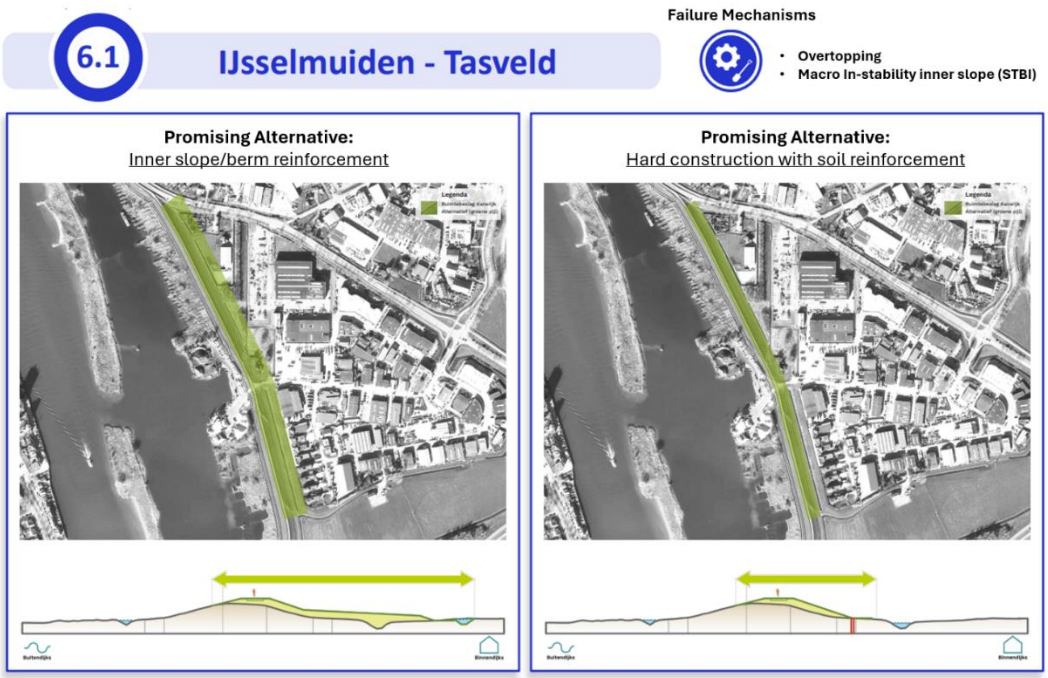


Figure 60. Proposed variants IJsselmuiden-Tasveld (DODelta, etl., 2025)

Dike Section 6.2: IJsselmuiden- Spoorlanden

The durability score of the current situation of dike section IJsselmuiden-Spoorlanden is 1. Although this dike section has a very large width it is mainly composed of sand with a very thin cover. When the crest or inner talud cover is breached during overtopping, there will be no delay within the failure path and total failure will occur rapidly.

The first proposed variant is an inner talud soil reinforcement, which would increase the dike's durability by delaying the failure path for overtopping and altering the failure plane for macro-instability. Additionally, variant three uses a hard construction from the dike's base to its crest, which would lower internal stresses on the inner Talud, lessen the possibility of macro-instability, and retain the crest height in the event of overtopping. Overall, this section has a durability score of 4 with the proposed reinforcement variants.

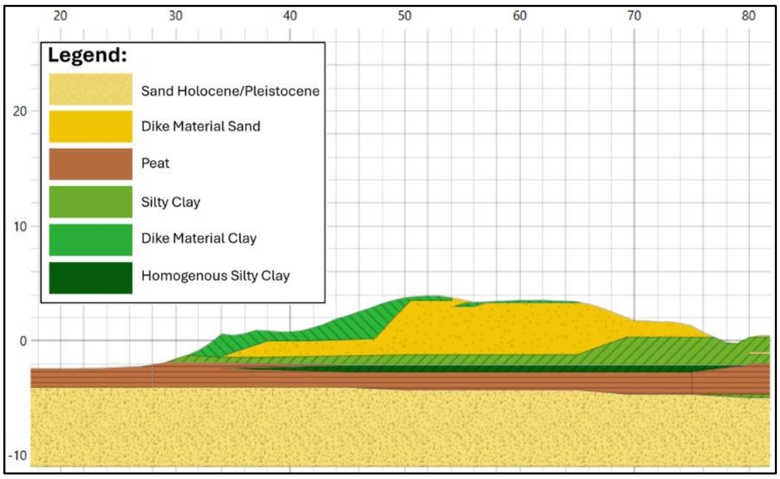


Figure 61. Soil composition and cross-section of dike section IJsselmuiden-Spoorlanden

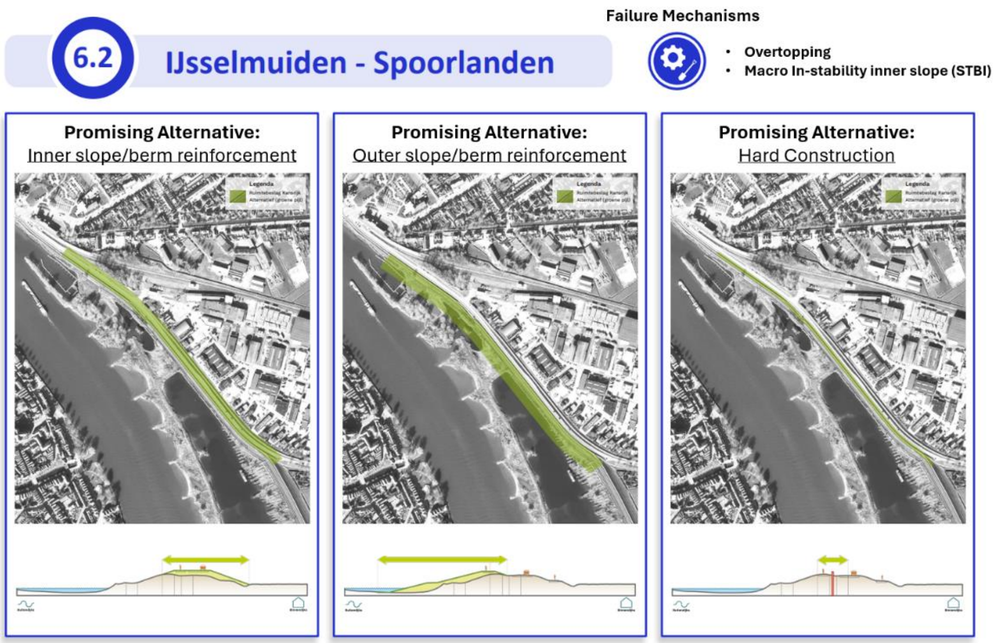


Figure 62. Proposed variants IJsselmuiden-Spoorlanden (DODelta, etl., 2025)

Dike Section 6.3: IJsselmuiden- Station

The durability score of the dike section IJsselmuiden-Station in its current state is 1. The dike has a steep outer slope and sand core. The expected failure mechanisms include overtopping and macro-instability. There are currently no elements present in this dike section that would delay or alter the failure path.

The proposed alternatives incorporate hard constructions into the dike to minimize the effects of the failure mechanisms. Variant one will cause a delay in the failure path due to the vertical hard construction maintaining the crest height. Variant two would implement a concrete stairway construction, which will improve the dike cover and reduce the impact of wave water run up; this variant will also create delays in the failure path. This dike section with the implementation of either variant has a durability score of 5.

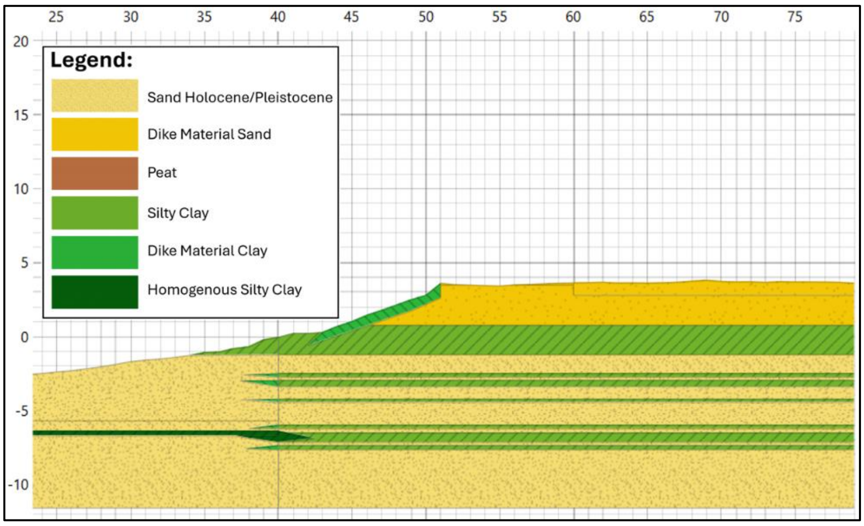


Figure 63. Soil composition and cross-section of dike section IJsselmuiden-Station

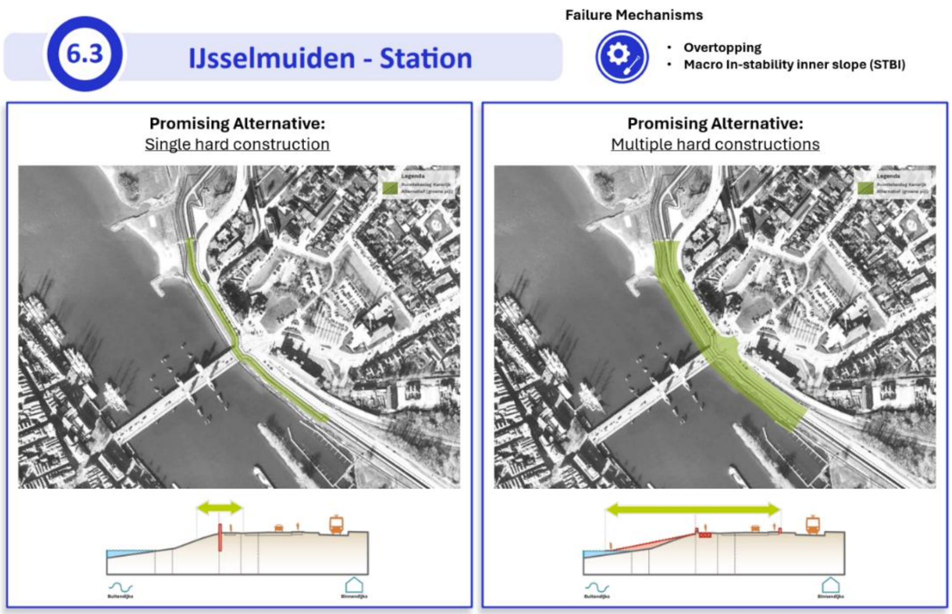


Figure 64. Proposed variants IJsselmuiden-Station (DODelta, etl., 2025)

Dike Section 6.4: IJsselmuiden- Frieseweg

Dike Section IJsselmuiden-Frieseweg is divided into sub-sections A and B; this is due to the difference in cross-section and soil composition. Each of the sub-sections will be analyzed separately.

