Hoedekenskerke freshwater dike storage system

The ideal situation

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Summary

As the year passes, keeping themselves afloat has become more challenging for the Netherlands. Climate change and sea level rise are primary factors influencing the maintenance and reinforcement of the country's dikes system. Therefore, a new Delta Plan has been implemented to make the dikes system climate-proof by 2050. Nevertheless, maintaining the dikes system is one of many problems the country faces. In 2022 a freshwater deficit was declared due to an average annual water shortage of 220 mm across the country. However, the impact is felt more in the agriculture industry. The topic of this research is designing a dike where freshwater can be stored in the rural area near the village of Hoedekenskerke. The main research question is, how can a freshwater storage unit be integrated into a dike while ensuring compliance with Dutch flood safety standards?

An area analysis was performed in the project location. The project area was discovered to consist of an inlaagdijk meaning parallel dikes. A primary dike and secondary can be found in the location, creating the Hoedekenskerke polder. The soil conditions of the area are mainly sand, clay, and peat. Considering the fundamental failure mechanisms of overflow and overtopping, the dike's crest height must consider the sea level rise, the soil settlement, the storm surge level, and the wave run-up to prevent flooding.

Using the Bishop method, along with D-stability software, the dike's macro-stability is calculated. The worst scenario was considered for this calculation, where two situations were developed. The dike will have an inner berm in the first scenario, whereas in the second scenario, it will not. Resulting in different safety factors, which were then compared with the design safety factor calculated with the Bishop formula. The final result is situation two due to being the most optimal solution. The result will require less construction materials and space, reducing the construction cost.

There are several methods in which freshwater can be stored in combination with a dike. In this research, seven solutions were developed and graded by a MCA to find the most suitable solution. It was discovered that constructing an aquifer under the dike system is the most effective solution. Since it optimizes, space and a large quantity of fresh water can be stored.

To conclude, the Netherlands is looking towards developing innovations and preventing flooding. The climate is constantly changing, and the sea level seems to be rising; the country is creating solutions to fight this problem.

1.0 Introduction

1.1 Problem statement

Dike design

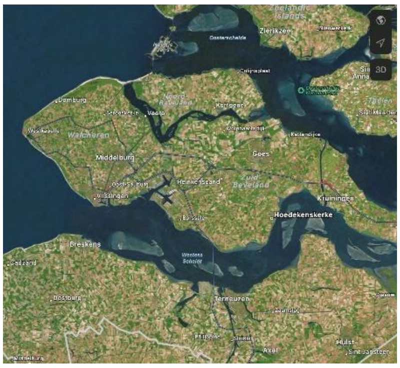


Figure 1: project location

The Netherlands faces a never-ending task, building, reinforcing, and maintaining dike systems. In addition, the country needs to bear with severe consequences of environmental changes, subsidence, and sea level rise, significantly impacting the Dutch dikes and Delta areas. Climate change refers to long-term shifts in temperatures and weather conditions, and it is caused by human activities such as pollution and the burning of fossil fuels. Consequently, there will be a rise in temperatures, intense drought, storms, melting of glaciers, and sea level rise. Moreover, settlement of the soil will occur due to lower groundwater tables.

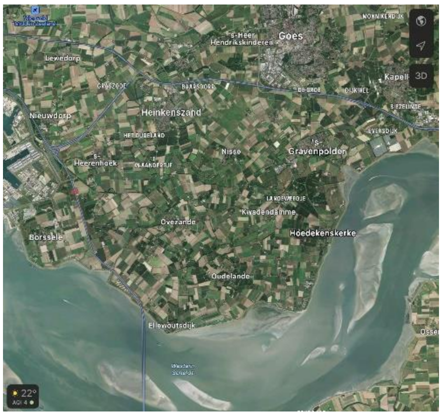


Figure 2: Project location

It has become more difficult for the Netherlands to protect against flooding due to sea level rise. Therefore, in 2014 a new Delta Plan was implemented; the country must be climate-proof by 2050, meaning the dikes must be adapted to the climate conditions (Uitgevers, 2014). After performing a safety assessment on the Dutch dikes, which are performed every twelve years, it was discovered that the dikes do not comply with the safety demands of the Dutch flood defense act. The coastline of Hoedekenskerke polder transect 353-372 needs reinforcement due to inner stability failure and environmental changes such as sea level rise and water temperature, but space is limited. The dike defends Hoedekenskerke's polder from Western Scheldt's basin, preventing the dike from expanding seaward. Therefore, it must instead extend landward. Agriculture fields that are located all around the dikes could be utilized to strengthen the dikes. The project, however, may be impacted by the fact that farmers do not often sell their land. Waterschap Scheldestromen aims to design an ideal dike situation that can adjust to climate conditions while complying with safety standards.

Freshwater shortage

In 2022, the government announced a freshwater deficit, where Dutch water companies may not meet water provisions by 2030 (NL-Times, 2022). Waterschap Scheldestromen's goal is to investigate possible designs of a freshwater facility that can also be integrated with the ideal dike design. Storing freshwater benefits farmers and society since 16% of the economy depends on freshwater supply. The report Expat Info claims a 220-millimeter deficiency in average annual precipitation across the nation (Info, 2022).

The Netherlands has experienced a water shortage five times in the past 22 years, so this is not the first instance. The inhabitants, however, would not be aware of the water deficit because it has a more significant effect on the farming and shipping sectors. The increasing frequency of droughts, along with population growth, salinization of the soil, and pollution from industry, agriculture, and households, are the main contributors to the water deficit. A "de facto water shortage" statement was put into place in August 2022, prioritizing critical locations where there is a shortage of fresh water (NL_Times, 2022).

1.2 Research question (s)

The fundamental research inquiry is, in light of the problem statement:

> How can a freshwater storage unit be integrated into the dike of Hoedekenskerke while ensuring compliance with Dutch flood safety standards?

Secondary questions were developed to provide structure to the research and help answer the fundamental question:

1. *What type of storage systems are available? Do they work well when combined with a dike?*
2. *What are the conditions of the project location?*
    a. The role of the site, soil characteristics, pre-existing structure, and space availability will be examined.
3. *What are the stakeholder's design requirements?*
4. *How can the storage system be integrated?*
    a. Determining the location of the storage system, whether it will be close to, within, or a portion of the dike.
5. *What is the optimum design of a dike with an integrated water storage system?*
    a. *Determining which calculations can deliver the optimum design of the dike.*

1.3 Research objectives

The main aim of this research is to design a dike suitable for its surrounding environment, and that also complies with the following:

- A flood defense system according to regulations of WBI (Wettelijk Beoordelingsinstrument)
- Fresh water storage system, the dike can store water as a secondary primary function

1.4 Outline

This research will focus on creating an ideal situation rather than simply reinforcing an existing one. Therefore, the research has been divided into two sections. The first section investigation will be carried out to analyze the project locations, the basic requirements for a dike design, failure mechanisms, safety assessment, different types of freshwater facilities, and the need for freshwater. The second section will use the information from the first sections to create a concept design. Furthermore, alternatives will be created and graded with the Multi-Criteria Analysis (MCA) method, leading to a more in-depth technical design. Finally, this design will develop the functions, technical requirements, regulations, materials, and final results.

1.5 Reading guide

A milestone was created to manage and provide a clear view of the processes involved in the research proposal. First, a list of actions and their corresponding tasks was created and found in Figure 3. Next, a Gantt chart was made with Team Gantt to keep track of the progress of the thesis report and proposal within the given timeframe. It serves as a guide and helps measure the process. Finally, the plan indicates the actions and tasks undertaken throughout the research's timeline and shows their accompanying deadline to complete the thesis proposal/report. For details, see Appendix A, in-depth details document master plan.

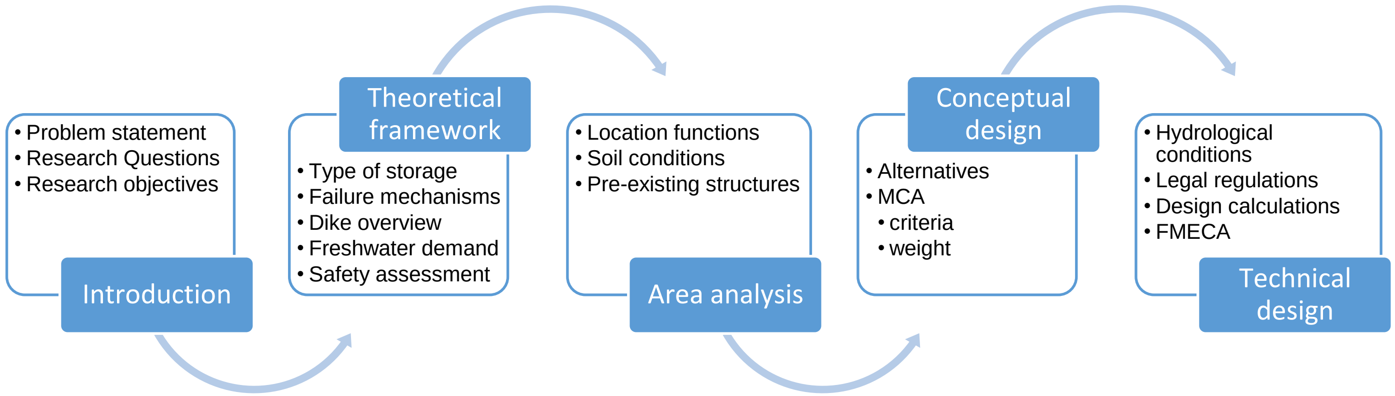


Figure 3: Thesis action overview

2.0 Theoretical framework

The main concepts from the primary and secondary questions will be addressed in this section. Firstly, an overview of the essential elements of a dike will be given. Furthermore, a dike's failure mechanisms and safety assessment will be discussed. Secondly, a brief description of the freshwater demand and type of facilities will be introduced. Lastly, an evaluation of published works will be reviewed.

2.1 Dike overview

A dike is a flood defense system that retains water under extreme circumstances. A dike's design must withstand high water levels, wave run-up, wave attack, and overtopping. Moreover, it needs to be stable and impermeable. Figure 4 shows the fundamental aspects of a dike.

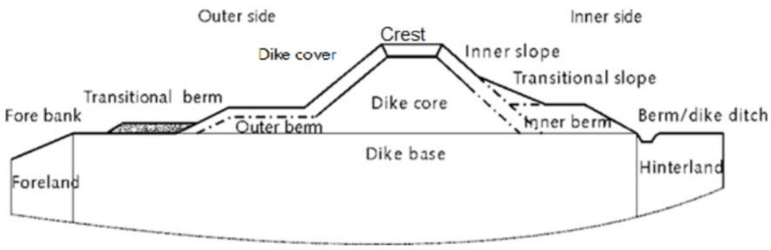


Figure 4: Basic element of a sea dike (Jonkman S. , Jorissen, Schweckendieck, & Bos, 2017)

The crest is an essential variable of the dike since it should be able to withstand extreme water levels. The revetment consists mainly of concrete, asphalt, stones, and grass, and it should withstand expected wave attacks. An outer berm is implemented to break and slow down waves, while in some cases, it is also used as a maintenance road. On the other hand, the inner berm prevents instability and piping.

Furthermore, the slope on the outer side impacts the wave run–up and stability, while the inner slope only impacts the stability. The core and base of the dike consist of different types of soils. For instance, sand and gravel which is stable but permeable, clay is impermeable but deforms when it is wet; and peat is also impermeable, but it is easily compressed and unstable for dikes (Jonkman S. , Jorissen, Schweckendieck, & Bos, 2017).

Factors that influenced the dike design are the loads on the dike, subsoil conditions, material availability, cost, and experience concerning the dike constructions. The dimensions of the dike depend on the design loads; in the case of a sea dike, high waves will form during a storm. For such scenarios, a shallow outer slope, a dike revetment of stone or concrete, or an outer berm can be applied.

On the other hand, in a river, the waves are smaller, and the outer berm is not applied. The inner berm tends to have a flat slope which provides stability during high water periods with a core of sand. River dikes prevent flooding from water flowing into the land by the major rivers Rhine and Meuse. At the same time, drainage ditches systems, canals, windmills, and pump stations keep the low parts dry for habitation and agriculture (Jonkman S. , Jorissen, Schweckendieck, & Bos, 2017). Figure 5 shows an example of a river dike profile.

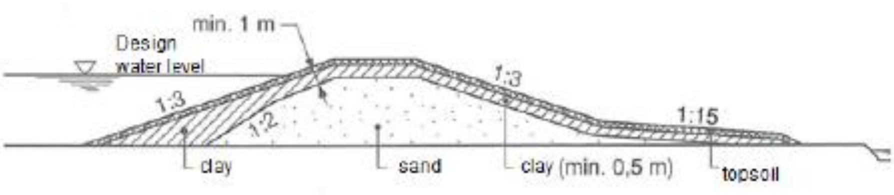


Figure 5: River dike profile (Jonkman S. , Jorissen, Schweckendieck, & Bos, 2017)

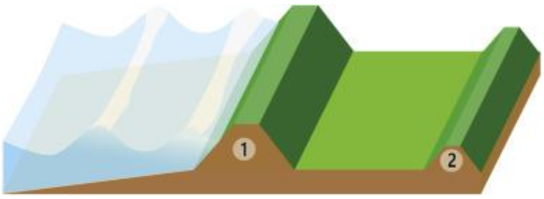


Figure 6: Inlaagdijk cross-section (Marijnissen, Kok, Kroeze, & Loon-steensma, 2021)

The project location consists of an inlaagdijk (parallel dikes), meaning the placement of a dike behind an existing dike to prevent the polder's inundation in the event of a dike failure. The inlaagdijk came into existence around 1920. The inlaagdijk was constructed due to the failure stability of the primary dike and due to coastline inland movement. The natural flood disaster 1953 was a historical mark in Zeeland due to dike failure. The flood was a spring tide in combination with a heavy northwest storm. The storm had created a 1000 km field with a wind speed of 10.

The sea level surged to an extreme height of 4,55 m above Normal Amsterdam level (NAP), in which the dikes could not be restrained, and a breach came into existence.
The dike could not cope; the flood took 1836 lives and destroyed approximately 4300 households. A storm surge is when the wind elevates the water level exceeding the mean sea level.

The flood of 1953 is known in history due to its extreme heights; however, in Zeeland's flooding history, the flood of 1911 had a significant impact during spring tide, while March 1906 flood inundated 25 polders. The floods occurred due to the poor conditions of the dike, the consequences of poor maintenance, and poor investments/reinforcements. Furthermore, due to post-war reconstruction after 1945, the government gave less priority to flood protection. However, after the 1953 disaster, The Netherlands learned the importance of maintenance of flood defenses, establishing extremely severe safety standards for flood defenses (ZeeuwsArchief, 2023) (Rijkswaterstaat M. o., 2023).

2.2 Failure mechanisms

Coastal flood defense structures react differently when exposed to sea forces. A failure mechanism is a relationship between the type of structure, functional components, and the types of loads that can cause it to fail. Different mechanisms can cause a dike to breach when a flood defense structure like a flood embankment or dam fails. For example, a flood embankment breach happens when water floods over or through it so quickly that it erodes the material and creates a hole for flood water to pass through. Therefore, describing the failure mechanism when designing and analyzing the risk of a coastal flood defense system is crucial. Figure 7 shows an overview of the failure mechanism in a dike.

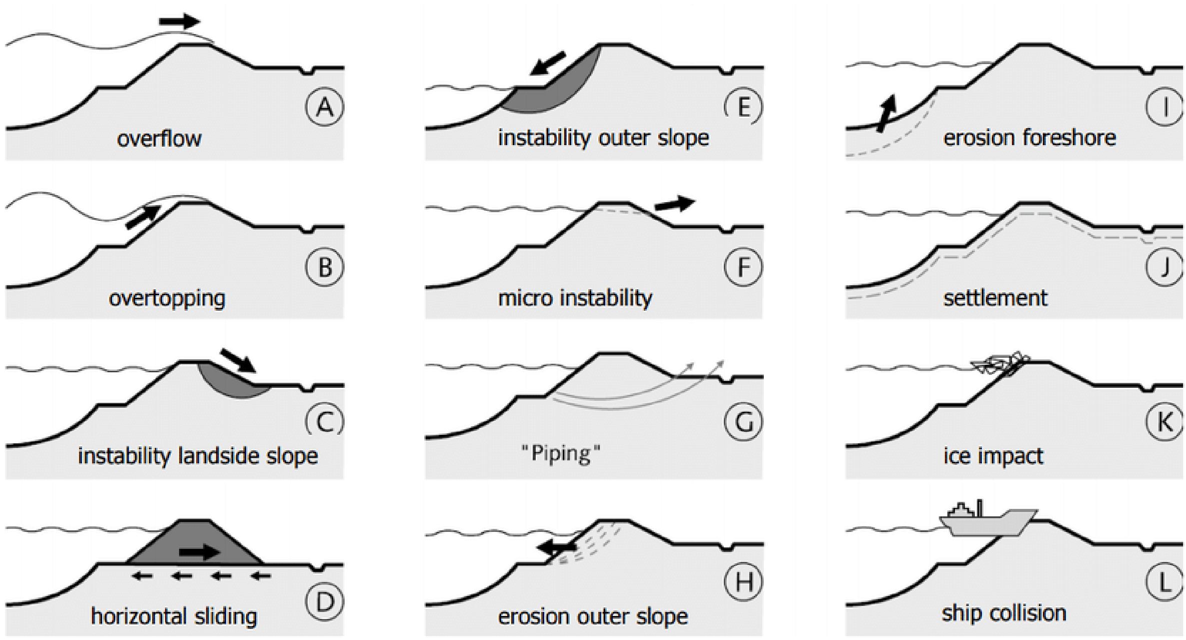


Figure 7: Failure mechanisms of a dike (Jonkman S. , Jorissen, Schweckendieck, & Bos, 2017)

For the research, a description of relevant failure modes in Figure 7 regarding the topic of the research is given (Boer, Jeurink, & Kappe, 2021):

1. Overflow [A]: When the water level is higher than the crest of the dike, water may flow over and enter the polder. It can also soak the dike. The inner slope may erode due to flowing water resulting in a breach. A preventive measurement is to increase the dike crest height. Another method can be to design a non-erodible inner slop with a significant layer of clay.

2. Overtopping [B]: Similar to the overflow mechanism, the water level is combined with a significant wave height. Flooding can occur due to erosion of the inner slope. Preventive measures are to use erosion-resistance revetment, increase the dike's height, and

reduce the inner embankment's angle slope resulting in reduced velocity, reducing the erosion force.

3. Piping [G]: The first ground soil layer is often made of impermeable layers, thus, clay and peat. The groundwater that passes along the boundary carries sand boils from the sand layer and creates a pipe corridor. Due to the water pressure difference between layers, the water burst into the polder. Preventive measures against piping are to expand the seepage path, installing filters allowing water to be drained or filters that can also retain the sand when water is being drained.

4. Micro–stability [F]: When there is an extended period of high water level, water can transfer to the dike core and flow out again. The seepage water [the flow out water] can carry sand particles from the dike core, resulting in the dike losing its strength or the embankment sliding. A preventive measure is to reduce the slope angle of the inner embankment and install a drainage system.

5. Macro-stability of inner talus [C]: The inner talus losses its strength due to saturation. The sand and clay are not compressed, resulting in the dike to liquefy. The dike becomes unstable, and it settles due to its weight. Preventive measures can be to decrease the inner slope angle. Furthermore, strengthening the dike by constructing a sheet pile wall, anchors, seepage ditch, and inner shoulder can regulate the stability.

6. Erosion of outer embankment/talus [I]: can occur due to wave action caused by wind, vessels, and currents. The outside of the dike can erode [wear down], resulting in a dike breach. Erosion can be prevented by reducing the force of wave attack; this can be done by using heavier revetment such as crushed stones, asphalt, or concrete block, creating a foreshore with stone or natural materials, and reducing the angle of the outer talus.

2.3 Safety assessment

The safety assessment instrumentation 2017 (WBI 2017) is based on the regulations for determining hydraulic loads and strength and the procedural regulations for assessing the safety of flood defenses. The WBI 2017 is divided into three sections:

- Procedure for assessing the safety of flood defenses: Describe the procedure to be followed for the assessment and reporting requirement.
- Regulations determining hydraulic loads for flood defenses: Describe the methods used to determine the hydraulic loads on flood defenses.
- Regulations for determining the strength and safety of flood defenses: describe how the flood barrier must be assessed to evaluate the entire barrier's safety performance.

For this research, a basic description of the WBI's procedure for assessing the safety of flood defenses will be given to have an overview of the safety assessment of flood defenses. The procedure assessment consists of three phases, preparation, execution, and reporting. In the preparation phase, existing information regarding the route to be assessed is gathered. Afterward, an assessment strategy and a strategy to obtain missing information are developed. Finally, after this phase is completed, the execution phase begins.

The execution phase begins with a general filter, which filters at the dike section level (trajectniveau) and the section level (vakniveau). The general filter at the section level selects dike sections in which the probability of flooding is greater or less than the signaling value. The dike/ barrier must be reinforced when the signaling value is exceeded. There is sufficient time to perform reinforcement measures. The goal of the signaling value is to complete reinforcement measurements before the lower limit is exceeded. The dike/barrier does not comply with the maximum allowable flood probability or failure rate.

The filter aims to use the time and resources available for water boards efficiently while initiating assessments based on the new safety approach. After selecting the dike section, the water board performs a safety assessment based on the results of the Safety Netherlands on the map (Veiligheid Nederland in kaart: VNK) project and expert judgment. The VNK project has marked the flood probability and risks on a large scale in the Netherlands, based on the knowledge level in 2006.

The dike section level must meet the criteria of the section level filter. In case of a greater flood probability than the signaling values, the dike section level applies if:

- The section is included in the VNK project results, which provide a table for sections with a flood probability of factor 90 more significant than the signaling value, see Appendix G
- The water board can demonstrate that the new judgment incorporated in WBI 2017 and the barrier's changes, in comparison to the VNK, do not lead to a substantially smaller flood probability for the section

On the contrary, in case of a more negligible flood probability than the signaling values, the dike section level applies if:

- The section is included in the VNK project results, which provide a table for sections with a flood probability of factor 100 more minor than the signaling value; see Appendix G.

- The water board can demonstrate that the new judgment incorporated in WBI 2017 and the barrier's changes, compared to the VNK, do not lead to a substantial increase in flood probability for the section.

When the dike section meets the criteria of the section-level filter, the water board makes a safety assessment of the section based on the results of the VNK project and expert judgment. Filtering at the section level is implemented per section per test track. The section is divided into compartment-level filters in which a tailored test is performed and subject-level filters. For performing a subject-level filter, the following criteria must be met:

- Performing a generic test for a subject with one or more tracks does not lead to a reliable assessment.
- The results of a tailored test lead to a similar outcome as applying the regulations from the WBI 2017 with less effort.

If the criteria are met at the section level, the water board performs a custom test. However, when the conditions still need to be met, the assessment is carried out by conducting genetic tests. The assessment is continued according to the testing procedures. The test procedure is stepwise, going from global, simple, and generic to sharp, complex, and site-specific. This means that the level of detailed information will increase with the next test, and the accuracy can determine into which category the judgment falls. There are four types of tests:

- Simple test: carried out per section and test track.
- Detailed test per section: carried out per section and test track.
- Detailed test per section: The test is performed for the entire dike section, combined section, or test track.
- Tailor-made test: performed per section and test track for the entire dike.

If the generic tests are not applicable, a custom test is made to perform a site-specific and advanced analysis. When the available filter at the section meets the conditions or the tests are carried out, the water board prepares the safety assessment of the section, which is expressed in the category. The categories outline which sections do and do not meet the standards. After the execution phase, the water board must report the results to the ministry (Millieu, 2016).

