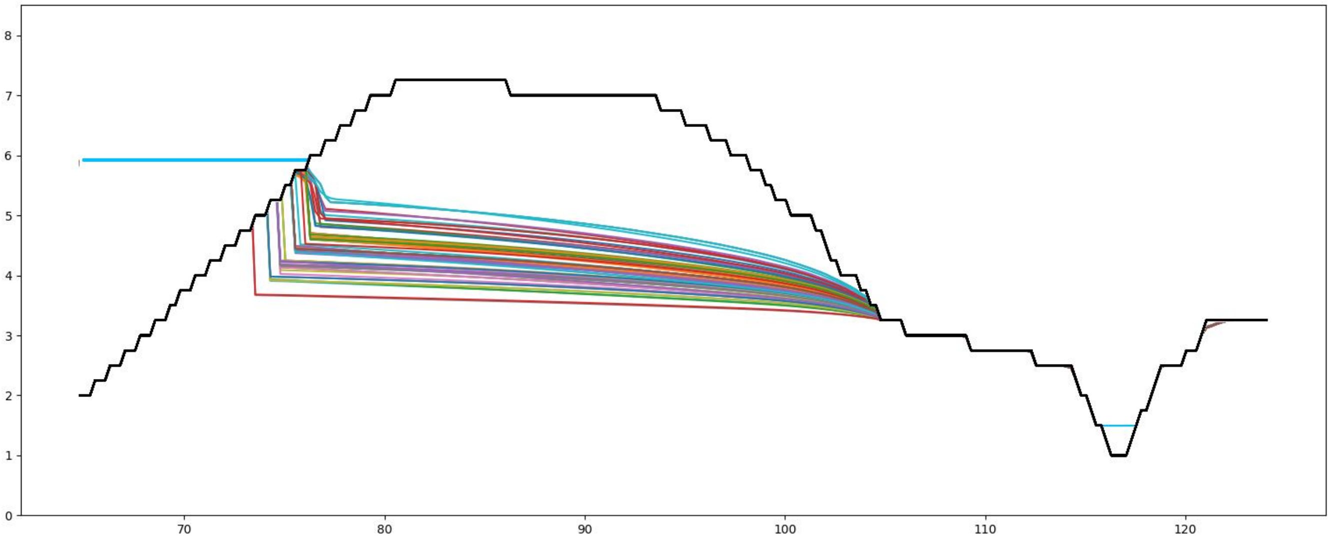


# A PROBABILISTIC ASSESSMENT OF THE PHREATIC LINE

## Bachelor Thesis


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Witteveen + Bos

UNIVERSITY OF TWENTE.

## PREFACE

This bachelor thesis is the product of my graduation research in order to obtain my bachelor degree in Civil Engineering at the University of Twente. This research was carried out from April to June 2023.

I would like to thank my supervisor from Witteveen+Bos, Thomas Naves, for his guidance and expertise, which helped me to set up this research and helped me to stay on track. I also want to thank my supervisor from the University of Twente, Pauline Overes, for her contributions to the research and for helping me with the scientific aspect of the research.

At last, I want to thank my colleagues from Witteveen+Bos, especially team geotechnics Deventer and team geo-hydrology, for helping me out with my questions and including me in the team. I enjoyed working in the pleasant work environment within Witteveen+Bos.

Tom Manenschijn
Deventer, June 2023

## SUMMARY

The Netherlands has 3,700 kilometres of flood defences. To ensure sufficient protection and maintenance of these flood defences safety analyses are performed regularly (IJsselwerken Zwolle-Olst, 2021). These safety analyses are performed by assessing failure mechanisms. In the assessment of some failure mechanisms, the phreatic line is needed as input. In the current practice, the phreatic line is determined using schematizations and assumptions, which are not always accurate, especially when the phreatic line has to be schematized with wave overtopping. Therefore, the research objective of this bachelor thesis is to use an existing method to express the phreatic line in a confidence interval or probability. The goal of this probabilistic approach is to gain more insight into the variables that affect the phreatic line. Where one of the variables is wave overtopping. This results in the following research question and sub-questions:

**How can the phreatic line be expressed in a probability or confidence interval?**

1 What variables are important when determining the phreatic line?
2 Which methods are there to determine the phreatic line and which method is the most suitable?
3 How can the most suitable method be applied to express the phreatic line in a probability or confidence interval?
4 How does this derived phreatic line fit into the safety philosophy for the design of a flood defence?

The first step in this research is to identify variables that affect the phreatic line and define these parameters for the case study. Three types of variables are identified; soil parameters, water levels and parameters related to wave overtopping. The variables related to water levels and wave overtopping are defined for a 1/3000 years recurrence time with Hydra-NL (Rijksoverheid, 2020), which is the recurrence time used to assess STBI for the dike section from the case study. Based on the sensitivity analysis it is decided which variables are going to be modelled stochastically. These are the specific yield, infiltration capacity and hydraulic conductivity of the clay layer, sand core and clay covering.

Subsequently, the most suitable model has to be selected. This is done based on three criteria; applicability, accessibility and suitability for a probabilistic approach. Out of the four possible groundwater flow models, MODFLOW is selected as the most suitable model because:

- The software can be used in combination with a scripting tool and the programme has a relatively short simulation duration. This means that MODFLOW is very suitable for a probabilistic analysis.
- MODFLOW is more accessible than other models.
- MODFLOW is considered an international standard for groundwater modelling.

After this, a MODFLOW model is used to perform groundwater flow calculations. A Monte Carlo simulation is herein used as probabilistic approach. 76 simulations are performed, where for every simulation some of the input parameters are extracted from a distribution with possible values. The results from these simulations are used to express the phreatic line in a certain level of confidence, herein is assumed that the highest phreatic line is the worst-case scenario. Eventually, a Python code is written to determine this level of confidence. In the code, the y coordinates of the phreatic line are sorted from low to high. Subsequently, the code extracts the y coordinate that is higher or equal to the pre-defined percentage of the possible y coordinates. This results in the phreatic line with a certain level of confidence. For example, a 90% level of confidence indicates that it can be said with 90% confidence that the actual phreatic line is located at or below the phreatic line with the 90% level of confidence.

In the final sub-question, it is discussed how this probabilistic phreatic line fits into the safety philosophy for assessing flood defences in the Netherlands. For this, the phreatic line with different levels of confidence is compared to schematizations, both with and without wave overtopping. Partly based on the comparison is concluded, that it is a realistic possibility to include the probabilistic approach in the current safety philosophy because the model can be used to determine the phreatic line both with and without wave overtopping. Furthermore, the advantages of this probabilistic method and the insights this method can give are discussed. One of the advantages is that the probabilistic method gives an insight into the range of possible phreatic lines. Thus also giving insight into the effect of changing variables on the phreatic line. This makes it possible to apply the probabilistic part of the model in practice. Namely, to use it in a fully probabilistic assessment of the macro-instability failure mechanism. Additionally, the probabilistic phreatic line can provide an insight into the uncertainty of the phreatic line due to unknown parameter values and this uncertainty can be mitigated by using a high level of confidence.

All in all, the probabilistic approach used in this study is proposed as a method to determine the phreatic line in a probability or confidence interval.

## TABLE OF CONTENTS

## LIST OF SYMBOLS

| | | |
|---|---|---|
| a | Hydraulic conductivity anisotropy ratio | [-] |
| a | van Genuchten fitting parameter | [-] |
| β | Compressibility of water | $[m^2/N]$ |
| dh/dx | Hydraulic head difference | [m/m] |
| ε | Brooks & Corey exponent | [-] |
| g | Gravitational acceleration | $[m/s^2]$ |
| h | Water level relative to NAP | [m+NAP] |
| h | Suction | [kPa] |
| $h_{m0}$ | Significant wave height | [m] |
| $h_s$ | Significant wave height | [m] |
| K | Hydraulic conductivity | [m/d] |
| $K_h$ | Horizontal hydraulic conductivity | [m/d] |
| $K_s$ | Saturated hydraulic conductivity | [m/d] |
| $K_v$ | Vertical hydraulic conductivity | [m/d] |
| m | van Genuchten fitting parameter | [-] |
| $m_v$ | Compressibility of soil | $[m^2/N]$ |
| n | Porosity | [-] |
| $\rho_w$ | Density of water | $[kg/m^3]$ |
| q | Flux (Darcy) | $[m^3/s/m^2]$ |
| Ss | Specific storage | $[L^{-1}]$ |
| Sy | Specific yield | [-] |
| T | Timestep in the model | [hours] |
| V | Total volume of the soil | $[m^3]$ |
| $V_v$ | Volume of voids/pores | $[m^3]$ |
| θ | Volumetric water content | [-] |
| $\theta_{resid}$ | Residual water content | [-] |
| $\theta_{sat}$ | Saturated water content | [-] |

## List of Abbreviations

| | |
|---|---|
| CSV | Comma-Separated Values |
| CFVD | Control-Volume-Finite-Difference method |
| FEM | Finite Element Method |
| GHB | General Head Boundary package in MODFLOW |
| GWF | Ground Water Flow model of MODFLOW |
| GWT | Ground Water Transport model of MODFLOW |
| NAP | Normaal Amsterdams Peil |
| STBI | Macro-instability of the inner slope |
| STBU | Macro-instability of the outer slope |

# 1 INTRODUCTION

Flood defences are an important part of the Dutch infrastructure. 59% of the Netherlands can be flooded by water from the sea or rivers (Milieudefensie, 2022). Therefore, the Netherlands has 3,700 kilometres of flood defences to protect the country against floods. Without these flood defences, large parts of the Netherlands would regularly inundate. Currently, the chances of higher water levels occurring are getting higher as a result of climate change (Rijkswaterstaat, 2023a). This emphasizes the importance of the flood defences and its maintenance. To ensure sufficient protection and regular maintenance of these flood defences safety norms are implemented in the Netherlands.

In January 2017 a new norm for flood protection in the Netherlands was implemented (Kok et al., 2016). Before 2017, the norm was expressed in a return period of a water level. Nowadays, the norm is expressed in a probability of flooding. The most prominent reason for switching to this new approach was that the new norm can express the degree of protection against flooding as the probability of flooding depends on both the strength of the flood defence and the hydraulic factors (water levels, wave overtopping etc.). Additionally, the new norm is based on the flood risk, this incorporates both the chance of flooding and the consequences of flooding (deaths and monetary damage).

This new method also allows wave overtopping to occur, as long as this does not cause dike failure (Kampman, 2021). This was not the case in the old method. Allowing more wave overtopping has some significant advantages (Wijnstra, 2021). One of the advantages is that a dike where more wave overtopping is allowed needs less space. This is because the dike does not need to be that high and thus it can be less wide as well. Also, a smaller amount of scarce materials is needed, and dike improvement costs are lower.

Within this new assessment of dikes, the phreatic line plays an important role because it is needed to assess some dike failure mechanisms. These are processes that can lead to dike failure. However, the schematization of the phreatic line is based on assumptions, which are not always accurate. Additionally, the phreatic line is affected by wave overtopping, which is more common within the current dike assessment method. The effect of wave overtopping on the phreatic line is also not accurately estimated in the current schematizations. Since the phreatic line is essential in assessing the flooding probabilities of a dike, it is important to estimate it accurately.

## 1.1 Current State of the Art

In the current practice, the technical report by TAW (2004) is used to estimate the phreatic line. Here, different schematizations are provided based on several characteristics of the dike, such as soil types. These schematizations are not useful for overtopping discharges higher than 1 l/s/m (Rijkswaterstaat, 2017). When high wave overtopping discharges occur, the report suggests assuming that the dike is fully saturated (TAW, 2004). This is however a very conservative assumption, which is not ideal because these types of conservative assumptions can lead to inefficient dike designs.

This research is a continuation of the research by Yaghi (2022). In this study, the probabilistic and semi-probabilistic approaches for assessing macro-instability of the inner slope were compared. One of the recommendations of this research is that a more detailed analysis of the phreatic line with wave overtopping could have resulted in a more accurate probabilistic assessment of the macro-instability failure mechanism. Additionally, de Loor (2018) concluded that the method by TAW (2004) on the effect of infiltration on the phreatic line is too conservative. Therefore, it can be concluded that more insight is needed into the phreatic line and variables that affect the phreatic line, such as wave overtopping.

Research has been done on alternative methods to determine the phreatic line. In Dorst (2019) it was investigated if a numerical model could more accurately estimate the phreatic line in extreme conditions. The programme used for this is MODFLOW (USGS, 2022a). The research showed that a numerical model can be used to accurately estimate the phreatic line (Dorst, 2019). There are however some drawbacks to the model that was used. Firstly, extensive calibration of the data was necessary to make the model sufficiently accurate. Secondly, pore pressure measurements are necessary to calibrate the model.

In another research, the programme PlaxFlow (from PLAXIS) was used to model the phreatic line (Bentley Systems, 2023a). This study looked into the effects of wave overtopping on the phreatic line (de Raadt et al., 2015). The model they used was verified by calibrating the calculations with standpipe measurements. This resulted in a phreatic line that is safe to use for calculations. Another result from this study was that the assumptions in the guidelines (TAW, 2004), among which the assumption that the dike is fully saturated, proved to be too conservative (de Raadt et al., 2015). This research is a case study that was applied to the Afsluitdijk, which is a sea-dike. However, little is known about how applicable these results are to river dikes.