The current cross-section of Jsselmuiden-Frieseweg (A) has a durability score of 1. This section of the dike has a sand core, low crest height, small width and a gradual slope. There are currently no durable elements that would delay the failure path processes once the clay cover is breached. When considering the proposed reinforcement variants for section (A) the durability score is 2. A soil reinforcement to the inner or outer talud would create a slight delay in the failure path. The durability of this dike section could still be improved.

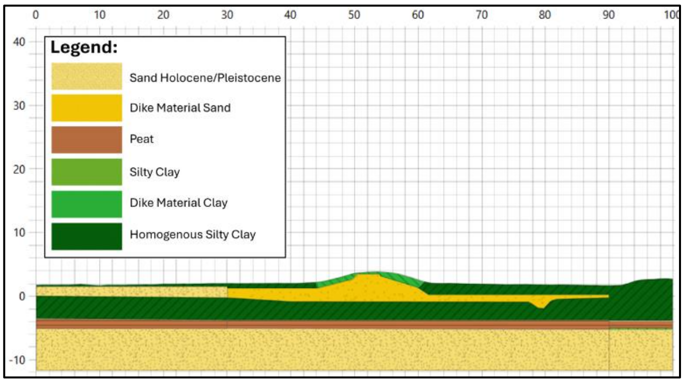


Figure 65. Soil composition and cross-section of dike section IJsselmuiden-Frieseweg (A)

IJsselmuiden-Frieseweg (B) in its current state has a durability score of 2. This is due to its clay core, large width and gradual slopes. The failure path of overtopping would be delayed due to the characteristic properties of clay. When considering the proposed reinforcement alternatives for section (B) the durability score is 4. Increasing the width and height while maintaining a gradual slope makes the dike more durable. The durability of this dike section with the proposed reinforcement variant is sufficient.

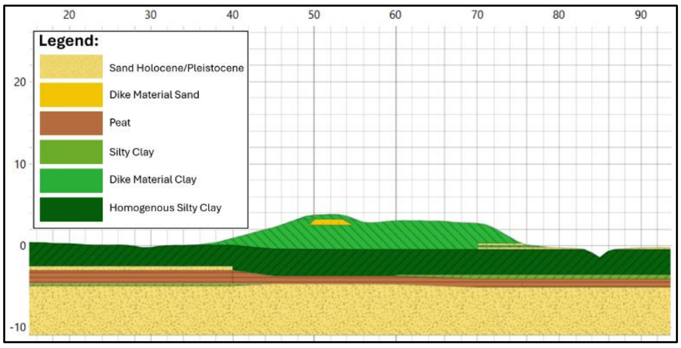


Figure 66. Soil composition and cross-section of dike section IJsselmuiden-Frieseweg (B)

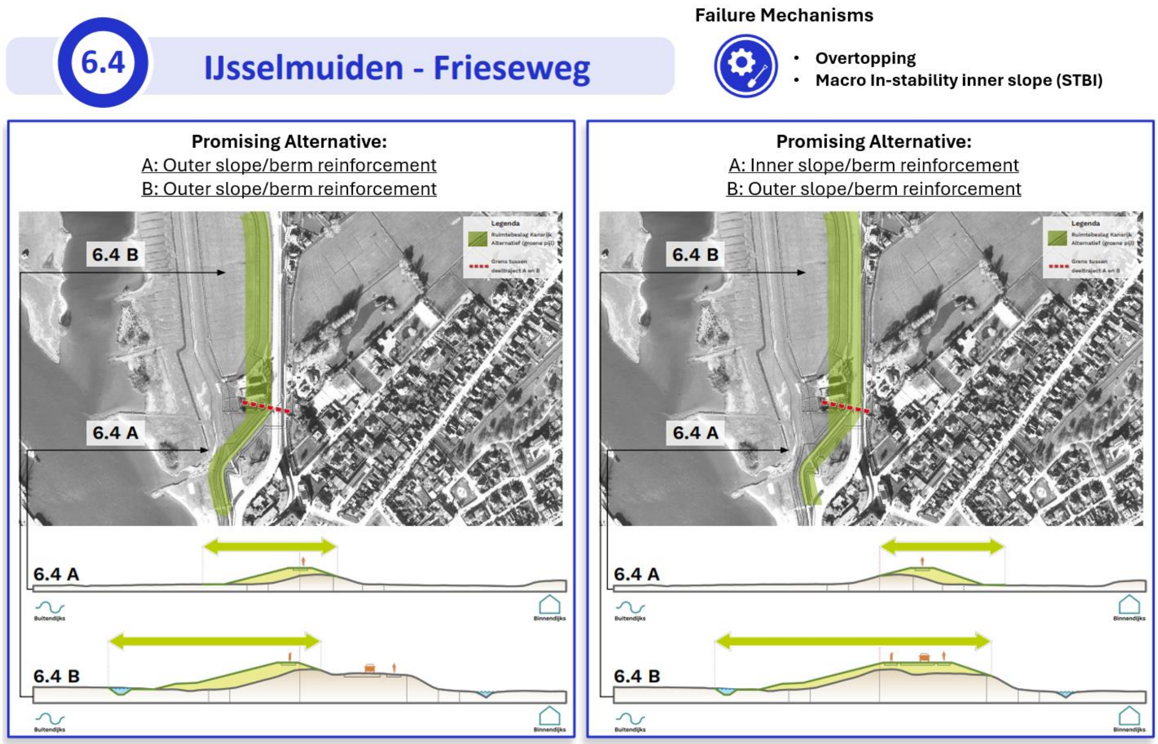


Figure 67. Proposed variants IJsselmuiden-Frieseweg (DODelta, etl., 2025)

Dike Selection Conclusion

Durability scores of each dike segments were determined by analyzing how their elements might, in theory, cause a delay in the failure path. The justification of the durability scores was supported by literature and well-informed assumptions. The educated assumptions were made based on theoretical knowledge about the failure processes of dikes.

Section De Naters was the only trajectory out of the six dike sections and sub-sections that was critical for every criteria in Table 8. Taking into account both the current situation and the proposed VKA variant situations, dike section De Naters obtained the lowest durability scores and was one of the sections with the most failure mechanisms. This section offers the optimal situation for structural analysis for a durable dike as macro-instability and overtopping are present. Additionally, it is located west of Wilsum and experiences more severe hydraulic conditions because of the wind and current patterns. Dike section De Naters is, therefore, the most suitable dike trajectory for carrying out a thorough durable dike reinforcement study.

Appendix 3: Literature Review (Durable Dike Elements)

On the 12th of September, 2024, a workshop was completed within the research group (Team Taaie Dijken Klimaatrobuust). The research group is one of the key stakeholders for this Mastenbroek-IJssel dike robust variant study. This research team is also composed of members who represent other key stakeholders for this study. During the fourth climate robust workshop, the experts of this research group were divided into three groups and asked to create a durable dike cross-section, specifically for the dike reinforcement project Wolferen-Sprok (Podt, 2024). The results of this workshop were then theoretically justified and consolidated into a report, which will be used for this literature review.

The Wolferen-Sprok dike failure mechanisms include overtopping and instability (Soepboer, 2018). This dike experiences the same structural failure mechanisms as the Mastenbroek-IJssel dike. Therefore, a feasible assumption of the theoretical durable dike variants could also apply to this study, as no additional technical factors were considered.

In the following sub-sections of this appendix, a visualization of the cross-sections will be provided, as well as the theoretical defense as to how the reinforcement elements function and how they can increase a dike's overall durability. It is important to note that the approach to dike durability for this study focuses on limiting the impact and effects of flooding due to dike failure and not the complete prevention of a breach and flooding overall.

Inner Berm Soil Reinforcement:

Although it's a standard reinforcement solution, expanding the inner berm of the dike can increase the overall robustness. This is due to the additional time it would take to erode the extra soil during the failure process. "Extra soil = extra durability," (Podt,2024). Therefore causing a delay in the failure path and reducing the impact of flooding due to a dike breach. This reinforcement method does increase the spatial use required; however, it is a more natural alternative. When implementing this alternative the serviceability life considered is at least 50 years.

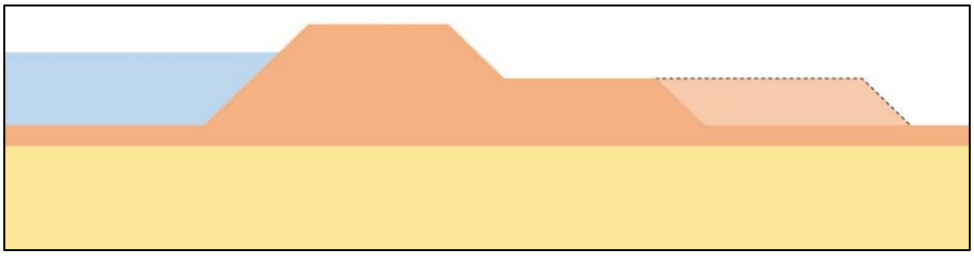


Figure 68. Inner berm soil reinforcement (Podt, 2024)

Double Dike Water Reservoir System:

A double dike water reservoir system, also referred to as a double dike, implements a sleeper dike on the landward side of the existing dike. In this case the sleeper dike has a smaller cross-section than the existing dike, and holds excess water in the event of overtopping. This decreases the speed of flood waters and acts as a reservoir for excess water. This water reservoir created between the two dikes also helps counteract against piping, due to the opposite acting pressure of the large body of water (Podt, 2024). The water reservoir also acts as an additional storage system for excessive rainwater.

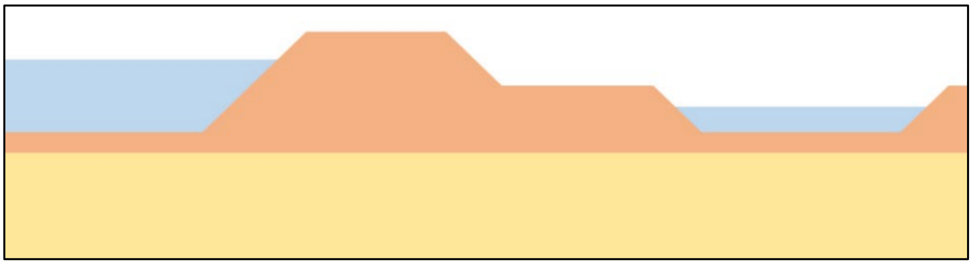


Figure 69. Double dike water reservoir system (Podt, 2024)

Sheet-pile Wall (1m Above Ground Level):

The implementation of a sheet-pile wall in the inner talud of the dike just until 1m above ground level already creates an obstruction against the failure mechanism of piping. This then creates a delay in the failure path making the dike more robust. The concept is that the pipe will still form just at a reduced speed causing a delay, then once the dike starts to fail structurally the sheet pile will take over to relieve the excess forces, reduce the speed of erosion, and act as a obstruction to water flowing in the polder. The sheet-pile construction on the inner talud instead of at the toe of the dike is expected to be more expensive (Podt). Additionally, the taller the sheet pile wall, the larger the obstruction and the greater the delay in the failure path.