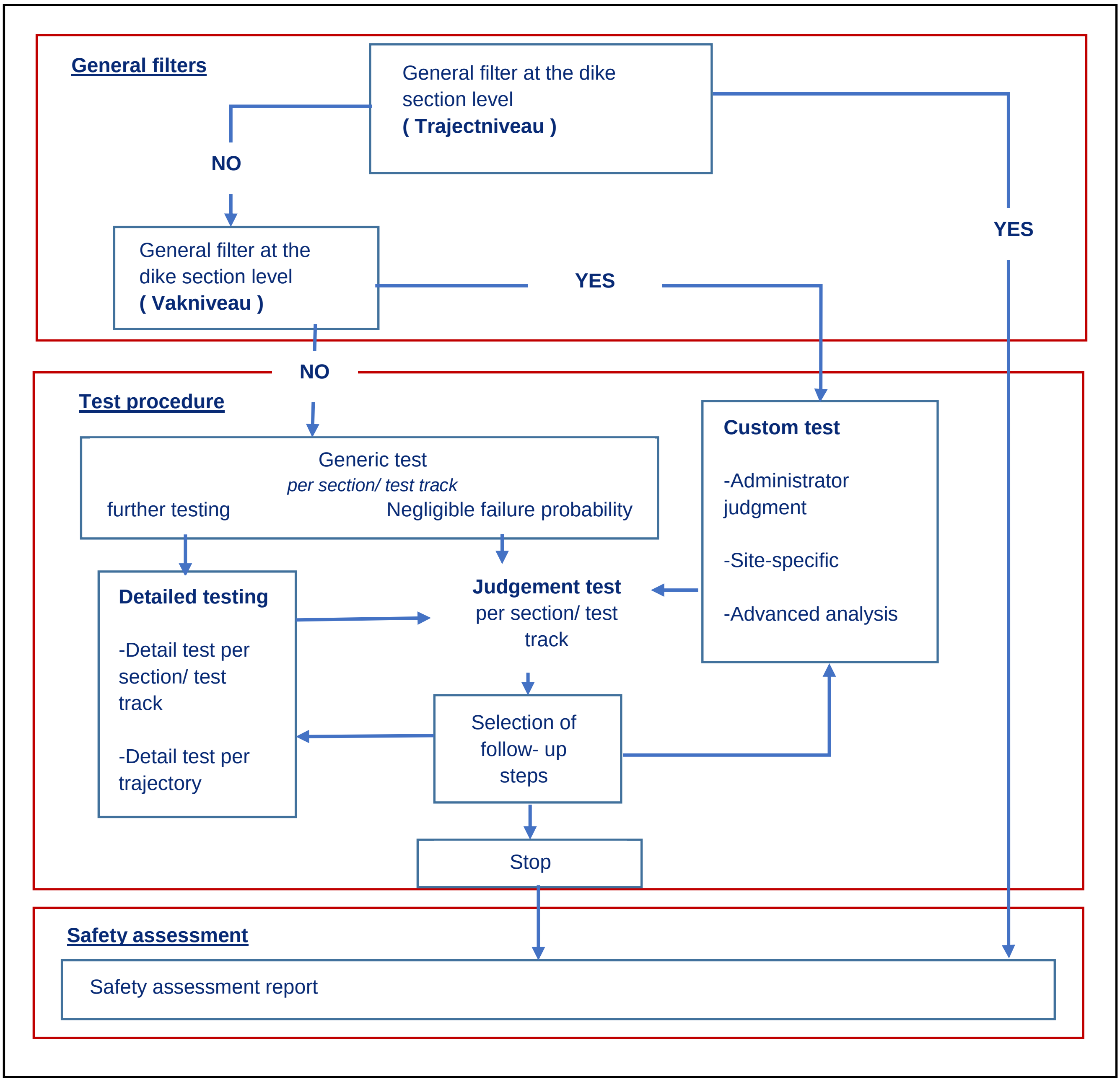
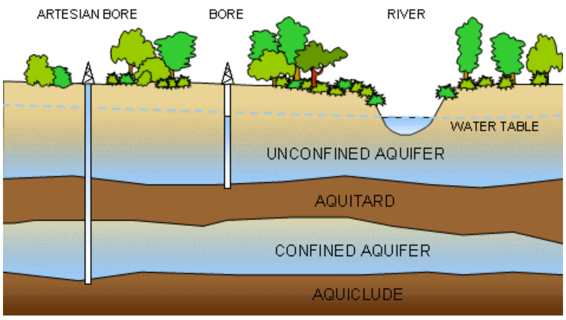


Figure 8: Overview of safety assessment

2.4 Storage Facilities

There are two ways freshwater can be stored, natural or artificial.
Natural reservoirs are:

- Groundwater: a long-term reservoir of the natural water cycle
- Aquifers: large capacity underground reservoir.
- Lakes
- Rivers



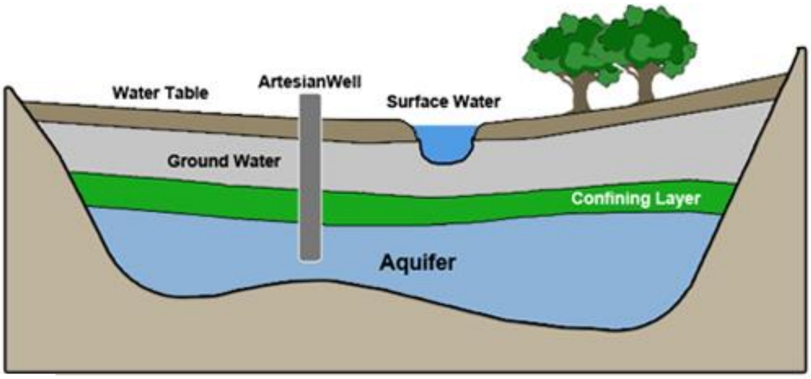


Figure 9: Example of aquifer

Artificial reservoirs:

- Holding ponds
- Dam reservoir: an artificial lake where water is stored by constructing a dam across a river/sea. The dam controls the amount of water that flows out of the reservoir.
- Water tower: store water and manage flow at elevated heights by regulating and maintaining pressure and water level throughout the system.
- Tanks: Surface/ underground water storage with various capacities and volumes.
- Rain barrels

Figure 12: Example of a dam reservoir

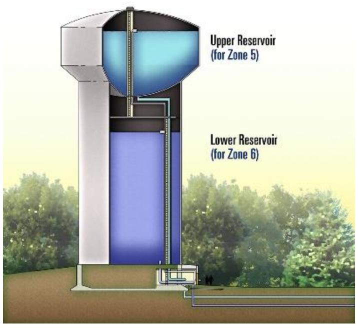


Figure 11: Example of a water tower

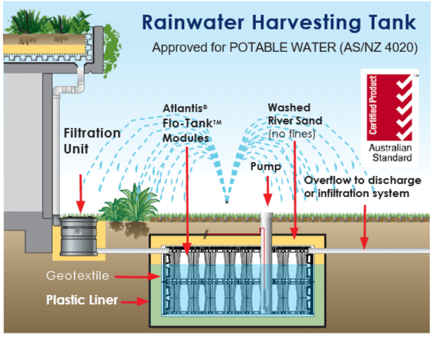


Figure 10: Example of underground reservoir

2.5 Freshwater demand

The Netherlands is surrounded by water, and under normal circumstances, there is abundant surface water to supply the country's demand. However, on August 2022, a water shortage of level 1 scaled to level 2. Water shortage is defined when there is a small amount of precipitation in the Netherlands and a small water inflow from the Rhine and Meuse Rivers.

In the Netherlands, an average of 1.5 million liters of water per person per year is used. From 2003 to 2017, there was a 4% domestic drinking water decrease. However, due to precipitation shortage and intense drought, water usage increased. It resulted in 302 million meter cubic of water usage in the agriculture sector in 2018, which was 150% more than the previous year (Eilers, 2021). Therefore, Rijkswaterstaat and water boards will observe the water level throughout the year and take measures where it is necessary.

When a water deficit is in store, the National Water Distribution Coordination Committee (LCW) will gather and look at the water levels, evaporation, and consumption (Rijksoverheid, 2018). Afterward, the committee will determine whether demands exceed the water supply; an alert will be given if there is a shortage.

A shortage system alert was established in 2015 to categorize the level of the water shortage (Nieuws, 2022) and what measurements the Dutch water supply companies need to take, meaning:

- Level 1: Water deficit in-store/ approaching
- Level 2: An actual water shortage
- Level 3: National crisis

On April 1st each year, the dry season in the Netherlands begins, where water temperature rises, plants grow faster, and the water demand and risk of water shortage increases. The different seasons in the Netherlands have their characteristics regarding river discharge and supply, droughts or flooding, and water demand.

In the Netherlands, the amount of precipitation varies from the region. Thus, not all regions receive the same amount of precipitation. Sandy soils depend entirely on rainwater, the central area south and east of the Netherlands and Zeeland (Ministrie, 2022).

Therefore, the concept of droughts differs per region per year. Water deficit can have different causes, for instance:

- Climate change: In a national government report, it has been stated that an increase of 1.7 Celsius degree in temperature in the last 130 years.
- Extreme weather: More extended periods of drought will lead to drying up water supply sources.

- Wastewater and water quality: which decreases the availability of drinking water.

The government has developed software that estimates whether a wet or dry period is approaching, Droogtemonitor (waterstaat, 2023).

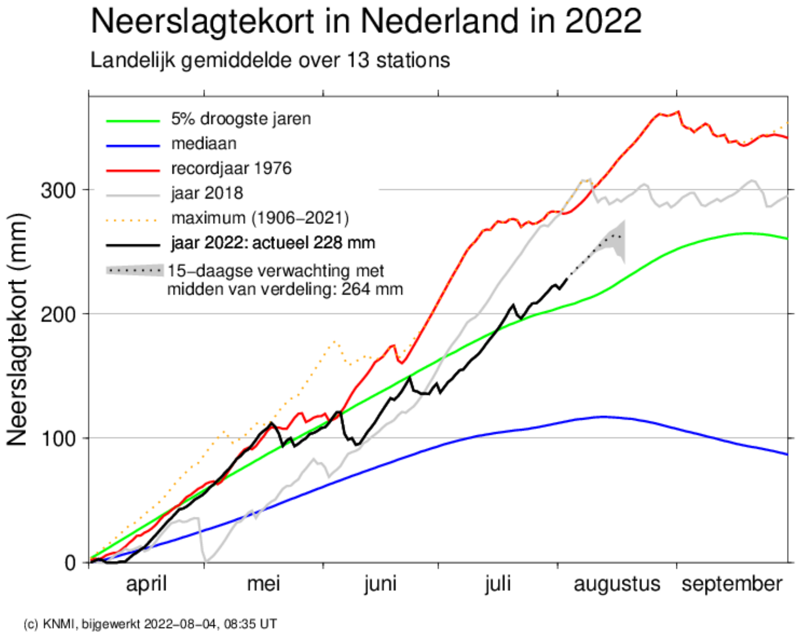


Figure 13: Precipitation shortage in 2022 (mm) (Stadjer, 2022)

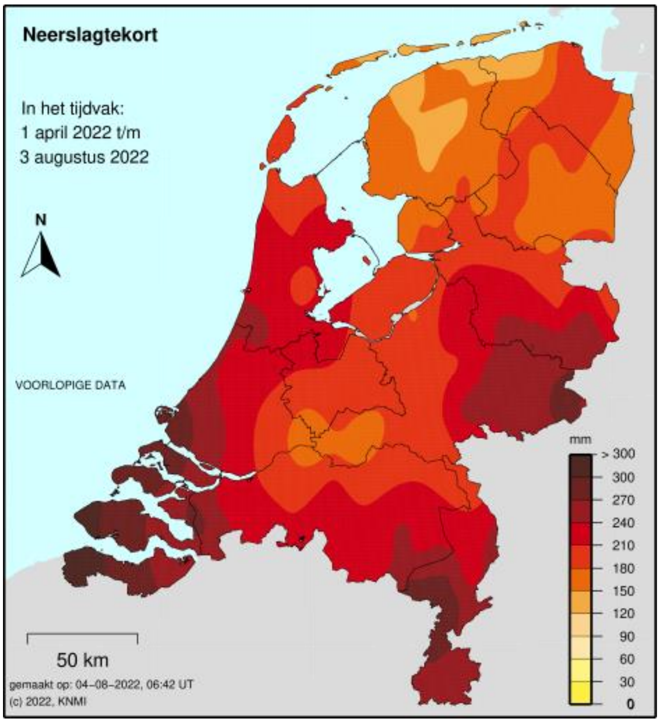


Figure 14: Precipitation rate in 2022 (mm), (Stadjer, 2022)

2.6 Literature review

The literature review aims to investigate over-published works regarding dike storage and rainwater harvesting. Conducting a review will help determine if the report's subject matter is innovative or has been previously explored in the industry. Additionally, the topic of collecting rainwater will be addressed.

After gathering information, it was discovered that storing water within a dike is a new topic in the industry and has yet to be used or designed in other countries. Nevertheless, there have been published works regarding using a dike in combination with a separate water storage system. For instance, the published work of Utrecht University concerning double dikes (University, 2017), where parallel dikes are designs, and the area in between can have different purposes (Belzen, Rienstra, & Bouma, 2021) or where a dike surrounds a lake or a pond, e.g., in London and Iceland. However, those published works will not be discussed further in this research.

As for harvesting rainwater, climate change is a significant factor since it will increase the frequency and intensity of precipitation, mainly in Western Europe and the Netherlands. Also, it will disturb the balance between wet and dry periods. The Netherlands drainage system is designed for a peak capacity of 20 mm of rain in 1 hour; the present drainage capacity cannot cope with future climate conditions. Therefore, storing rainwater in tanks and aquifers can decrease the potential health risks that surface rainwater runoff can cause.

The quality of the stored water depends on factors such as the roof material, the length of dry periods, the application of the first flush, and the environmental conditions. There are two types of contaminants in rainwater, chemical, e.g., sulfate, nitrate, ammonium, iron, copper, cadmium, lead, zinc, and microbiological. Though the concentration level of contaminants is low, the Dutch drinking water policy does not allow collected water to be used for purposes other than flushing the toilet. Therefore, intense water treatment must be performed according to local standards if rainwater is used for drinking.

In the period between 2006 and 2016, there was an increase in precipitation of 814 mm to 856 mm in the Netherlands. After collecting information from 325 stations across the country, it was discovered that 50% of rainwater could be stored. The average roof surface is 60 m2, and the daily usage of water per Dutch family is 95.6 m3 in which 41 m3 of rainwater can be stored, enough to cover the water demand (Hofman-Caris, Bertelkamp, Waal, Brand, & Hofman, 2019).

3.0 Area analysis

Figure 15: Project location

The project location lies on the northern side of Hoedekenskerke village and is considered a natural reserve area, see Figure 15. This location was chosen because the dike needs maintenance and modification according to the new regulations. The other reason was to preserve the natural area.

Preserving the natural area will help mitigate weather events and provide space for plants and animals to adapt to the surrounding. Furthermore, it creates natural ecosystems and provides a natural space for tourists and villagers to enjoy.

Figure 16: Road transportation through location

A site observation was performed to investigate the environmental surrounding of the project location, see Appendix B. The location is mainly surrounded by agricultural fields with small ditches transporting excess water during rainfall. Furthermore, it is also used as the irrigation system for the fields, and when the ditch is next to a dike, it adds stability to the structure. The area is also used as a transportation method since the road Inlaagdijk van Hoedekenskerke passes through. Along with the Hoedekenskerke village, several small waterbodies surround the area. The trajectory the project location falls into is trajectory 355 dike pile to 365 + 50 m dike pile.

3.1 Soil conditions

To visualize the soil structure distribution of the project location, boring obtained from Waterschap Scheldestromen and Dinoloket was used. Table 1 shows the boring numbers and source where the boring is obtained, and Figure 18 shows where the boring was taken. The schematization of the soil structure of the project location mainly consists of fine to coarse sand layers, clay, and peat; see for more detail, see Figure 17.

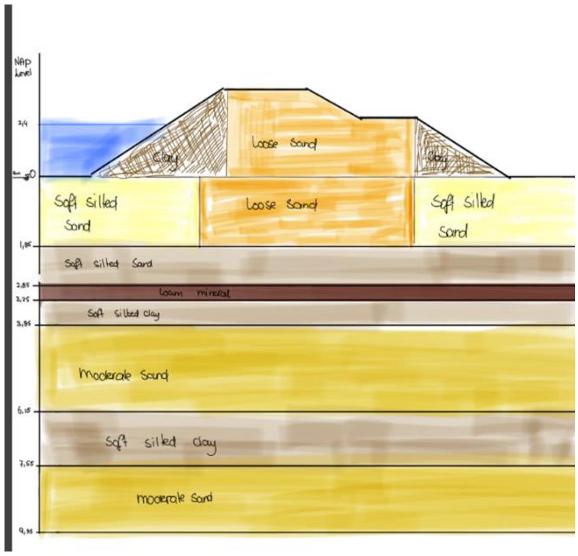


Figure 17: Project location soil layer distribution

Table 1: Boring detail information

Boring source	Boring number
Waterschap Scheldestromen	B48H0853; B48H0903 [B05]
Dinoloket	B48H0814; B48H0850; B48H1485; B48H0904; B48H0820

Figure 18: Boring test locations

Table 2: Soil parameters properties

Soil type	Natural volumetric weight γ_{nat} [kN/m^3]	Saturated volumetric weight γ_{sat} [kN/m^3]	Effective cohesion C'_d [kN/m^2]	Effective angle of fiction $\varphi'd$ [°]
Sand	17	19	0	23
Clay	15	15	0.3	18.7
Calais clay	17	18	2.6	16
Peat	10	10	1.5	21.3
Holland peat	10	10	1.5	23

3.2 Pre-existing structure

A primary flood defense protects the natural reserve area and Hoedekenskerke village. The defense consists of two dikes after each other. Figure 19 shows an overview of the flood defense of the project area. The primary dike [facing Western Scheldt basin] has a crest level of 7.95 m NAP while the secondary dike has a crest level of 2.78 m NAP. Further details on the materials of the dike can be seen in 10.5 Appendix E: Materials & design detail cross-section of the primary dike.

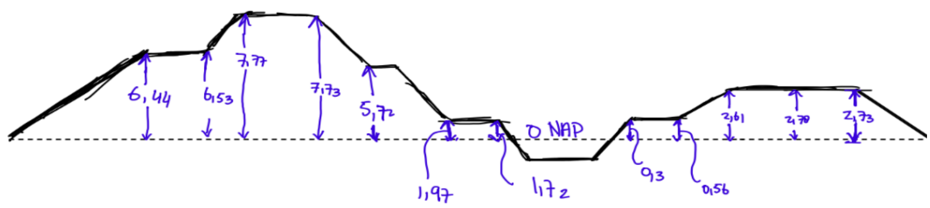


Figure 19: Dike cross-section of Hoedekenskerke polder

3.3 Stakeholder analysis

The stakeholders that are involved in the Hoedekenskerke project can be divided into sections:

- Regularly engage
- Actively Consults
- Maintain interest
- Monitor

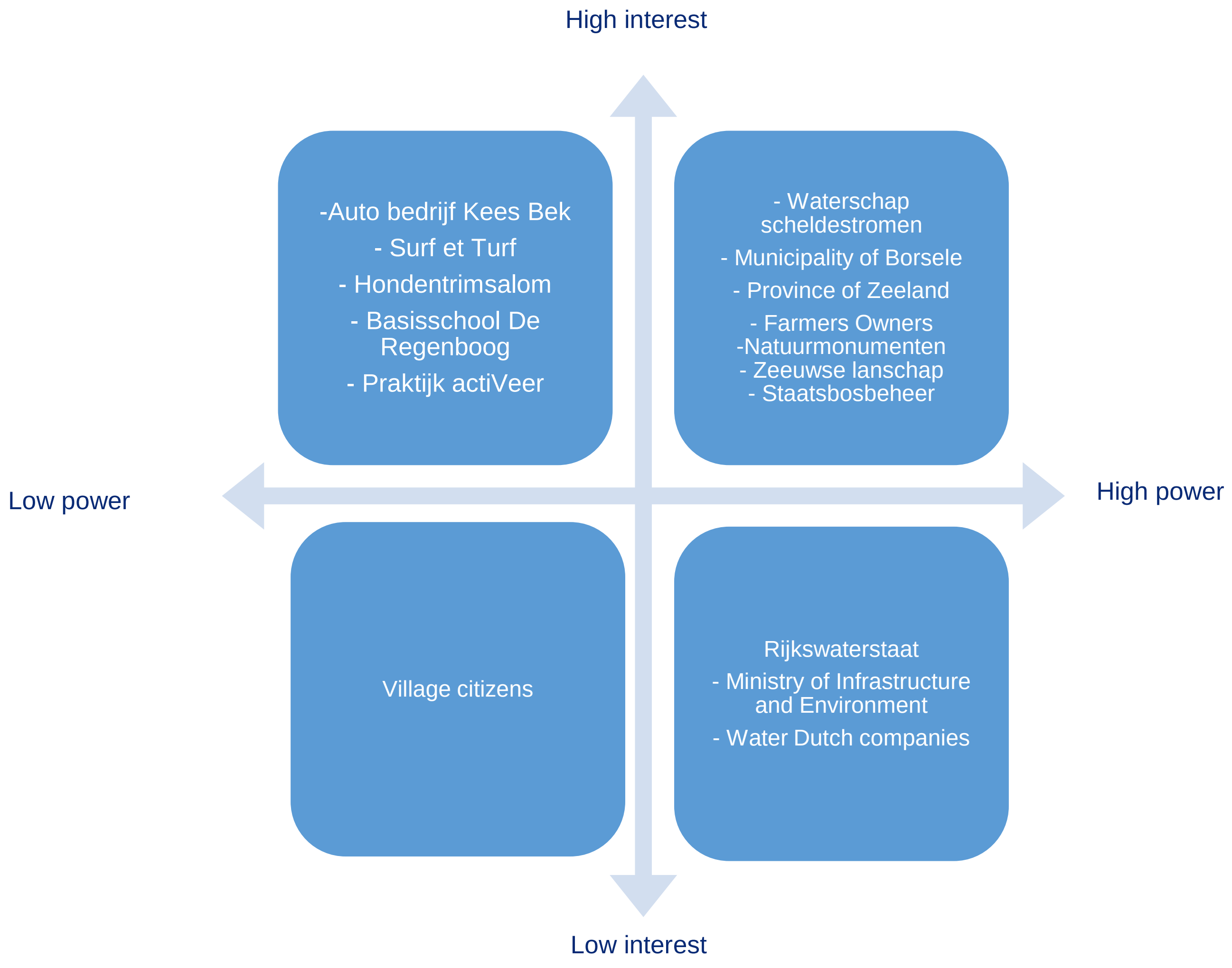


Figure 20: Power interest diagram (Goverment of the Netherlands , n.d.)

For the stakeholder Waterschap Scheldestromen, the interest mainly lies in providing flooding protection and safety for the municipality of the project location. Furthermore, solving the problem concerning the water shortage is also one of the stakeholder's main interests.

As for the remaining regularly engaged stakeholders, the main interest lies in assessing that the structures being designed and constructed by Waterschap comply with new safety standards and guidelines and bring safety to the citizens. The nature protection organization aims to preserve and protect natural areas. Making sure no harmful impact occurs on the environment and the surrounding area.

The actively consults stakeholders; the main interest lies in how the project of Hoedekenskerke is being carried out. Possible partnerships can be developed in the future, and the project can be used for other locations with similar problems in the Netherlands.

The maintain interest stakeholders are primarily interested in how the project can influence their business since it will take place where customers can access their business. Also, safety is a factor that the stakeholder is interested in.