Schwiersch et al. (2021) proposed an entirely different approach compared to that of de Raadt et al. (2015) and Dorst (2019). In this research, the phreatic line was determined probabilistically using analytical calculation methods. Herein, the saturated hydraulic conductivity was used as a stochastic value. This approach resulted in a range of phreatic lines in a dike body. This research is therefore a great example of how to include values of which the exact value is not known in determining the phreatic line. Namely, by defining a possible distribution of possible values for a parameter and using this distribution to calculate a distribution/range of possible phreatic lines. However, the effects of wave overtopping are not included in this research. One of the conclusions of this study is that the analytical approach is not applicable to more complex cross-sections since the analytical methods cannot deal with more complex cross-sections. The authors recommend using FEM (finite element method) for more complex cross-sections.

## 1.2 Problem Statement

All in all, the current state of the art shows that insight into the phreatic line and the variables that affect this phreatic line is lacking in some cases. One of the variables in which more insight is needed is the effect of wave overtopping on the phreatic line. Therefore, it will be investigated if a probabilistic analysis provides more insight into the phreatic line and the variables affecting it and if this probabilistic approach can be used to express the phreatic line in a confidence interval or probability.

## 1.3 Research Dimensions

### Research Objective and Scope

The research objective of this bachelor thesis is to use an existing method to express the phreatic line in a confidence interval or probability. The goal of the probabilistic approach is to gain more insight into the variables that affect the phreatic line. The failure mechanism macro-instability of the inner slope (STBI) will be taken into account when defining input variables and when making modelling choices. This is done because the main application of the phreatic line is to assess some failure mechanisms. Where STBI is one of these failure mechanisms.

### Research Questions

**Main question:**

How can the phreatic line be expressed in a probability or confidence interval?

**Sub questions:**

1 What variables are important when determining the phreatic line?
2 Which methods are there to determine the phreatic line and which method is the most suitable?
3 How can the most suitable method be applied to express the phreatic line in a probability or confidence interval?
4 How does this derived phreatic line fit into the safety philosophy for the design of a flood defence?

### Commissioning Party

The commissioning party for this project is Witteveen+Bos. Witteveen+Bos is a Dutch consultancy and engineering firm, which provides services in the field of water, infrastructure, environment and construction. The outcome of this project is relevant to Witteveen+Bos because they concern themselves with dike-strengthening projects, in which the phreatic line plays an important role. Witteveen+Bos also works on the dike-strengthening project of the dike section between Zwolle and Olst. This dike section will be used as a case for this research and is therefore a relevant topic for Witteveen+Bos. Additionally, this research was conducted under the supervision of Thomas Naves (Witteveen+Bos) and Pauline Overes (University of Twente).

## 1.4 Case to be Studied

The focus of this research will be on a case. Namely, the dike trajectory 'Duursche Waarden'. This dike trajectory is part of the IJsseldijk, which is a 28.9-kilometre-long dike section between Zwolle and Olst (IJsselwerken Zwolle-Olst, 2021). The dike trajectory Duursche Waarden is 1.4 kilometres long and is located south of Wijhe, this can be seen in Figure 1. This dike section is a primary flood defence, this means that this dike directly protects the hinterland against high water (Rijkswaterstaat, 2023b). These primary flood defences are assessed based on the new flood safety norm as mentioned in the introduction. This was also done for the dike section Zwolle-Olst, safety analyses were performed on the dike section between Zwolle and Olst in order to investigate the impacts of the new safety norm (IJsselwerken Zwolle-Olst, 2021). It turned out that for 28.4 out of the 28.9 kilometres measures needed to be taken to ensure that the dike section meets the new safety norm.

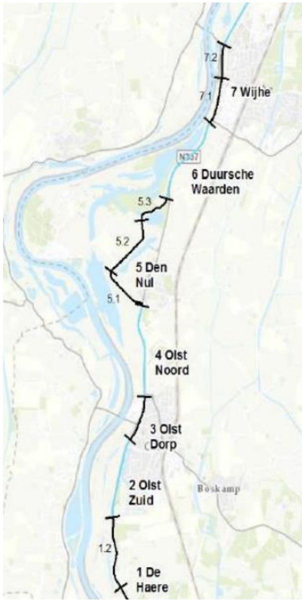


Figure 1, Part of the IJsseldijk with its trajectories (IJsselwerken Zwolle-Olst, 2021)

In this study, the phreatic line will be examined for this case. This means that a representative cross-section of this dike will be used to determine the phreatic line. This will also include the use of variables that are applicable to the case.

## 1.5 Research Structure

The report is divided into steps where each chapter covers a sub-question. Chapter 2 is a theoretical framework in which background information for the research is provided. In chapter 3, variables that are important when determining the phreatic line are identified and defined for the case study. In chapter 4, possible methods to determine the phreatic line are identified and the most suitable method is chosen based on the defined criteria. In chapter 5, the process is described on how the phreatic line is expressed in a confidence interval or probability. In chapter 6, the results (phreatic line expressed in a confidence interval or probability) are interpreted by discussing how the derived phreatic line fits into the current safety philosophy for assessing flood defences. Finally, the discussion, conclusion and recommendations can be found in chapters 7, 8 and 9.

# 2 THEORETICAL FRAMEWORK

In this chapter, background information will be provided on topics that are linked to this research. Starting with the phreatic line: the phreatic line is the position in a dike where the water pressure is, in theory, equal to the atmospheric pressure (Rosenbrand, 2020). This means that the phreatic line is the groundwater level within a dike, an example of this can be seen in Figure 2.

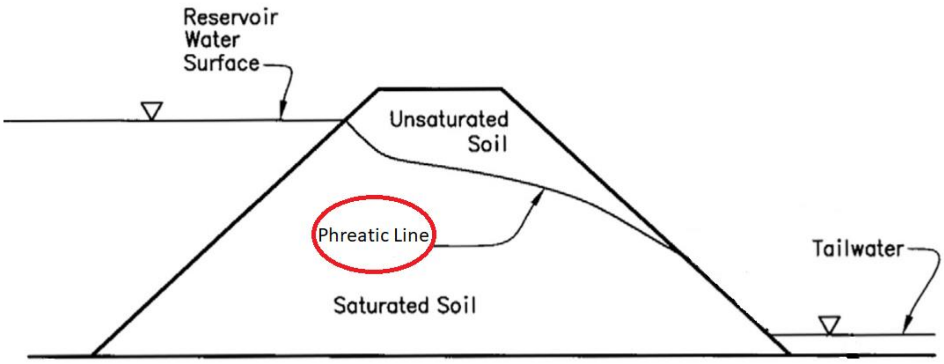


Figure 2, Phreatic line in a dike (Ministry of Forests, 2020)

The soil below the phreatic line is saturated. Above the phreatic line is a zone in which groundwater is present, this is called the capillary zone or the unsaturated zone (Rosenbrand, 2020). Here, water is flowing upwards due to capillary forces. The level of saturation in the capillary zone decreases with height above the phreatic line. Generally, the phreatic line is affected by water flowing in and out of the dike, due to the water level on the inside and outside of the dike, wave overtopping, precipitation and evaporation.

Another important concept for this research is wave overtopping. When wave overtopping occurs, water splashes over the dike irregularly (Deltares, 2014b). Wave overtopping is caused by a combination of high water levels and large wave heights (due to wind or shipping). Wave overtopping is an important failure mechanism for sea dikes, but less so for river dikes. Nevertheless, wave overtopping can still occur at river dikes. Wave overtopping can cause water to infiltrate within the dike (Galema et al., 2006). This infiltration affects the phreatic line.

## 2.1 Groundwater Flow

Groundwater processes, such as groundwater flow have to be considered when determining the phreatic line. Darcy's law can be used to describe the flow of a fluid through a homogeneously permeable medium (Darcy, 1856). The equation for Darcy's law can be seen in Equation 1.

$$q = \frac{Q}{A} = -K_s \frac{dh}{dx}$$

Equation 1, Formula for Darcy's Law (Darcy, 1856)

Where q (the flux in $m^3/s/m^2$) is the specific discharge defined as the product of the saturated hydraulic conductivity ($K_s$ in m/s) and the hydraulic head difference (can also be seen as a difference in pressure) ($\frac{dh}{dx}$ in m/m) (Darcy, 1856).

According to Kampman (2021): 'Darcy's law is valid for saturated soils, as they are generally homogeneously permeable, assuming the soil structure is homogeneous and isotropic'. However, the equation can be extended so that it can be used for unsaturated soils. In that case, the saturated hydraulic conductivity should be replaced with the hydraulic conductivity ($-K_s$ to $-K$) (Shaw et al., 2017). Situations can occur where the fluid is flowing from saturated soil to unsaturated soil (Kampman, 2021). This means that the soil is not homogeneously permeable because the hydraulic conductivity depends on the saturation of the soil. This causes a complex situation because the flux through the soil and the permeability of the soil are dependent on each other.

It is also possible that there is no difference in head and thus no flow, this is called a hydrostatic system. A characteristic of a hydrostatic system is that the hydraulic head is fixed (Linquip TechNews, 2020). Because there is no difference in hydraulic head, there is also no flow, which can also be seen in Darcy's law. On the left side of Figure 3, a hydrostatic system can be seen, the system on the right side of Figure 3 is non-hydrostatic. The lines represent the relation between the depth and respectively the head caused by the elevation, the head caused by the water pressures and the total hydraulic head (sum of the elevation head and pressure head). In the hydrostatic system, the hydraulic head here is constant and thus no groundwater flow occurs. In the non-hydrostatic system, the water level lies at 0.75m, this causes a difference in hydraulic head. The difference in hydraulic head causes a downward flow in this example because the water flows from high pressures to low pressures.

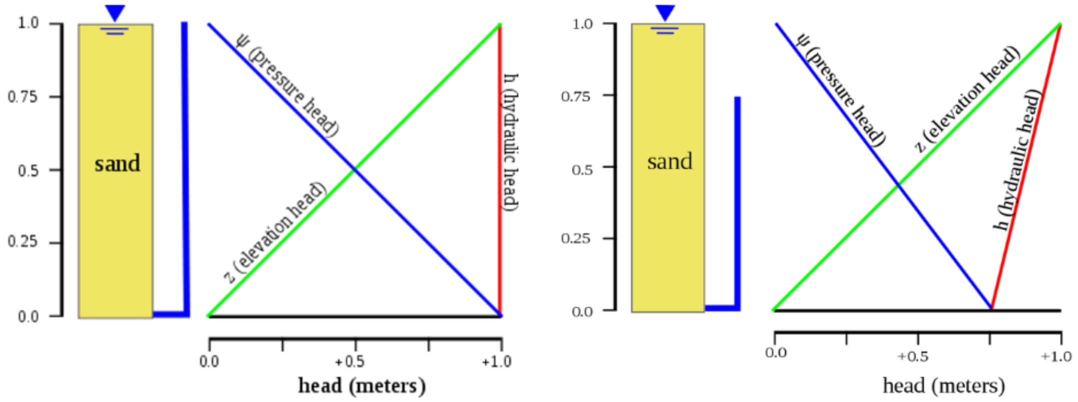


Figure 3, Example of the difference between hydrostatic and not hydrostatic (Linquip TechNews, 2020)

An example of the effects of hydraulic head and water pressures on the groundwater flow in a dike. can be seen in Figure 4. When high water levels occur, the water pressure near the toe of the dike gets high (red part in figure). This has the consequence that the water flows through the clay layer into the sand layer because the pressure here is lower. Eventually, the water flows through the soil underneath the dike into the dike, due to the difference in hydraulic head. This is however not the only way the groundwater can flow, it can also flow directly through the clay covering into the core of the dike. These groundwater flows have a profound effect on the phreatic line since they can cause the phreatic line to rise.

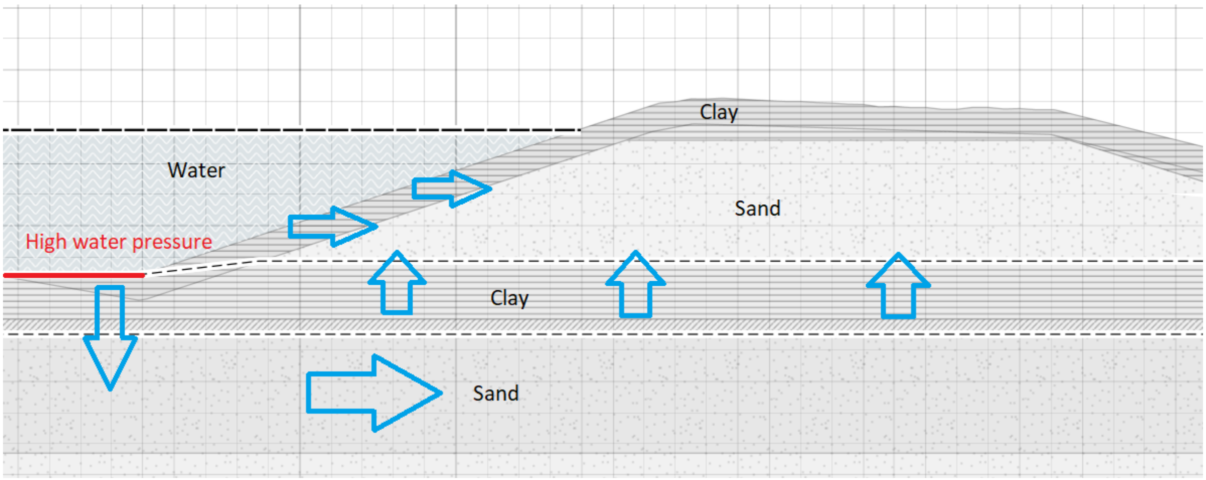


Figure 4, Example groundwater flow in a dike (Deltares, 2023)

### 2.1.1 Suction

In the soil below the phreatic line, the pore water pressure is positive (Tarantino & Di Donna, 2019). In the soil above the phreatic line, the pore water pressure is negative. When the soil is unsaturated, there is more space for water than the amount of water present (Kampman, 2021). This causes the water that is retained between the soil particles to apply suction between particles. Therefore, a negative pore water pressure is also called suction. This means that the degree of saturation affects the pore-water pressure of the soils.