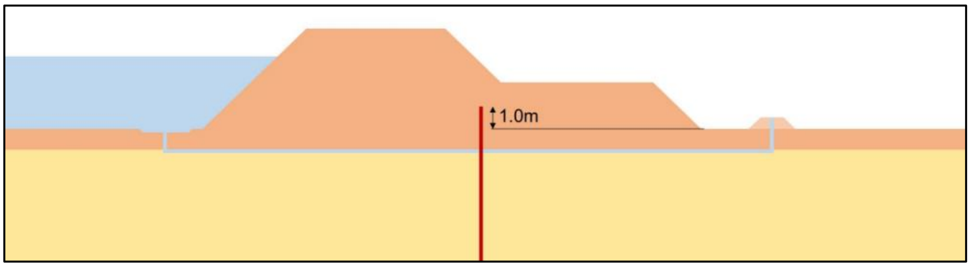


Figure 70. Sheet-pile wall, 1m above ground level (Podt, 2024)

Increased Dike Width:

With a soil reinforcement to make the overall dike wider, it also increases the rate at which the dike is eroded to the point of complete collapse in the event of a breach (Podt, 2024). This creates a delay in the failure path. It is important to note that a clay soil reinforcement would be more effective as it is more cohesive and has a reduced erosion rate compared to sand. Increasing the width of the dike is not always optimal as it also increases the spatial use, which in some cases can be a constraint. Making the dike wider also means that in the case of a macro-instability failure more of the dike body will remain intact, increasing the structural integrity and delaying the failure process. Typically, a macro-instability failure leads to a substantial crest height reduction and then the failure of overtopping takes over and increases the flood impact.

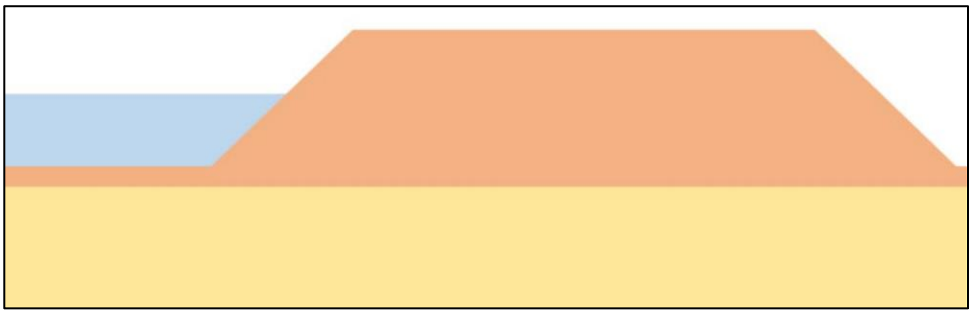


Figure 71. Increased dike width (Podt, 2024)

Berm Heightening with Clay:

Increasing the berm height with a clay soil reinforcement increases the robustness of the dike as there is a larger cohesive cover to be eroded in the event of failure, thus creating a delay in the failure path (Podt, 2024).

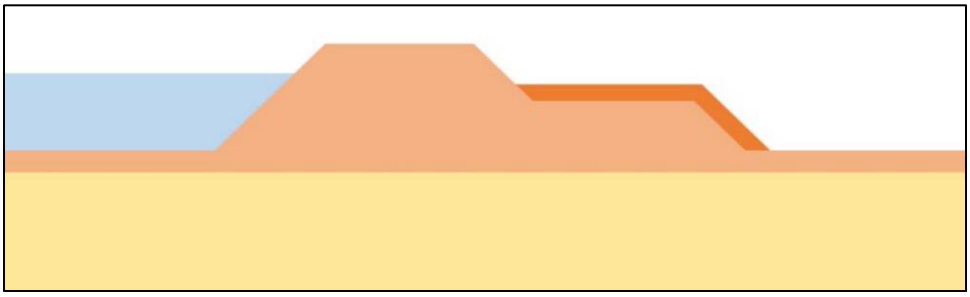


Figure 72. Berm heightening with clay (Podt, 2024)

Improving Soil Erosion Characteristics:

Improving the dike's erosive properties through incorporating lime (calcium oxide) into the soil increases the durability, as it creates a delay in breach growth and failure path. Lime can be mixed in place and added to pre-existing dikes, making it easy to implement (Podt, 2024). In this case lime is used to increase the cohesive properties of clay. However, it is also possible to incorporate it in the sand. Adding lime to clay or sand reduces the presence of bentonite and increases the soils erosive strength. The use of lime to increase a dikes erosive strength has been applied and tested in the Hedwigepolder; however, the overuse of lime can cause an ecological issue (Podt, 2024).

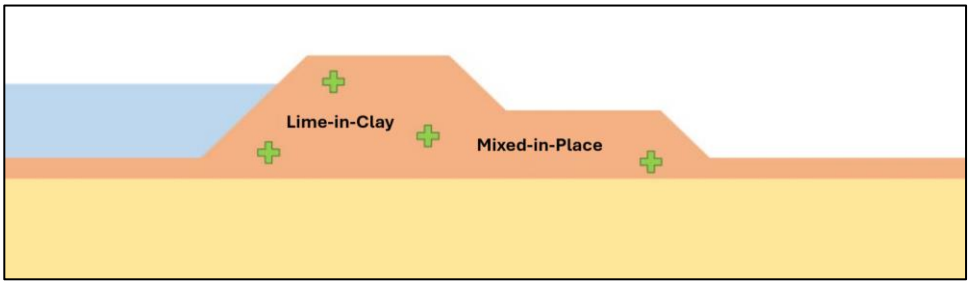


Figure 73. Improving soil erosion characteristics (Podt, 2024)

Incline Reduction of the Outer Slope:

Altering the dikes geometry to create a gentler slope and increase ground mass improves the overall durability (Podt, 2024). The gentler slope incline reduces the effect of wave water runup, creating softer hydraulic conditions which act on the dike. The reduced hydraulic conditions delay the breaching and failure process, as well as the erosion of the extra dike material.

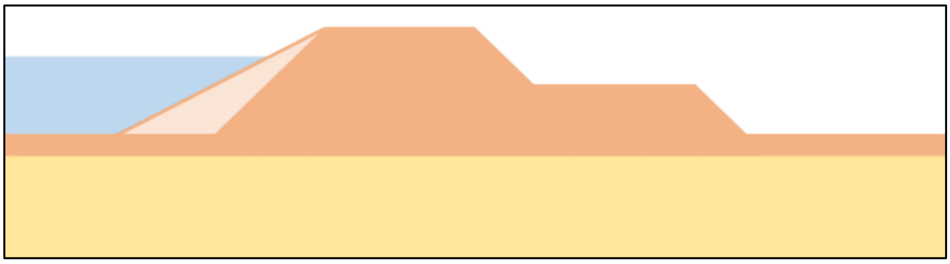


Figure 74. Incline reduction of the outer slope (Podt, 2024)

Vegetated Foreshore:

Implementing vegetation to the foreshore of a dike can dampen the golf impact acting on the outer talud of a dike. This reinforcement increases the dikes durability by reducing the impact of flood waters (Podt, 2024). Further research on the effects of golf reduction due to foreshore vegetation was conducted by Deltares and has proved successful, and is a good nature based solution. This alternative takes into account flood protection and biodiversity.

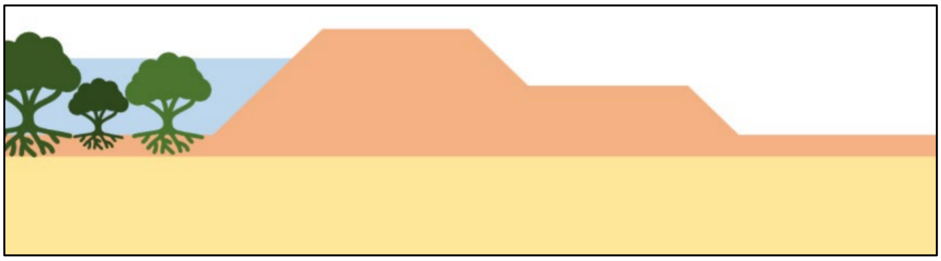


Figure 75. Vegetated foreshore (Podt, 2024)

Hard Construction in the Outer Dike Zone:

By strengthening the dike's structural integrity, a cofferdam inspired design would increase the dikes durability. As seen in the picture below, short sheet-pile walls are installed in the outer dike zone and the inner talud. In the case of a traditional singular sheet pile wall there is no opposing soil to hold the wall in place in the event of dike collapse. Therefore, the coffer dam concept is more efficient. Conventional sheet pile walls are less expensive, less extensive, and durable, as they significantly slow down the failure path. The cofferdam concept anchors the sheet-pile wall in the inner talud to another sheet-pile wall outside of the failure plane. The construction will remain intact in the event of a complete dike collapse, making it even more resilient than the more common alternative (Podt, 2024). This construction would serve as a dam, retaining the water to the height of the wall. This is a costly but very effective reinforcing method that maximizes the use of space.

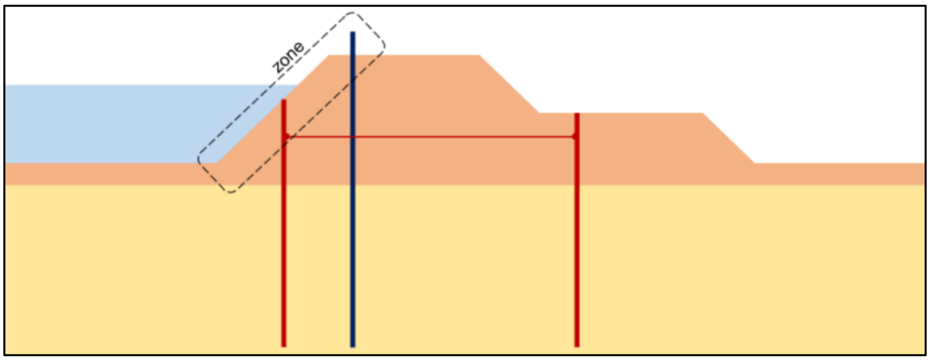


Figure 76. Hard construction in the outer dike zone (Podt, 2024)

Erosion Reduction Elements and Filter Construction:

Robust elements including a hard foundation at the crest, a rougher and larger revetment on the outer slope, and a filter construction create delays the failure path and lessen the impacts of floods, which increases the dike's robustness (Podt, 2024). The reduction factor for wave water run-up takes into account the larger and rougher revetments on the outer slope. Erosion is slowed down by the crest's hard foundation and the rate of erosion caused by piping during overtopping can be decreased with a gravel box filter construction (Podt, 2024). All details considered, these elements would make a dike more durable.