As for the monitor stakeholder, the main interest concern their safety and how the project can influence their daily activities. This stakeholder holds low power; however, the power and interest can increase if not monitored.

4.0 Methodology

The purpose of this report is to investigate possible solutions on how freshwater facilities can be integrated into a dike system, but also in developing an optimum dike design by the new Delta plan and resulting in solving the problems of a dike reinforcement in Hoedekenskerke and the freshwater demand.

To approach the problems, the report was divided into two sections. The first section performs an investigation, while the second section is design-based. To begin with, research questions were developed in correlation with the problem statement. Furthermore, a theoretical framework was developed to answer the following questions:

- *What type of storage systems are available?*
- *What are the conditions of the project location?*
- *What are the stakeholder's design requirements?*
- *How can the storage system be integrated?*

It was discovered that water can be stored artificially and naturally in two ways. Each method has different types of storage methods. The most suitable methods for this research are aquifer, underground, holding pond, and water tower.

Also, the project location consists of parallel dykes called inlaagdijk in Dutch. Agricultural fields and natural areas surround the area. The soil layers mainly consist of sand, clay, and peat layers. Moreover, an analysis of existing structures in the project location was performed to gain insight into which materials were used to design the existing structures and the failure modes of the structures. Furthermore, a literature survey was done to create possible solutions that can be used.

To identify the stakeholder’s requirements, an analysis was conducted. Not only did the theoretical framework answer the question, but it also introduced the essential elements required to design a dike, the failure mechanisms of a dike, and how the dike is being assessed.

The following section will focus on answering the questions:

- Determining the location of the storage system
- What is the optimum design of a dike with an integrated water storage system?

Firstly, a conceptual framework will be created in correlation to the theoretical framework. This will develop the location placement of where and how can the freshwater facility be integrated. Based on the theoretical framework and literature review, alternatives will be developed.

Which later on will be graded with a Multi-criteria Analysis (MCA). The criteria that will be used to grade the alternatives will be based on factors such as the optimum design of a dike, space limitation, storage capacity, and environmental impact. The MCA results will be further developed by creating a more in-depth solution design where the hydrological, legal, and boundary conditions will be looked at. Finalizing the optimal solution and final design.

4.1 Methods

The data used for this report is based on existing data from the organization Waterschap Scheldestromen regarding the location Hoedekenskerke. The criteria for selecting data was dike pile (dp) 355 – 365 dp, which minimized the data collection by 60 %.

The type of data used to complete the first section of the report was mixed between quantitative and qualitative data. Most of the data was secondary; however, primary data from the site observations was used in the area analysis. Furthermore, software such as Google Maps, Google Explorer, Microsoft Excel, and Microsoft Word was also utilized while performing the research.

To perform the macro-stability calculations, the software D-stability was used. D-stability is a soft soil engineering software for analyzing slip planes and embankments. The software contains the three-limit equilibrium method, Spencer, Bishop, and Uplift Van, which supports undrained and drained materials. In each construction stage, the safety factor is calculated to administrate the safety of the design.

5.0 Conceptual Framework

In this chapter, an ideal dike sketch will be developed based on estimated dimensions. The placement of the storage system will also be discussed. Furthermore, variants will be developed based on the information gathered in the theoretical framework. This chapter will create a basic design which will be further developed in the technical design chapter. Lastly, the variants will be discussed and graded using MCA in the following chapter.

5.1 Concept design

For the research, the project location section with the coordinates 51º25’37,9 N 3º55’05,2 E to 51º25’47,5 N 3º55’13,5 E will be used to design the ideal dike with a water storage system. Selecting the location will make future calculations, limitations, and boundary conditions less complicated.

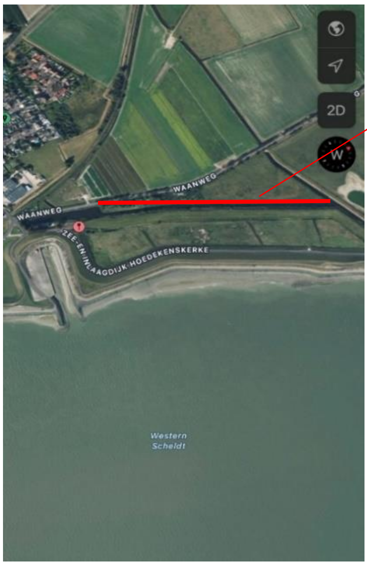


Figure 20: Placement of dike design

Furthermore, a concept dike design was created to develop a final design sketch. However, the dimensions of the drawing are estimations, and the actual dimensions will be calculated in the technical design chapter. The sketch will also estimate the quantity of water storage the variants can store. The design consists of an outer talus with a slope of 1:3, a length of 555 meters, and a width of 30 meters. The crest has a distance of 5 meters with a height of 10 meters. Since the dike is a secondary dike and inlaagdijk [parallel dike], the side facing the primary dike will have a berm, while the inland side of the dike will not have a berm with a length of 5 meters. The scale of the inner talus of the dike will consist of a slope of 1:4 based on the data of 2.1 Dike overview; see Figure 21 for visual detail.

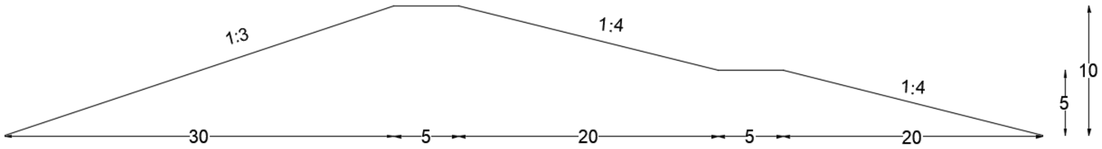


Figure 21: Dike design sketch

The placement of the water storage system will be inside the dike itself. Placing the storage system inside the dike will save space which is limited in this situation. It also eliminates evaporation, maximizes water quality, and provides long-term storage. When developing the final design, regulations concerning natural reserve areas should be considered. Inlaag is primarily a natural area and is mainly used for meadow, marsh, and seabirds for feeding and nesting habitat.

5.2 Alternative 1: Dike core storage

The concept for this alternative is to create a storage compartment using clay layers on the seawards and landward sides. The clay will create the space required to store rainwater for the farmers. The water will recover using a pump and filter system to prevent the sand from leaving the dike core. The area will also be closed off from the bottom with a clay layer to prevent water from infiltrating the underground soil layers.

The clay will also add stability to the dike by preventing the dike from increasing the pore pressure. An incensement in pore pressure reduces the soil shear strength causing liquefaction of the soil and reducing the internal friction. Furthermore, it also increases the mobility of the soil, resulting in the soil moving horizontally.

Thus, the dike will move horizontally due to the increased water pressure reducing the soil strength because the total stress does not change and stays the same. However, the water pressure increase due to storing rainwater, reducing the effective stress. See Figure 21 for the relations between parameters.

WATER PRESSURE:

$$p_o = H_w \gamma_w$$

EFFECTIVE PRIMARY STRESS:

$$\sigma_o' = H_w \gamma' + (H - H_w) \gamma_d$$

TOTAL PRIMARY STRESS:

$$\sigma_o = \sigma_o' + p_o$$

Figure 21: Relation between soil parameters and water pressure

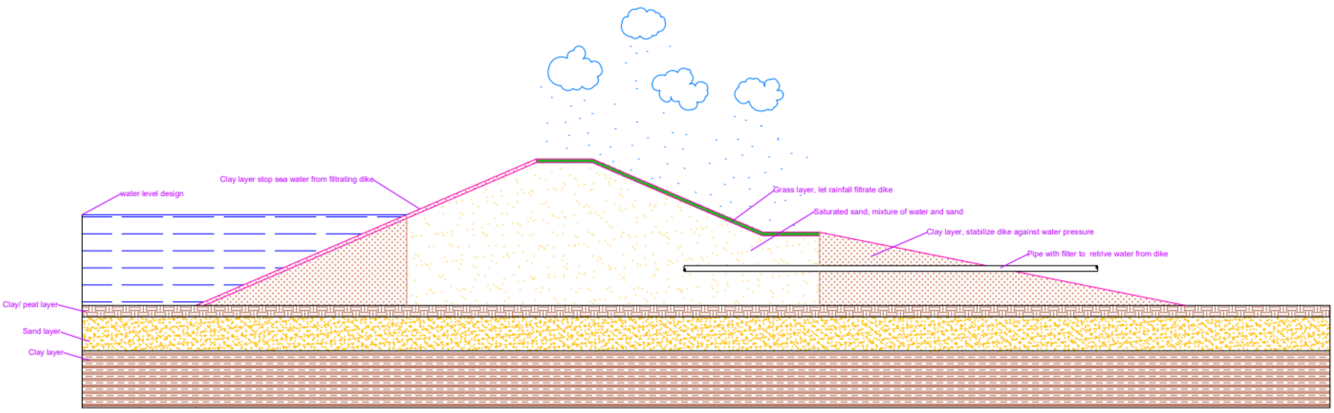


Figure 22: Dike storage sketch

5.3 Alternative 2: Single sheet pile wall storage

The idea behind this alternative is to use a sheet pile in the dike structure to add support and prevent soil movement. A sheet pile wall can control seepage due to its watertight interlocks, reducing leakage. The benefits of a sheet pile are:

- Earth-retaining structure for slope protection
- Support against the collapsing of soft soils
- Various range of lengths, sizes, and steel options
- Temporary or/and permanent structure
- Close-fitting interlocks to form an effective water seal
- Prevention of tides and stabilized structure

The sheet pile will be placed on the seaward side of the dike. The wall will prevent water from leaking into the outer slope and stabilize the structure against horizontal movement. The clay layers will lie on the hinterland side of the dike, preventing water from leaking toward the polder and creating a balance between the soil stress and water pressure. The clay layers and the wall will create a compartment where rainwater can be stored in sandy soils. The compartment will be sealed off from the bottom with clay. Water recovery will be performed with a pipeline pump and filtering system.

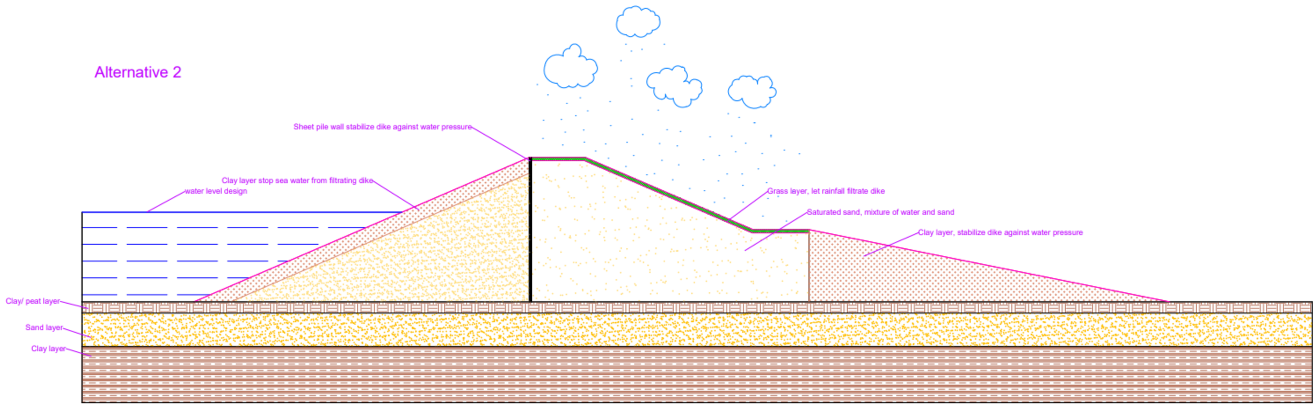


Figure 23: Single sheet pile storage sketch

5.4 Alternative 3: Single Geotextile/foil wall storage

A geotextile is a polymer/ fabric used as a base layer. It can separate the soil layers and improve the ground soil. There are two methods of geotextile, permeable and impermeable. A porous geotextile layer will allow water to infiltrate. However, it will stop fine particle soil from penetrating or leaving the layer. Conversely, an impermeable geotextile layer is designed to prevent water from infiltration or leaving the layer.

For research, an impermeable geotextile will be used. The goal is to create a wall using the impermeable geotextile material. The division will keep the sand facing the primary dike in place. The rainwater will be stored in the remaining dike core, thus a mixture of rainwater and sand. The second purpose of the wall is to prevent the water and the sand on the landside from moving and mixing with the sand layer facing seawards. A clay layer will be placed on the inner talus of the dike. The clay layer will prevent the dike from moving horizontally due to the water pressure stored in the dike since the pore strength of the soil will decrease. The clay will act similarly to the wall preventing the dike from moving horizontally. A pump system with a filtering system will transfer the rainwater from the core when the water is required.

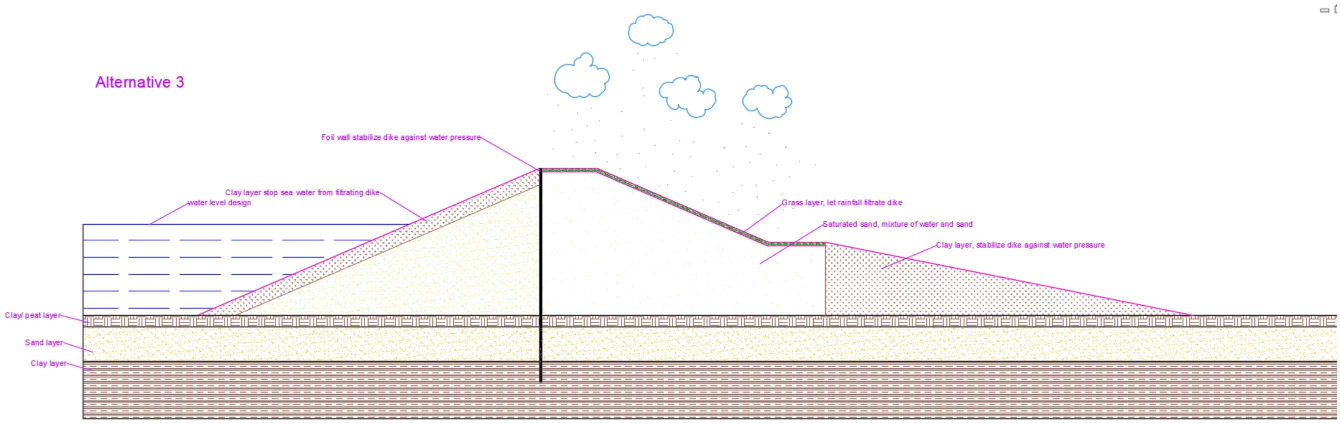


Figure 24: Single geotextile/ foil wall storage sketch

5.5 Alternative 4: Double Geotextile/foil wall storage

This alternative has the same idea as the alternative of a Singular geotextile/ foil wall. An impermeable geotextile material will be used to create the wall. However, there will be two walls instead of one.

The two walls will create a confined area inside the dike core where rainwater can be stored. The walls will help stabilize the dike's soils by preventing them from moving. Furthermore, it also helps against the horizontal movement of the dike due to the weakening of the ground caused by the stored water. The core will be sand on the seaward and landward sides of the walls, followed by a geotextile layer and a clay layer to prevent water from penetrating the dike. Moreover, grass will be used above the clay layer to cover the dike.

The benefits of using geotextile are that it protects against erosion, separates different types of soils, prevents weeds from growing while protecting the plants, and is also used in reinforcement in drainage, construction, and engineering works (Wilde, 2022). Furthermore, there are different types of impermeable geotextile, for instance, polypropylene (PP) which a roll of 1mm * 2m* 40 m can cost about 841.85 pounds (Drainagepipe, 2023), high-density polyethylene (HDPE) (RainSmart, 2012), low-density polyethylene (LDPE) and linear low-density polyethylene(LLPE) which a roll of 1mm*2m*50 m cost 742.15 pounds.

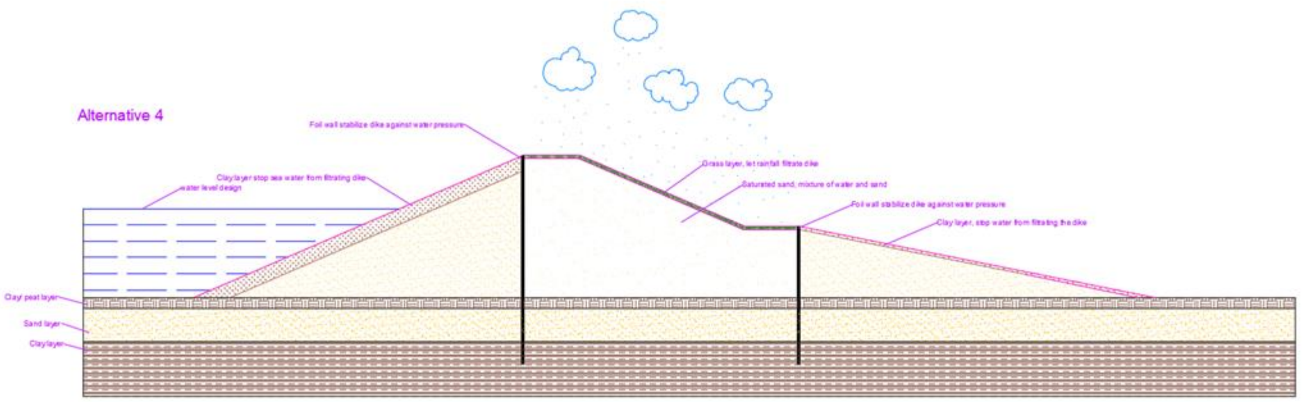


Figure 25: Double geotextile/ foil wall storage sketch

5.6 Alternative 5: Double sheet pile wall storage

This alternative has the same concept as alternative 2. However, in this alternative, there will be used two sheet pile walls instead of one. Behind the sheet pile walls, there will be sandy layers with a clay layer above, preventing water from infiltrating the sand. In the crest area, grass will be placed above the sand soils to let water infiltrate the dike core. A sheet pile for a permanent structure can cost up to 90 euros to 140 euros with a depth of 15 meters. The cost can variate depending on the design material, purpose of the sheet pile, and depth.

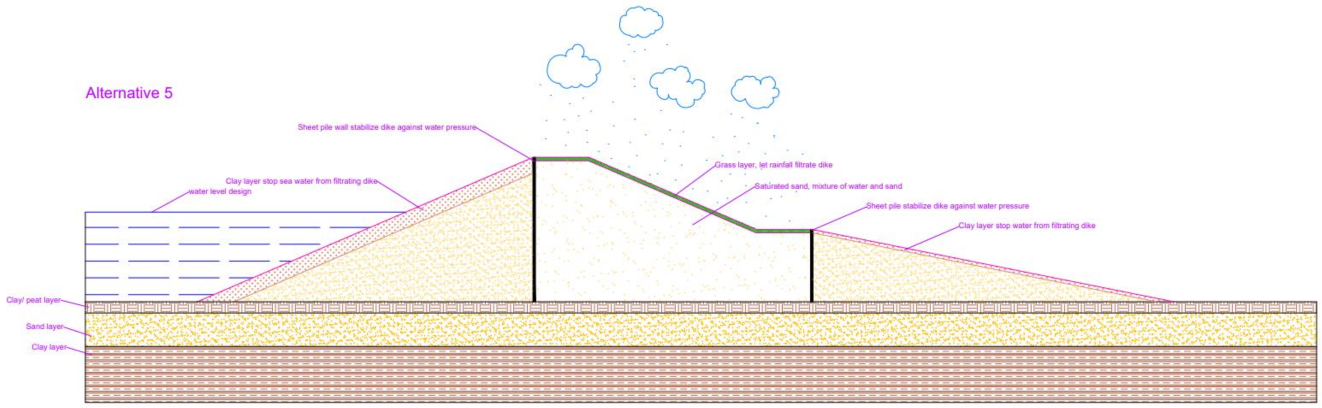


Figure 26: Double sheet pile wall storage sketch

5.7 Alternative 6: Aquifer storage

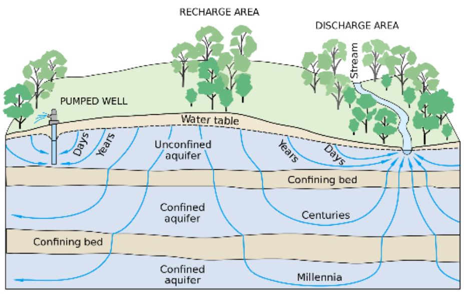


Figure 27: Aquifer zones (Wikipedia, Aquifer, 2023)

An aquifer is an underground water-bearing body of rock and sediment. There are two types of aquifers, confined and unconfined, see Figure 27. Confined aquifers have layers of impermeable soils above them. In contrast, an unconfined aquifer lies below permeable soil. An aquifer can be categorized according to the type of sediment or soil in which it can be composed. The rate at which the water moves depends on the sediment permeability. The amount of water stored in an aquifer can variate depending on the seasonal precipitation. An aquifer can become contaminated if pesticides, herbicides, and toxic materials infiltrate the soil layers. An aquifer can also naturally filter the water by forcing it to penetrate between the sediment's tiny pores (Society, 2022).

A manufactured aquifer stores excess water and improves water quality for future use. An example of an aquifer is the Great Man-Made River in Libya (Wikipedia, Great Man-Made River , 2023), which uses a network of pipelines to pump the water out of the aquifer and supply it across the country. Another example is Austin's Plan, an ongoing project to create an underground aquifer. The aquifer will supply 296035200 m3 of water (Buchele, 2022).

An unconfined aquifer will be created using sand as a source for this alternative. The dike will be stabilized against the horizontal movement with clay soils, stopping the water filtrating in and out of the aquifer. Furthermore, a sheet pile will be placed at the toe of the dike to prevent seepage. A pipeline network will also be used to recover water from the aquifer. As for the project's cost, Austin's Plan can be used to estimate the total cost, including the recovery, which costs 24 million dollars (Buchele, 2022).

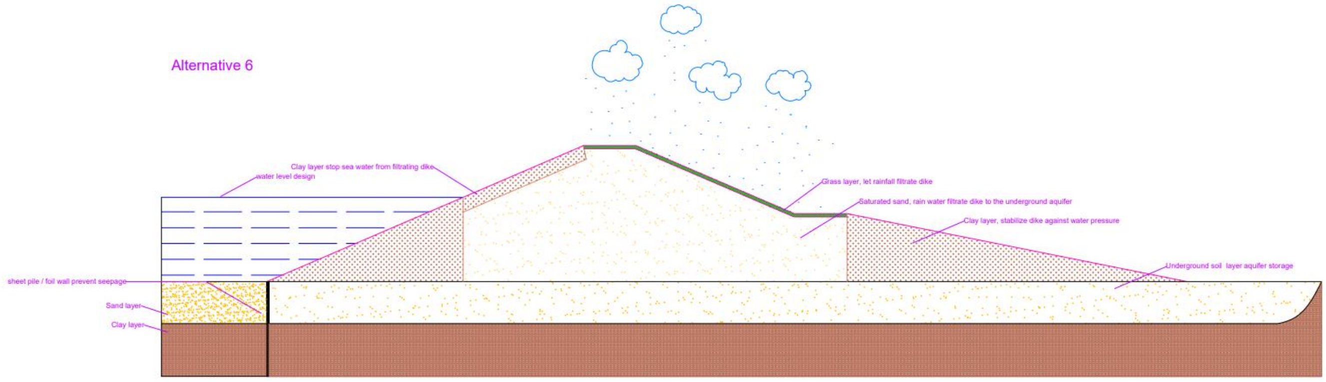


Figure 28: Aquifer storage sketch

5.8 Alternative 7: Underground tank storage

An underground cistern system is a water storage tank placed in the ground soil layers, see Figure 29. The advantages of using an underground tank are frost protection, limited space required, cooler temperatures, and low algae growth rate. On the other hand, the disadvantages are pump maintenance, difficulty access, and the high investment cost.