## 2.2 Failure Mechanisms

The phreatic line is an important factor for assessing two failure mechanisms macro-instability and micro-instability. Macro-instability can occur on both the inner and the outer slope of a dike. In the case of macro-instability of the inner slope (STBI), the strength of the soil decreases because of higher water pressures in the soil and dike (Deltares, 2014a). This means that the balance of opposing forces within the soil of the dike is no longer present. This causes large parts of the soil to slip along a circular slip plane. This process can be seen in Figure 5.

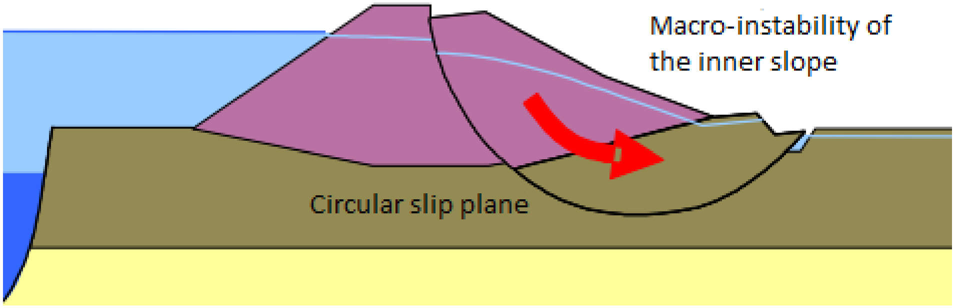


Figure 5, Macro-instability of the inner slope ('t Hart et al.,2016)

Macro-instability of the outer slope (STBU) works differently than for the inner slope. If the phreatic line rises in height, for example, due to high water levels or precipitation, the water pressure will increase and this will result in a decrease in the shear strength of the soil (van der Zaag, 2019). This reduces the stability of the dike. When the water level is high the chance of STBU occurring is minimal because the high water level against the outer slope of the dike produces a counteracting moment. However, the chances of STBU occurring are higher when the high water levels drop (van der Zaag, 2019). If the water levels drop too quickly, the phreatic line does not have enough time to follow, in this case, the phreatic line is still higher than normal. Because the phreatic line is still high, the shear strength of the dike is relatively low. Furthermore, the counteracting moment provided by the outer water level has disappeared. All this in combination with the increased weight of the saturated soil in the dike can cause the outer slope to slip.

Micro-instability refers to the loss of stability of relatively thin soil layers at the inner side of the dike, this happens under influence of groundwater flowing through the dike ('t Hart et al., 2016). Problems that occur because of micro-instability are caused by a high phreatic line in the dike. Micro-Instability can occur at sand dikes or dikes with a sand core that is protected by an impermeable layer of clay (Deltares, 2014c). When high water levels occur, the phreatic line rises and water can flow through the dike. This causes softening, the coating is pushed up and cracks and subsidence occur. This exposes the sand core and washes out material. This process can be seen in Figure 6.

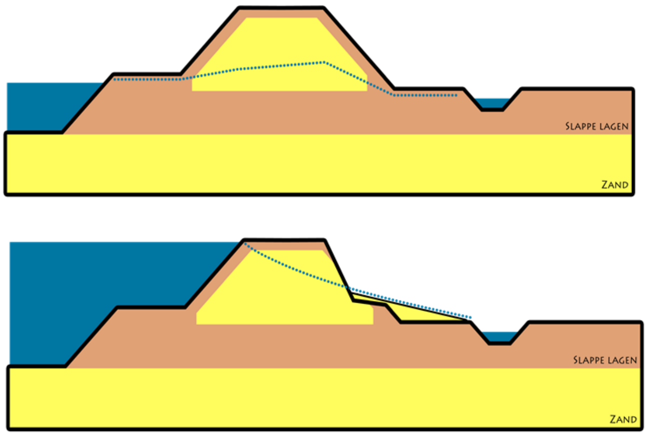


Figure 6, Micro-instability (Deltares, 2014c)

## 2.3 Schematizations for the Phreatic Line

As previously discussed, the phreatic line plays an important factor in assessing two failure mechanisms. Therefore, different schematizations of the phreatic line are available in order to use the phreatic line for these assessments.

Currently, a distinction is made between 2 scenarios for determining the phreatic line; an wave overtopping discharge lower than 1 l/s/m and an wave overtopping discharge higher than 1 l/s/m (TAW, 2004). Furthermore, schematizations for the phreatic line were made specifically for the case study area.

### 2.3.1 Schematization without Wave Overtopping

The schematizations for the phreatic line without wave overtopping (wave overtopping discharge < 1 l/s/m) are defined by TAW (2004). Herein, the schematizations depend on the type of dike. There are four profiles for dikes:

- Clay dike with a clay or peat soil layer below the dike.
- Clay dike with sand below the dike.
- Sand dike with a clay or peat soil layer below the dike.
- Sand dike with sand below the dike.

Here, only the schematization for a sand dike with a clay or peat soil layer below the dike will be discussed because this type of dike is common within the case study area. This schematization can be seen in Figure 7.

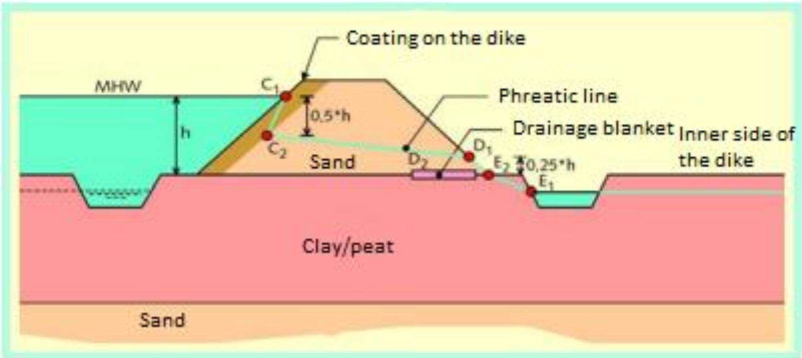


Figure 7, Schematization of the phreatic line for a sand dike with a clay or peat soil layer below the dike (low overtopping discharge) (TAW, 2004)

As can be seen in the figure the points C1, C2, D1, D2, E1 and E2 have to be determined. The points are determined based on the characteristics of the dike (TAW, 2004). The points are determined as follows:

- C1: point on the outer slope of the dike at the height of the water level (h)
- C2 (with coating): At the inner side of the coating at 0.5*h
  C2 (without coating): point C2 should be excluded, phreatic line runs from C1 to D1/D2
- D1: point on the inner slope of the dike at 0.25*h
- D2 (with drainage blanket): D2 is located in the middle of the drainage blanket, the phreatic line runs from C1/C2 to D2.
  D2 (without drainage blanket): D2 should be excluded, the phreatic line runs from C1/2 to D1.
- E1: Only applicable when there is a ditch at the inner side of the dike, located at the water level of the ditch.
- E2: Point on the inner toe of the dike.

### 2.3.2 Schematization with Wave Overtopping

Schematizations for the phreatic line with a wave overtopping discharge higher than 1 l/s/m are not defined by TAW (2004). In the report, it is stated that if no water pressure measurements are available for a dike section, conservative estimates or groundwater flow calculations should be used to determine the water pressures. This report functions as a guide to performing those estimates and calculations. The lack of validated calculation models that can quantify the effects of wave overtopping on the phreatic line is mentioned as the reason that conservative estimates are used for determining the effects of wave overtopping.

Furthermore, Rijkswaterstaat (2017), also known as OI2014v4, which is a report that is used as a design guideline for dikes, states that TAW (2004) is only useful for wave overtopping discharges lower than 1 l/s/m. The report suggests to assume that the dike surface is fully saturated when the wave overtopping discharge is higher than 1 l/s/m. This is however a conservative assumption, which is not ideal because too conservative assumptions can lead to unnecessary dike-strengthening measures and money wasted on these measures. However, the background report also states that it is possible to use groundwater flow models or an alternative method to schematize the phreatic line with wave overtopping. This alternative method calculates the rise in meters of the phreatic line as a result of wave overtopping (van Hoven, 2016).

The first step in the alternative method is to calculate for how many hours water can infiltrate within the dike. In order to do this different water levels are extracted from the water level course of a high water level event (van Hoven, 2016). For each hour of this high water level event the water levels, significant wave height and wave overtopping discharges are determined. Subsequently, the percentage of time for which a layer of water is present on the crest and slope of the dike is extracted from the relation between the wave overtopping discharge, significant wave height and this percentage of time (Figure 12). This results in a total duration in which infiltration as a result of wave overtopping takes place. The next step is to calculate the amount of water that infiltrates within the dike body. The infiltration capacity can be used for this. Together with the time in hours where infiltration takes place, the infiltration capacity can be used to determine the amount of water that infiltrates. In the final step, the rise of the phreatic line in meters is calculated. The rise of the phreatic line can be calculated by dividing the amount of water that infiltrates by the effective porosity. This method is still conservative since it does not take water flowing out of the dike into account and water is directly added to the phreatic line, while this takes time in reality (van Hoven, 2016). However, it is less conservative than assuming a fully saturated dike.

### 2.3.3 Phreatic Line Schematizations Zwolle-Olst

For the dike-strengthening project for the dike section Zwolle-Olst a hydrological study was conducted (Klop & van Meekeren, 2021). The goal of this study was to determine the impacts of wave overtopping on the phreatic line. Additionally, schematizations of the phreatic were made based on the outcomes of this hydrological study. These schematizations were used in assessing some failure mechanisms within the dike-strengthening project. The schematizations are determined by doing groundwater flow calculations for different scenarios (each scenario has different input). Where eventually the most conservative outcome, thus the highest phreatic line, was used as schematization.

The schematizations are dependent on several factors; the material of the dike, clay coating on the dike, road on top of the dike and particularities (for example, the width of the dike's crest and piping measures). The schematization that can be used for the dike from the case study can be seen in Figure 8.

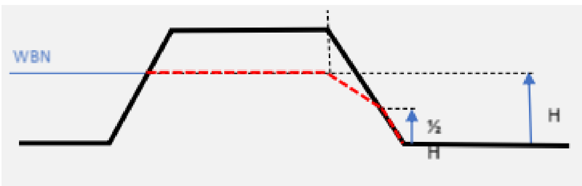


Figure 8 Phreatic line schematization for the case Zwolle-Olst (Klop & van Meekeren, 2021)

# 3 IMPORTANT VARIABLES THAT AFFECT THE PHREATIC LINE

In this chapter, the first sub-question will be answered. Namely, what variables are important when determining the phreatic line? Firstly, the important variables will be identified through literature research. After this, the values of the identified variables will be determined for the case study in order to use these variables to determine the phreatic line.

## 3.1 Identification of Important Variables

Within the identified variables a distinction can be made between three types of variables; soil parameters, water levels and parameters related to wave overtopping. Therefore, these types of variables will be discussed separately.

### 3.1.1 Soil Parameters

In general, the soil composition of the dike plays an important role, such as the location of a clay layer within a dike. The soil composition is important because the values of the soil parameters depend on which soil type is present. For example, water flows more easily through sand than clay. In practice, the soil types in a dike are often determined with soil surveys.

#### Hydraulic Conductivity

Hydraulic conductivity can be defined as the ability of a fluid to flow through soil (Saravanan et al., 2019). The degree of saturation plays an important role when determining the hydraulic conductivity. When a soil is saturated the ability of a fluid to flow through the soil is expressed in the saturated hydraulic conductivity ($K_s$).

As explained in section 2.1, suction occurs in unsaturated soils. In order to determine the hydraulic conductivity in unsaturated soils, a hydraulic conductivity curve is needed. The hydraulic conductivity curve displays the relation between the suction and the hydraulic conductivity of the soil (Kampman, 2021). There are different methods to describe this relation. The van Genuchten model is the most commonly used relation between the suction and hydraulic conductivity of a soil (van Genuchten, 1980). The van Genuchten model can be described by the formula in Equation 2.

$$K(h) = K_s \frac{(1-(ah)^{n-1} * (1+(ah)^n)^{-m})^2}{(1+(ah)^n)^{m/2}}$$

Equation 2, van Genuchten formula for the hydraulic conductivity curve (van Genuchten, 1980)

Where K is the hydraulic conductivity (m/s) as a function of the suction h (kPa), $K_s$ is the saturated hydraulic conductivity (m/s) and m, a and n are fitting parameters (van Genuchten, 1980). Another model that can be used for the hydraulic conductivity in the unsaturated zone is the Brooks & Corey model (Brooks & Corey, 1966). The Brooks & Corey model is a relation between the volumetric water content (θ) and the hydraulic conductivity. The formula for this relation can be seen in Equation 3.

$$K(\theta) = K_s \left[\frac{\theta - \theta_{resid}}{\theta_{sat} - \theta_{resid}}\right]^{\varepsilon}$$

Equation 3, Brooks and Corey equation for the hydraulic conductivity curve (Brooks & Corey, 1966)

Where $K_s$ is the saturated hydraulic conductivity (L/T), $\theta_{resid}$ is the residual water content (-), $\theta_{sat}$ is the saturated water content (-) and ε is the Brooks & Corey exponent (-) (Brooks & Corey, 1966).

In Figure 9 a comparison between the van Genuchten and Brooks & Corey model for an identical situation can be seen. Goorabjiri & Rasoulzadeh (2015) conclude that the van Genuchten model is more suitable to model the hydraulic properties of soils than the Brooks & Corey model. In this research the groundwater flow in a forest floor was simulated with both the van Genuchten and Brooks & Corey models, the parameters for the models were obtained through calibration. Eventually, the results of the models were compared to measurements and the van Genuchten model turned out to be more accurate since the RMSE (Root Mean Square Deviation) was lower.