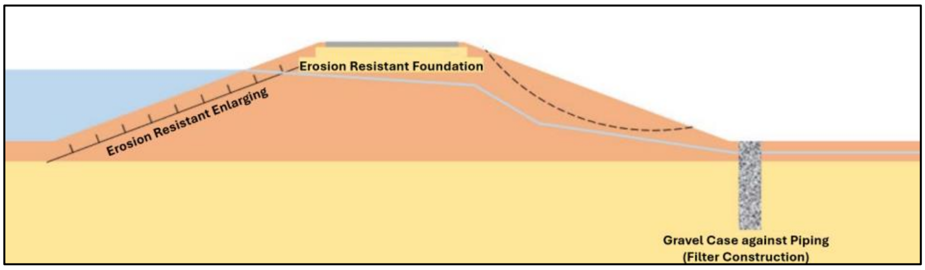


Figure 77. Erosion reduction elements and filter construction (Podt, 2024)

Flexible Sheet-pile Wall:

Installing a commonly used sheet-pile wall within the dike increases the dikes durability. The minimum crest height considered during a breach is the height of the sheet-pile wall, this consideration decreases the impacts of a flood due to dike breach. Anchoring a sheet-pile wall provides stability through rigidness, whereas a more flexible unanchored wall is more likely to deform. An anchor with a lower resistance strength which would only serve to lessen the deformation of the sheet-pile wall in the case of a breach could be installed to combine flexibility and structural stability (Podt, 2024).

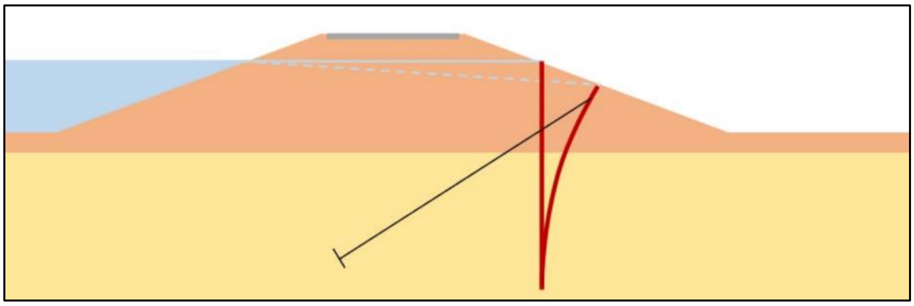


Figure 78. Flexible sheet-pile wall (Podt, 2024)

Stepped Water System with Filter Construction:

A stepped water system with a filter construction allows overtopping to occur in the event of an extreme weather event, however the excess water is then stored in the two water basins. This design considers a hard revetment on the inner and outer slope which reduces erosion during overtopping. The filter construction is installed to reduce the probability that piping would occur during high tide (Podt, 2024). This is a very robust solution as erosion of the dike is reduced delaying the failure path of overtopping, a filter construction delays the failure path of piping and the impact of the flood is further reduced by storing initial flood water in the water basins.

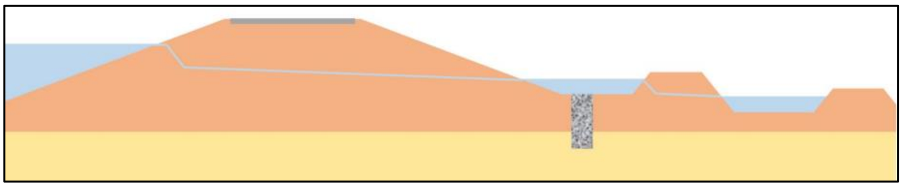


Figure 79. Stepped water system with filter construction (Podt, 2024)

Appendix 5: Meeting with Experts

Variant Workshop with Water Board Drents Overijssel Delta:

During an interactive workshop experts from the WDOD were asked for their input to determine which of the robust reinforcement alternatives is the most feasible. Attendees of this workshop included Peter Hopman and William Ouwehand from the water board, Barbara Bouman from TAUW, and myself as the workshop organizer. This workshop took place online on March 31st, 2025 from 13:00 until 15:10.

The workshop began by providing the attendees with all of the relevant project and research background information. The criteria used to assess each of the alternatives for feasibility were the same previously defined criteria from the VKA phase of this reinforcement project. The attendees were asked if the weight of these criteria should be evenly distributed, or if they found certain criteria more relevant. It was decided that all the criteria should be equally weighted as this project has a variety of stakeholders and each criteria is more important to specific stakeholders. Each of the three robust reinforcement alternatives was presented to the attendees. Additionally, information on each alternative can be found in report section 3.3.

Based on the presented reinforcement alternatives and pre-defined criteria each of the experts filled in the Multi-criteria-analysis individually. This process involved each expert assigning a sufficiency score to each criteria for each alternative, as well as the option to provide additional feedback. The experts were able to provide their results anonymously using Microsoft Forms.

Individual MCA Results:

Variant 1:					
Response	Respondent	Area Impact	Technical Feasibility	Cost-Effectiveness	Sustainability
	1	Partially sufficient	Partially sufficient	Insufficient	Insufficient
	2	Very sufficient	Partially sufficient; Insufficient	Insufficient	Partially sufficient; Insufficient
	3	Partially sufficient; if you have occupy space on the outer side of the dike and apply vegetation in the foreland	Partially Insufficient; Flexible sheet piling, do we have experience with that. does that require specific management?	Partly sufficient; Constructions and anchors are expensive.	Partially sufficient; Sheet piling needs to be replaced in 100 years and anchors as well.
Variant 2:					
Response	Respondent	Area Impact	Technical Feasibility	Cost-Effectiveness	Sustainability
	1	Partially sufficient	Partially sufficient	Insufficient	Insufficient
	2	Partially sufficient; Insufficient	Insufficient	Insufficient	Insufficient
	3	Very Sufficient; No to little impact on surroundings, it stays within the dike profile	Very sufficient; Provided the cofferdam is constructed where two sheet pile walls in the crest.	Insufficient; Double sheet piling for overtopping is not common and very costly.	Insufficient; the structure has a life span of 100 years. You then have to replace everything.
Variant 3:					
Response	Respondent	Area Impact	Technical Feasibility	Cost-Effectiveness	Sustainability
	1	Partially sufficient	Partially sufficient	Partially sufficient	Partially sufficient
	2	Partially sufficient; Insufficient	Partly sufficient; note that a double dike should be made to provide water storage. Also, lime in clay can be replaced with all clay. Vegetation in foreshore to reduce elevation issue.	Partially sufficient	Very sufficient

	3	Partly sufficient; As it is, you don't use much additional land. The question is whether this is enough and whether you shouldn't put the dike 100 m further. In that case you use a lot of land and it probably does become insufficient.	Partially sufficient; the first catch basin you have to regulate the runoff well under daily conditions, otherwise it becomes a wet mess. Drainage is an option here only management costs of it are high.	Very sufficient; compared to the other options, this is much cheaper because no hard structures are implemented.	Partially sufficient; the system is robust and continues to work. However, the higher the water levels, the less time gained for evacuation.

Table 20. Feedback from experts during MCA workshop

Once each of the three experts completed their surveys the results were discussed as a group. This group discussion allowed a definite conclusion to be made on the suitability of each alternative based on the criteria. The feasibility of each alternative was then decided on through the agreement of each expert advice. It was eventually decided that none of the presented alternatives would become the final reinforcement design. The expert advice was that a fourth design be made including the strongest aspects from alternatives one and three. The results of this discussion are displayed below.

Final MCA Results from group discussion after individual choices:

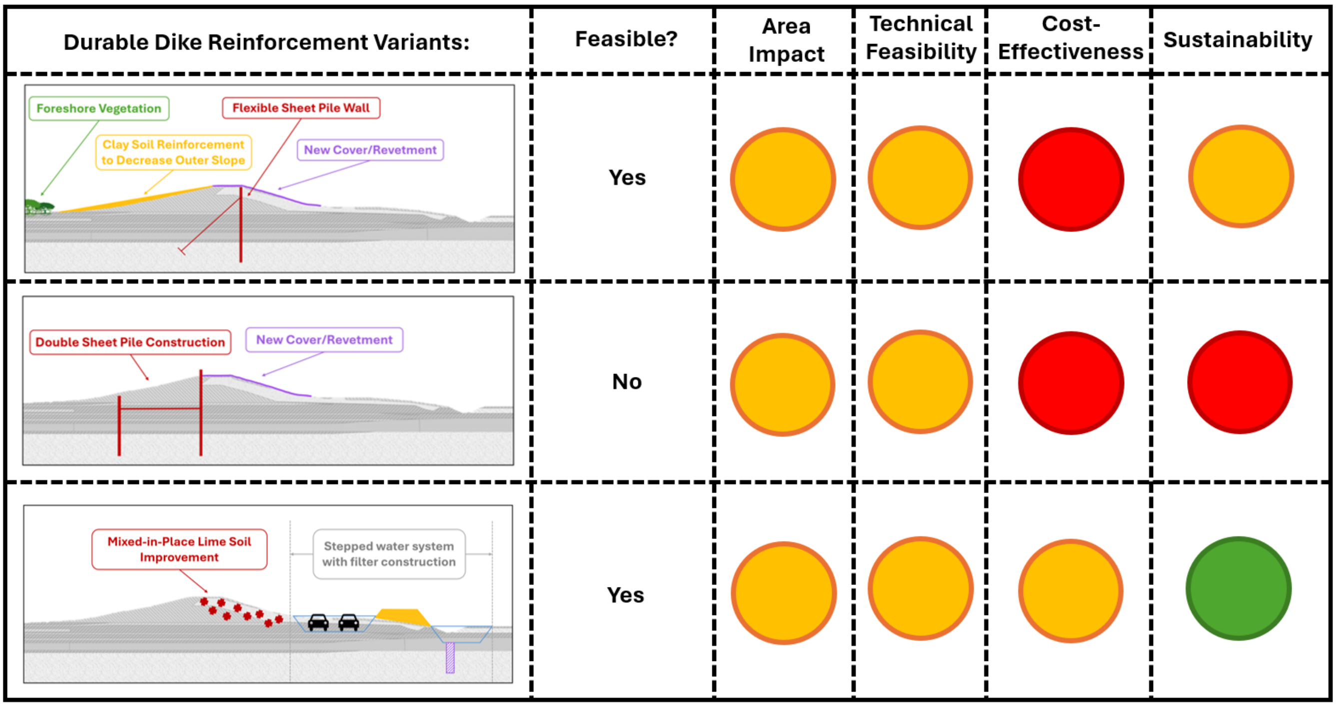


Figure 35. Multi-Criteria Analysis Results

Expert Meeting for Final Design Variant:

As a result of the expert workshop on March 31st, 2025 a definite final reinforcement design was not concluded. Therefore, an expert meeting with Frank den Heijer a Sustainable River Management Lecturer/researcher from Hogeschool Arnhem Nijmegen was organized. The meeting took place online on April 1st, 2025 from 13:00 until 14:00.

During this meeting four different reinforcement designs were presented. These designs were each a variation of robust elements from the original alternatives one and two presented during the workshop with the water board. Frank den Heijer offered his professional advice on which of the four designs is the most robust and how the elements my effect the failure path of the dike. His advice is relevant to this research goal as he is an expert on the implementation and concepts of robust dikes. Provided below is the final robust reinforcement design for dike section De Naters, as a result of this expert meeting.