For this alternative, the clay layers on the seawards and landwards side play a significant role. The clay will prevent horizontal movement of the dike due to the weak pore strength of the soil. The rainwater will infiltrate the sandy dike core to tank the filtering pipeline. Moreover, the water will be stored in the tank and recovered using a pump system when required.

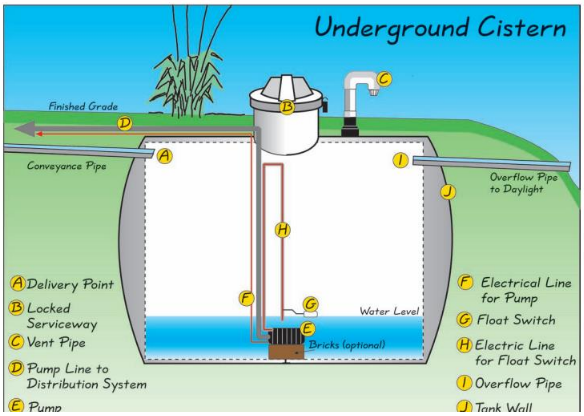


Figure 29: Underground Cistern tank (engineer, sd)

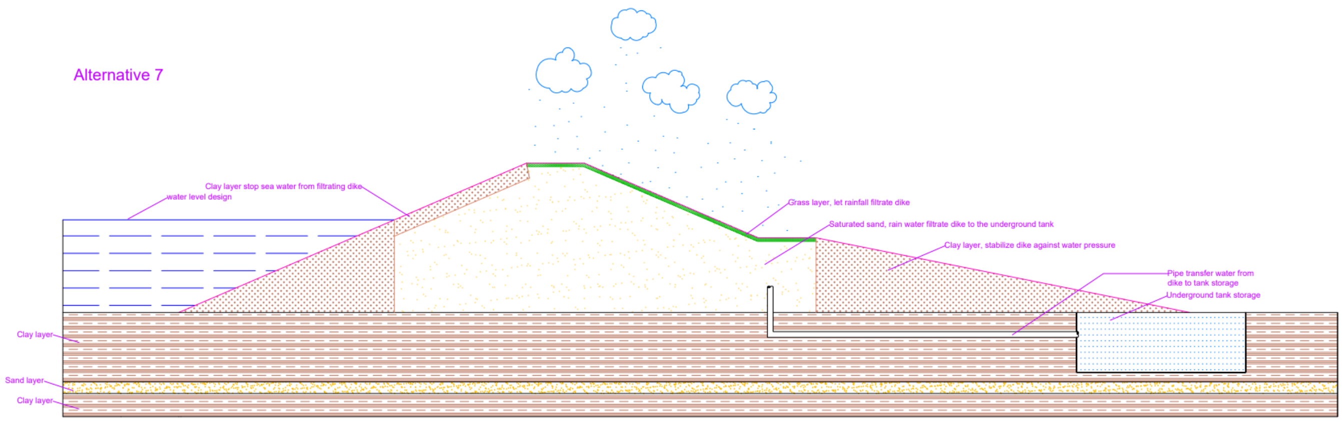


Figure 30: Underground tank storage sketch

6.0 Multi-Criteria Analysis

Multi-criteria analysis is a tool that analyzes and evaluates variables with scores and rates. An MCA aims to reduce the number of variables to a reasonable solution with the criteria based on the initiative objectives. The MCA is performed based on the steps shown in Figure 31.

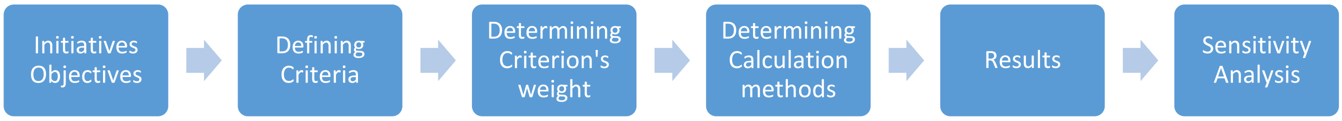


Figure 31: Steps to a MCA

The MCA's primary goal is to identify a suitable variable to store rainwater with a dike while maintaining its stability and water quality. To achieve this, criteria were established and assigned weights, as outlined in the "criteria" section. In addition, a calculation method was also determined, as described in the "calculation method" section. A sensitivity analysis will follow the MCA results to ensure the final solution is the winning variant despite modifying the MCA parameters. Developing the final variant will occur in the chapter Technical Design.

6.1 Criteria & Weight

Table 3: MCA criteria definition

Criteria	Definition	Weight (%)
Cost	An estimation indication of the money required to build the structure. In the construction cost, the labor work and maintenance are considered.	20
Environmental impact	The impact of constructing the dike on the surrounding flora and fauna. Considering if the process will cause any pollution, changes in the soil quality, deforestation, and habitat creation.	10
Adaptation	The dike can adapt to future standards and conditions regarding climate. The dike can be easily modified.	15
Water storage quantity	An estimation indication of the amount of water the variants can store. The dimensions and data are retrieved from the area analysis and concept design chapter.	20
Water stress stability	Due to increase pore pressure, the soil tends to move horizontally, causing instability. Since the effective stress does not change to decrease the pore pressure, the soil stress must increase. This criterion considers how the soil stress increases to stabilize the pore pressure in the structure.	13
Water quality	The design ensures that rainwater quality is protected from salinization and seepage, making it suitable for use in agriculture.	12
Maintainability	Considering the technical maintenance, how easy is it to maintain the design construction for the water boards?	10

6.2 Calculation method

A scale ranging from 1 to 5 will be utilized to assess performance, with a score of 1 representing the lowest performance and a score of 5 indicating the highest level of performance. Each criterion will be assigned a weight, and the resulting score will be calculated by multiplying the criterion score by its assigned weight and a factor of 10. For example, if a criterion has a weight of 20% and receives a score of 4, its final score will be $4 * 0.20 * 10 = 8$.

MCA formula:

$$Final\ score = criteria\ scale * criteria\ weight * 10$$

6.3 Results

After setting the initiative's objectives, defining the criteria and their weight, and determining the calculation method, the variants were graded using Microsoft Excel. The concept design sketch was utilized to determine the water storage capacity of the alternatives. The unit of measurement used for water storage was m^3 per m. To give a grade to the calculation results of the water storage, a grade scale was created from 0 m^3 per m to 1000 m^3 per m; see Table 4 below.

Table 4: Water storage grading criteria

Water storage quantity grading system

Storage grading	
M^3 per m	Grade
0 – 250	1
250 – 350	2
350 – 500	3
500 – 700	4
700 - 1000	5

Results	
Variant	M^3 per m
1	337.5
2	221
3	223
4	277.4
5	281.2
6	730
7	630

After performing the MCA, the winning variant was the Aquifer storage facility, followed by the Dike core storage facility and underground storage facility as second and third place.
See Table 5 for an overview of MCA grading results, and for more detail, see the MCA Excel file. Appendix H thoroughly explains the scale and the reasoning behind the variants. Chapter 7 of this report will further describe and develop the aquifer storage facility.

A sensitivity analysis is unnecessary for the grading system results because they are already significant on the scale. However, if the analysis were done, it would involve changing the weight of the criteria to compare different results with those of the MCA. However, in this situation, the winning variant is still the same despite the weight variation.

Table 5: MCA results overview

Criteria	Weight (%)	Variant 1: Dike core storage	Variant 2: Single sheet pile wall storage	Variant 3: Single geotextile/ foil wall storage	Variant 4: Double sheet pile wall storage	Variant 5: Double geotextile / foil wall storage	Variant 6: Aquifer storage	Variant 7: Underground water storage
		Scale	Scale	Scale	Scale	Scale	Scale	Scale
Cost	20	4	2	3	1	2	3	3
Environmental impact	10	4	3	3	3	3	4	3
Adaptation	15	4	3	3	3	3	5	3
Water storage quantity	20	2	1	1	2	2	5	4
Water stress stability	13	3	5	5	5	5	3	3
Water quality	12	3	4	4	5	5	3	3
Maintainability	10	4	3	3	3	3	3	3
Total	100	33.5	27.8	29.8	29	31	38	32

7.0 Technical Design

7.1 Boundary Conditions & Requirements

The hydraulic boundary conditions were retrieved from the info center of Rijkswaterstaat (Rijkswaterstaat, Waterhoogte, sd) and the hydrological predictions from the KNMI (HR2006). The relevant values are as follows:

Water levels m t.o.v NAP

- Standard: 3.4 m
- Average High: 3.6 m
- Average Low: 2.83 m
- Storm Surge: 4.15 m
- Extreme: 5.9 m

7.2 Design crest level & talus

When determining the design crest level of a dike, the failure mechanisms of wave overtopping and overflow (**2.2 Failure mechanisms**) should be considered. Since the primary purpose of the crest is to withstand extreme water level conditions. The sum of the sea level rise, the soil settlement, the storm surge level, and wave run-up determines the Design crest level.

Subsidence is the gradual settlement or sink-in of the land surface. The surface rise and fall along with the groundwater table due to rainfall and evaporation. The causes of subsidence can be pressure on the soft soil, such as clay and peat, dehydration of the soft soil, and extraction of minerals, such as gas and salt. The consequence of subsidence can be the increased risk of flooding, damaging foundations, and additional investment in water management. The subsidence of the timeframe 2020 -2100 on an extreme situation: water level rise and significant climate change can be seen in Figure 32. The subsidence will be expected to be 10 cm in Hoedekenskerke in the year 2100.

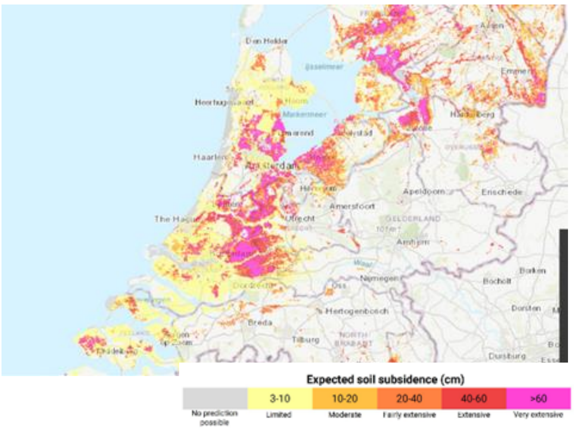


Figure 32: Netherlands' subsidence (Deltares, sd)

Figure 33: Average year sea level rise (cm) (Waterstaat, 2023)

According to the climate dashboard, there is expected to be a level sea by the year 2100 of 85 cm (Waterstaat, 2023), while in the year 2050, the sea level rise is expected to be 32 cm in an extreme situation, Figure 33: Average year sea level rise (cm)Figure 33. The sea level rise of 2100 was used to calculate the crest height.

Microsoft Excel software was combined with the wave run-up formula to calculate the wave run-up.

Wave run-up formula:

$$Z0 = fr * 8 * Hs * tan(\alpha) * cos(\beta) * (1 - B/L)$$

The data required was retrieved from the HR2006, which resulted in a wave run-up of 1.654 meters. Thus the design crest level is equal to:

$$Crest\ level\ design\ =\ 0.85\,m\ +\ 0.1\,m\ +\ 1.654\,m\ +\ 5.9\,m\ =\ 8.5\,m$$

7.3 Macro & micro stability of inner berm

This section will calculate the macro stability inwards towards the hinterland (STBI) using the software D-stability. The relevant hydraulics loads for macro-stability are:

- The water level at standard: which is 3.4 m
- Low outer water level for assessing the outer slope: 2.83 m
- Water level curve to determine the phreatic surface: 5.9 m

Various methods have been developed to analyze the stability of the slope. The methods assumed that the soil fails along a circular slip plane. The slip plane is then divided into slices bounded by vertical interfaces. The most commonly used methods are:

- Fellenius method
- Bishop method

Fellenieus method is the oldest method and assumes no forces between the slices. The sliding soil wedge is divided into 10 or 20 slices. The formula is the following:

$$F = \frac{\sum\{[c + (\gamma h \cos^2\alpha - p)\tan\phi]/\cos\alpha\}}{\sum \gamma h \sin\alpha}.$$

The Bishop method is frequently used method in Engineering works due to being consistent regarding the vertical equilibrium. The method does not neglect the forces between the slices but assumes that the resultant force is horizontal (Verruijt, 2001). The Bishop method is used to calculate the inner berm's macro stability, and the formula is:

$$F = \frac{\sum \dfrac{c + (\gamma h - p)\tan\phi}{\cos\alpha(1 + \tan\alpha\,\tan\phi/F)}}{\sum \gamma h \sin\alpha}.$$

7.4.1 Positioning of aquifer

There are two possibilities in which the aquifer position can be created. The first option is to create the aquifer underneath the clay layer. However, determining the aquifer water pressure can be challenging due to salt groundwater from the Western Scheldt that forms a seepage stream inland. Since there are three situations in which the seepage stream and the aquifer can interact:

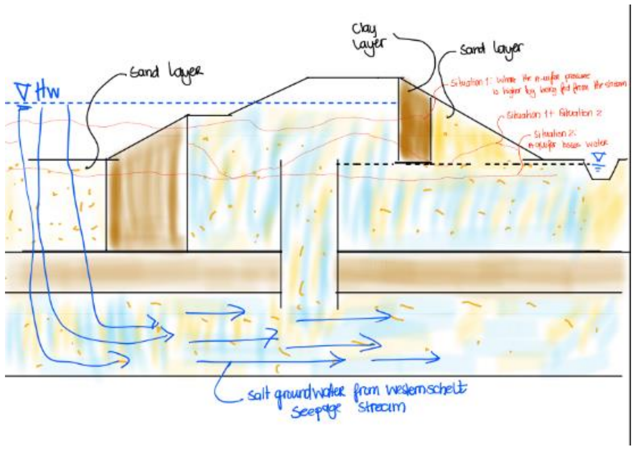


Figure 34: aquifer under clay layer

- Situation 1: The aquifer gains water from the seepage stream, thus the water storage in the aquifer increases
- Situation 2: The stream gains water from the aquifer; thus, the water storage in the aquifer decreases
- Situation 1 + Situation 2: There are areas where the aquifer gains water from the seepage stream, and there are locations where the stream gains water from the aquifer

The other option is to create the aquifer above the clay layer and separate the salt groundwater from the aquifer. Where the aquifer pressure can be determined by the high water level, in this option, the aquifer lies right under the dike, where water can also be stored in the dike. Due to available known data, option two is being used. In Figure 36**Error! Reference source not found.**, the aquifer pressure is visual, which is determined by the high water level of the Western Scheldt, which is dropped by 2.5 meters and runs with a slope of 1:15.

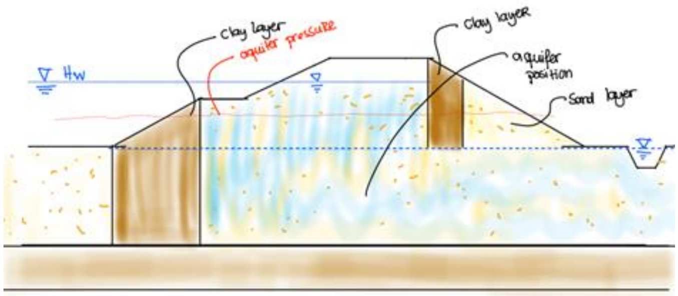


Figure 35: Aquifer above clay layer

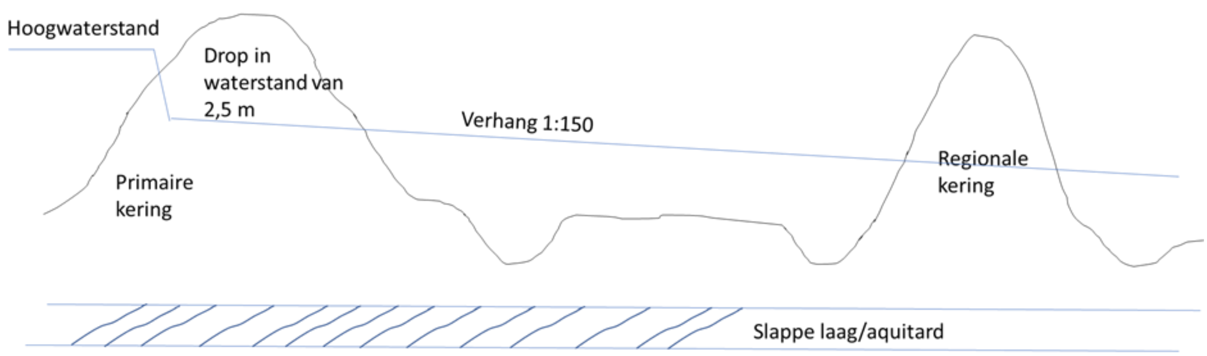


Figure 36: Aquifer's pressure line

7.4.2 Safety factor calculation

The failure probability requirement for macro-stability is calculated with the formula in Figure 37.
The safety factor is then calculated with a safety analysis using the semi – probabilistic method. The relation between the probability of failure and the stability safety factor can be seen in Figure 38. While the correlation between the damage factor and the probability of failure can be seen in Figure 40

$$P_{eis,dsn} = \frac{f \cdot P_{norm}}{\left(1 + \frac{a \cdot L}{b}\right) P_{f|inst}}$$

Figure 37: failure probability requirement (Rijkswaterstaat, 2021)

$$\beta_i = (F_{d;i}/\gamma_d - 0{,}41)/0{,}15 \quad \text{en} \quad P_{f;i} = \Phi(-\beta_i)$$

Figure 38: Correlation between stability factor and probability of failure (Rijkswaterstaat, 2021)

$$\gamma_n = 0{,}15 * \beta_{eis,dsn} + 0{,}41 \quad \text{en} \quad \beta_{eis,dsn} = -\phi^{-1}(P_{eis,dsn})$$

Figure 40: Correlation between damage factor and probability of failure (Rijkswaterstaat, 2021)

According to the water safety portal, the flood probability of the dike trajectory 30-2 is 1/3000 chance with a dike trajectory length of 22 km see Figure 39.
The following factors regarding the formula for inwards macro stability (STBI); see table below.

The formula given properties for STBI		
Sign	Number	Units
P_{norm}	1/3000	
$P_{f/set}$	1,00	
a	0,03	
f	0,04	
b	50,00	m
L	22000	m

Figure 39:Rural flood probability (Waterveligheidsportaal, 2023)

Microsoft Excel calculated the probability of failure, safety factor, and B. The probability of failure resulted in a factor of:

$$P\ eis, dn = \frac{0.4 * \left(\frac{1}{3000}\right)}{(1 + \frac{0.033 * 22000}{50}) * 1} = 8.59E - 7$$

$$ßeis, dsn = -Norm.Inv(8.59\ E - 7) = 4.78402$$

$$\gamma n = 0.5 * 4.78402 + 0.41 = 1.1276 -> safety\ factor$$

7.5 Results

7.5.1 Current situation

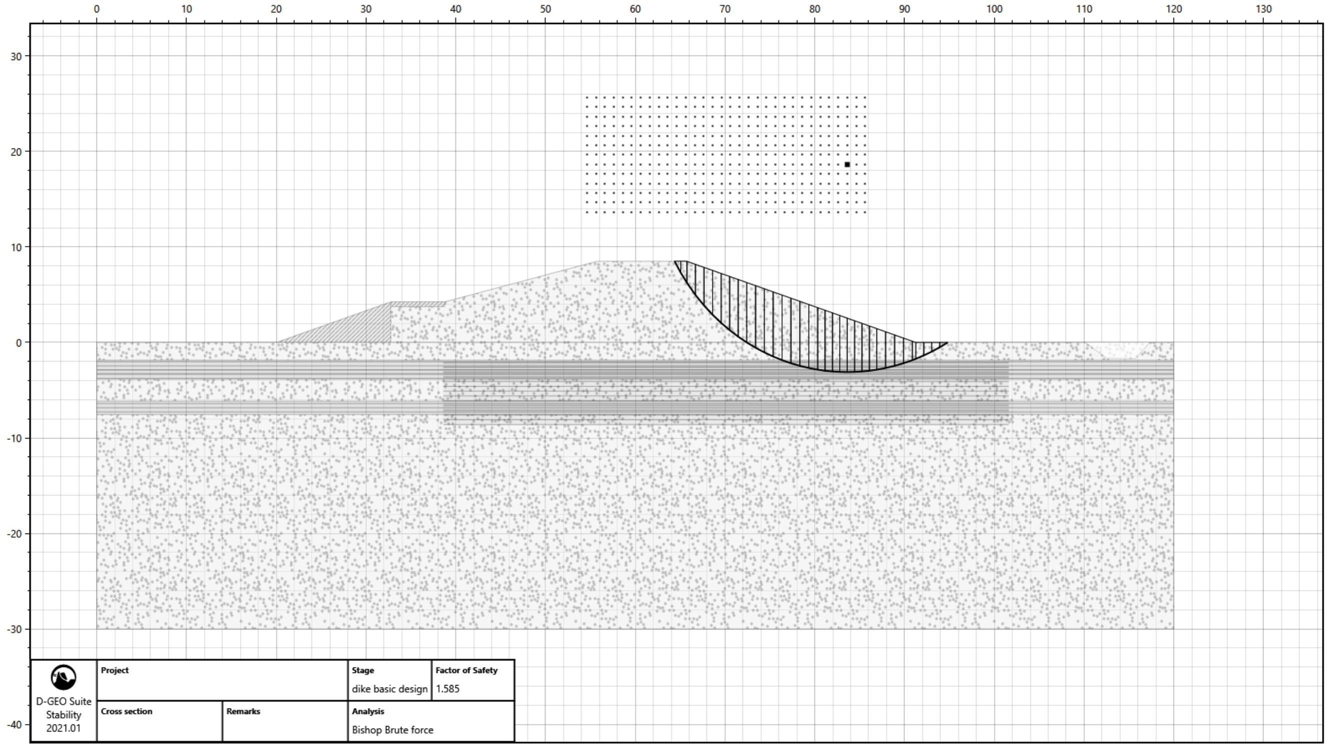
For the current scenario, the dike only consists of clay layers on the seaward side of the dike. The clay will prevent saline water from penetrating the dike since it is impermeable.

However, in this scenario, the water table needs to be defined in comparison to the following situations where the phreatic and aquifer pressure lines are defined. The soil state, soil conditions, and pre-overburden pressure are defined in this situation. The pre-overburden pressure (POP) is the maximum effective vertical overburden stress that a particular soil type has reached in the past.

Results

Safety factor	
Safety factor	1.585
Slip circle	
Center	83.610 ; 18.640
Radius	21.740 m
Entry point	64.380 ; 8.500
Exit point	94.798 ; 0.000
Maximum height of slice	6.819 m
Lowest level of slip circle	-3.100
Calculation input	
Analysis method	Bishop (Brute force)
Bottom left grid point	54.610 ; 13.640
Resolution	1.000 pt/m
Number of grid points	32 x 13
Z bottom tangent line	-8.600
Resolution	2.000 l/m
Number of tangent lines	14
Move grid	Yes
Slip plane constraints	Yes
Minimum circle depth	5.000 m
Minimum slip plane length	5.000 m
Zone A constraints	No
Zone B constraints	No

After selecting the method of Bishop Bruce, it resulted in a safety factor of 1.59, higher than the calculated safety factor of 1.13, and a slip circle with a radius of 21.74 meters. As for the calculation constraints, it has a slip plane with a minimum circle depth of 5 meters and a slip plane length of 5 meters. In Appendix I:10.9.3.1 Current scenario, more information can be found regarding the shear stress, effective stress, and profile.