Additionally, Dorst (2019) states that the van Genuchten model is a more accurate representation of reality since more soil parameters are included in the model.

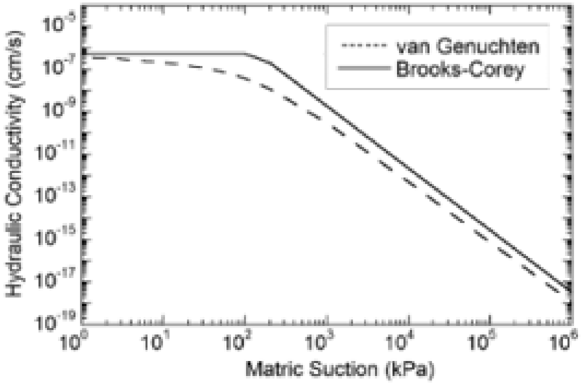


Figure 9, Comparison van Genuchten and Brooks & Corey (Schanz, 2007)

For the model to be used, a simplification has been made regarding the hydraulic conductivities of the unsaturated zone. Flow through the unsaturated zone will not be modelled. This has as a consequence for the model that the hydraulic head rises quicker because it is not delayed as a result of flow through the unsaturated zone. This simplification is somewhat conservative since the water that infiltrates is directly added to the phreatic line. Normally, the water would flow through the unsaturated zone first before it is added to the phreatic line. This assumption has been made because it is difficult to model flow through the unsaturated zone accurately. Firstly, because this process takes a significant amount of time. Also, extra parameters have to be specified, which could increase the uncertainty of the model. This means that from now on in this report when the hydraulic conductivity is mentioned, the saturated hydraulic conductivity is meant by this.

### Hydraulic Anisotropy

Hydraulic anisotropy can be described as the ratio between vertical and horizontal hydraulic conductivities (Priono et al., 2017). A system is anisotropic if there is a difference between the vertical and horizontal hydraulic conductivities. If both the vertical and horizontal hydraulic conductivities are equivalent the system is isotropic. Often, the hydraulic conductivity is higher in the horizontal direction than in the vertical direction. In the section about hydraulic conductivity, horizontal hydraulic conductivity was discussed. The formula for the hydraulic conductivity anisotropy ratio can be seen in Equation 4.

$$a = \frac{K_v}{K_h}$$

Equation 4, Hydraulic conductivity anisotropy ratio (Dorst, 2019)

Where a is the hydraulic conductivity anisotropy ratio, $K_v$ is the hydraulic conductivity in vertical direction and $K_h$ is the hydraulic conductivity in horizontal direction.

### Specific Yield and Specific Storage

In a system where both saturated and unsaturated soils are present, groundwater storage occurs (Dorst, 2019). There are two storage mechanisms: phreatic storage and elastic storage. According to Dorst (2019), 'Phreatic storage occurs when the soil is not fully saturated and is caused by a rise of the groundwater table.' The capacity of the phreatic storage is expressed as the specific yield ($S_y$). The specific yield is described by Todd & Mays (2005) as 'the ratio of the volume of water that, after saturation, can be drained by gravity to its volume'.

Elastic storage occurs when the effective stress changes. This is the case when the pore water pressures in the soil change, but the total stress remains the same. Here, the space between pores, which can be filled by water, changes (TAW, 2004). The specific storage ($S_s$) is the characteristic parameter for elastic storage and can be described as the volume of water released from storage per unit volume of soil, per unit change in hydraulic head (Uffink, 1982). The specific storage can be calculated with the formula in Equation 5.

$$S_s = \rho_w g(m_v + n\beta)$$

Equation 5, Formula for the specific storage (TAW, 2004)

Where $\rho_w$ is the density of water ($kg/m^3$), g is the gravitational acceleration ($m/s^2$), $m_v$ is the compressibility of the soil ($m^2/N$), n is the porosity (-) and β is the compressibility of water ($m^2/N$) (TAW, 2004)

The specific yield and specific storage do affect the phreatic line since these variables are related to groundwater storage. A decrease in the specific yield or specific storage is likely to cause the phreatic line to rise because less space is available for groundwater storage if these variables decrease.

#### Porosity

In order to calculate the specific storage, the porosity is needed as input. Within soils, some portions are not occupied with solid materials, these portions are called voids or pores (Todd & Mays, 2005). These pores can be occupied by groundwater. The porosity of a soil can be described as the ratio between the volume of voids/pores and the total volume of the soil. A formula for the porosity can be seen in Equation 6.

$$n = \frac{V_v}{V}$$

Equation 6, Porosity ratio (Todd & Mays, 2005)

Where n is the porosity (-), $V_v$ is the volume of voids/pores and V is the total volume of the soil.

### 3.1.2 Water Levels

The water level behind the dike is an important factor when determining the phreatic line. In the schematization from TAW (2004) (Figure 7) can be seen that the location of the phreatic line of the dike is based on the water level (h). Which indicates its importance. More water can infiltrate when the water level is higher, as a result of higher water pressures, which causes more groundwater flow to occur. The height of a water level is expressed in m+NAP. In the Netherlands, all heights are measured relative to the same level, the 'Normaal Amsterdams Peil' (NAP) (Rijkswaterstaat, 2023c). Therefore, a water level is expressed in meters relative to the NAP. A height of 0 m+NAP is approximately equal to the average sea level of the North Sea.

High water levels occur in flood waves. A flood wave can be defined as temporarily higher water levels in a river as a result of an increased river discharge (Rijksoverheid, 2023). A water level course illustrates what a flood wave looks like. In Figure 10 the solid/blue line represents the water level course. The temporarily high water levels become apparent in this figure.

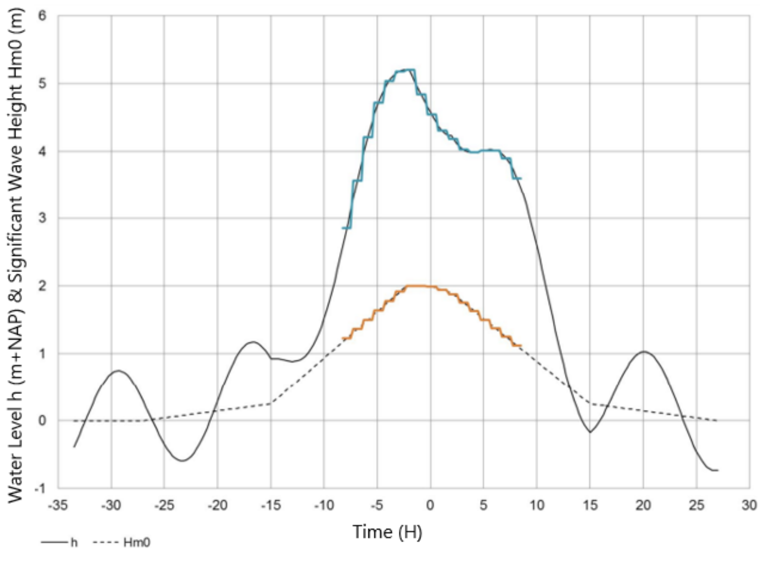


Figure 10, Example of a high water level course, where the solid line is the water level (van Hoven, 2016)

Within the assessment of flood defences water levels are often determined using recurrence times. A recurrence time can be defined as the probability in years that a certain event will occur (Informatiepunt Leefomgeving, 2023). For example, a water level that occurs once every 10,000 years. Each dike section has a norm for the recurrence time of events it should be able to withstand. A programme that is often used to calculate the water level for a given recurrence time is Hydra-NL. Hydra-NL is a probabilistic model that calculates the hydraulic loads (water level, wave conditions, wave overtopping) (Rijksoverheid, 2020). Hydra-NL is used for the assessment of Dutch flood defences.

### 3.1.3 Wave Overtopping

When wave overtopping occurs, water splashes or waves over the dike irregularly (Deltares, 2014b). This can cause water to infiltrate within the dike (Galema et al., 2006). Which affects the strength of the dike. Wave overtopping is expressed in l/s/m, which is the discharge per meter of dike (TAW, 2004). The amount of wave overtopping is affected by the height of the dike because the probability of wave overtopping occurring is higher at lower dikes. In practice, dikes can be raised to reduce the effects of wave overtopping. There are also other variables related to wave overtopping that play an important role. These will be discussed below.

#### Significant Wave Height

The significant wave height is the mean wave height of the highest 33% of the wave heights measured in a certain time period (Rijkswaterstaat, 2023d). As can be seen in Figure 11. The significant wave height is expressed in meters and is indicated as $H_s$ or $H_{m0}$.

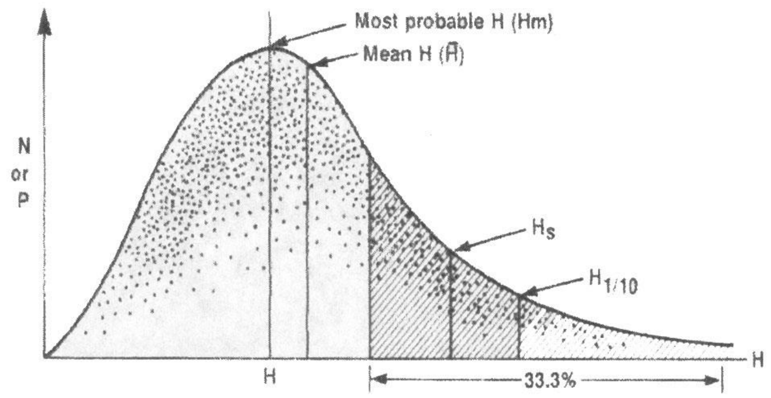


Figure 11, Significant wave height (Ainsworth, 2006)

#### Infiltration Duration:

The infiltration of water due to wave overtopping is affected by the significant wave height, in combination with the wave overtopping discharge. Therefore, the phreatic line is also affected by this since infiltration can cause the phreatic line to rise. The amount of water that infiltrates within the dike depends, among others, on the duration that a layer of water is present on the crest and slope of the dike (van Hoven, 2016). The thickness of this layer does not matter. However, infiltration due to wave overtopping can only occur if this layer of water is present. In Figure 12, the relation between the percentage of time for which a layer of water is present on the dike and the significant wave height, for several wave overtopping discharges, can be seen.

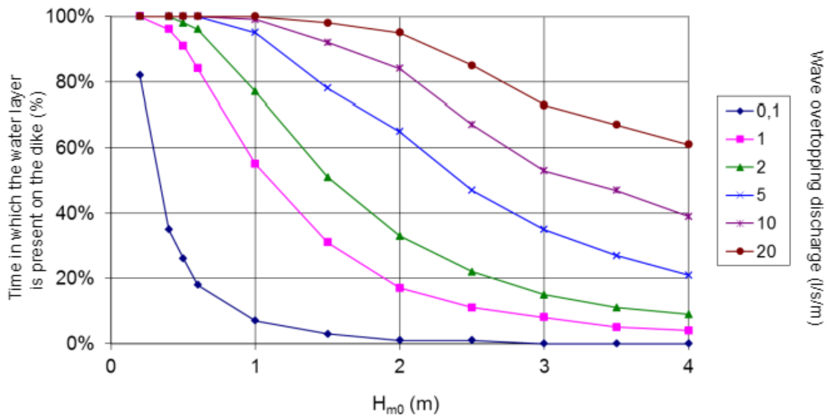


Figure 12, Relation between the percentage of time for which a layer of water is present on the dike and the significant wave height, for several wave overtopping discharges (van Hoven, 2016)

It is notable that, for an equal wave overtopping discharge, the percentage of time for which the water layer is present on the dike is higher when the significant wave height is lower. When the significant wave height is low, more waves will come over the dike in rapid succession (van Hoven, 2016). This has the consequence that a layer of water is always present on the dike. When the interval between waves becomes larger, which occurs when the significant wave height gets higher, the slope and crest of the dike sometimes fall dry. This means that the infiltration temporarily stops.

**Infiltration Capacity**

When, as a result of wave overtopping, water is present on the crest and slope of a dike, water will infiltrate within the dike with a certain flow rate (van Hoven, 2016). This flow rate is called the infiltration capacity. The infiltration capacity is dependent on the pressure of the water on the dike and the hydraulic conductivity of the dike's soil. The water pressure on the dike is minimal since the layer of water on the dike is often only a few centimetres thick.

It can be concluded that time is also an important variable because the amount of water that infiltrates depends on how long the infiltration takes place. Additionally, a unit of time is mentioned in two variables that are related to wave overtopping. Namely, the infiltration capacity, which is expressed in the amount of water that can infiltrate in a day. Time is also mentioned in the percentage of time in which a layer of water is present on the dike body and thus the duration in which infiltration takes place. Furthermore, the duration of wave overtopping is also linked to the water level course of a flood wave from Figure 10. Namely, because wave overtopping can only occur at the peak of the flood wave. Therefore, the duration of a flood wave is also something to consider.

## 3.2 Defining Variables for the Case Study.

### 3.2.1 Dike Geometry and Soil Types

In order to define the soil parameters that will be used as input for the model, the cross-section that will be studied needs to be known. The cross-section can be seen in Figure 13, it is a representative cross-section of the soil composition of the dike trajectory from the case study area. The crest of the dike is at 7 m+NAP and the outer toe is at 2 m+NAP, which means the dike is 5 meters high. It can be seen that the dike-cross section consists of 4 layers. The soil parameters have to be defined for each soil layer separately. The cross-section was provided by Witteveen+Bos.