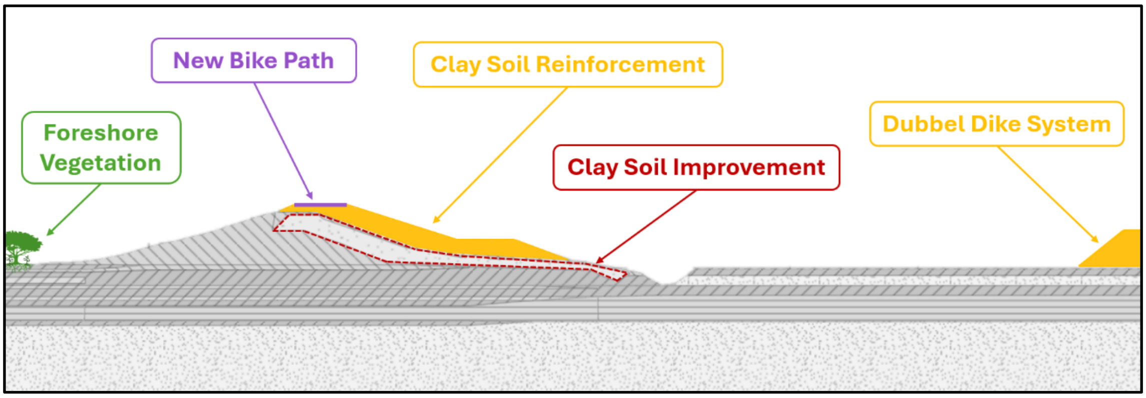


Figure 36. Durable dike design for further research

Appendix 6: Field Observations

On March 29th, 2025 a field visit was made to the research project location, dike section De Naters. Within this appendix on site photographs will be provided, as well as observations made. All figures are provided in order from the start to end of the dike trajectory.

Dike section De Naters experiences excessive animal burrowing. The displacement of dike material due to these animals compromises the structural integrity of the dike. Within the failure path of overtopping the cover layer is initially breached due to hydraulic erosion, however in this case the clay cover is already breached. This breached cover leaves the sand core exposed to excessive erosion in the presence of overtopping. If not corrected the dike failure process of overtopping will be accelerated, increasing flood consequences.

Additionally, it was observed that the road at the base of this dike section is in insufficient condition and already needs to be updated, therefore relocating the road in the design would be a feasible option. The bridge located over the dike creates a height restriction, which should be considered in the final design. It is also important to note that a water control inlet and electrical poles are also located with this project area. The observations made during this field visit aided in creating a realistically feasible final durable dike design.








Appendix 7: Previous Reinforcements within Dike Section De Naters

This appendix provides technical drawings and details of previous reinforcements which were implemented within dike section De Naters. These drawings were provided by TAUW.

Dike section De Naters consists of three sections 13, 14 and 15 and of these three sections the most prominent reference point was chosen during the VKA phase. Section 13 using the reference point of D108, Section 14 uses reference point D115 and section 15 uses reference point D120. This was a simplification made as each of the sub sections of this dike section contain multiple reference points all of which only slightly differ. This simplification was used in making the D-stability models of each section made by TAUW during the VKA phase. Each of these three sub sections and their corresponding reference points will be provided below.

Dike Section 13 Reference Point D108:

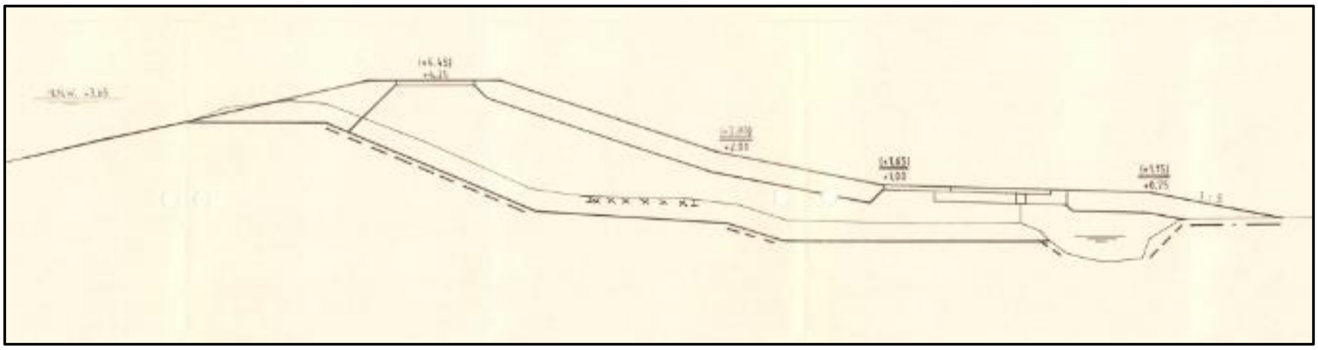


Figure 80. Technical cross-sectional drawing from 1989 of D108

Dike Section 14 Reference Point D115:

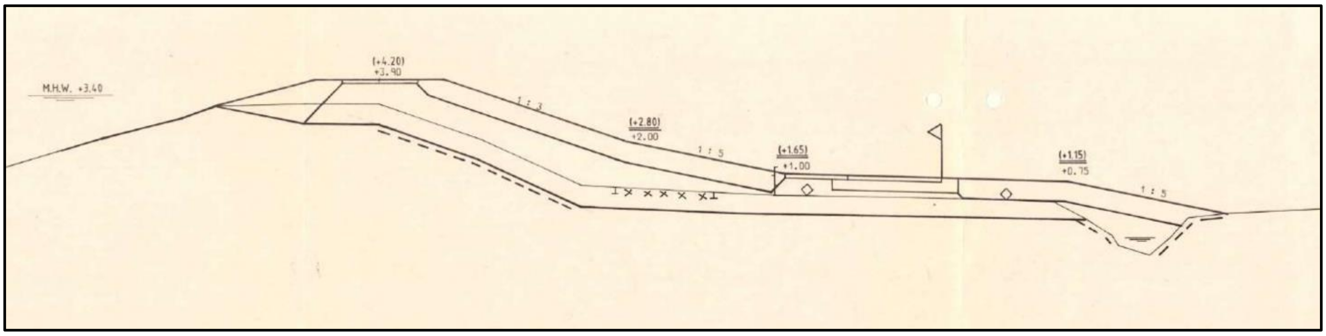


Figure 81. Technical cross-sectional drawing from 1989 of D115

Dike Section 15 Reference Point D120:

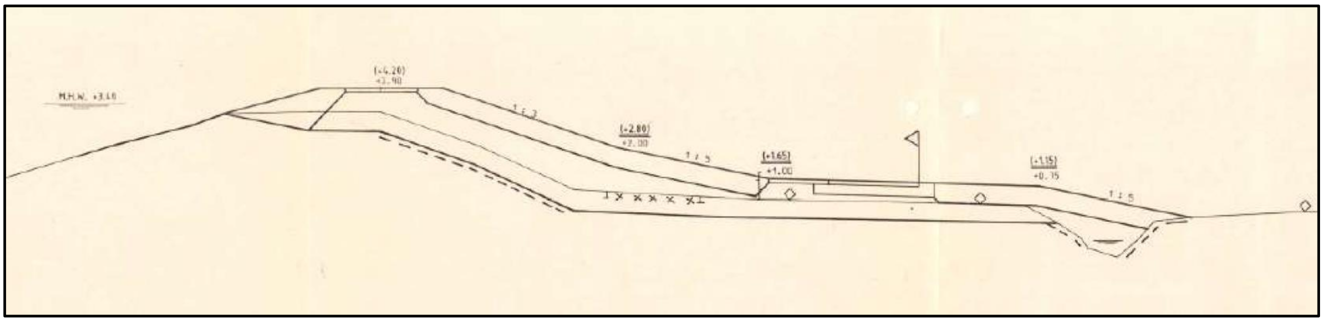


Figure 82. Technical cross-sectional drawing from 1989 of D120

Appendix 8: Durable Dike Design Macro-stability Calculations

The D-stability model of the current situation of dike section De Naters reference point D115 from the VKA phase of this project was provided by TAUW. This model includes the dikes current geometry relative to NAP, soil composition within and around the dike, the material properties of each soil type, the stages of each layer, and the initial water lines. D-stability is used to determine if a dike design satisfies the required safety factor, more specifically inner macro-stability for this research. This appendix covers the processes carried out and specifications of the data used to create the D-stability model for the durable dike design. In order for the durable dike reinforcement design to be deemed structurally sound it must meet the required design safety factor for inner macro-stability. Specifications on how the required design safety factor were determined can be found in section 2.10. For the results of this inner macro-stability calculation refer to section 4.2.

Building the D-Stability Model for the Durable Dike Design

The model provided by TAUW of the current situation for reference point D115 is used as the base for modeling the durable dike reinforcement design. The base model provided by TAUW is shown in figure 83. All adjustments made to this base model to create the reinforcement design will be documented in this appendix. The soil material properties used in this model will not be altered and can be reference in figure 17. The properties of the reinforcement material can be found in figure 84 below, as they are not provided in the data retrieved from Green Rivers in figure 17. No alterations where made to the state of the layers in this model, as new additions of soil will not have a pre-overburden pressure like the pre-existing layers.

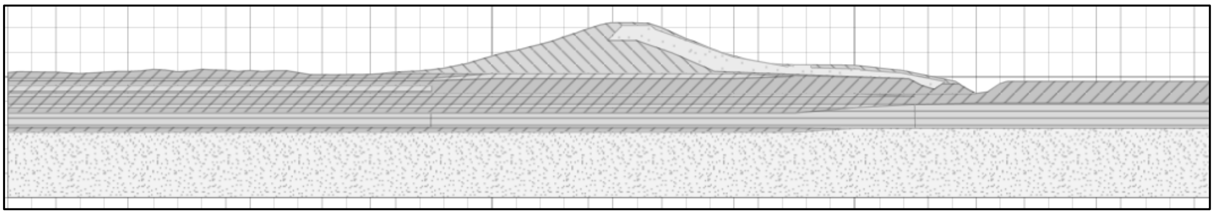


Figure 83. D-stability model of current situation at reference point D115

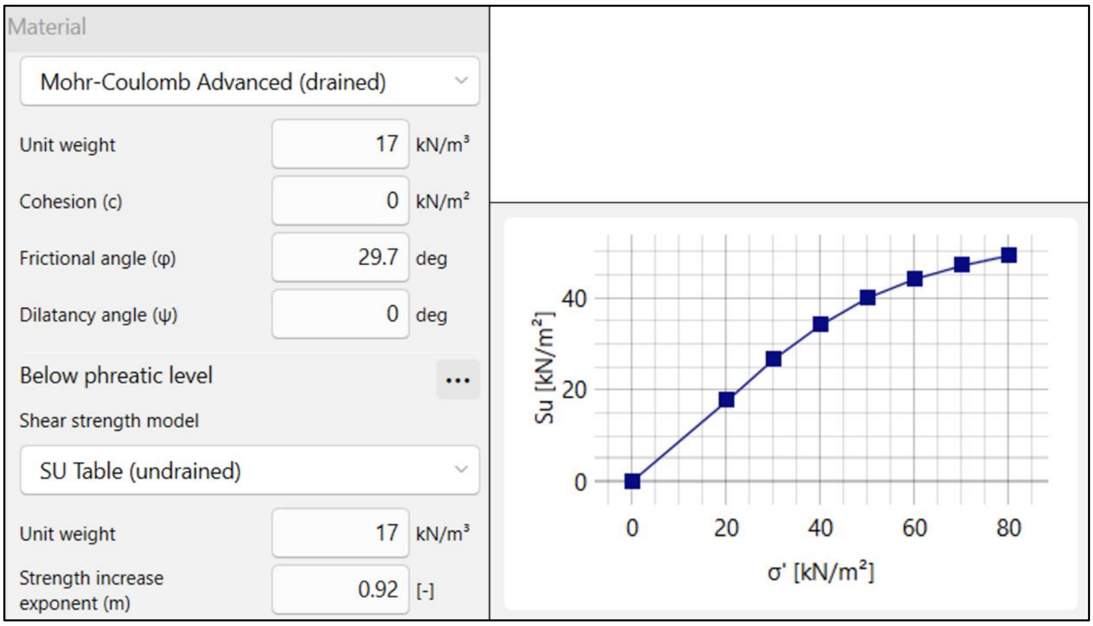


Figure 84. Material properties of the clay reinforcement material

Model Geometry Alterations:

The first alteration made the base model was extending the land on inward side of the dike to the length of 200m. This change allows for the double dike to be placed 100m away from the inner toe of the current dike. During this extension the ground level was altered to more realistically reflect this new span of land. The new ground level inputted in the model is the average reference depth -0.09m NAP. AHN (Actueel Hoogtebestand Nederland) was used to obtain this data which can be referenced in figure 85.