7.5.2 Scenario 1: Dike with inner berm

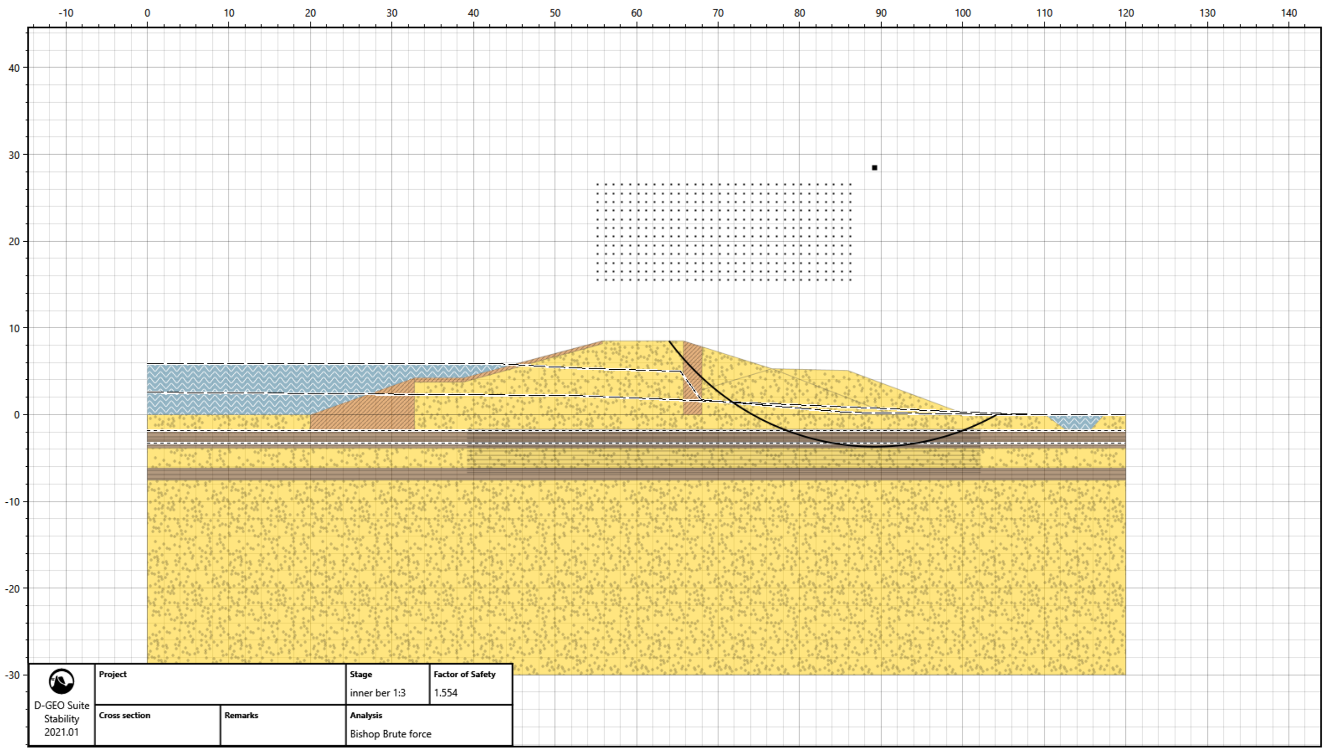
For this situation, an inner berm is placed in the dike's landside to stabilize the structure. In comparison with the current, situation 1 has the phreatic line and the aquifer pressure defined, thus the water table. On the seaward side, clay creates a confined area where the freshwater can be stored and would not mix with the saline water.

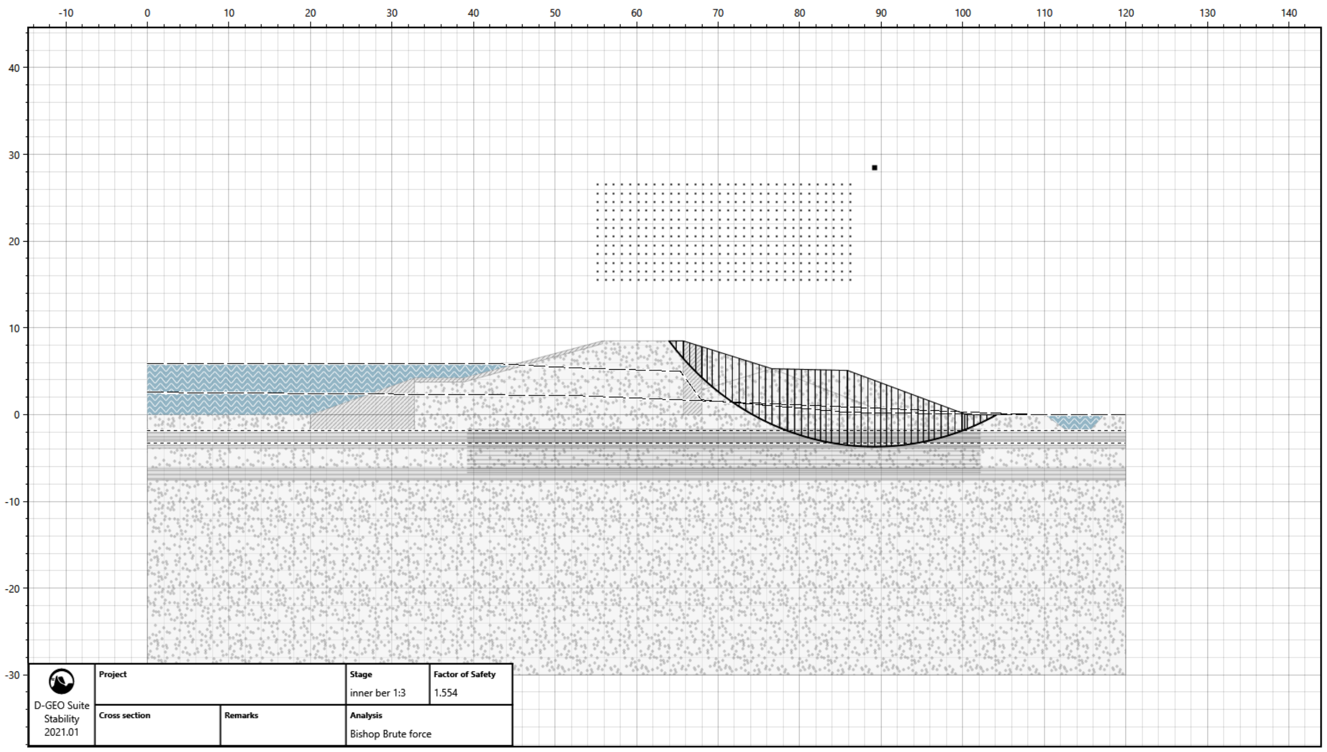
The berm has a width of 10 meters and a slope of 1:3. As for the calculation constraints, it is the same as the current situation, a slip plane with a minimum circle depth of 5 meters and a minimum slip plane length of 5 meters.

After selecting the calculation method of Bishop Brute force, it resulted in a safety factor of 1.55, higher than the calculated safety factor of 1.13, and a slip circle with a radius of 32.2 meters. In Appendix I: 10.9.3.2 Scenario 1, more information regarding shear stress, total stress, effective stress, and the profile can be found.

Results

Safety factor	
Safety factor	1.554
Slip circle	
Center	89.200 ; 28.510
Radius	32.200 m
Entry point	63.972 ; 8.500
Exit point	104.131 ; -0.019
Maximum height of slice	8.617 m
Lowest level of slip circle	-3.690
Calculation input	
Analysis method	Bishop (Brute force)
Bottom left grid point	55.200 ; 15.510
Resolution	1.000 pt/m
Number of grid points	32 x 12
Z bottom tangent line	-6.690
Resolution	2.000 l/m
Number of tangent lines	11
Move grid	Yes
Slip plane constraints	Yes
Minimum circle depth	5.000 m
Minimum slip plane length	5.000 m
Zone A constraints	No
Zone B constraints	No





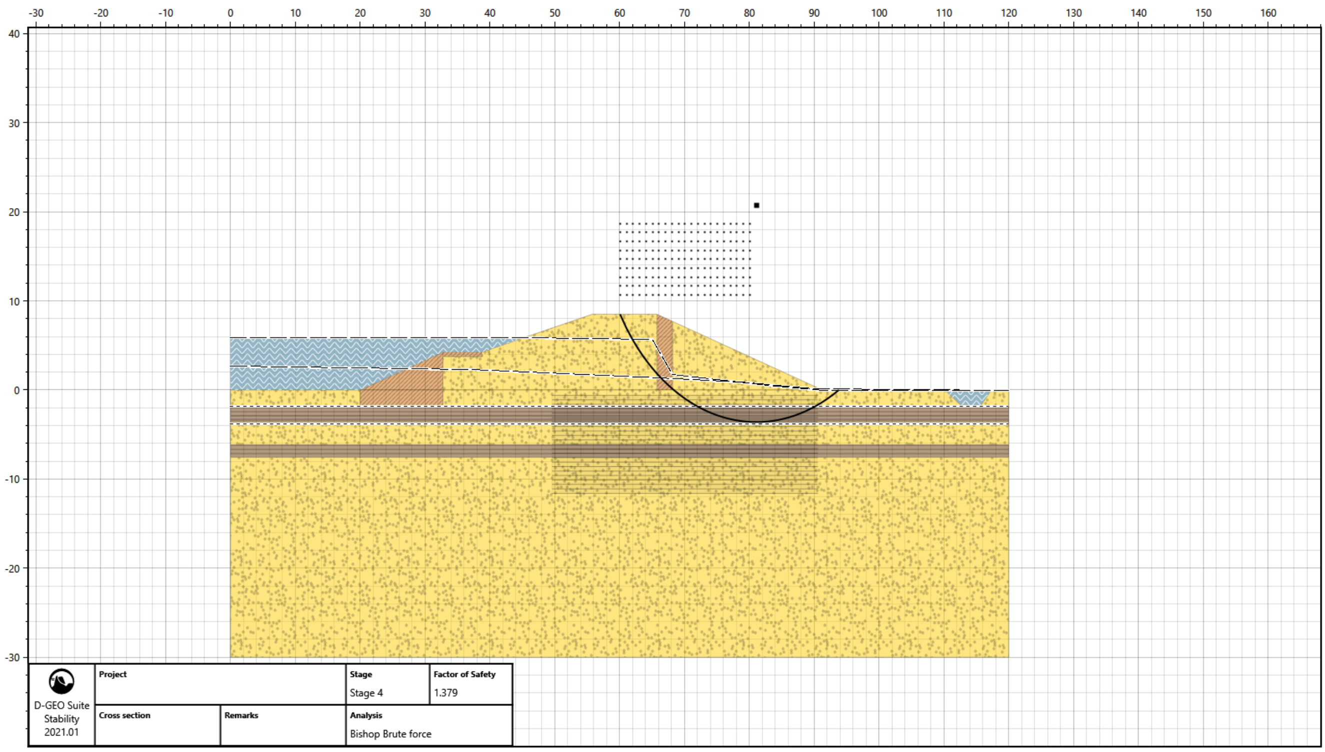
7.5.3 Scenario 2: Dike without inner berm

This situation is the same as the current scenario; however, this scenario has the phreatic line and the aquifer pressure defined. On the seaward side, clay creates a confined area where the freshwater can be stored and would not mix with the saline water. While on the landward side, a small clay layer prevents the water from penetrating the landward sand layers.

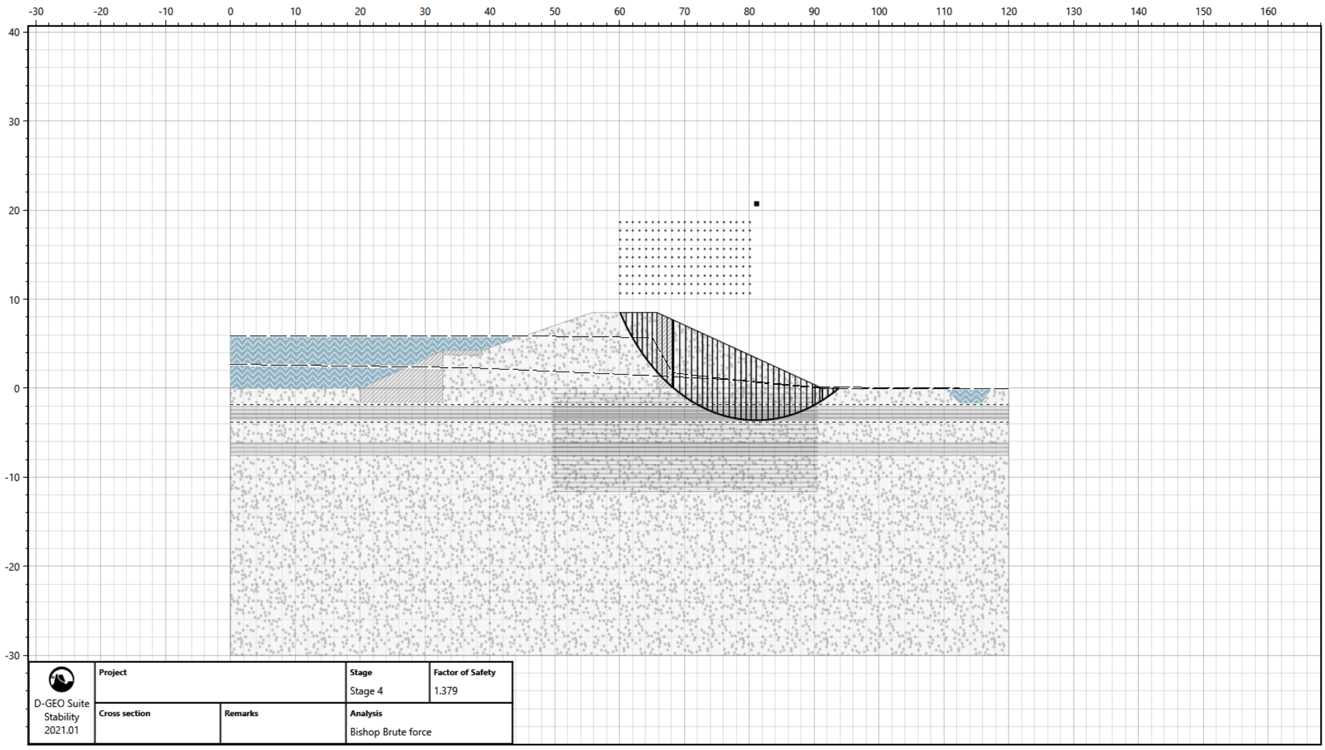
After selecting the calculation method of Bishop Brute force, it resulted in a safety factor of 1.38, a higher safety factor than 1.13, and a slip circle with a radius of 24.28 meters. As for the calculation, constraints are the same as the current situation: a slip plane with a minimum circle depth of 5 meters and a minimum slip plane length of 5 meters. In Appendix I:10.9.3.3 Scenario 2, more information can be found regarding shear stress, total stress, pore pressure, and the profile can be found.

Results

Safety factor	
Safety factor	1.379
Slip circle	
Center	81.060 ; 20.680
Radius	24.280 m
Entry point	60.056 ; 8.500
Exit point	93.782 ; 0.000
Maximum height of slice	8.309 m
Lowest level of slip circle	-3.600
Calculation input	
Analysis method	Bishop (Brute force)
Bottom left grid point	60.060 ; 10.680
Resolution	1.000 pt/m
Number of grid points	21 x 9
Z bottom tangent line	-11.600
Resolution	2.000 l/m
Number of tangent lines	23
Move grid	Yes
Slip plane constraints	Yes
Minimum circle depth	5.000 m
Minimum slip plane length	5.000 m
Zone A constraints	No
Zone B constraints	No



D-GEO Suite Stability 2021.01
Project
Stage
Stage 4
Factor of Safety
1.379
Cross section
Remarks
Analysis
Bishop Brute force



D-GEO Suite Stability 2021.01
Project
Stage
Stage 4
Factor of Safety
1.379
Cross section
Remarks
Analysis
Bishop Brute force

7.6 Final results

For the final design, situation 2 is the most optimal solution since there will be less materials and space required for the construction. Also, the situation still has a macro-stability safety factor of 0,25 higher than the design safety factor of 1.13.

The design consists of an outer berm of a 1:4 slope with a width of 6 meters. The outer talus has a slope of 1:3 and a cross-section length of 12.75 meters. While the inner talus has a cross-section length of 25.5 meters and a slope of 1:3. The dike ditch will lie 8 meters away from the structure with a grade of 0.1%. The ditch will add stability to the dike. Six meters from the dike toe, a sheet pile will be placed at a depth of 5 meters passing through the clay layer, reaching for the second sand layer. Placing a sheet pile in this section will minimize or prevent seepage from the Western Scheldt infiltrating the aquifer and mixing the fresh, stored water. The crest level is 8.5 meters with a width of 10 meters, designed with a storm surge level of 5.9 meters NAP. Figure 45 shows the final design for the freshwater storage dike facility.

The outer talus consists of several soil materials. The first layer is grass with a thickness of 0.1 meters, followed by a turf layer of 0.1 meters. After the turf layer, a geotextile layer will be placed to prevent water from infiltrating the dike section. The outer talus core will consist of clay, while the inner talus will be out of sand. Above the grass layer, flowers, herbs, and forbs will be planted to enhance the natural area and create a new ecosystem while protecting the dike from erosion. Forbs are herbaceous plants that are not graminoids, thus wildflowers. Examples of forbs are:

Figure 42: Common nettle forb

Figure 41: Creeping thistle forb

Figure 43: Bramble forb

Figure 44: Catch weed forb

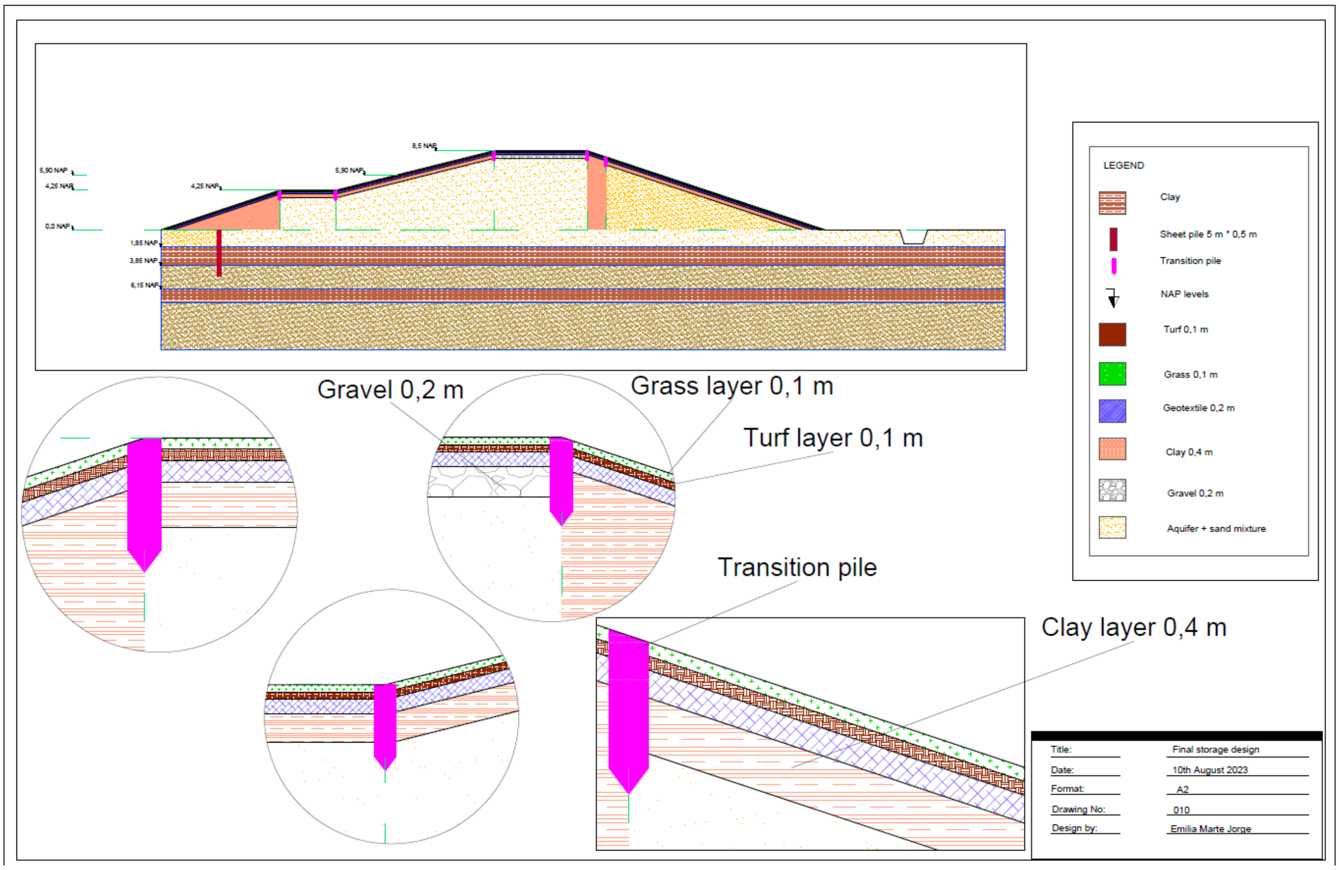


Figure 45: Dike fresh water storage final design

8.0 Conclusion & Recommendation

The report will be concluded by answering the main research question: How can a freshwater storage unit be integrated into the dike of Hoedekenskerke while ensuring compliance with Dutch flood safety standards?

Firstly the area consists of parallel dikes; thus, a primary and secondary dike can be found in the location. For the research, the secondary dike needs to be modified to comply with the regulations of WBI 2017 [beoordelingsinstrumentarium] (Water management). Furthermore, the location is also considered a natural area, so natural area protection regulations should be considered.

There are several ways freshwater can be stored. However, when combined with a dike, seven possible solutions were developed. An MCA-graded system was used to identify the most optimal and suitable solution. It was discovered that an aquifer combined with a dike system was the most optimal solution. The design will consist of a confined aquifer under the dike saving space.

When designing a dike according to Dutch flood regulations, several factors were considered when calculating the dike's crest height design. The Bishop formula calculated the safety design factor for the dike's macro-stability. The D-Stability software was used for the macro-stability, where two situations were created from the final design and calculated. The two situations gave different macro-stability safety values compared with the safety design factor. The second situation was the most optimal, minimizing the construction space required.

In conclusion, the final solution will be an underground aquifer without an inner berm. Clay layers were used to create a confined aquifer. A sheet pile wall will be placed 6 meters from the toe of the dike to prevent salinization and increase the quality of the stored fresh water. The dike is designed to withstand extreme weather conditions and failure mechanisms such as overtopping, overflow, and macro-stability. A grass top layer will cover the dike to preserve the natural area and enhance new ecosystems by planting flowers, herbs, and forbs, see Figure 46.The aquifer design would make it possible to supply fresh water for the farmers and give more insight into how an aquifer can be used. However, due to the overlay of the report, the information provided could be more extensive, and further research should perform. Following the recommendation of how further research should take place to deepen the knowledge of this research.

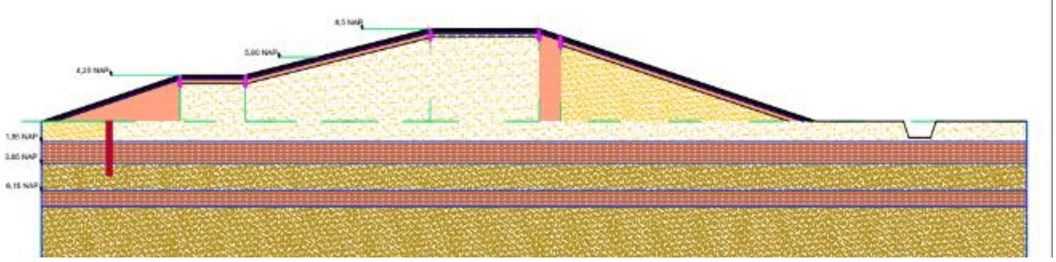


Figure 46: Final solution sketch

8.0.1 Recommendation

It is recommended:

1. To performs a CPT in the project location to identify the actual soil conditions of the Western Scheldt.
2. To perform an analysis to check how the seepage stream formed by the Western Scheldt influences the pressure of the aquifer.
3. To research aquifers being used in the Netherlands
4. To identify whether the final solution can be practical, considering Western Scheldt's soil conditions.
5. Analyze the seasonal precipitation intensities in the Netherlands
6. To perform a Macro-stability test based on the finding of the seasonal precipitation intensity to identify the design's minimal and maximal water storage capacity.
7. Research which pump system is most suitable for the final design.
8. To perform a cost and environmental impact assessment.