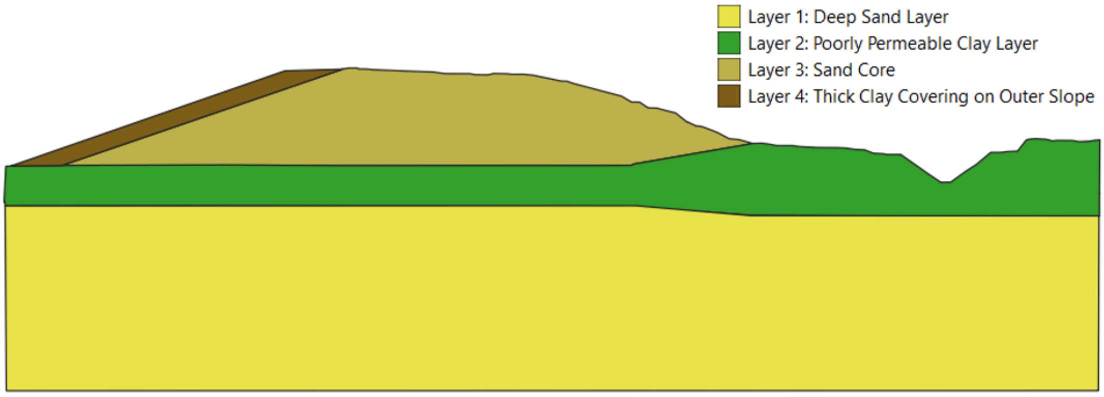


Figure 13, The cross section to be studied (provided by Witteveen+Bos)

### 3.2.2 Soil Parameters

In Table 1 initial estimations of the soil parameters can be seen. Later on in this research in section 5.3, it will be determined which parameters are going to be modelled stochastically, based on the results from the sensitivity analysis. For this, the initial estimations will be used. The reasoning behind the values for the hydraulic conductivities ($K_s$) and specific storage (Ss) can be found in Appendix I

Table 1, Initial estimations of soil parameters

| | $K_s$ (m/d) | a (-) | Ss ($L^{-1}$) | Sy (-) |
|---|---|---|---|---|
| Layer 1 (Sand) | 15 | 0.66 | 5.42E-04 | 0.31 |
| Layer 2 (Clay) | 0.05 | 0.33 | 5.40E-03 | 0.06 |
| Layer 3 (Sand) | 5 | 0.66 | 5.42E-04 | 0.31 |
| Layer 4 (Clay) | 0.01 | 0.33 | 5.40E-03 | 0.06 |
| Source | See Appendix I | (TAW, 2004) | See Appendix I | (Morris & Johnson, 1967) |

### 3.2.3 Wave Overtopping and Water Levels

Next to the soil parameters, the variables regarding wave overtopping and water levels are needed as input for the model. These variables are linked to a certain recurrence time. For the STBI failure mechanism in the case study area, the recurrence time is 1/3000 years (IJsselwerken Zwolle-Olst, 2021). Therefore, this recurrence time will be used in order to determine the variables regarding wave overtopping and water levels. This means only one value will be chosen for these variables. It is decided to model these variables deterministically because also only one recurrence time is used to assess failure mechanisms in the Netherlands. The assessment of failure mechanisms is also the main application of the phreatic line.

In order to obtain some of the input needed regarding wave overtopping and water levels Hydra-NL was used. Within Hydra-NL the 1/3000-year recurrence time was used as input, next to the location of the dike and the geometry of the dike. With this, Hydra-NL calculated the water level, wave overtopping discharge and significant wave height for the given recurrence time. The outcome of this can be seen in Table 2.

Table 2, Output from Hydra-NL for a 1/3000 years recurrence time

| Parameter | Value |
|---|---|
| Water Level | 5.925 m+NAP |
| Wave Overtopping Discharge | 1.181 l/s/m |
| Significant Wave Height | 1.212 m |

With the data from Table 2, the percentage of time for which a layer of water is present on the dike can also be determined. In order to do this, the relation between the wave overtopping discharge, significant wave height and the percentage of time infiltration takes place (Figure 12) was used. From this relation is extracted that for approximately 50% of the time, a layer of water is present on the dike body.

Another variable of interest is the duration of wave overtopping (Rijkswaterstaat, 2022). According to Rijkswaterstaat (2022), this duration is 6 hours. This makes the duration in which infiltration occurs 3 hours because the layer of water is present on the dike body for 50% of the time and infiltration can only occur if there is water on the dike.

The values discussed in this section will be used as input for the model. Finally, the infiltration capacity should be defined. The infiltration capacity of clay dikes or sand dikes with clay covering lies between 0.864 and 8.64 m/d (van Hoven, 2016). Wave overtopping tests in the Netherlands show an average infiltration capacity of 2,16 m/d. However, in order to implement the infiltration capacity for the model, more knowledge about the model is needed. This will therefore be discussed in section 5.1.2.

## 3.3 Conclusion

All in all, it became apparent in this chapter that a significant amount of variables/inputs are involved in determining the phreatic line. 3 types of variables were identified; soil parameters, water levels and parameters related to wave overtopping. In Table 3 an overview of these variables can be seen, in combination with some general variables that are needed. The most influential parameters are going to be modelled stochastically, based on the sensitivity analysis.

Table 3, An overview of the identified variables

| General variables | Soil Parameters | Water levels | Variables Related to Wave Overtopping |
|---|---|---|---|
| Cross-section of the dike with a distinction of soil types and a geometry of the dike | Hydraulic conductivity | Recurrence time | Wave overtopping discharge |
| | Anisotropy ratio | Water level | Significant wave height |
| | Specific yield | | % of time for which a layer of water is on the dike |
| | Specific storage | | Duration in which infiltration occurs |
| | Porosity | | Infiltration capacity |

# 4 MOST SUITABLE METHOD TO DETERMINE THE PHREATIC LINE

In this chapter, the second sub-question will be answered. Namely, which methods are there to determine the phreatic line and which method is the most suitable? The goal of this chapter is to select the most suitable method that will be used to express the phreatic line in a probability or confidence interval. In order to select the most suitable method, assessment criteria and possible methods need to be identified first. After this, the most suitable method will be selected out of the identified methods based on the defined criteria.

## 4.1 Assessment Criteria

### Applicability

The method has to be suitable. In other words, it should be possible to define input parameters (for example different types of soil, water levels, wave overtopping etc.). Additionally, it should be possible to model soil behaviour in a situation where both saturated and unsaturated soil is present. Finally, the model should be able to determine the phreatic line, based on the defined input.

### Accessibility

The method should be accessible through Witteveen+Bos, the University of Twente or for free.

### Suitability for Probabilistic Approach

It should be possible to use the selected method in combination with a probabilistic approach since this is an important aspect of the research. Within this criteria two factors are import. Firstly, it is desirable to run the model through a scripting tool since this is the most efficient way to do multiple simulations.

Secondly, the duration of simulations is important since multiple simulations must be done in a probabilistic analysis. These simulations could take a lot of time. Therefore, a model with a short duration of simulations would be favourable. However, it is good to mention that the simulation duration is a factor that depends on some variables. For example, the simulation duration is dependent on the processing speed of the computer that is used. It also depends on how extensive the model that is used for simulation is. All these variables make it difficult to assess this criterion objectively. On the other hand, this criterion does give an approximation of which model is relatively fast and which model is not.

## 4.2 Identification of Possible Methods

Here, methods that can be used to determine the phreatic line are identified. The methods that will be identified are groundwater flow models. There are also analytical models available to determine the phreatic line, but these are not suitable for this research. Firstly, analytical methods can estimate the phreatic line in simple cross-sections, but for more complex cross-sections, which is the case for this project, groundwater flow models are recommended (Schwiersch et al., 2021). Secondly, an important aspect of this research is wave overtopping, it is however not possible to compute the effect of wave overtopping on the phreatic line with analytical methods.

### Seep/W

Seep/W is a software that is used for modelling groundwater flow in porous media (GeoStudio, sd). It is possible to define different soil types where for each soil type different parameters can be defined according to the van Genuchten model (van Genuchten, 1980). Furthermore, it is possible to model wave overtopping by inserting infiltration as a boundary condition (Kampman, 2021). Seep/W makes use of the finite element method (FEM). This is a numerical method where the soil of the dike and below the dike gets divided into a number of smaller elements for which some balancing equations are solved (de Loor, 2018). After the equations are solved for the smaller and simpler elements, the elements are put together to approximate a solution for the entire, more complicated model.

It can be concluded that Seep/W is applicable for modelling the phreatic line and defining input parameters. Van de Voort (2019) showed that Seep/W can be used in a probabilistic analysis. Seep/W does however have a disadvantage regarding its accessibility. The software is not accessible through Witteveen+Bos or the University. It is possible to access the software through a free trial, but this only lasts for 14 days. This is therefore not ideal. Also, Seep/W has a relatively long simulation duration of 20 minutes (van de Voort, 2019).

### PlaxFlow

PlaxFlow is a component of PLAXIS 2D. PLAXIS 2D is software that is used to model a wide range of geotechnical problems (Bentley Systems, 2023b). PLAXIS also makes use of the FEM. PlaxFlow itself calculates pore water pressures in the soil and it includes the effect of changing hydraulic circumstances (de Loor, 2018). It is possible to model transient groundwater flow in PlaxFlow. Additionally, soil types can be defined in the model and unsaturated soil behaviour can be modelled through the van Genuchten model (van Genuchten, 1980), amongst others (Dorst, 2019). Wave overtopping itself is not a component of PlaxFlow, but it can be modelled as infiltration (de Raadt et., 2015).

PlaxFlow does have a significant disadvantage, Witteveen+Bos has a limited number of licenses for PLAXIS, due to the high cost of a license. This means that is not likely that a license will be available for this research. Another disadvantage of PlaxFlow is that the simulation duration is relatively long. According to colleagues at Witteveen+Bos, who have experience with the software, the simulation duration is between 10 and 30 minutes. On the other hand, PlaxFlow does fit the applicability criterion because input parameters can be defined, wave overtopping can be modelled and unsaturated soil behaviour can be modelled. PLAXIS does have a module for performing a probabilistic analysis such as a Monte Carlo simulation (Manoj, 2017). This module can be used to run multiple PLAXIS simulations sequentially with different input values for each simulation. However, the module is not accessible through a scripting tool.

### MODFLOW

MODFLOW is a hydrologic modelling software that is used to simulate groundwater flow, amongst other things (USGS, 2022a). The software is considered to be the international standard for groundwater modelling. Within MODFLOW packages can be installed for additional possibilities within the programme. The unsaturated-zone flow package can be used to model unsaturated soil behaviour (Dorst, 2019). The Brooks & Corey model is used for this (Brooks & Corey, 1966), instead of the more commonly used van Genuchten model. Wave overtopping can be modelled in MODFLOW by adding a permanent layer of water on the outside of the dike, this results in the occurrence of infiltration (Klop & van Meekeren, 2021).

Based on the above, it can be said that MODFLOW fits the applicability criterion. It does however have a slight disadvantage that the Brooks & Corey model is used instead of the more commonly used van Genuchten model. MODFLOW does fit the accessibility criterion as well because it is accessible through Witteveen+Bos. Finally, the FloPy package can be added to MODFLOW to run the programme through a scripting tool, Python in this case (Bakker, et al., 2016). In general, it takes 5 to 10 minutes to simulate the phreatic line in MODFLOW. The possibility to run the programme through a scripting tool makes it easier to use the model probabilistically.

### COMSOL

COMSOL is software that makes use of the FEM, it is used within multiple fields in physics and engineering (COMSOL, 2023a). An add-in within COMSOL, subsurface flow, can be used to model flow in porous materials (COMSOL, 2023b). Within the subsurface flow add-in, it is possible to model unsaturated soil behaviour according to the van Genuchten and Brooks & Corey models (van Genuchten, 1980) (Brooks & Corey, 1966). On the other hand, COMSOL offers a huge range of flexibility which makes it more difficult to learn. Additionally, no simple direct way was found to model wave overtopping or infiltration in the manual (COMSOL, 2023b).

It can be concluded that COMSOL might not be the most suitable model according to the applicability criterion. The reason for this is that no approach was found on how to implement wave overtopping in the subsurface flow add-in. It does however fit the other two criteria well. Firstly, because the software is accessible through Witteveen+Bos. Secondly, because COMSOL can be run through a MATLAB file, which means that it should be possible to use a probabilistic approach (Dorst, 2019). Finally, COMSOL has an acceptable run time of about 10 minutes per simulation. This is according to colleagues at Witteveen+Bos who have worked with a similar model before.

## 4.3 Selection of the Most Suitable Method

The information from section 4.2 has been summarized into advantages (+), disadvantages (-) and neither of both (0). An overview of this can be seen in Table 4. This table provides a clear overview of the possible methods and can be used to select the most suitable method.

Table 4, Advantages and disadvantages of possible models

| | Applicability | | Accessibility | Suitability for probabilistic approach | |
|---|---|---|---|---|---|
| | Unsaturated soil behaviour | Wave overtopping | | Scripting tool | Simulation duration |
| Seep/W | + | + | 0 | - | - |
| PlaxFlow | + | + | - | 0 | - |
| MODFLOW | - | + | + | + | + |
| COMSOL | + | - | + | + | 0 |

Two models do not comply with one of the criteria because of a significant disadvantage. The first model is PlaxFlow, the model has as a disadvantage that it is not accessible due to the limited number of licenses available at Witteveen+Bos. This makes the model fail to comply with the accessibility criterion. The second model is COMSOL, this model has as a disadvantage that no approach to implement wave overtopping was found. This makes COMSOL fail to comply with the applicability criterion since wave overtopping is an important aspect of this research. Thus, it can be concluded that PlaxFlow and COMSOL are not the most suitable methods.