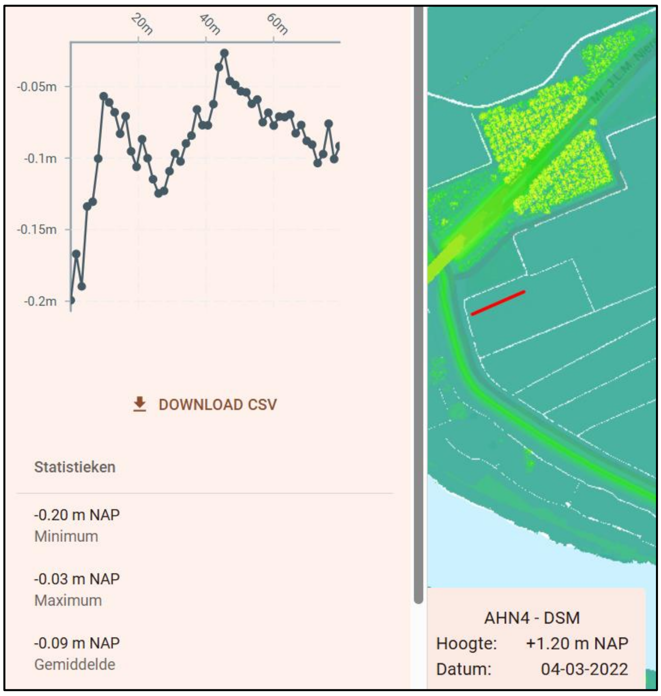


Figure 85. AHN average land height for the stretch of land between the primary dike and the double dike

Additional layers were added to the model in order to implement the soil reinforcement on the inner talud of the primary dike and the new double dike construction. In order to add the inner talud soil reinforcement the channel next to the dike needed to be relocated. To make this relocation an coordinate based excavation was made. The dimensions of the channel in this process where left unchanged. Below in table 21 the new points added to the model to create each of these new layers and the excavation are provided.

Element	Layer ID	Point Coordinates [X;Y]
Soil reinforcement inner Talud	L4	49.833;4.41
		51.453;4.95
		51.799;4.41
		52;4.403
		53;4.371
		53.626;4.17
		54;4.05
		54.356;3.89
		54.846;3.67
		55;3.601
		55.465;3.39
		56;3.148
		57;2.78
		58;2.361
		58.445;2.19
		59;1.977

		60;1.695
		61;1.435
		61.516;1.334
		63.095;1.05
		64;0.964
		64.94;0.947
		65;0.946
		65.44;0.952
		66.44;0.943
		68;0.94
		69;0.936
		70;0.914
		71;0.818
		72;0.697
		73;0.587
		73.873;0.51
		75.97;0.08
		78.361;-0.41
		78.672;-0.63
		79;-0.862
		80;-1.415
		81;-1.275
		81.962;-0.63
		82;-0.604
		82.598;-0.09
		76.97;1.282
		64.603;1.9
		55.453;4.95
		Close layer at (49.833;4.41)
Double Dike	L2	141;-0.09
		148.77;2.5
		150.77;2.5
		158.54;-0.09
		Close layer at (141;-0.09)
Channel	(excavation)	87.598;-0.09
		87.909;-0.63
		88.237;-0.862
		89.237;-1.415
		90.237;-1.275
		91.199;-0.63
		91.237;-0.604
		91.835;-0.09

Table 21. Alterations and additions made to point in the geometry of the D-stability model

<u>Model Material Alterations:</u>

Each of the additional geometry layers for the inner soil reinforcement and the double dike were both assigned the material properties of the reinforcement material. The properties of this material are provided in figure 84. The existing sand layer on the inner talud of the dike was changed from sand to the reinforcement material, this represents to clay soil improvement. No adjustments were made to the land extended to 200m due to insufficient available data. There were an insufficient amount boring samples made in the area located between the current dike and where the double dike would be located, as can be seen in figure 86. The soil composition was assumed to remain constant to that of the inner side of the dike. This assumption is relevant as the boring data retrieved from a point in the agricultural land, as shown in figure 87, is almost the same soil composition as what is provided in the D-stability model. The assumption will be made that the area between these two points will remain relatively consistent as the distance is not large. The adjusted soil composition of the D-stability model can be referenced in figure 88. The original soil composition in the D-stability model was made based on boring and CPT data provided by the WDOD.

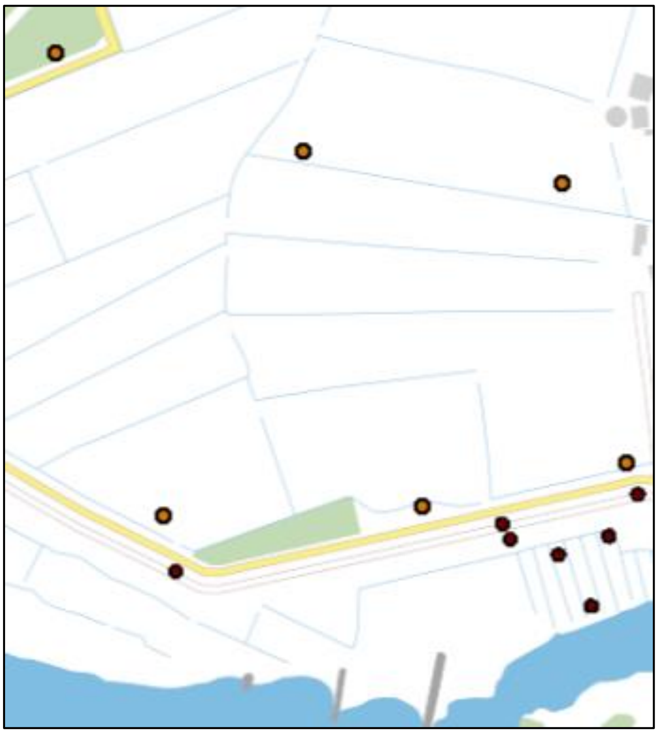


Figure 86. Soil sample data available from Dinoloket

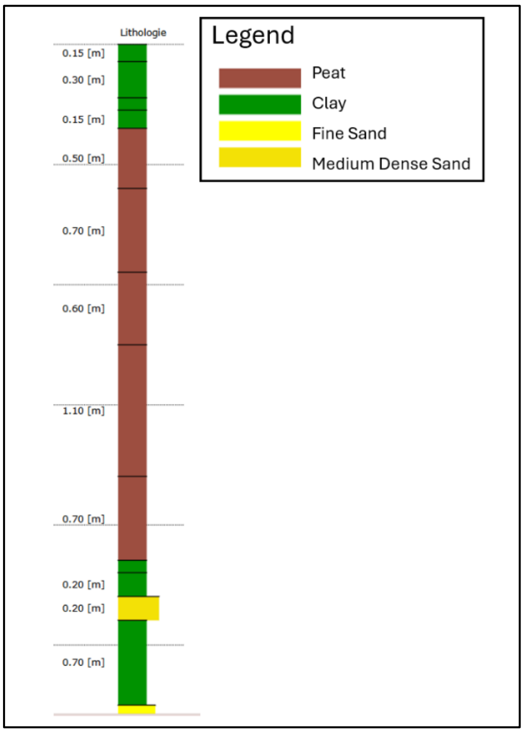


Figure 87. Soil composition near scope location

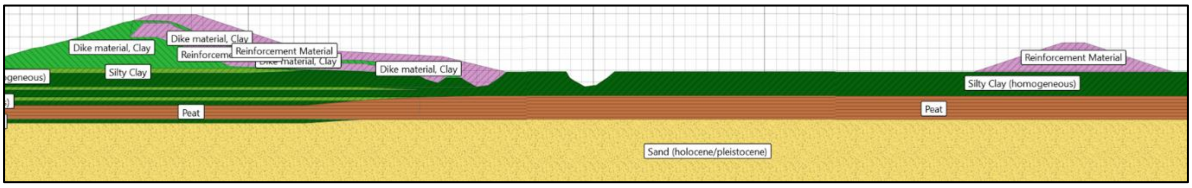


Figure 88. Soil composition of the adjusted D-stability model

Model Water Alterations:

The phreatic, rise height and the top reference water lines were adjusted in the D-stability model for the reinforced cross-section. These water lines were established using data form the TUN document from the VKA phase of this project and theoretical methods from the D-stability manual. The top water reference line was adjusted to follow the same path as the adjusted geometry, as explained above. The phreatic line for the stages daily circumstances 2024 and for the design year 2080 were not adjusted in height, as these values were identified in the TUN reference document. These water lines were adjusted in horizontal placement to align with the new crest width and berm of the reinforced dike cross-section. The rise height water lines were only adjusted for the stages of 2080. This water line was increased by 20cm to counteract the effect of ground settlement expected for the year 2080. The expected high water level (WBN) acting on the primary dike for the design year 2080 is +3.24m NAP, which takes into account a climate scenario of 1:3000 years (van Meekeren et al., July 2024). The high water level assumed for the double dike is +2.5m NAP, as the outer water level is expected to reach the entire height of the double dike in the event of a flood. The phreatic water lines for the primary dike and double dike were both calculated using the data provided in the D-stability manual for clay dikes, this method can be found in figure 89. To calculate the path of the rise height water line at WBN the counter active pressure near the channel needed to be determined. This is due to the fact that in the location near the channel bursting of the soil due to water pressure is expected. Due to the expected bursting of soil the counter acting water pressure needs to be reduced and put in equilibrium. This process was done by finding at what point the weight of the water is equal to that of the counter acting soil beneath that point, creating an equilibrium in forces so that bursting will not occur. Table 22 provides all of the water lines in the model and there correspondents relative to (x,y).