8.1 Discussion

The interpretation and limitations of the research will be discussed in the discussion. For starters, the soil conditions and characteristics samples of the project location were taken from an area close to the primary dike or locations near the project area. However, there needs to be more certainty about the actual soil conditions of the area, influencing the final design dimensions. Furthermore, the seepage stream formed by the Western Scheldt basin can also influence the final design. The seepage stream makes it complex to create an aquifer in practice since it influences the quantity and quality of the water to be stored by the aquifer.

The calculations of macro-stability were performed for the worse situation where there is a storm surge, not considering the different seasons. Seasonal precipitation can influence the inner talus stability of the dike. Since it can determine the maximum and minimum storing water capacity. Moreover, it can also tell the quantity of water that is permitted to pump out. The method of extracting water in this research is discussed in a general tone and does not define the most suitable and efficient pump system for the final design.

Due to the project being a concept design, surveying and interviewing the farmers was not executed, which gave only theoretical information about the stakeholders' requirements. To obtain more accurate information regarding the stakeholders' wishes and demands, surveying and interviewing should be done. The recommendation should be taken into action to enhance the information and knowledge gathered in this research. Based on this information also more accurate interpretation of the needed capacity of the storage can be made.

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10.0 Appendices

10.1 Appendix A: Project planning

Project Name: Bachelor Thesis Internship

Project Start: Monday, February 6, 2023

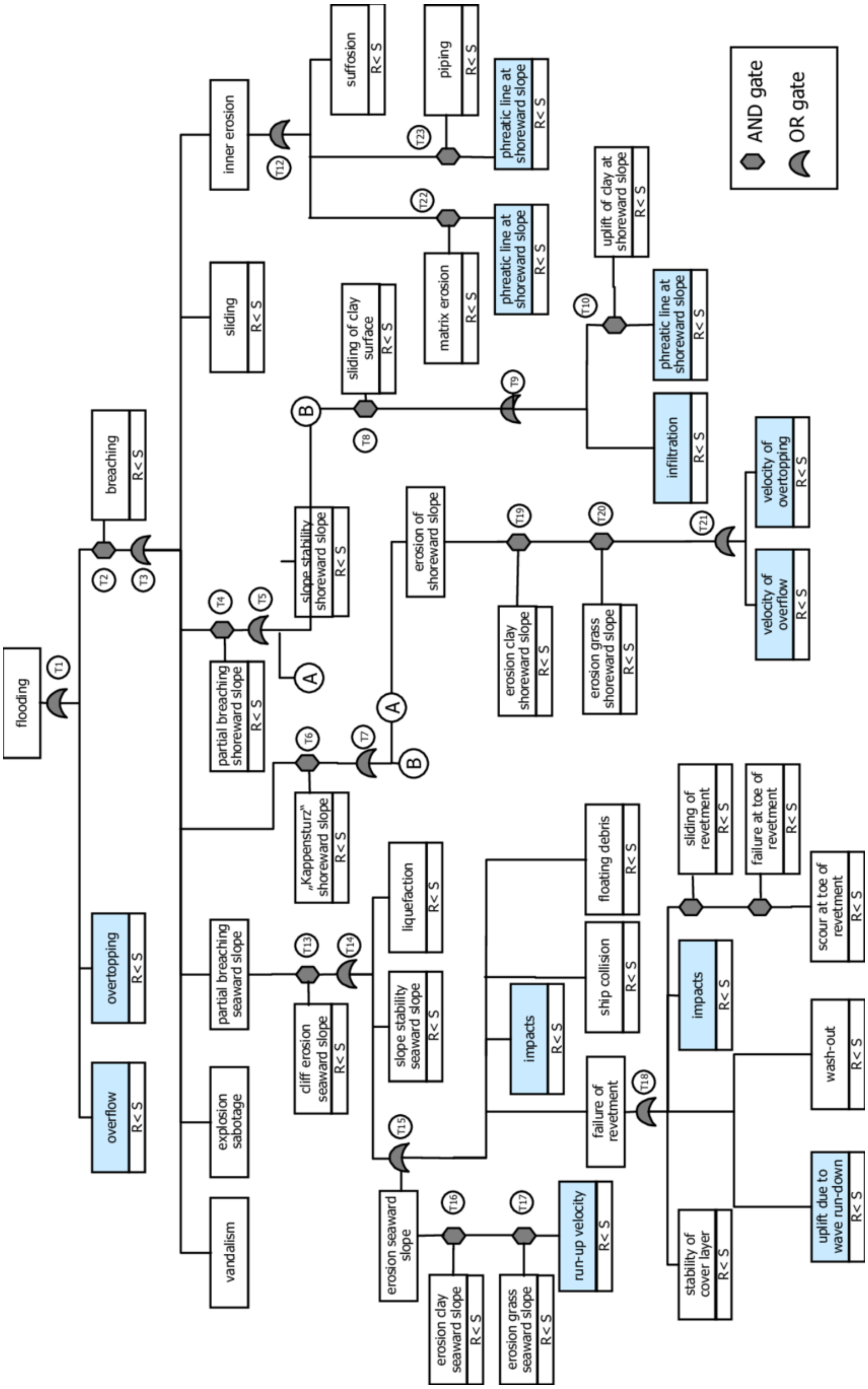
Progress legenda: Completed | Working | Not completed | Need fix

Goal	Accions	Task	Start	End	Progress
THESIS	Kick- off	Introduction	6-feb	6-feb	
		Intern topic	6-feb	6-feb	
	Start-Up document	Read graduation form	7-feb	7-feb	
		Introduction	7-feb	7-feb	
		Professional competences to be aquired	8-feb	9-feb	
		Provisional statement of research	9-feb	10-feb	
		Research Questions	9-feb	10-feb	
		Proposal/Report Table of context	10-feb	13-feb	
	Introduction	Intro--background knowledge	13-feb	14-feb	
		Problem Statement	15-feb	16-feb	
		Research question update	16-feb	16-feb	
		Research Objectives	16-feb	17-feb	
		Research outline	17-feb	17-feb	
	Update	In-Company supervisor P_Introduction	20-feb	21-feb	
	Milestone	Write down to do list & submission dates	21-feb	22-feb	
		Create Excel Gantt chart	22-feb	23-feb	
		Write down time	22-feb	24-feb	
	Update	Hz supervior P_ Introduction + Milestone	22-feb	27-feb	
		Supervisor_ email+qs: Proposal + planning	27-feb	28-feb	
	Subtitles for headings	currntsitu_litrew_stkholdr_results_appendices	22-feb	24-feb	
	Methodology	Methodological approach headings	23-feb	24-feb	
		Methods heading	24-feb	27-feb	
	Update	Supervisor_meeting: P_methodology+ subtitle	27-feb	28-feb	
	Theorectical Framework	Area Analysis	28-feb	2-mrt	
		Literature review	28-feb	3-mrt	
		Stakeholder analysis	2-mrt	6-mrt	
	Update	Supervisor_email+qs:stakehold_situ_Litrew	2-mrt	2-mrt	
	Theorectical Framework	Requirements			
		Technical Requirements	2-mrt	6-mrt	
		Functional Requirements	1-mrt	2-mrt	
	Update	Supervisor_meeting/feed: P_theo_sub	6-mrt	7-mrt	
	Theorectical Framework	Conception design			
		Introduction + alternative 1	2-mrt	6-mrt	
		Altenative 2	6-mrt	7-mrt	
		Alternative 3	7-mrt	8-mrt	
	Methodology	Multi Criteria Analysis			
		Criteria	28-feb	2-mrt	
		Weight/ Cal_Method	2-mrt	3-mrt	
		Results	8-mrt	10-mrt	
		Proposal Appendices	23-feb	10-mrt	
	Update	Hz supervior Proposal draft	7-mrt	8-mrt	
		Supervisor_email: final proposal	10-mrt	10-mrt	
	Submission 1	Poster A4	10-mrt	13-mrt	
	Fixes	Final proposal report updates_grammar_spellin	13-mrt	17-mrt	
		Update master plan + second block subheading	16-mrt	17-mrt	
	Submission 2	Project propasal & draft portfolio	20-mrt	20-mrt	
	Results	Hydrolic conditions	17-mrt	22-mrt	
		Detail design	22-mrt	28-mrt	

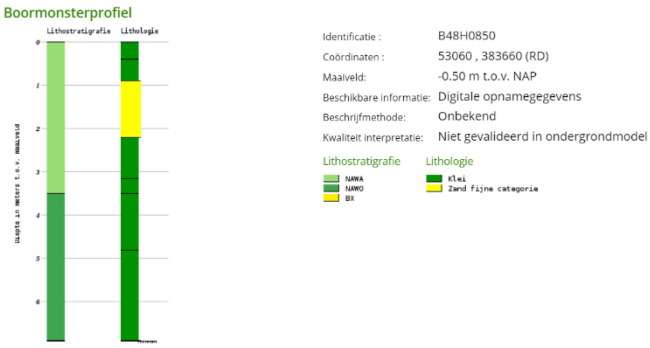
10.2 Appendix B: Site Observation

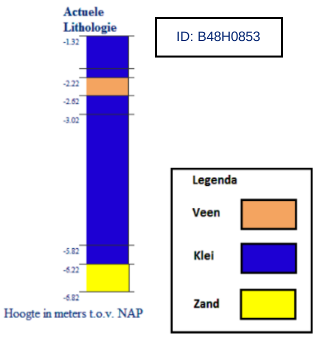
On February 27th, 2023, supervisors Jelle-Jan Pieterse and Samantha van Schaick discussed the project location. The exposition aimed for the interns to understand better what they were working with and how the area looked.

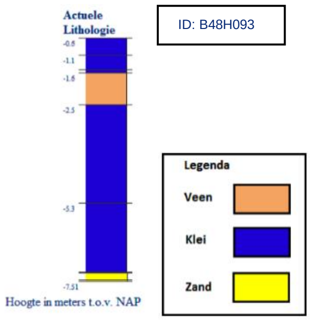
10.3 Appendix C: Simplified event fault tree for a dike

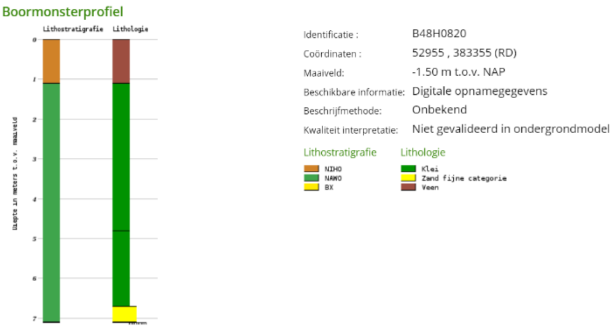


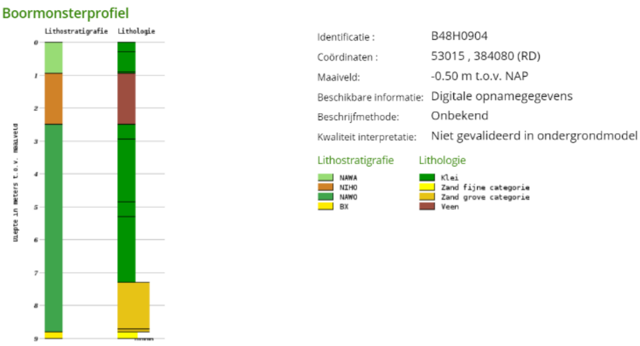
10.4 Appendix D: Schematization of soil layers

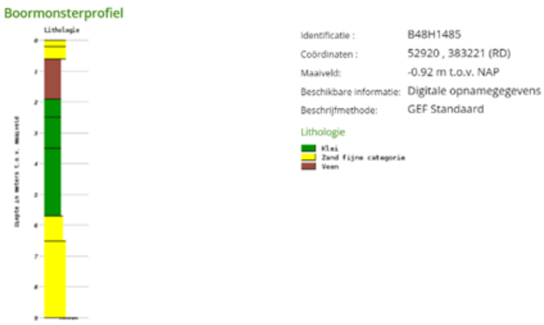




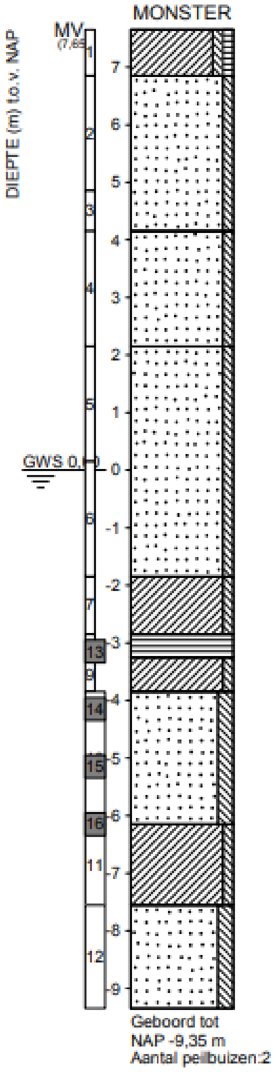








10.4.1 Waterschap Scheldestromen Hoedekenskerke B05:



DIEPTE NAP [m]

MONSTER	LAAG	VAN	TOT	BESCHRIJVING
1	1	7,65	6,85	klei, zwak siltig, zwak humeus
2	2	6,85	4,15	zand, zwak siltig 'BR'
3	3	4,15	2,15	zand, zwak siltig, schelpen 'TBR GR'
4	4	2,15	-1,85	zand, zwak siltig, schelpen 'GR'
5	5	-1,85	-2,85	klei, zwak siltig
6	6	-2,85	-3,25	veen, mineraalarm
7	7	-3,25	-3,85	klei, zwak siltig
8	8	-3,85	-6,15	zand, matig siltig 'GR'
9	9	-6,15	-7,55	klei, zwak siltig
10	10	-7,55	-9,35	zand, matig siltig 'GR'

Einde Boring B 05 (DP359.5 kr)

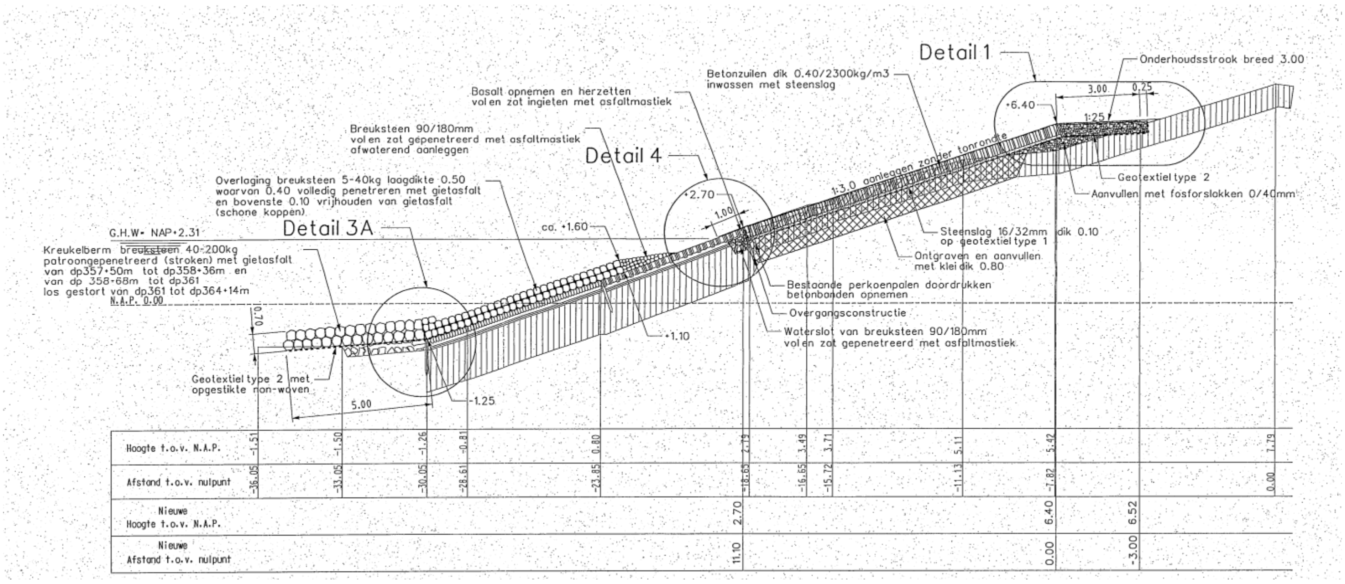
maaiveld: NAP 7,65 m
X = 0,00 m Y = 0,00 m (RD)

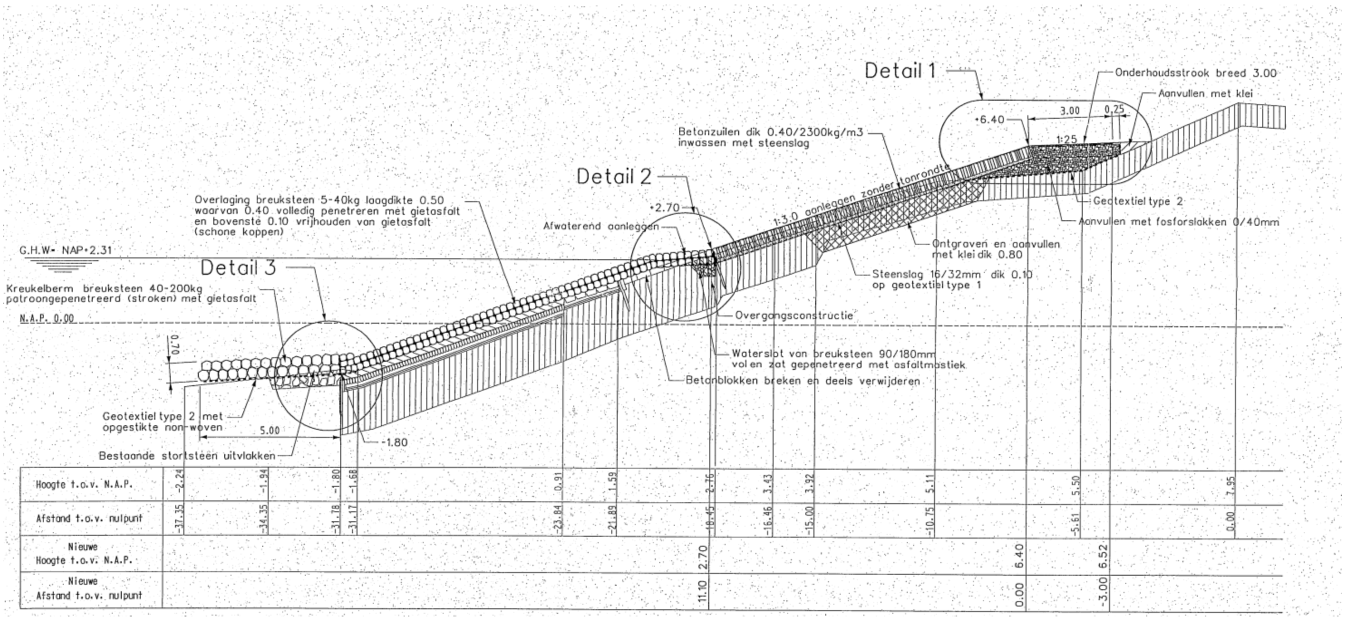
Grontmij	Telefoon Telefax	datum 2007-02-05	get. -
Hoedekenskerke B05 -		--1206-0059-000	gez.
		BIJL. -	A4

Translation:

- Klei = clay
- Zwak siltig = soft silted
- Zwak humeus = soft humid
- Zand = sand
- Schelpen = sea shells
- Veen = peat
- Matig siltig = moderate silted
- GWS = ground water level

10.5 Appendix E: Materials & design detail cross-section of the primary dike





10.6 Appendix F: Safety Assessment category

Category	Safety judgment category designation
A+	The flood probability of the dike section is much less than the signaling value. Therefore, the Dike section is more than satisfactory than the signaling value.
A	The flood probability of the dike section is less than the signaling value. The Dike section applies to the signaling value.
B	The flood probability of the dike section is greater than the signaling value but less than the lower limit. Therefore, the Dike section applies to the lower limit value but not the signaling value.
C	The flood probability of the dike section is greater than the signaling value and the lower limit. Therefore, the Dike section does not meet the signaling value or the lower limit.
D	Flood probability in the dike section is much greater than the signaling value and the lower limit. Therefore, the Dike section is within the lower limit.

10.7 Appendix G: General filter signaling values

10.7.1 Greater than signaling value

Factor 90 more significant than the signaling value

	Beheeraleringsder	Traject
1	Rivierenland	16_4
2	Vallei & Veluwe	45_1
3	Rivierenland	43_5
4	Schieland en de Krimpenerwaard/Rijnland/Stichtse Rijnlanden	14_1
5	Rivierenland	43_4
6	Rivierenland	43_6
7	Hollands Delta	20_3
8	Rivierenland	16_3
9	Stichtse Rijnlanden	44_1
10	Rivierenland	43_3
11	Aa en Maas	36_3
12	Scheldestromen	30_3
13	Scheldestromen	30_2
14	Schieland en de Krimpenerwaard	15_3

10.7.2 Smaller than signaling value

Factor 100 is smaller than the signaling value

	Beheerder	Traject
1	RWS	3_1
2	Delfland	14_5
3	Delfland	14_6
4	Hollandse Delta	18_1
5	Hollandse Delta	20_1
6	Scheldestromen	27_1
7	Zuiderzeeland	7_1
8	Vallei en Veluwe	46_1
9	Amstel, Gooi en Vecht	13_a1

10.8 Appendix H: MCA Results

10.8.1 Variant 1: Dike core storage

Criteria	Weight (%)	Scale	Final score	Explanation
Cost	20	4	8	The cost of the design is inexpensive. It is similar to the cost of constructing a dike. The cost of the drainage system and maintenance is included.
Environmental impact	10	4	4	The Environmental impact will have similar to when constructing a dike. The impact will affect the flora and fauna of the area negatively. However, it will not be on a large scale.
Adaptation	15	4	6	The variant is developed for futuristic climate change but not for futuristic water demand. Therefore, as time passes, the water storage of the dike will require an increase in storage to comply with the water demand.
Water storage quantity	20	2	4	Based on the concept design sketch, the variant's water storage capacity was estimated using a grading system for quantity. The design was found to store 337.5 cubic meters per meter.
Water stress stability	13	3	3.9	Clay layers stabilize the dike against water stress pressure and horizontal force. The layers prevent the clay and dike from moving horizontally, and the soil stress balances against the water pressure.
Water quality	12	3	3.6	Clay layers are utilized to avoid mixing freshwater and saline water. Clay is impermeable and prevents the seawater/ saline water from infiltrating the dike. However, a small percentage of filtration of seawater and seepage can still occur.
Maintainability	10	4	4	The structure is maintainable. The pump needs regular maintenance aside from maintaining the dike.