The two other models, Seep/W and MODFLOW, do comply with the criteria, but both models have some slight disadvantages. Eventually, MODFLOW has been selected as the most suitable method. Firstly, the software can be used in combination with a scripting tool and the programme has a relatively short simulation duration. MODFLOW is therefore very suitable for a probabilistic analysis. Secondly, MODFLOW is an international standard for groundwater modelling. This means that the programme is widely used within different fields of engineering. The programme is also more commonly used within Witteveen+Bos than Seep/W. Thirdly, because Seep/W can only be accessed for 14 days, this can cause problems if the application of the model to express the phreatic line in a confidence interval or probability takes longer than expected.

It is however good to mention that MODFLOW does have a disadvantage. Namely that it is only possible to model the flow in the unsaturated zone with the Brooks & Corey model and not with the more commonly used van Genuchten model. The van Genuchten model is also more accurate than the Brooks & Corey model (Goorabjiri & Rasoulzadeh, 2015). For this research, this disadvantage is not significant since the unsaturated zone is not going to be modelled. It is however good to take this disadvantage into consideration. Unless the fact that this is a disadvantage of MODFLOW, it does not outweigh the advantages of MODFLOW in comparison to the other models.

# 5 EXPRESSING THE PHREATIC LINE IN A PROBABILITY OR CONFIDENCE INTERVAL

In this chapter, MODFLOW will be used to express the phreatic line in a confidence interval. The goal of this chapter is to answer the third research question: How can the most suitable method be applied to express the phreatic line in a probability or confidence interval? Before this question can be answered a few steps have to be taken. Firstly, an explanation will be given about the model set up and the model output. More explanation about MODFLOW 6 and its packages can be found in Appendix II. Secondly, a sensitivity analysis will be performed. Thirdly, the implementation of the probabilistic approach into the model will be explained. In the final part of this chapter, the model results will be used to express the phreatic line in a confidence interval or probability.

## 5.1 Model Set Up

In this study, the model set up is based on an already existing model which was used for the hydrological study mentioned in section 2.3.3 (Klop & van Meekeren, 2021). The model is provided by Witteveen+Bos This model will be adapted to model the phreatic line probabilistically for the cross-section of the case study. In order to do this FloPy will be used in combination with MODFLOW 6. FloPy is a package that can be used to run MODFLOW through a scripting tool (Python), instead of the graphical user interface (Bakker, et al., 2016). The advantage of this is that it is easier to implement a probabilistic approach in Python. Additionally, data analysis and visualization are very accessible in Python.

### 5.1.1 Model Grid

In order to use the cross-section from the case study in MODFLOW, the cross-section has to be translated into a grid. The first step herein is to draw the cross-section in QGIS (QGIS, 2023). Within QGIS each soil layer is drawn as a polygon in order to specify the different soil types. After this, the QGIS file is translated into a model grid in the Python script. This model grid consists of cells with a size of 0.25m by 0.25m. A soil type has been assigned to each cell. Within MODFLOW, the smaller the cell size, the more accurate the results and the longer the simulation time. The cell size has been set to 0.25m to obtain an accurate distinction between soil layers and to prevent the simulation time from getting too high. The model grid can be seen in Figure 14, where every colour represents a different soil layer.

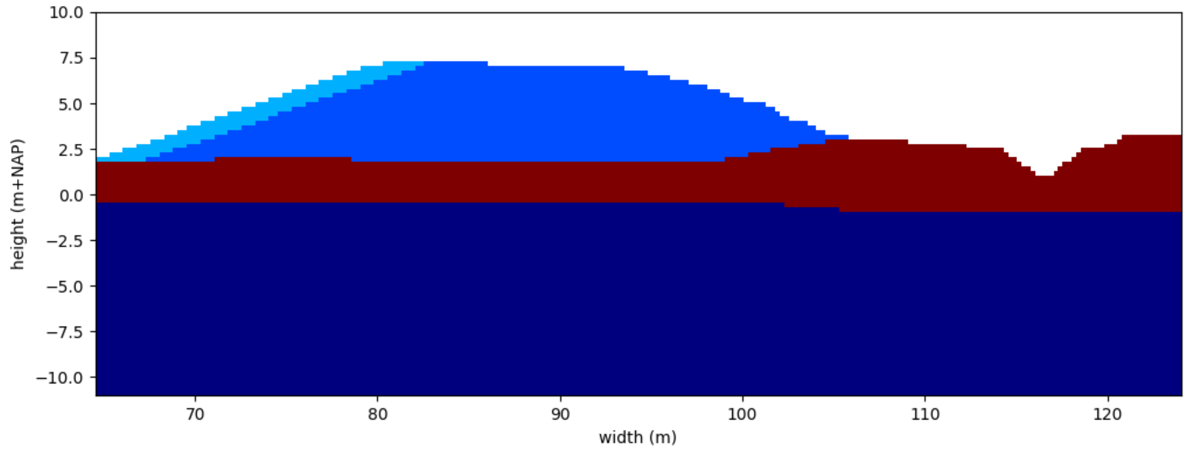


Figure 14, Model Grid

### 5.1.2 Wave Overtopping in the Model

Within the model, the general head boundary (GHB) package has been used to model wave overtopping. Wave overtopping is modelled as a layer of water on the crest and slope of the dike. It is assumed that infiltration as a result of wave overtopping occurs from just above the water level until the inner toe of the dike. The layer of water on the dike has a resistance towards the dike body. The higher the resistance, the less water can infiltrate. This resistance factor has to be obtained through calibration since it is not known what resistance factor matches with the correct infiltration capacity.

As discussed in 3.2.3, the infiltration capacity of clay dikes or sand dikes with clay covering lies between 0.864 and 8.64 m/d (van Hoven, 2016). Where the most ideal value would be 2.16 m/d as this was an average result of wave overtopping tests. For this calibration, initial estimations for the soil parameters from Table 1, in combination with a water level of 5.925 m+NAP, were used. In the calibration process, the value of the resistance was changed to see how this affects the infiltration capacity of the dike. The results of the calibration can be seen in Figure 15, here it can be seen that a resistance factor of 0.5 corresponds best to an infiltration capacity of 2.16 m/d.

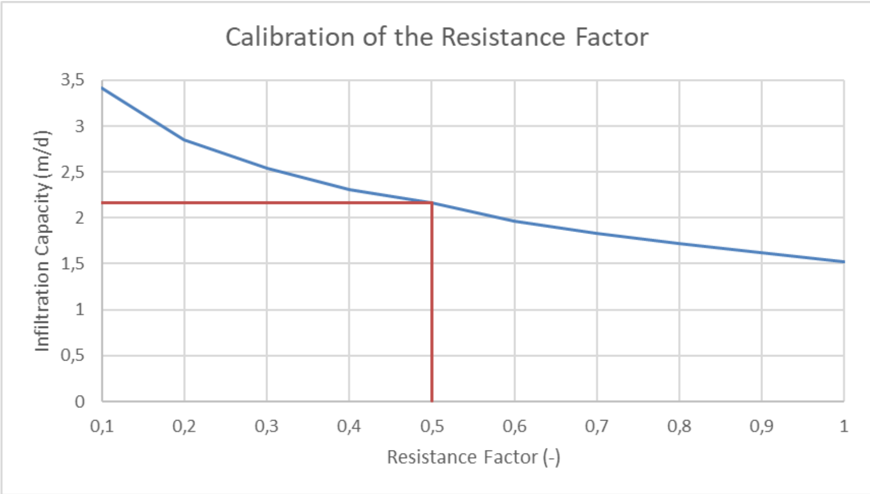


Figure 15, Calibration results

Within the model, different timesteps are implemented. The first step is the initial phreatic line (T=0), here the phreatic line is determined before infiltration as a result of wave overtopping has occurred. After this, the model simulates the effect of infiltration as a result of wave overtopping on the phreatic line for 3 hours, as defined in section 3.2.3. Where for each hour, the location of the phreatic line is stored; T=1 for 1 hour, T=2 for 2 hours and T=3 for 3 hours.

## 5.2 Model Output

In order to obtain results the model as described in this chapter has been used for simulation. The model has two types of output. The first type of output is the amount of infiltration in m/d, this output has been used for the calibration of the resistance factor. The second type of output is a cross-section of the dike in which the saturated and unsaturated cells are indicated. In these cross-sections, the part of the dike that is coloured is saturated and the white part is unsaturated. Also, the colour scale indicates the hydraulic head in the dike. Two examples of these cross-sections can be seen in Figure 16 and Figure 17. These figures are calculated by using the initial estimations of the soil parameters from Table 1, and the defined variables from section 3.2.3. In Figure 16, the phreatic line without wave overtopping is displayed (T=0 in the model). In Figure 17, the phreatic line with the effects of wave overtopping is displayed (T=3 in the model).

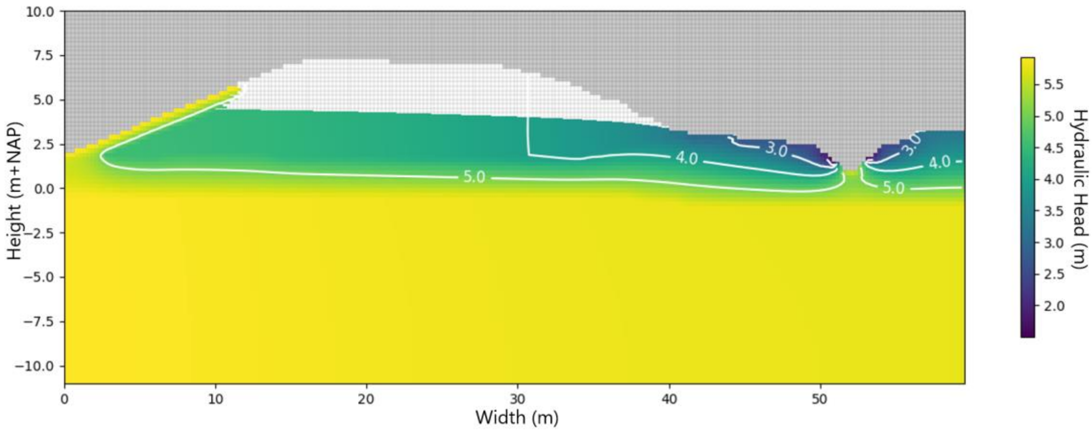


Figure 16, Cross-section model output without wave overtopping (T=0)

In Figure 16, a drop in the phreatic line can be seen through the clay covering. Due to the low conductivity of this covering less water can infiltrate within the dike. After the drop, the phreatic line flows relatively straight towards the inner toe of the dike. Compared to the case including wave overtopping, some similarities can be found. Namely, the exit point of the phreatic line is located near the inner toe of the dike. Additionally, the drop in the phreatic line due to the clay covering is present in both figures.

On the other hand, the effect of wave overtopping does become clear in Figure 17. Firstly, water infiltrates within the clay covering of the dike, this can be seen in the left side of the dike due to the increase in saturated cells. Secondly, the phreatic line has risen in the core of the dike. This rise starts where the clay covering ends. The core of the dike has a higher hydraulic conductivity than the covering and thus more water can infiltrate here.

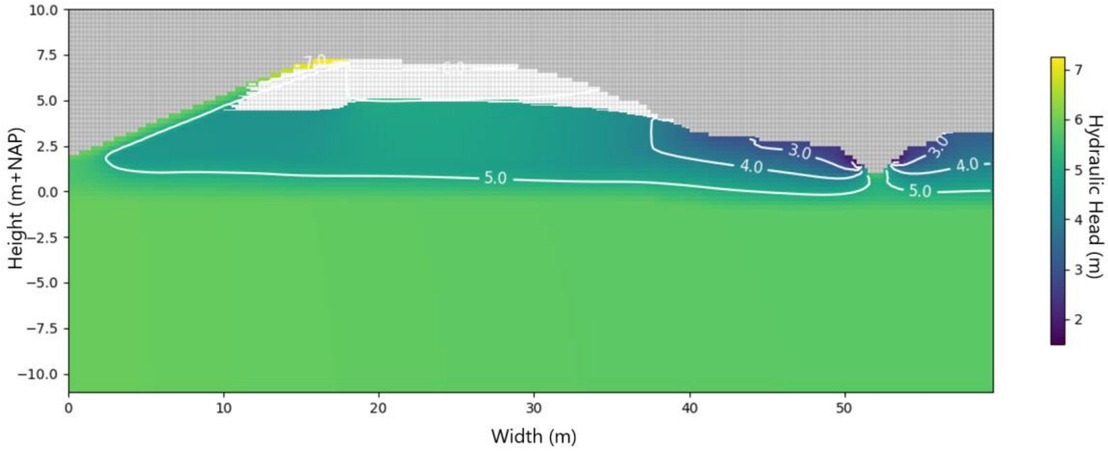

Figure 17, Cross-section model output with the effects of wave overtopping (T=3)

The cross-section with saturated cells is translated into a phreatic line, where the x and y coordinates of the phreatic line are stored per 0.25m, for each of the 4 timesteps. In order to obtain this phreatic, for each x coordinate, the model finds the first unsaturated cell, looking from the bottom. The height of this cell is then the value of the y coordinate. After this, the coordinates can be used to plot the phreatic line using Python. This process can be seen in Figure 18. This method of storing the phreatic line does however have a disadvantage since it can only store one y coordinate per x coordinate. This has the consequence that the saturated cells in the clay covering at the left side of the dike are not excluded, this can be seen in Figure 18. This disadvantage is however not significant because the amount of saturated cells that are excluded is low compared to the total amount of saturated cells in the dike.