P	**Cases 1A and 1B Clay dikes (see Figure 11.1)**
A	Intersection of the river water level with the outer slope (determined automatically).
B	River water level minus offset, with default offset 1 m, limited by minimum value $Z_{B;initial}$, see section 11.1.3.2.
C	River water level minus offset, with default offset 1.5 m, limited by minimum value $Z_{C;initial}$, see section 11.1.3.2.
D	Linear interpolation between point C and point E, unless the user defines an offset $D_{offset;user}$ with respect to the surface level.
E	Surface level at dike toe minus offset, with default offset 0 m.

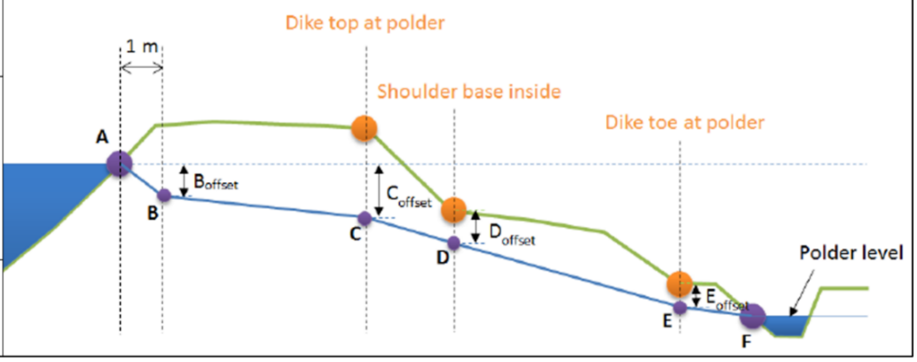


Figure 89. Schematization of the phreatic plane for clay dikes (van der Meij, 2023)

Water Line Type; Stage	Coordinates of Line
Rise Height Line; Primary dike daily situation 2024	(0;-0.6)
	(200;-0.6)
Phreatic Line; Primary dike daily situation 2024	(0,-0.6)
	(34.5;-0.6)
	(51.453;0.5)
	(55.453;0.5)
	(64.603;-1)
	(200;-1)
Rise Height Line; Primary dike daily situation 2080	(0;-0.4)
	(200;-0.4)
Phreatic Line; Primary dike daily situation 2080	Same as (Phreatic Line; Primary dike daily situation 2024)
Rise Height Line; Primary dike WBN 2080	(0;2.03)

	(78.598;1.9)
	(82.598;0.947)
	(87.598;0.947)
	(89.237;-0.546)
	(91.835;0.947)
	(200;0.947)
Phreatic Line; Primary dike WBN 2080	Start (0;3.24)
	A= (46;3.24 WBN)
	B= (47;2.24)
	C= (55.453;1.74)
	D=(64.603;1.122)
	E=(82.598;-0.09)
	F=(88.486;-1)
Rise Height Line; Double dike daily situation 2024	Same as (Rise Height Line; Primary dike daily situation 2024)
Phreatic Line; Double dike daily situation 2024	Same as (Phreatic Line; Primary dike daily situation 2024)
Rise Height Line; Double dike daily situation 2080	Same as (Rise Height Line; Primary dike daily situation 2080)
Phreatic Line; Double dike daily situation 2080	Same as (Phreatic Line; Primary dike daily situation 2080)
Rise Height Line; Double dike WBN 2080	Same as (Rise Height Line; Primary dike WBN 2080)
Phreatic Line; Double dike WBN 2080	Start (62.804;2.5)
	A= (148.77;2.5 WBN)
	B= (149.77;1.5)
	C= (150.27;1)
	E=(158.04; -0.09)
	End (200;-0.09)

Table 22. D-stability model altered water lines (van Meekeren et al., July 2024)

Calculation Method:

The calculation method of Uplift-Van is used in the D-stability model to analyze the safety factor of the durable dike design. As a result of this method an actual safety factor for the durable dike design is obtained. These results can be found in section 4.2. In order for the design to be considered stable against the failure of inner macro-instability the actual safety factor must be greater that the pre-determined required design safety factor. An active circle, a passive circle, and a horizontal bar between them make up a slip plane according to the Uplift-Van technique. The equilibrium of the horizontal forces operating on the compressed area between the active and passive slip circles is used to calculate the actual safety factor of a design (van der Meij, 2023).

Appendix 9: Flood Modeling Process

A 3Di flood model was used to simulate the breaching of dike section De Naters at reference point D115. The base 3Di model of the province OverIJssel was provided by the WDOD. Alterations to this model were then made to replicate a brittle dike cross-section, the durable dike design, and a two models for a sensitivity analysis. All alterations made to the original base model in order to create the desired scenarios are documented in table 23 along with the corresponding revision number.

This appendix will cover the steps taken to build the models on which the results of this research are based. The theory used within this model has been previously discussed within the theoretical framework section of the main report. The water depth maps which are the results of this flood model can be found in section 4.3. The results manager in the 3Di modular interface was used to obtain the maximum water depth raster's. To obtain the data for breach width and discharge through the breach over time 3Di live was used during while the simulation was running. The data retrieved from 3Di live was processed with Excel to create visualizations of the data.

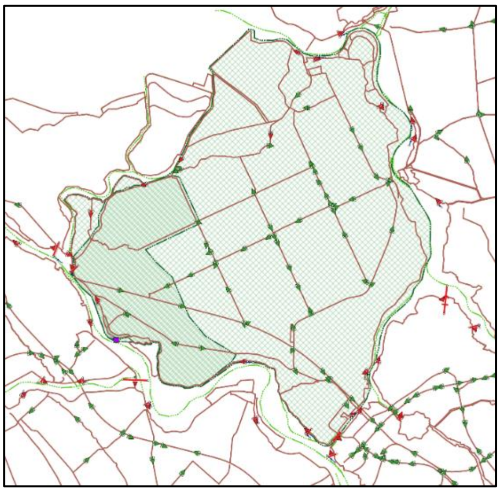


Figure 90. Project scope for flood area (green)

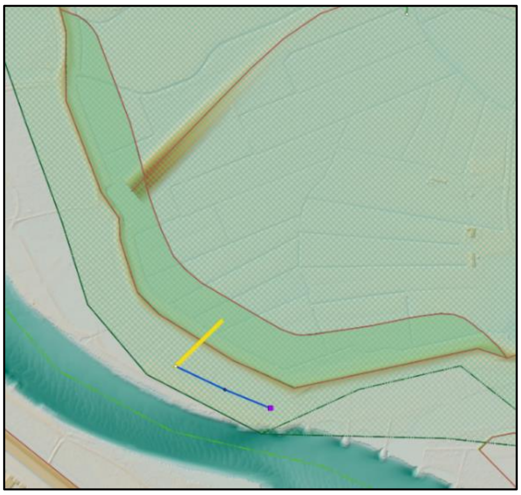


Figure 91. Zoomed in view of De Naters in the model

Revision #	Changes made
1	Copy of the Basismodel_calamiteiten; revision 26 downloaded from the WDOD
2	Obstacle for double dike added with a crest height of +2.5m NAP
3	Grid refinement size was changed to a scale of 40.000m with layers of 1, 2 and 6
	Three grid refinements were added for the areas which detailed flood data is the most important
4	Hydraulic 1D and 2D boundary conditions were updated based on new decisive flood wave for this project scope
	Minimum breach depth was changed from 0 to ground level for this area which is -0.41m NAP
	All orifices outside of the pre-defined grid refinements were deleted from the model, as they were not needed for this project and were slowing down the model
	1D boundary condition added (ID 4) this was added to input the values for the dominant storm hydraulic conditions. This boundary has a direct connection to the channel (ID 30 and 24). The breach (ID 24) used for this simulation is based on the conditions connected to this node.

	Orifices (1331, 1332, 1333, 1334) were removed from the model as they were giving and error and were not relevant to the area of study
5	Time step changed from 60 to 30
	Node (ID 23149) within the computational grid was changed from a node with storage to without and drain depth was changed from null to -3
6-13	All changes made in these revisions were reverted back and revision 14 is a continuation of revision 5
14	Grid refinement was changed from 40 to 20
	Levels of all grid refinements were changed to layers 7, 3 and 1
	Level 1 grid refinement was assigned to the double dike reservoir area
	Level 3 was assigned to grid refinement areas within the Mastenbroek polder with heavy infrastructure
	Level 7 was assigned to all areas outside of the level 1 or 3 grid refinements
15	The DEM map was edited using the Serval plugin. The opening under the bridge behind the primary dike was deepened and enlarged as the grid wasn't picking up the actual height of the area correctly. This allows the water to flow to both sides of the double dike
	The length of the bridge obstacle was also short , as it was previously modeled to close off the area under the bridge which is not a realistic representation of the actual situation
16	Obstacles for dike section De Naters (ID 111437, ID 109590, ID 109589, ID 111436 - 1110404) crest level changed to +4.95. It was originally 10m and that is not the actual dike with the reinforcement.
17	In revision 16 the crest level of the breach 24 was not adjusted with the new dike height of 4.95m NAP, therefore that was adjusted in this revision.
18	All reinforcements were removed (the double dike obstacles), breach 24 was changed to sand and given a crest height of 3.9m NAP and all ID's for section De Naters was adjusted from 4.95m to 3.9m
19	Obstacle ID's for dike section De Naters were set to 10 m as well as the crest level for breach 24
20	Breach ID 24 was changed from sand to clay
21	Based on revision 17, breach 24 was changed from clay to sand.
22 and 23	Revisions did not run properly therefore they were deleted.
24	retest of revision 17 but with crest height De Naters 5.3
25	Based on revision 17 the obstacles for the double dike and (ID 111437, ID 109590, ID 109589, ID 111436- 1110404) were changed to a crest height of +4.95m NAP. Breach 24 was changed the clay and a max height of +4.95 as well.
26	Breach 24 was changed from clay to sand.
27	Double dike obstacles were omitted and obstacles (ID 111437, ID 109590, ID 109589, ID 111436- 1110404) were changed to a crest height of +5.3m NAP. Breach 24 was given a height of 5.3m instead of 4.95m.
28	Based on revision 25 however the mentioned obstacles and breach 24 were set to a crest height of 3.9m NAP.
29	Based on revision 25 with the double dike obstacles omitted.

Table 23. Alterations made to the original 3Di base model with corresponding revision numbers

Breach Modeling

Dike breach modeling in 3Di is done by adding a potential breach line to an obstacle and channel. A desired crest level in m NAP can be assigned to the obstacle in the attribute table and hydraulic conditions can be assigned to a channel through nodes. The code behind the potential breach function in 3Di is based on the method discussed in section 2.9. Within the attribute table of a potential breach in 3Di the crest height, maximum breach depth, dike material and channel association can be assigned. The attribute table overview for a potential breach can be seen in figure 92. Currently in 3Di there is only a material function for sand and clay, therefore dikes which are partly sand and clay cannot be modeled at this time with the functions provided. This is not an issue for the purposes of this research as the brittle dike is modeled with sand and the durable dike alternative is entirely clay. However, modeling the current dike cross-section or other types of soil reinforcements would not currently be possible within this software.