10.8.2 Variant 2: Single sheet pile wall storage

Criteria	Weight (%)	Scale	Final score	Explanation
Cost	20	2	4	Sheet pile walls, in general, are expensive. For example, a sheet pile wall can cost up to 90 to 140 euros per m2 with a depth of 15 m. Therefore leading to a budget increment in the dike design project.
Environmental impact	10	3	3	The Environmental impact that single sheet pile storage will have is similar to when constructing a dike. The impact will affect the flora and fauna of the area negatively. However, it will not be on a grander scale.

Adaptation	15	3	4.5	The variant is developed for futuristic climate change but not for futuristic water demand. Therefore, as time passes, the water storage of the dike will require an increase in storage to comply with the water demand.
Water storage quantity	20	1	2	Based on the concept design sketch, the variant's water storage capacity was estimated using a grading system for quantity. The design was found to store 221 cubic meters per meter.
Water stress stability	13	5	6.5	The sheet pile wall gives structural support to the dike and prevents horizontal movement of the structure due to water pressure.
Water quality	12	4	4.8	The rainwater is stored in the center of the dike with a clay layer that will prevent salinization and seepage. Moreover, the sheet pile wall also protects the stored water, which prevents the water from mixing.
Maintainability	10	3	3	The structure is maintainable. However, there will be a period when the sheet pile wall will need to be maintained, which can cost a lot of money, aside from maintaining the dike.

10.8.3 Variant 3: Single geotextile/foil wall storage

Criteria	Weight (%)	Scale	Final score	Explanation
Cost	20	3	6	Compared to the cost of a sheet pile wall, a foil wall is less expensive. Nevertheless, it will still have an impact on the project budget.
Environmental impact	10	3	3	The Environmental impact will have similar to when constructing a dike. The impact will affect the flora and fauna of the area negatively. However, it will not be on a grander scale.
Adaptation	15	3	4.5	The variant is developed for futuristic climate change but not for futuristic water demand. Therefore, as time passes, the water storage of the dike will require an increase in storage to comply with the water demand.
Water storage quantity	20	1	2	Based on the concept design sketch, the variant's water storage capacity was estimated using a grading system for quantity. The design was found to store 223 cubic meters per meter.
Water stress stability	13	5	6.5	The foil wall should give similar structural support as a sheet pile wall to the dike and prevents horizontal movement of the structure due to water pressure.
Water quality	12	4	4.8	Storing rainwater in the center of the dike with a clay layer will prevent salinization and seepage. Moreover, the foil wall protects the freshwater from mixing with the saline water.

Maintainability	10	3	3	The structure is maintainable. However, there will be a period when the foil wall will need to be maintained, which will increase the maintenance budget. Also, the pump needs regular maintenance aside from maintaining the dike.

10.8.4 Variant 4: Double sheet pile wall storage

Criteria	**Weight (%)**	**Scale**	**Final score**	**Explanation**
Cost	20	1	2	Sheet pile walls, in general, are expensive. For example, a sheet pile wall can cost up to 90 to 140 euros per m2 with a depth of 15 m. Therefore, the design cost will be close to 50% extra cost as variant 2, leading to a budget increment in the dike design project.
Environmental impact	10	3	3	The Environmental impact that single sheet pile storage will have is similar to when constructing a dike. The impact will affect the flora and fauna of the area negatively. However, it will not be on a larger scale.
Adaptation	15	3	4.5	The variant is developed for futuristic climate change but not for futuristic water demand. Therefore, as time passes, the water storage of the dike will require an increase in storage to comply with the water demand.
Water storage quantity	20	2	4	Based on the concept design sketch, the variant's water storage capacity was estimated using a grading system for quantity. The design was able to store 277.4 cubic meters per meter.
Water stress stability	13	5	6.5	The sheet pile wall gives structural support to the dike from both sides and prevents horizontal movement of the structure due to water pressure.
Water quality	12	5	6	The collected water will be stored in the space formed by the sheet pile walls. This area is restricted, which prevents the blending of saltwater and freshwater and restricts seepage.
Maintainability	10	3	3	The structure is maintainable. However, there will be a period when the sheet pile wall will need to be maintained or replaced, which can cost money, aside from maintaining the dike. Also, the maintenance cost of the pump will need to be added to the maintenance budget.

10.8.5 Variant 5: Double geotextile/foil wall storage

Criteria	Weight (%)	Scale	Final score	Explanation
Cost	20	2	4	Compared to the cost of sheet pile walls of variant 4, a foil wall is less expensive. Nevertheless, it will still have an impact on the project budget.
Environmental impact	10	3	3	The Environmental impact will have similar to when constructing a dike. The impact will affect the flora and fauna of the area negatively. However, it will not be on a large scale.
Adaptation	15	3	4.5	The variant is developed for futuristic climate change but not for futuristic water demand. Therefore, as time passes, the water storage of the dike will require an increase in storage to comply with the water demand.
Water storage quantity	20	2	4	Based on the concept design sketch, the variant's water storage capacity was estimated using a grading system for quantity. The design was able to store 281.2 cubic meters per meter.
Water stress stability	13	5	6.5	The foil wall should give similar structural support as a sheet pile wall to the dike and prevents horizontal movement of the structure due to water pressure.
Water quality	12	5	6	The collected water will be stored in the space formed by the foil walls. This area is restricted, which prevents the blending of saltwater and freshwater and restricts seepage.
Maintainability	10	3	3	The structure is maintainable. However, there will be a period when the foil wall will need to be maintained or even replaced. Therefore, an increment in the maintenance budget. Also, the pump needs regular maintenance aside from maintaining the dike.

10.8.6 Variant 6: Aquifer storage

Criteria	Weight (%)	Scale	Final score	Explanation
Cost	20	3	6	The cost of the design is expensive. More equipment will be needed to create the aquifer and the underground sheet pile wall usage.
Environmental impact	10	4	4	The Environmental impact will have similar to when constructing a dike. The impact will affect the flora and fauna of the area negatively. However, it will not be on a large scale.
Adaptation	15	5	7.5	The dike is designed according to the present and futuristic climate change. Moreover, the futuristic water demand is taken into account. Over time, the aquifer will expand, creating additional room for water storage.

Water storage quantity	20	5	10	Based on the concept design sketch, the variant's water storage capacity was estimated using a grading system for quantity. The design was able to store 730 cubic meters per meter.
Water stress stability	13	3	3.9	Clay layers stabilize the dike against water stress pressure and horizontal force. The layers prevent the clay and dike from moving horizontally, and the soil stress balances against the water pressure.
Water quality	12	3	3.6	Clay layers are utilized to avoid mixing freshwater and saline water. Clay is impermeable and prevents the seawater/ saline water from infiltrating the dike. In addition, a sheet pile wall is used in the underground layers to prevent seepage and mixing of the aquifer and saline water.
Maintainability	10	3	3	The structure is maintainable. However, there will be a period when the sheet pile wall will need to be maintained, which can cost a lot of money, aside from maintaining the dike.

10.8.7 Variant 7: Underground tank storage

Criteria	Weight (%)	Scale	Final score	Explanation
Cost	20	3	6	The cost of building the design should be similar to the cost of building a dike. However, due to the integration of the tank and pump system, the cost will increase by approximately 30 % more than building and designing a dike.
Environmental impact	10	3	3	The Environmental impact will have similar to when constructing a dike. The impact will affect the flora and fauna of the area negatively. However, it will not be on a large scale.
Adaptation	15	3	4.5	The dike is designed to withstand futuristic climate change. Therefore, it is essential to consider the future water demand. As time passes by, the water storage of the dike will increment to comply with the water demand. Therefore, the tank will also need replacement.
Water storage quantity	20	4	8	Based on the concept design sketch, the variant's water storage capacity was estimated using a grading system for quantity. The design was able to store 630 cubic meters per meter.
Water stress stability	13	3	3.9	Clay layers stabilize the dike against water stress pressure and horizontal force. The layers prevent the clay and dike from moving horizontally, and the soil stress balances against the water pressure.
Water quality	12	3	3.9	Clay layers are utilized to avoid mixing freshwater and saline water. Clay is impermeable and prevents the

				seawater/ saline water from infiltrating the dike. However, a small percentage of filtration of seawater and seepage can still occur.
Maintainability	10	3	3	The design is maintainable. The pump of the design will require maintenance every certain period, and the tank will also need to be maintained and cleaned when necessary. However, compared to the other alternatives, the maintenance cost for this alternative is relatively inexpensive.

10.9 Appendix I: Technical design resources & outcome

10.9.1 Soil type properties

Soil type		Representative average value of the soil properties												
Main name	Additional Info	Consistency 1)	γ 2) kN/M3	γsat kN/m3	qc 3)6) MPA	C' p	C's	Cc	Cα5)	Csw	E6 MPa	Ø'	C'	fundr kPa
Gravel	Slightly silty	Loose Moderate Fixed	17 18 19 or 20	19 20 21 or 22	15 25 30	500 1000 1200 or 1400	- - -	0.008 0.004 0.003 or 0.002	0 0 0	0.003 0.002 0.001 or 0	75 125 150 or 200	32.5 35 37.5 or 40	n/a	n/a
	Very silty	Loose Moderate Fixed	18 19 20 or 21	20 21 22 or 22.5	10 15 25	400 600 1000 or 1500	- - -	0.009 0.006 0.003 or 0.002	0 0 0	0.003 0.002 0.001 or 0	50 75 125 or 150	30 32.5 35 or 40	n/a	n/a
Sand	Clean	Loose Moderate Fixed	17 18 19 or 20	19 20 21 or 22	5 15 25	200 600 1000 or 1500	- - -	0.021 0.006 0.003 or 0.002	0 0 0	0.007 0.003 0.001 or 0	25 75 125 or 150	30 32.5 35 or 40	n/a	n/a
	Slightly silty		18 or 19	20 of 21	12	450 or 650	-	0.008 or 0.005	0	0.003 or 0.001	25 or 35	27 or 32.5	n/a	n/a
	Clay-like													
	Very silty		18 or 19	20 or 21	8	200 or 400	-	0.019 or 0.009	0	0.006 or 0.001	20 or 30	25 or 30		
	Clay-like													
Loam 4)	Slightly sandy	Soft Moderate Fixed	19 20 21 or 22	19 20 21 or 22	1 2 3	25 45 70 or 100	650 1300 1900 or 2500	0.168 0.084 0.049 or 0.030	0.004 0.002 0.001	0.056 0.028 0.017 or 0.005	2 5 10 or 20	27.5 or 30 27.5 or 32.5 27.5 or 35	0 2 5 or 7.5	50 100 200 or 300
	Very sandy		19 or 20	19 or 20	2	45 or 70	1300 or 2000	0.092 or 0.055	0.002	0.031 or 0.005	5 or 10	27.5 or 35	0 or 2	50 or 100
Clay	Clean	Soft Moderate Fixed	14 17 19 or 20	14 17 19 or 20	0.5 1.0 2.0	7 15 25 or 30	80 160 320 or 500	1.357 0.362 0.168 or 0.126	0.013 0.006 0.004	0.452 0.121 0.056 or 0.042	1 2 4 of 10	17.5 17.5 17.5 or 25	0 10 25 or 30	25 50 100 or 200
	Slightly sandy	Soft Moderate Fixed	15 18 20 or 21	15 18 20 or 21	0.7 1.5 2.5	10 20 30 or 50	110 240 400 or 600	0.759 0.237 0.126 or 0.069	0.009 0.005 0.003	0.253 0.079 0.042 or 0.014	1.5 3 5 or 10	22.5 22.5 22.5 or 27 5	0 10 25 or 30	40 80 120 or 170
	Very sandy		18 or 20	18 or 20	1.0	25 or 140	320 or 1680	0.190 or 0.027	0.004	0.063 or 0.025	2 or 5	27.5 or 32.5	0 or 2	0 or 10
	Organic	Soft Moderate	13 15 or 16	13 15 or 16	0.2 0.5	7.5 10 or 15	30 40 or 60	1.690 0.760 or 0.420	0.015 0.012	0.550 0.250 or 0.140	0.5 1.0 or 2.0	15 15	0 or 2 0 or 2	10 25 or 30
Peat	Not preloaded	Soft	10 or 12	10 or 12	0.1	5 or 7.5	20 or 30	7.590 or 1.810	0.023	2.530 or 0.600	0.2 or 0.5	15	2 or 5	10 or 20
	Moderately preloaded	Moderate	12 or 13	12 or 13	0.2	7.5 or 10	30 or 40	1.810 or 0.900	0.016	0.600 or 0.300	0.5 or 1.0	15	5 or 10	20 or 30
Variety Coefficient			0.05		-	0.25						0.10	0.20	

10.9.2 Macro-stability formulas

10.9.2.1 Failure probability requirement

$$P_{eis,dsn} = \frac{f \cdot P_{norm}}{\left(1 + \frac{a \cdot L}{b}\right) P_{f|inst}}$$

waarin:

$P_{eis,dsn}$	Faalkanseis voor macrostabiliteit in een doorsnede [per jaar].
P_{norm}	Overstromingskans van het dijktraject zoals vastgelegd in de Waterwet [per jaar].
f	Faalkansruimtefactor voor macrostabiliteit [-] (met waarde 0,04). De faalkansruimte 0,04 is benoemd voor macrostabiliteit binnenwaarts (STBI). Het is gebruikelijk (zie [18]) om voor macrostabiliteit buitenwaarts (STBU) hetzelfde faalkansbudget te gebruiken onder de aanname dat beide mechanismen niet tegelijkertijd optreden en één van beide faalkansbijdragen dan verwaarloosbaar kan worden geacht.
a	a verdisconteert twee fenomenen, 1) het niet substantieel bijdragen van alle dijkvakken in het traject aan de instabiliteitskans van het traject en 2) aanwezige correlatie tussen de instabiliteitskansen van de afzonderlijke dijkvakken [-]; 0,033.
L	Totale lengte van het dijktraject zoals vastgelegd in de Waterwet [m].
b	Representatieve lengte voor de analyse in een doorsnede [m]; 50 m.
$P_{f\|inst}$	Kans op falen gegeven een instabiliteit [-];1,0 voor STBI, 0,1 voor STBU.

10.9.2.2 Correlation between Safety factor, probability of failure, and damage factor

$\gamma_n = 0{,}15 * \beta_{eis,dsn} + 0{,}41$ en $\beta_{eis,dsn} = -\phi^{-1}(P_{eis,dsn})$

$\beta_i = (F_{d;i}/\gamma_d - 0{,}41)/0{,}15$ en $P_{f;i} = \Phi(-\beta_i)$

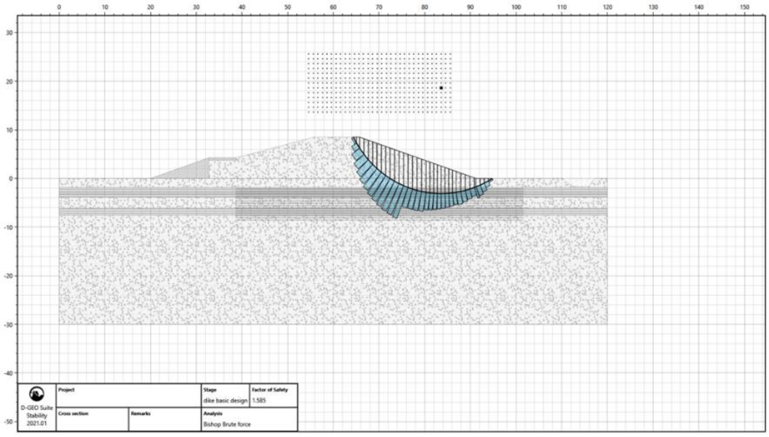
waarin:

γ_n	Schadefactor voor het faalmechanisme macrostabiliteit (-).
$\beta_{eis,dsn}$	Geëiste betrouwbaarheidsindex voor een doorsnede (-).
$P_{eis,dsn}$	Faalkanseis per doorsnede voor macrostabiliteit (per jaar).
β_i	Betrouwbaarheidsindex voor de doorsnede per scenario (-).
$F_{d;i}$	Berekende stabiliteitsfactor voor de doorsnede per scenario (-).
γ_d	Modelfactor (-).
$P_{f;i}$	Faalkans voor de doorsnede per scenario (per jaar).

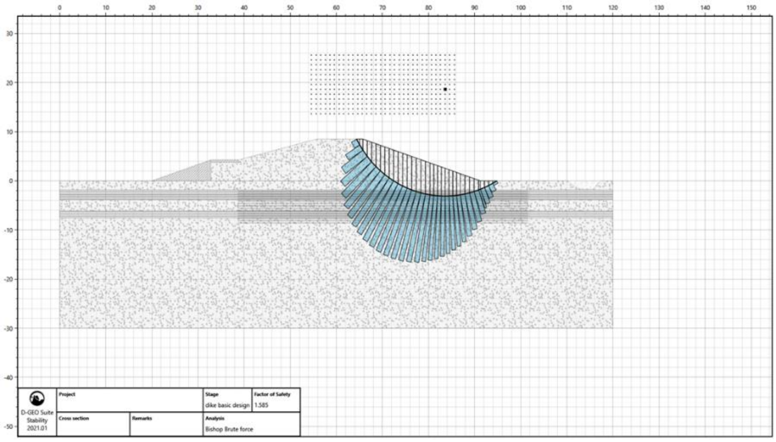
10.9.3 Results

10.9.3.1 Current scenario

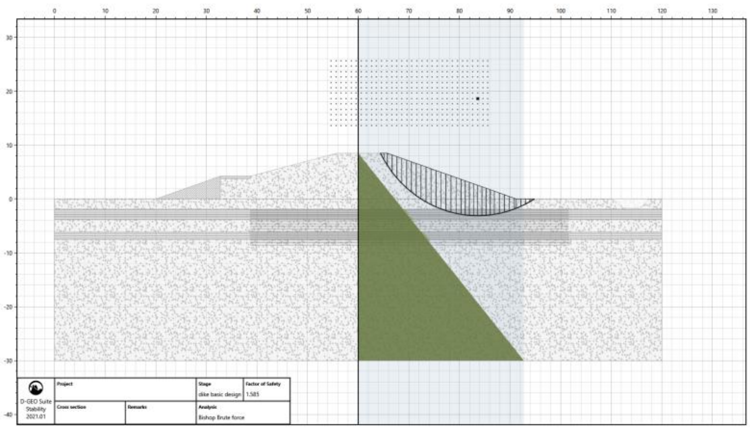
Shear stress



Effective stress



Profile inspector



Profile inspector

- Water pressure (ut)
- Excess water pressure (uex)
- Effective stress (σ')
- Load stress
- POP

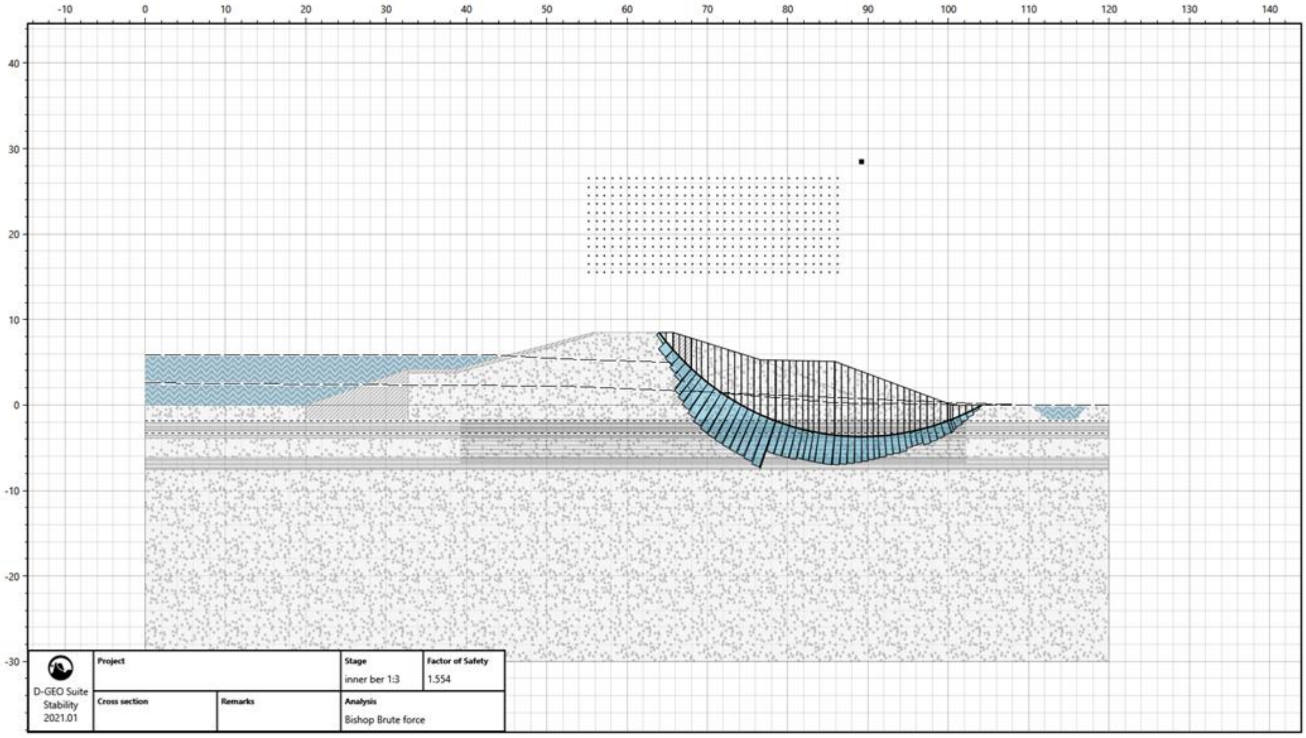
X

60

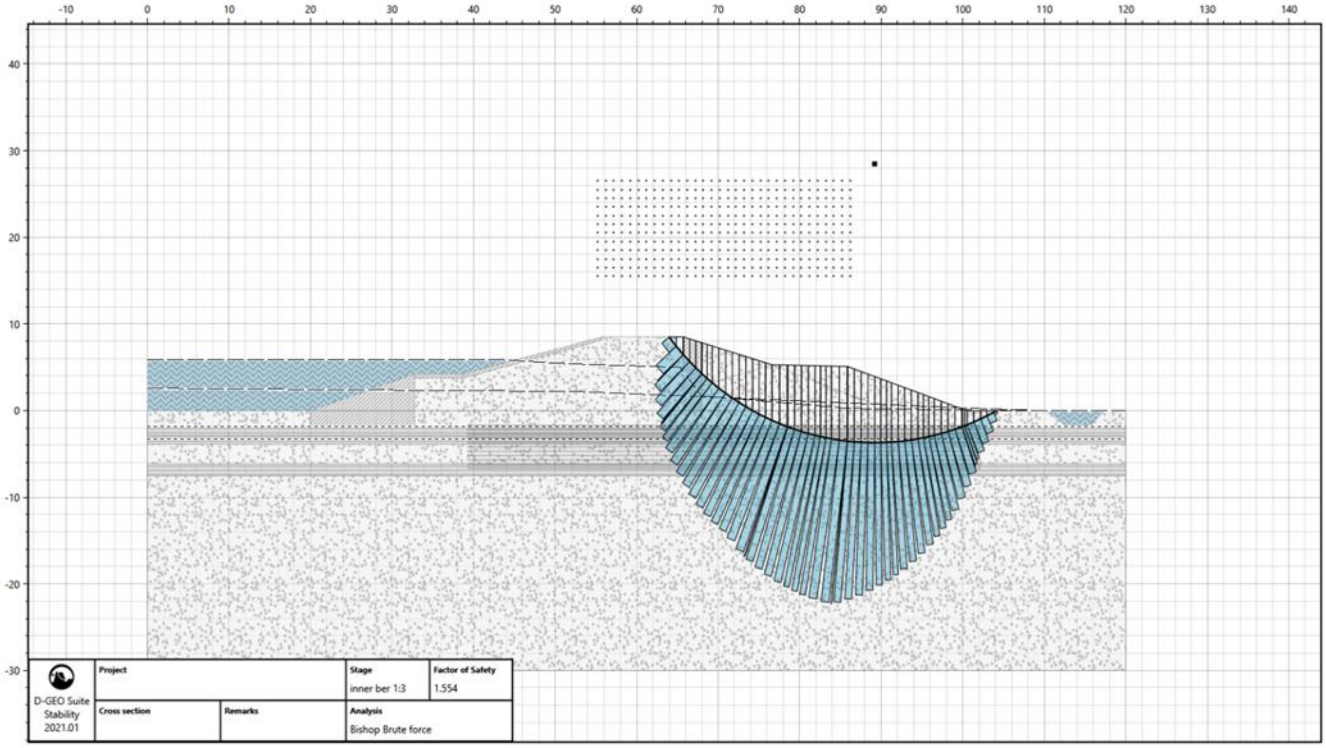
Z	Effective Above [kN/m²]	Effective Below [kN/m²]	Load Above [kN/m²]	Lc Be [kN
8.50	0.00	0.00	0.00	0.
0.00	144.50	144.50	0.00	0.
-1.85	175.95	175.95	0.00	0.
-2.85	192.95	192.95	0.00	0.
-3.25	199.75	199.75	0.00	0.
-3.85	209.95	209.95	0.00	0.
-6.15	249.05	249.05	0.00	0.
-7.55	272.85	272.85	0.00	0.
-30.00	654.50	654.50	0.00	0.