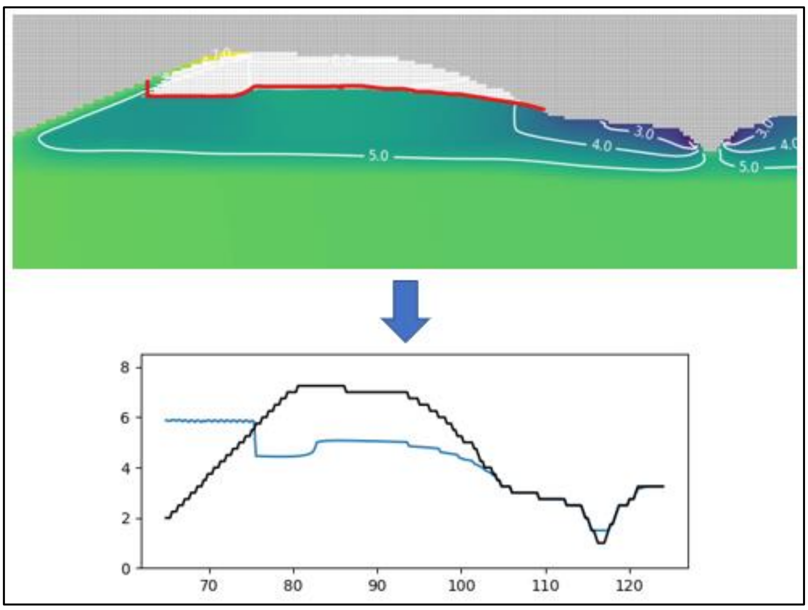

Figure 18, Process of storing the phreatic line as a CSV and using the CSV to plot the phreatic line

## 5.3 Sensitivity Analysis

Now that the way the model works and the output the model produces are known, a sensitivity analysis can be performed. This sensitivity analysis is based on a base scenario, based on the defined input from section 3.2, the values for this base scenario can be seen in Table 5. The parameters are one by one adjusted in order to see how the phreatic line is affected by this. This was done with the upper and lower boundaries of the variables, which can be seen in Table 5. Also, when the values for the specific yield, specific storage and anisotropy ratio are adjusted, these values are adjusted for each soil layer simultaneously. This is not the case for the hydraulic conductivity since these are adjusted for each soil layer separately. The results from this sensitivity analysis can be found in Appendix IV.

Table 5, Upper and lower boundaries of the parameters used for the sensitivity analysis

| | Lower Boundary | Base Scenario | Upper Boundary |
|---|---|---|---|
| $K_s$ (Layer 1) (m/d) | 5 | 15 | 30 |
| $K_s$ (Layer 2) (m/d) | 0.02 | 0.05 | 0.1 |
| $K_s$ (Layer 3) (m/d) | 1.5 | 5 | 10 |
| $K_s$ (Layer 4) (m/d) | 0.001 | 0.01 | 0.05 |
| Sy (-) | Sy multiplied by 0.75 | Sand: 0.31, Clay: 0.06 | Sy multiplied by 1.25 |
| Ss ($L^{-1}$) | Ss divided by 10 | Sand: 5.42E-04,<br>Clay: 5.40E-03 | Ss multiplied by 10 |
| Resistance Factor (-) | 0.25 | 0.5 | 1 |
| a (-) | a multiplied by 0.75 | Sand: 0.66, Clay: 0.33 | a multiplied by 1.25 |
| Water Level (m+NAP) | 5.425 | 5.925 | 6.425 |

These conclusions can be drawn from the sensitivity analysis, a more detailed representation of the sensitivities can be found in Appendix IV:

- The model is most sensitive to a change in the resistance factor or the hydraulic conductivity of the clay layer and sand core.
- The model is not sensitive to a change in the specific storage or the hydraulic conductivity of the deep sand layer.
- The model is moderately sensitive to a change in the remaining parameters. Namely, the specific yield, water level, anisotropy ratio and hydraulic conductivity of the clay covering.

A few things stand out in the results. Firstly, the highest rise of the phreatic line occurred when the hydraulic conductivity of the sand core was at its minimal value. This can also be seen in Figure 19. It becomes apparent that the rise of the phreatic line is significant in this case. It becomes apparent as well that for a lot of parameters, the rise or fall is around 20 to 25 centimetres. This is also the case for the resistance factor, as can be seen in Figure 20. This figure perfectly illustrates the effect of different amounts of infiltration on the phreatic line.

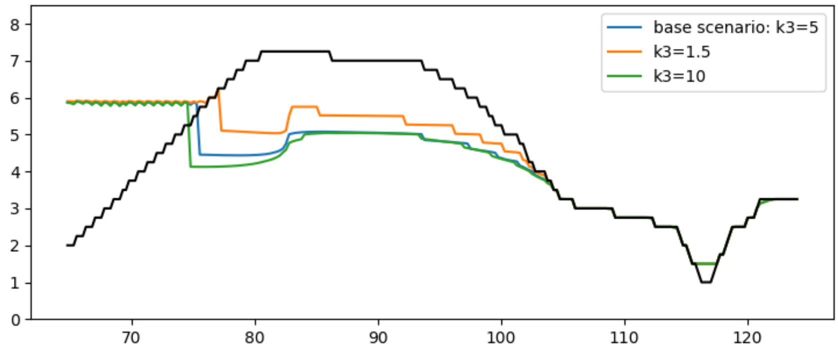


Figure 19, Sensitivity of the phreatic line to a change in hydraulic conductivity of the sandy core

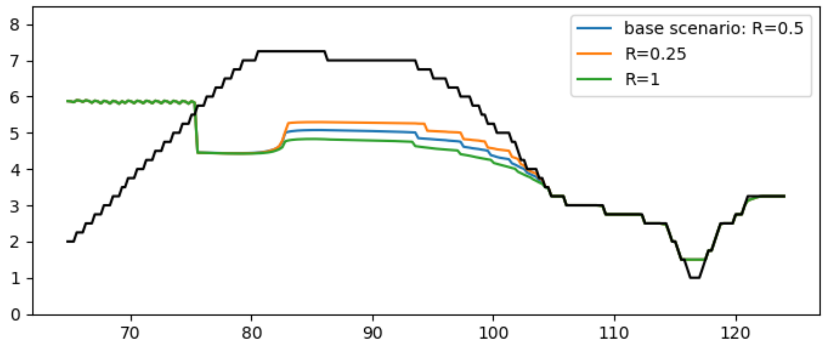

Figure 20, Sensitivity of the phreatic line to a change in the resistance factor

### 5.3.1 Stochastic Parameters

Here, it will be determined which parameters are going to be modelled stochastically. The most influential parameters will be modelled stochastically, based on the results from the sensitivity analysis (Appendix IV). The model is not sensitive to a change in the values for the specific storage (Ss) and hydraulic conductivity ($K_s$) of the deep sand layer. Therefore, these parameters will be modelled deterministically, with the initial estimations from Table 1. On the other hand, the model does show some sensitivity to a change in the hydraulic conductivity anisotropy ratio (a). Still, this parameter will be modelled deterministically since the anisotropy ratio only affects the hydraulic conductivities. The hydraulic conductivities will be modelled stochastically. Therefore, it can be concluded that it is unnecessary to model the hydraulic conductivity anisotropy ratio stochastically. This means that the initial estimations (Table 1) will be used as a value for the anisotropy ratio.

It became apparent in the sensitivity analysis that the model is moderate to highly sensitive to the remaining parameters: specific yield (Sy), the resistance factor and the hydraulic conductivity ($K_s$) of the clay layer, sand core and clay covering. Therefore, these parameters will be modelled stochastically. For each of the stochastic parameters, a distribution has been defined, where a certain probability of occurrence is assigned to each possible value. For the distribution of the resistance factor, a wider range has been assumed since, in combination with the high sensitivity of the model to this factor, the exact value of the infiltration capacity of the dike is not known. The distributions can be found in Appendix V. In defining these distributions was assumed that the average value is more likely to occur than the minimum or maximum value. An example of the distribution for the hydraulic conductivity ($K_s$) of the sand core of the dike can be seen in Figure 21.

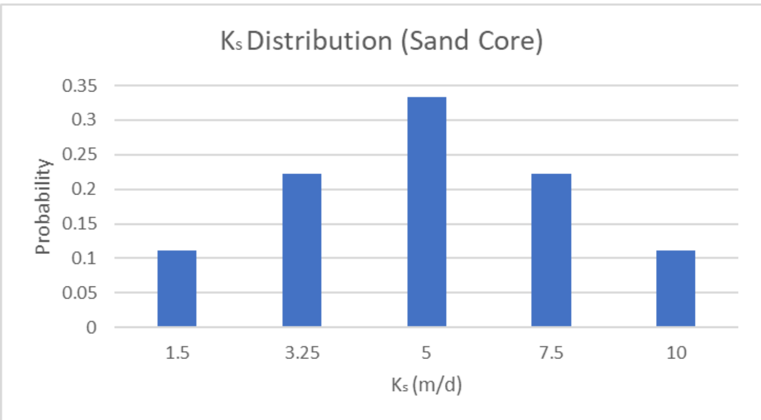

Figure 21, Distribution of possible hydraulic conductivities of the dike's sand core

## 5.4 Probabilistic Approach and Input

Now, the model as described in this chapter can be used to perform the probabilistic analysis. The probabilistic approach that will be used is the Monte Carlo simulation because this approach allows multiple variables to be modelled stochastically. Within the Monte Carlo simulation, the variables that are modelled stochastically are randomly chosen from the distributions in Appendix V. In order to perform this random sampling a Python code has been written. This code randomly extracts a value from the distributions for every simulation and thus changes the input for each simulation.

Another aspect of the Monte Carlo simulation is to determine the number of runs that are necessary to obtain accurate results. For this the confidence interval method was used with a level of confidence of 95% and a relative error of (1-0.95)/2 = 0.025, more explanation about this can be found in Appendix III. The results from the confidence interval method can be seen in Figure 22. From this figure can be concluded that a minimum of 76 simulations are necessary to obtain reliable results since the relative error is below 0,025 for 76 simulations.

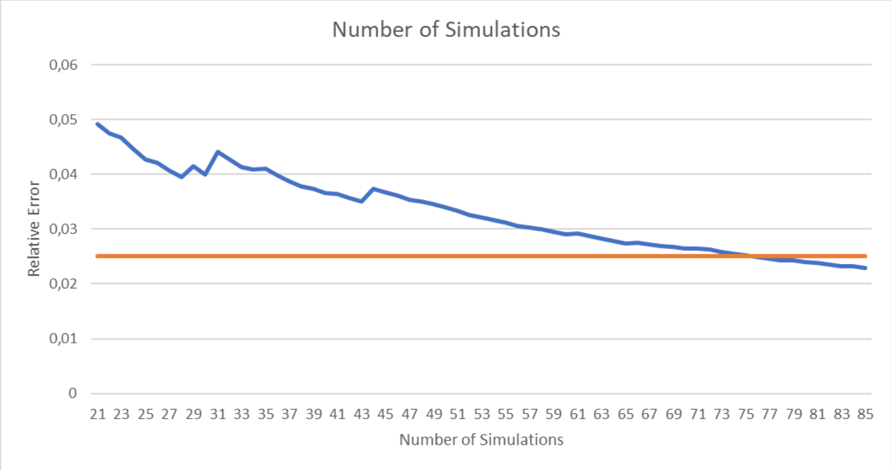


Figure 22, Necessary number of simulations

## 5.5 Expressing the Phreatic Line in a Confidence Interval

Now, the output from the probabilistic analysis can be used to express the phreatic line in a confidence interval. Firstly, 76 phreatic lines from the simulations are plotted into one figure. This results in a range of possible phreatic lines. However, this range does not provide any information about the level of confidence of the phreatic line. For determining the level of confidence of the phreatic line it is assumed that the highest phreatic line is the worst-case scenario. This means that a phreatic line with a 75% level of confidence indicates that it can be said with 75% confidence that the actual phreatic line is located at or below the phreatic line with a 75% level of confidence.

In order to obtain the level of confidence for the phreatic line a Python code has been used. In this code, the 76 phreatic lines and the desired level of confidence are used as input. How the code works will be explained with an example where the phreatic line with a 90% level of confidence has to be determined. Firstly, the model sorts the y coordinates from low to high for each x coordinate. This results in an array with 76 possible y coordinates for each x coordinate. Subsequently, the y coordinate that is higher or equal to 90 per cent of the possible y coordinates is extracted. This results in the coordinates of the phreatic line with a 90% level of confidence. These coordinates can be used to plot the phreatic line with a 90% level of confidence. The phreatic line with 90% confidence and the range of phreatic lines for T=0 can be seen in Figure 23, and for T=3 this can be seen in Figure 24.