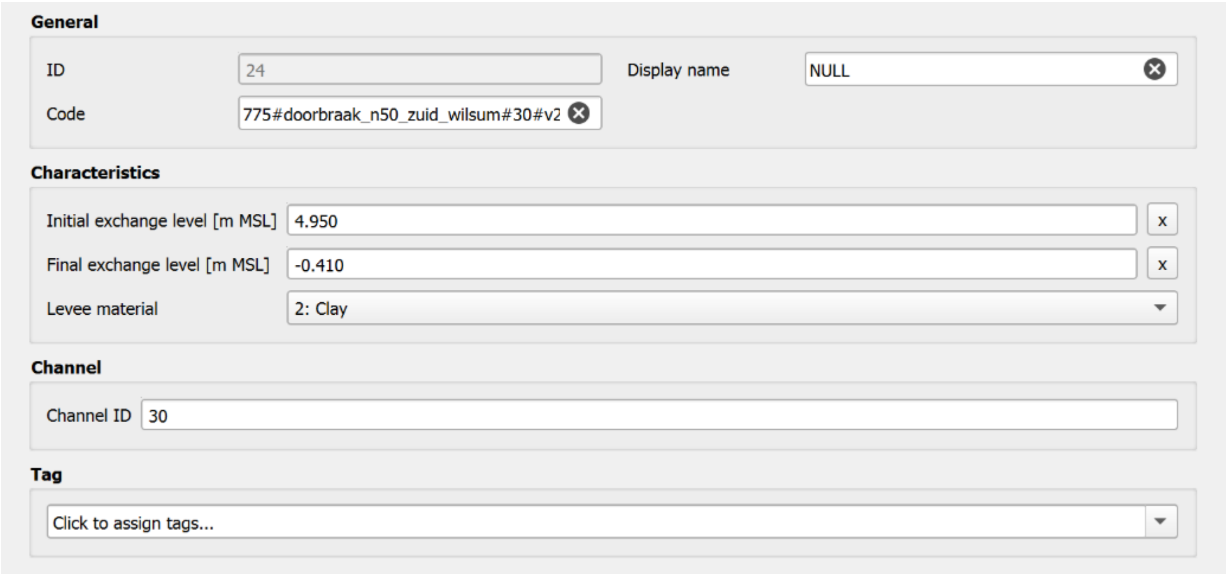


Figure 92. Attribute table overview for a potential breach in 3Di

Modeling Hydraulic Conditions for 1:3000 years

In figure 93, the decisive flood wave data for the IJsselmeer is provided in the format in which it was implemented into the model. This flood wave is for an environmental scenario with a chance of occurring 1:3000 years and has a high water golf of 2 hours at +3,3mNAP. The data provided for the IJsselmeer was implemented into the model under the location for the Ketelmeer. The hydraulic data for the IJssel river and De Vecht were left the same as the input provided by the WDOD for the scenario 1:1000 years. All of the hydraulic data must have the same time reference otherwise an error message occurs. Therefore spline interpolation was used to input the missing hydraulic data for the rivers. The data implemented into the 3Di model for both rivers is provided in figure 94. For a detailed explanation of why the following hydraulic data was chosen to be implemented into the model refer to section 2.1.2.

IJsselmeer 1:3000

Time (hours)	Water level NAP (m)
0	1.3
38	1.3
57	3.3
58	3.3
59	3.3
78	1.3
96	1.3
100	1.3
108	1.3
116	1.3
119	1.3
121	1.3
132	1.3
140	1.3
144	1.3
480	1.3

Figure 93. Hydraulic input for the Ketelmeer

De IJssel

Time (hours)	Discharge (m^3/s)	Interpolated Discharge
0	1,176.421	1,176.421
38		1,579.896
57		1,623.027
58		1,624.050
59		1,625.009
78		1,642.683
96	1,695.158	1,695.158
100	1,716.772	1,716.772
108	1760.0	1760.0
116		1760.0
119	1760.0	1760.0
121	1760.0	1760.0
132	1760.0	1760.0
140	1,731.678	1,731.678
144	1,717.517	1,717.517
480	528.0	528.0

De Vecht

Time (hours)	Discharge (m^3/s)	Interpolated Discharge
0	371.429	371.429
38		485.05
57		508.53
58		509.32
59		510.08
78		518.55
96	520.0	520.0
100	520.0	520.0
108	520.0	520.0
116	520.0	520.0
119	520.0	520.0
121	520.0	520.0
132	520.0	520.0
140	520.0	520.0
144	520.0	520.0
480	0.0	0.0

Figure 94. Hydraulic input for the IJssel river and De Vecht

Appendix 10: Crest Height Calculation

The software Riskeer 23.1 was used to determine the required crest height of a design based on the robust design standard. The Riskeer calculation file used to determine the required crest height during the VKA phase of this dike reinforcement project was provided. Imputing the reduced robust design standard per year under the crest height for each design scenario was the only alteration made to the original calculation file. The input and output of the HBN calculations for each design scenario can be found in the figures below. It is important to note that a standard of 1:25000 was used only when determining the height requirement for this project location (van Meekeren et al., July 2024). This standard for height requirements was determined based on the failure chance per failure mechanism. Riskeer 23.1 is only available in Dutch therefore below is a list of translated terms which are relevant for retrieving the required crest level.

Dutch Term	English Translation
HBN (Hydraulisch Belastings Niveau)	Hydraulic load level
Doelkans	Target probability
Betrouwbaarheidsindex doelkans	Reliability index of target probability
Berekende kans	Calculated probability
Betrouwbaarheidsindex berekende kans	Reliability index of calculated probability
Convergentie	Convergence
Hydraulische belastingenlocatie	Hydraulic load location
Dijkprofiel	Dike profile
Orientatie	Orientation
Dijkhoogte	Dike height
Kritiek overslagdebiet	Critical Flow Rate
HBN berekenen	Calculated hydraulic load level
Illustratiepunten inlezen	Read illustration point

Table 24. Translated terminology for the input and output of Riskeer 23.1

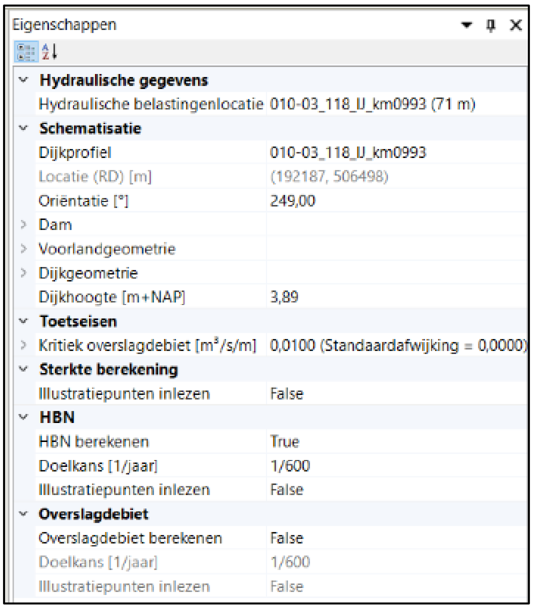


Figure 95. Input HBN Calculation 1:600 years

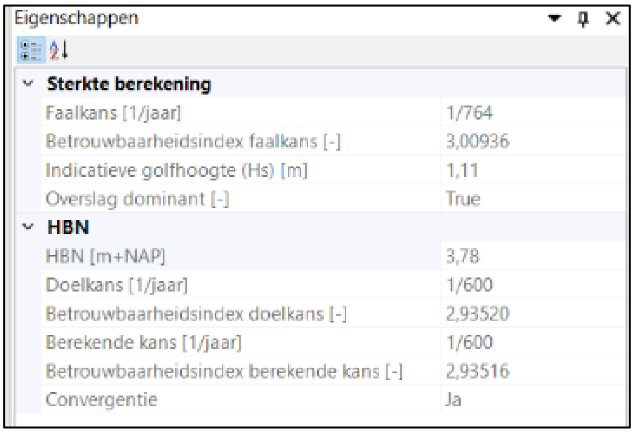


Figure 96. Output HBN Calculation 1:600 years

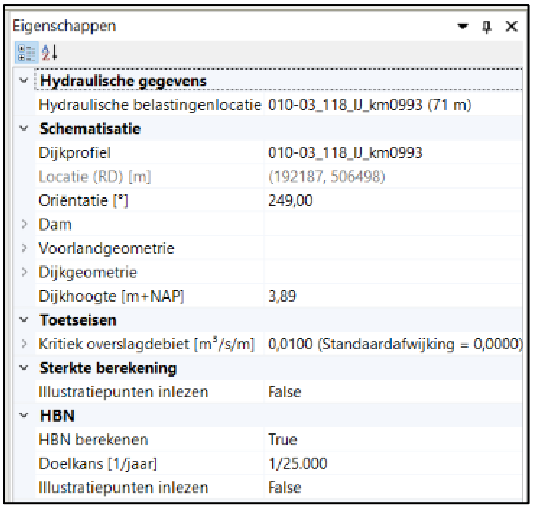


Figure 97. Input HBN Calculation 1:25000 years

Figure 98. Output HBN Calculation 1:25000 years

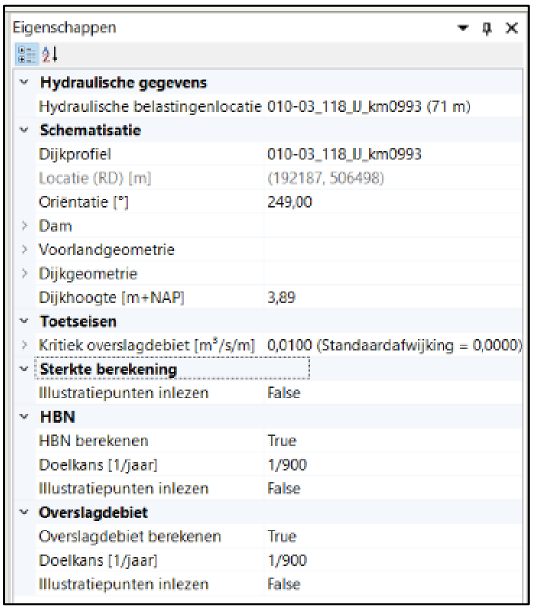


Figure 99. Input HBN Calculation 1:900 years

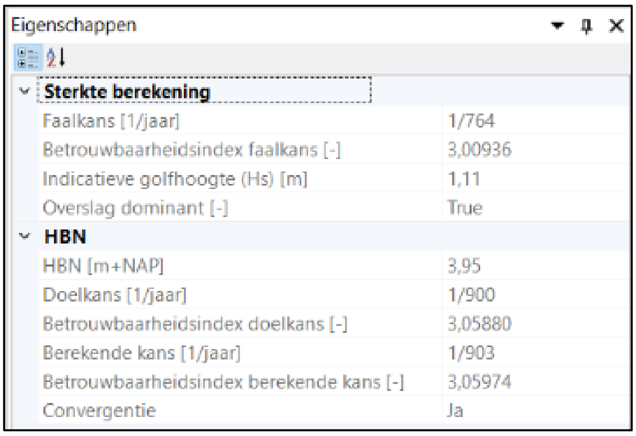


Figure 100. Output HBN Calculation 1:900 years

Appendix 11: Durable Dike Design Cross-Section