10.9.3.2 Scenario 1

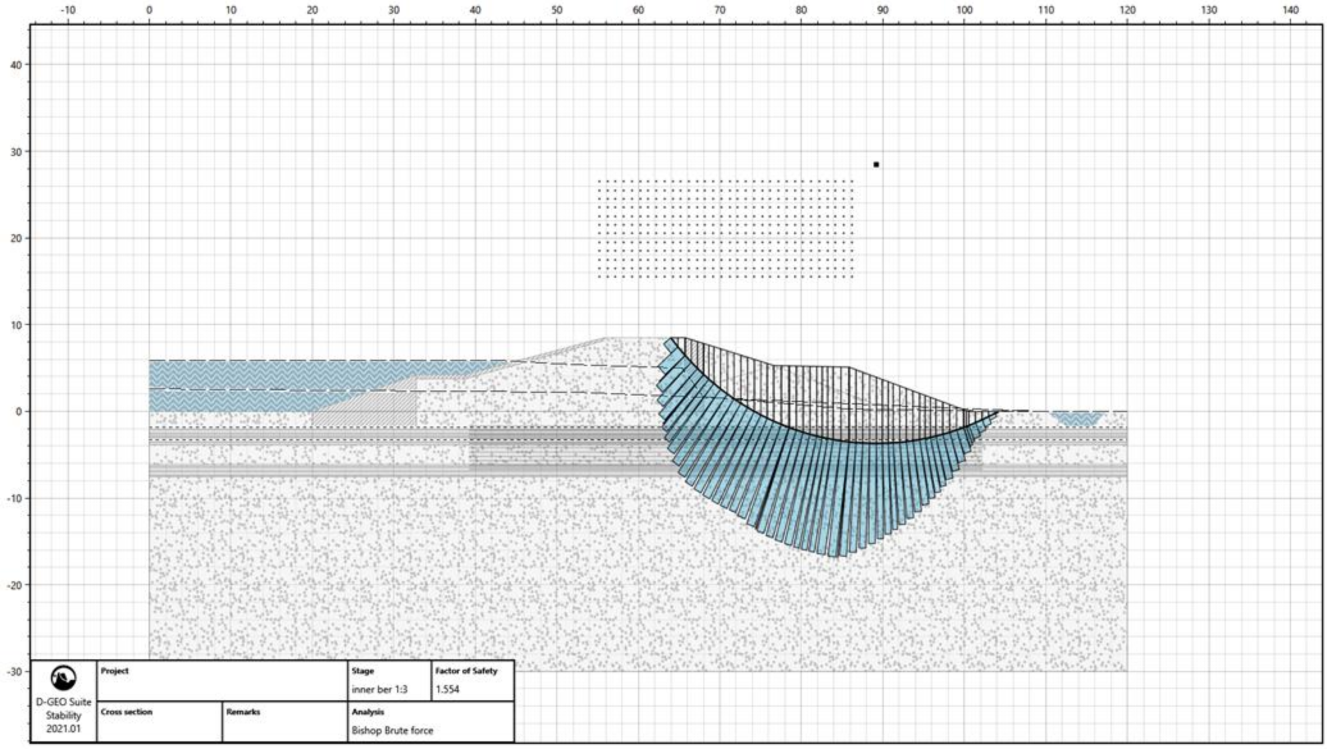
Shear stress



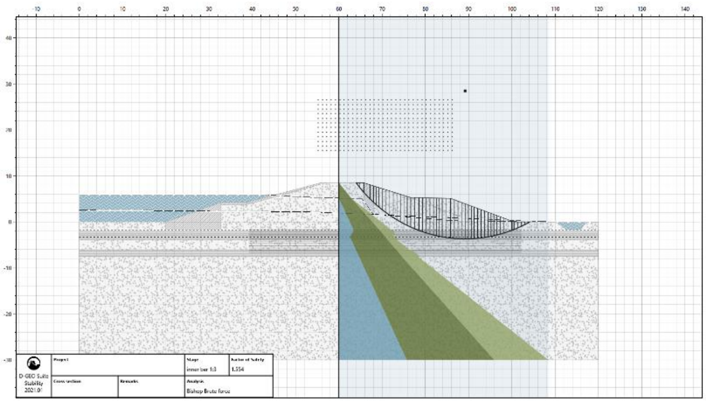
Total stress



Effective Stress



Profile Inspector



Profile inspector

- Water pressure (u$_t$)
- Excess water pressure (u$_{ex}$)
- Effective stress (σ')
- Load stress
- POP

X

60

Z	Water Above [kN/m²]	Water Below [kN/m²]	Excess Above [kN/m²]	Exce: Belo [kN/n
8.50	0.00	0.00	0.00	0.00
5.16	0.00	0.00	0.00	0.00
0.00	50.66	50.66	0.00	0.00
-1.85	68.81	68.81	0.00	0.00
-1.88	68.38	68.38	0.00	0.00
-2.85	56.19	56.19	0.00	0.00
-3.25	51.14	51.14	0.00	0.00
-3.85	57.03	57.03	0.00	0.00
-6.15	79.59	79.59	0.00	0.00
-7.55	93.32	93.33	0.00	0.00
-30.00	313.56	313.56	0.00	0.00

Profile inspector

- Water pressure (u$_t$)
- Excess water pressure (u$_{ex}$)
- Effective stress (σ')
- Load stress
- POP

X

60

Z	Load Above [kN/m²]	Load Below [kN/m²]	POP Above [kN/m²]	POP Below [kN/m²]
8.50	0.00	0.00	0.00	0.00
5.16	0.00	0.00	0.00	0.00
0.00	0.00	0.00	40.33	40.33
-1.85	0.00	0.00	54.78	64.78
-1.88	0.00	0.00	64.28	64.28
-2.85	0.00	0.00	52.09	42.09
-3.25	0.00	0.00	37.04	47.05
-3.85	0.00	0.00	52.93	42.93
-6.15	0.00	0.00	60.89	70.89
-7.55	0.00	0.00	84.63	74.63
-30.00	0.00	0.00	249.96	249.96

Profile inspector

- Water pressure (u$_t$)
- Excess water pressure (u$_{ex}$)
- Effective stress (σ')
- Load stress
- POP

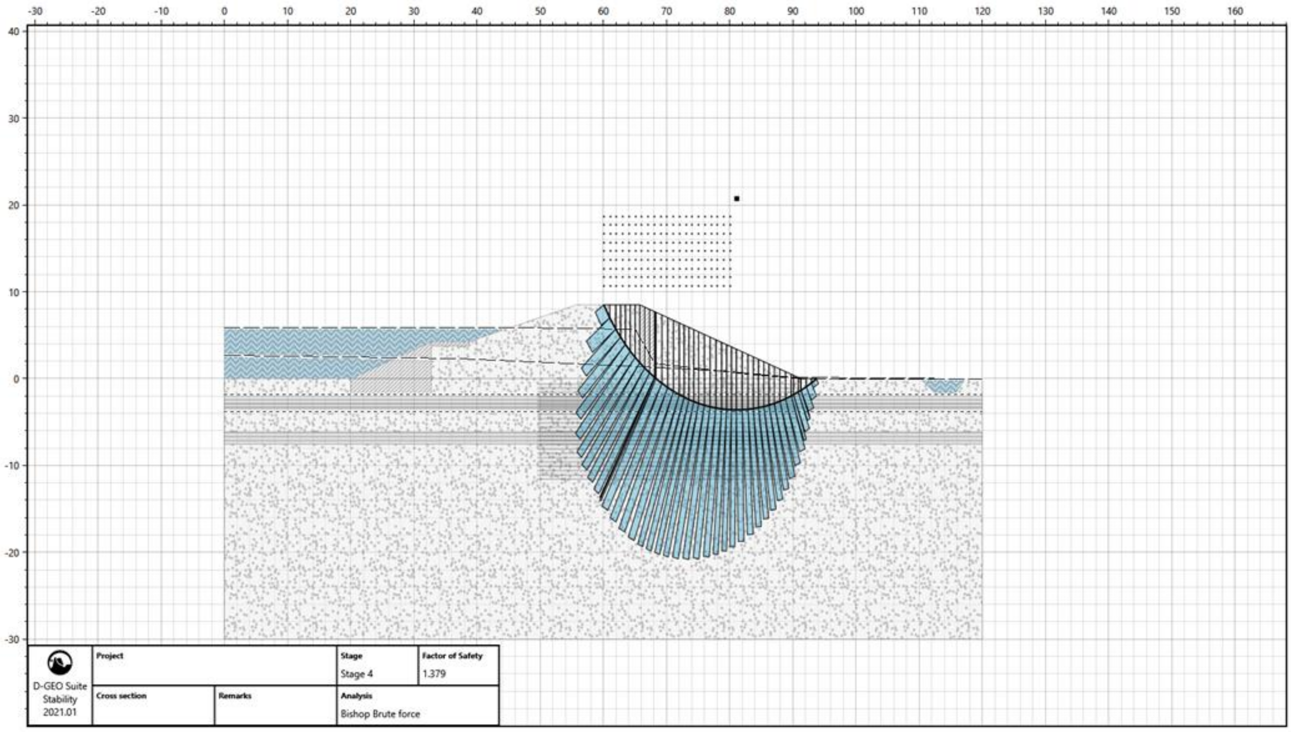
X

60

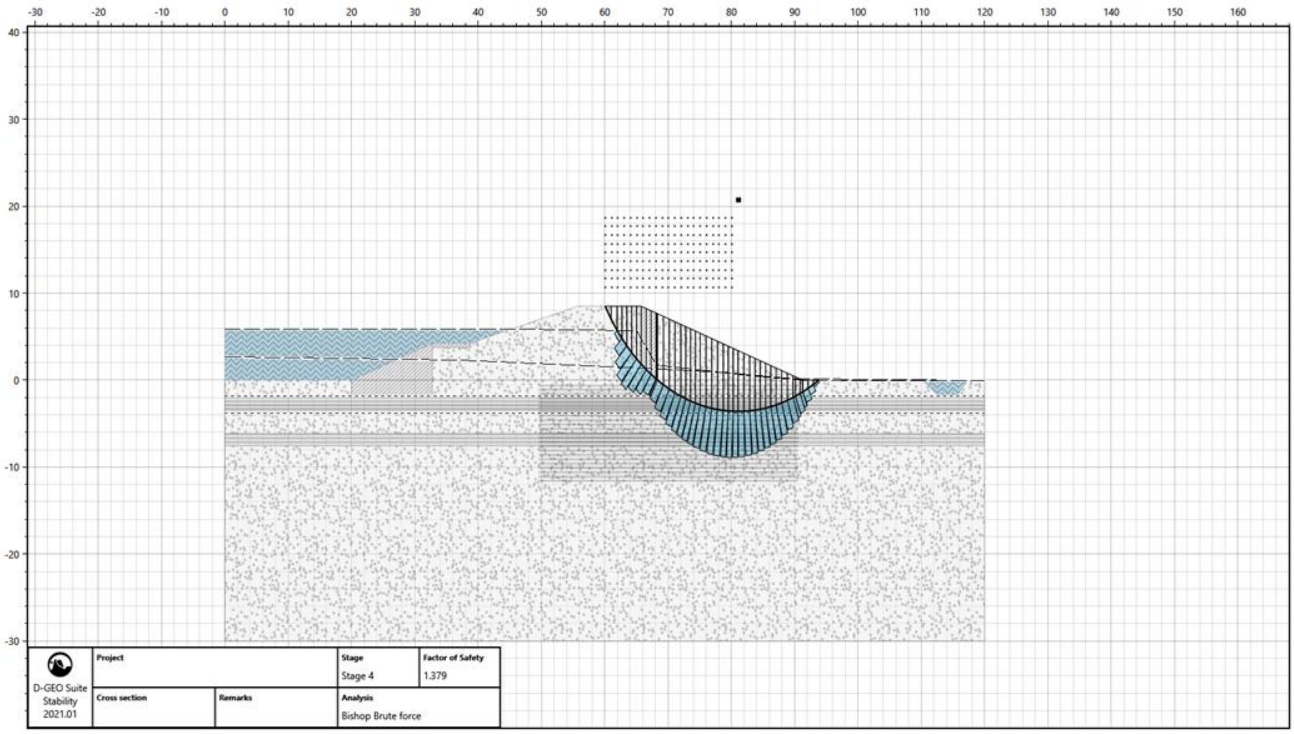
Z	Excess Below [kN/m²]	Effective Above [kN/m²]	Effective Below [kN/m²]	Load Above [kN/m²]
8.50	0.00	0.00	0.00	0.00
5.16	0.00	56.71	56.71	0.00
0.00	0.00	104.17	104.17	0.00
-1.85	0.00	121.17	121.17	0.00
-1.88	0.00	122.26	122.26	0.00
-2.85	0.00	150.86	150.86	0.00
-3.25	0.00	162.71	162.71	0.00
-3.85	0.00	167.02	167.02	0.00
-6.15	0.00	188.16	188.16	0.00
-7.55	0.00	198.22	198.22	0.00
-30.00	0.00	404.54	404.54	0.00

10.9.3.3 Scenario 2

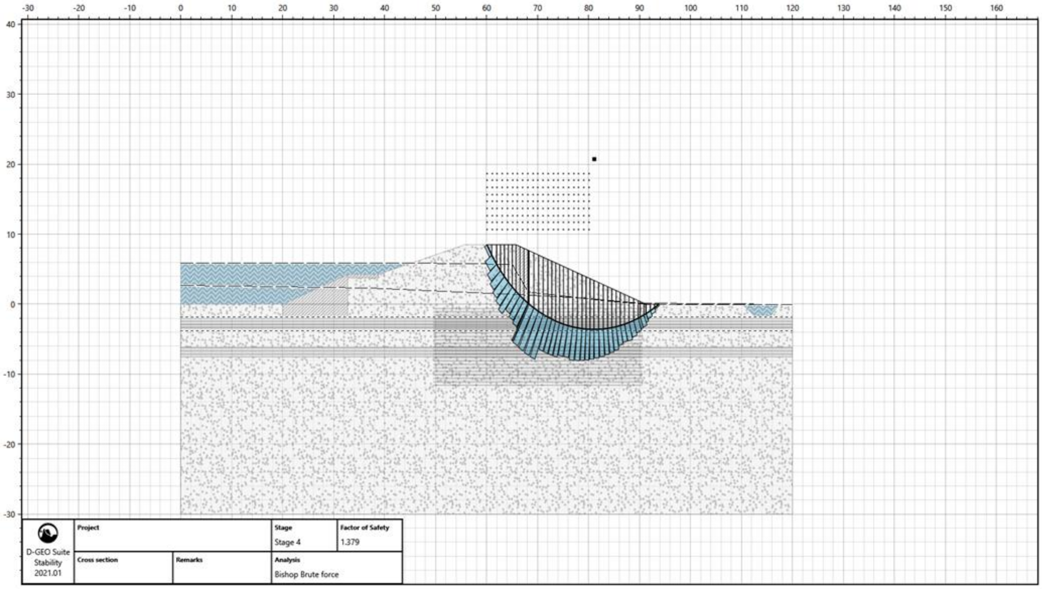
Total stress:



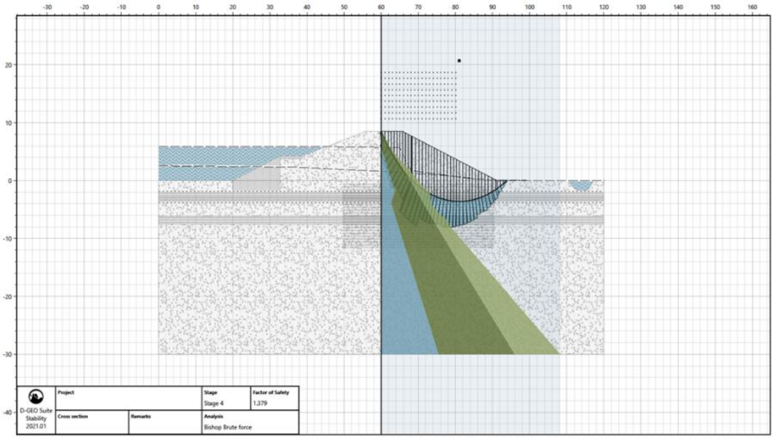
Pore pressure:



Shear stress:



Profile Inspector:



Profile inspector

- Water pressure (u_t)
- Excess water pressure (u_{ex})
- Effective stress (σ')
- Load stress
- POP

X: 60

Z	Effective Above [kN/m²]	Effective Below [kN/m²]	Load Above [kN/m²]	Loa Belo [kN/
8.50	0.00	0.00	0.00	0.0
5.73	47.11	47.11	0.00	0.0
0.00	99.76	99.76	0.00	0.0
-1.85	116.76	116.76	0.00	0.0
-2.85	144.21	144.22	0.00	0.0
-3.25	155.20	155.20	0.00	0.0
-3.85	171.67	171.67	0.00	0.0
-6.15	192.81	192.81	0.00	0.0
-7.55	202.88	202.88	0.00	0.0
-30.00	409.19	409.19	0.00	0.0

Profile inspector

- Water pressure (u_t)
- Excess water pressure (u_{ex})
- Effective stress (σ')
- Load stress
- POP

X: 60

Z	Water Above [kN/m²]	Water Below [kN/m²]	Excess Above [kN/m²]	Exce Belo [kN/n
8.50	0.00	0.00	0.00	0.00
5.73	0.00	0.00	0.00	0.00
0.00	56.20	56.20	0.00	0.00
-1.85	74.35	74.35	0.00	0.00
-2.85	63.89	63.89	0.00	0.00
-3.25	59.71	59.71	0.00	0.00
-3.85	53.43	53.44	0.00	0.00
-6.15	76.00	76.00	0.00	0.00
-7.55	89.73	89.73	0.00	0.00
-30.00	309.97	309.97	0.00	0.00

Profile inspector

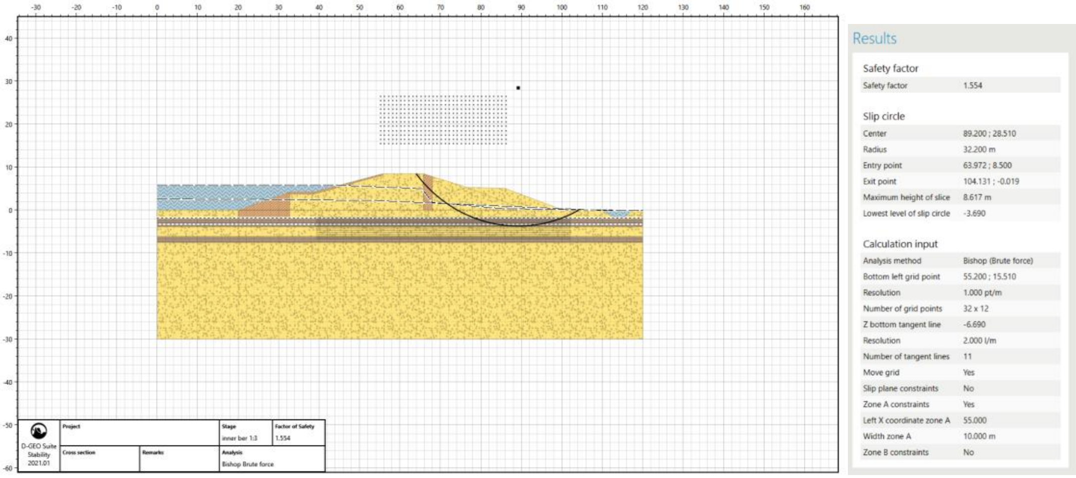
- Water pressure (u_t)
- Excess water pressure (u_{ex})
- Effective stress (σ')
- Load stress
- POP

X: 60

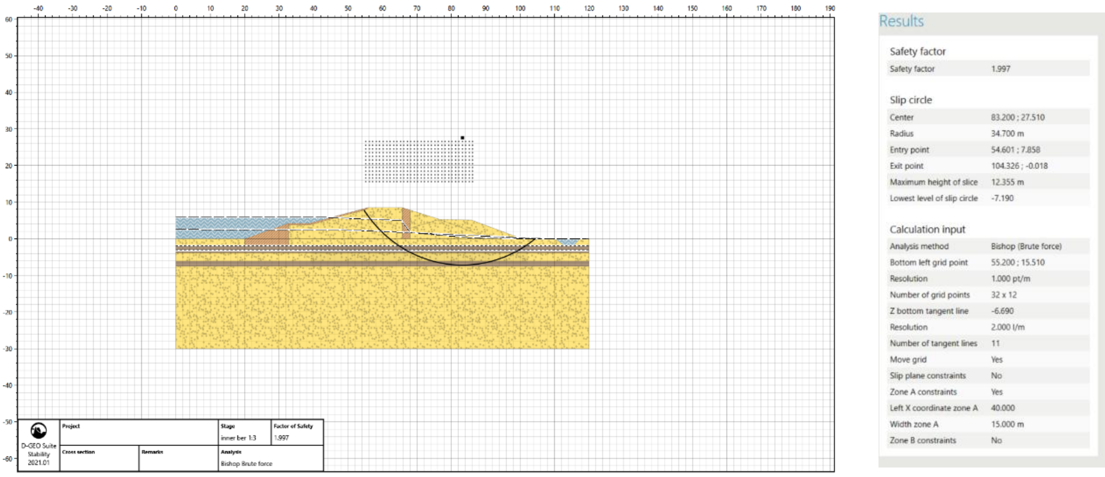
Z	Load Above kN/m²]	Load Below [kN/m²]	POP Above [kN/m²]	POP Below [kN/m²]
8.50	0.00	0.00	0.00	0.00
5.73	0.00	0.00	0.00	0.00
0.00	0.00	0.00	44.74	44.74
-1.85	0.00	0.00	59.19	69.19
-2.85	0.00	0.00	58.74	48.73
-3.25	0.00	0.00	44.55	54.55
-3.85	0.00	0.00	48.28	38.28
-6.15	0.00	0.00	56.24	66.24
-7.55	0.00	0.00	79.97	69.97
-30.00	0.00	0.00	245.31	245.31

10.9.3.4 Other D-Stability Trials

10.9.3.4.1 Inner berm constrains: zone A : x-coordinate: 50, width of zone A: 10



10.9.3.4.2 Inner berm constrains: zone A : x-coordinate: 40, width of zone A: 15



10.9.3.4.3 Current scenario inner berm constrains: zone A : x-coordinate: 40, width of zone A: 15