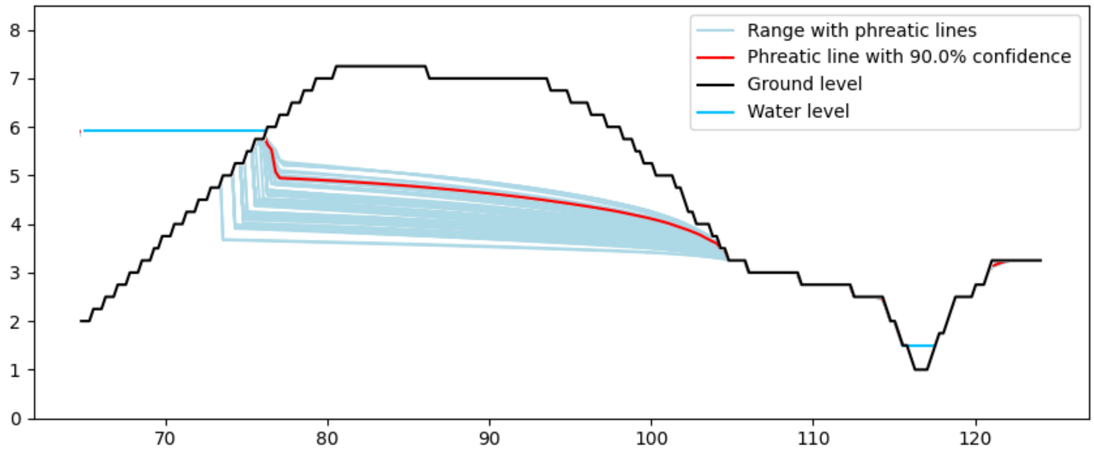


Figure 23, Phreatic line with 90% confidence for T=0

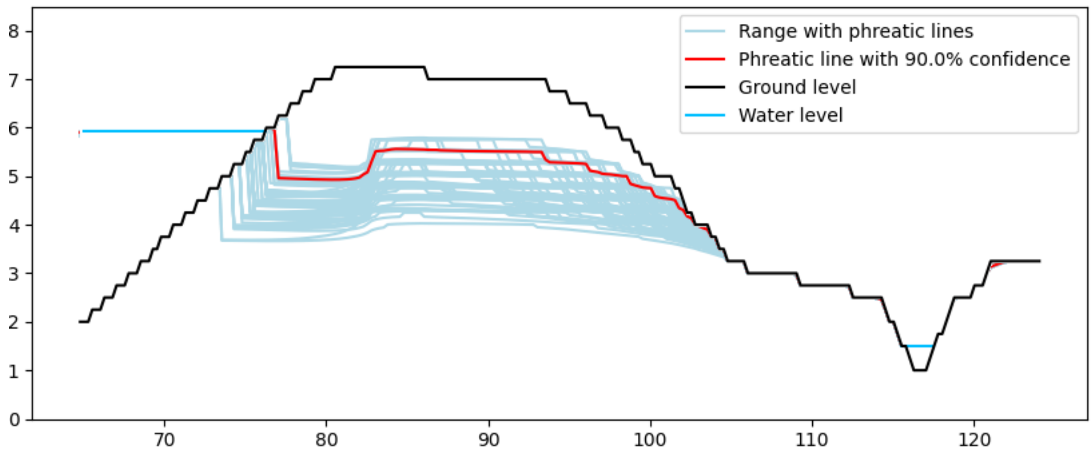

Figure 24, Phreatic line with 90% confidence for T=3

# 6 PHREATIC LINE IN SAFETY PHILOSOPHY

In this chapter, the final sub-question will be answered. Namely, how does this derived phreatic line fit into the safety philosophy for the design of a flood defence? The main goal of this chapter is to interpret the results of the previous chapter. The first step herein is to explain what the current safety philosophy is. After this, the phreatic line in a confidence interval will be compared to the current method that is used, for both a situation with and without wave overtopping. At the end of this chapter, it will be discussed if the phreatic line fits into the safety philosophy.

## 6.1 Current Safety Philosophy

As previously discussed in the introduction of this research, a new norm for flood protection was implemented in the Netherlands in 2017. This switch to a norm that works with probabilities of flooding is significant. Therefore, a report has been published by Rijkswaterstaat (2017) on how to work with this new norm, this report is also known as OI2014v4. This report can be seen as a manual to work with the new norm or new safety philosophy.

Within the new safety philosophy, the phreatic line is also mentioned. In OI2014v4 is stated that the schematizations from TAW (2004) can be used for situations where no wave overtopping occurs or where the wave overtopping discharge lower is than 1 l/s/m (Rijkswaterstaat, 2017). The schematization that corresponds to the dike studied in the case can be found in section 2.3.1 It is however also stated in OI2014v4 that schematizations/rules of thumb for the phreatic line with wave overtopping discharges higher than 1 l/s/m are not available. Therefore, a very conservative assumption is proposed. Namely, to assume that the dike is fully saturated. On the other hand, the background report of the safety philosophy states that it is possible to use groundwater flow models to determine the phreatic line with wave overtopping. Finally, the background report refers to an alternative method to schematize the phreatic line with wave overtopping (van Hoven, 2016). An explanation of this schematization can be found in section 2.3.2.

## 6.2 Situation without Wave Overtopping

The schematizations from TAW (2004) can be used for situations where no wave overtopping occurs or where the wave overtopping discharge lower is than 1 l/s/m, according to the safety philosophy (Rijkswaterstaat, 2017). In Figure 25, the schematization from TAW (2004) is compared to the phreatic line with 50% confidence and the phreatic line that is modelled with the deterministic parameters, for the deterministic phreatic line the soil parameters from Table 1 are used. Further, the water levels and wave overtopping duration are equal to the values used in the probabilistic analysis. In this figure, the phreatic lines are displayed without the effect of wave overtopping (T=0 in the model).

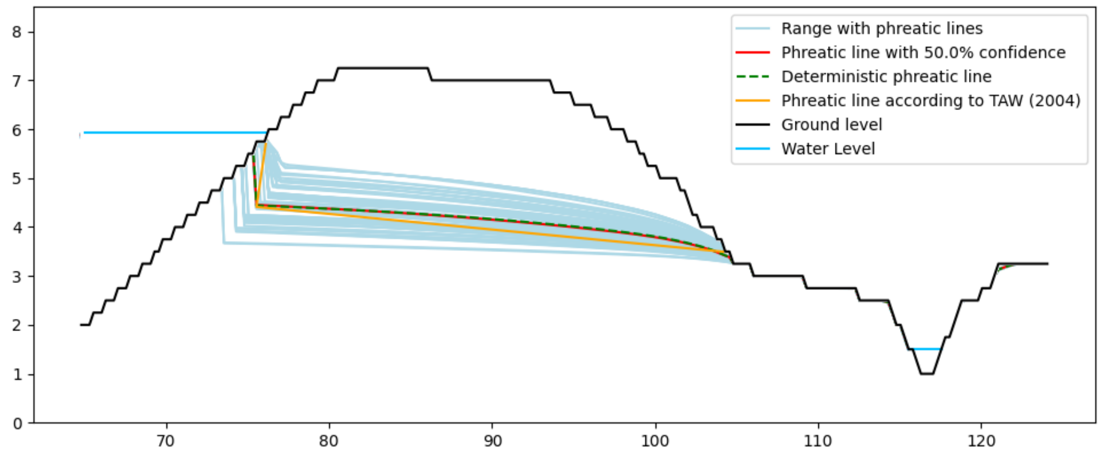


Figure 25, Comparison phreatic lines for T=0

In this comparison, a few things become apparent. Firstly, the deterministic phreatic line is almost identical to the phreatic line with 50% confidence. This does however make sense since the variables from the deterministic phreatic line are equal to the average values that were used in the probabilistic analysis. Secondly, the phreatic line from

TAW (2004) is located at approximately the same height as the deterministic phreatic line and the phreatic line with 50% confidence. Additionally, in the manual for assessing the macro-instability failure mechanism is stated that the average value of the phreatic line should be taken (Rijkswaterstaat, 2021), which is similar to a 50% level of confidence. These factors could indicate that average variables were used to determine the schematization from TAW (2004).

Furthermore, the comparison in Figure 25 can be seen as a validation of the model since the average value and phreatic line with a 50% confidence match the schematizations from TAW (2004) relatively well. This indicates that the model works as it is expected to work.

## 6.3 Situation with Wave Overtopping

In Figure 26, a comparison between the phreatic lines with respectively 50% and 95% confidence, the deterministic phreatic line and the schematization for the Zwolle-Olst dike-strengthening project (explained in 2.3.3) can be seen. Again, for the deterministic phreatic line, the soil parameters from Table 1 and a resistance factor of 0.5 are used. Furthermore, the water levels and wave overtopping duration are equal to the values used in the probabilistic analysis. For the phreatic lines in the figure infiltration due to wave overtopping has taken place for 3 hours (T=3 in the model).

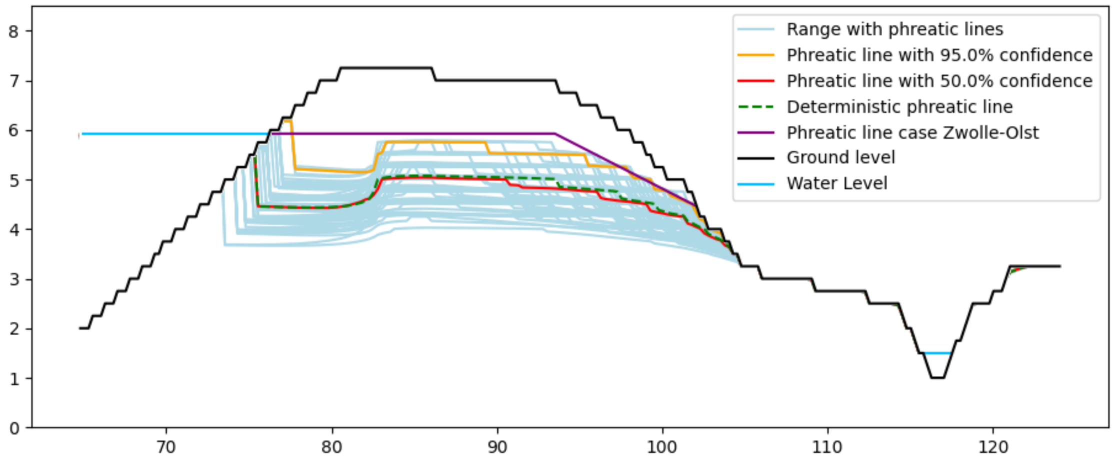


Figure 26, Comparison phreatic lines for T=3 hours

Again, it becomes apparent that the phreatic line with 50% confidence is quite similar to the deterministic phreatic line as this was also the case for a situation without wave overtopping. Besides, the results of the research show that the assumption that the dike is fully saturated, as stated in the safety philosophy, is conservative. At least for the type of dike studied in this research. The reason for this is that it can be said with 95% confidence that the phreatic line lies at or below the orange line in Figure 26. This line is significantly lower than the ground level at which the phreatic line would lie in case of complete saturation.

Furthermore, it can be seen that the phreatic line that was used in the dike-strengthening project Zwolle-Olst is higher than the phreatic line with 95% confidence. From this can be concluded that this schematization is relatively conservative. Therefore, the phreatic line that was used in this dike-strengthening project could have been determined more accurately. On the other hand, this schematization is more accurate than assuming a fully saturated dike.

The probabilistic method that is used in this research has some similarities to the alternative method mentioned in the safety philosophy. Firstly, in both methods the relation between the wave overtopping discharge, significant wave height and the percentage of time infiltration takes place (Figure 12) is used to determine the duration of time in which infiltration due to wave overtopping takes place. Secondly, the infiltration capacity is used in both methods to determine the amount of water that infiltrates.

Although the methods have some similarities, there are still some differences. Namely, in the probabilistic method, one water level is used, which is the highest water level for a certain recurrence time. The alternative method in the safety philosophy makes use of changing water levels that are extracted from the water level course of a high water level event. Therefore, the use of one high water level for the entire duration of the infiltration is less accurate because this high water level is not likely to occur for the entire duration of the wave overtopping event. It is however possible to include changing water level into the model for the probabilistic method. This would be a possible improvement of the model.

On the other hand, the alternative method does not take water flowing out of the dike into account, which the probabilistic method does. In the alternative method is also assumed that the rise of the phreatic line is uniform over the entire span of the dike. This is not accurate since the results of this research show that the phreatic line rises more in the middle of the dike than near the edges. From these factors together with the fact that the model is able to perform more accurate groundwater flow calculations can be concluded that the probabilistic approach is more accurate than the alternative method from the safety philosophy.

## 6.4 Probabilistic Approach to the Phreatic Line in the Safety Philosophy

It is a realistic possibility to include the probabilistic approach in the current safety philosophy because the model can be used to determine the phreatic line both with and without wave overtopping. The use of groundwater flow models is also mentioned in the safety philosophy as a possible method to determine the phreatic line with wave overtopping. This means that the probabilistic approach can be used to determine the phreatic line (more accurately in some cases) instead of using schematizations or assumptions.

The probabilistic part of the model has also an advantage in that it gives an insight into the range of possible phreatic lines. It therefore also gives an insight into the effect of changing variables on the phreatic line. This is useful when the values of some variables are uncertain and the effect of these uncertain variables needs to be known. Additionally, it can be used to assess the accuracy of assumptions or schematizations, as was done in sections 6.2 and 6.3 (both with and without wave overtopping).

This probabilistic aspect of the model can also be used in practice. Namely, if some parameters are uncertain and the phreatic line is modelled probabilistically, the confidence level of the phreatic line can be chosen based on the range of phreatic lines and how uncertain the parameters are. This in combination with the range of phreatic lines provides insight into the uncertainty of the phreatic line and this uncertainty can be mitigated by using a high level of confidence. Another application of the probabilistic phreatic line would be to use it to probabilistically assess the macro-instability failure mechanism. Herein, different levels of the phreatic line can be used to calculate the failure probability and safety factor for macro-instability probabilistically.

# 7 DISCUSSION

In this research, a method is proposed to probabilistically determine the phreatic line and express it with a level of confidence. The probabilistic approach provides insight into how changing variables affect the phreatic line. The probabilistic approach can also be used to mitigate the effect of uncertain parameters by using a high level of confidence. However, some assumptions and simplifications should be taken into account when applying the results of this research.

### Dike Types

In this research, one specific cross-section was studied. It is therefore not known whether the results also apply to other cross-sections or dike types. It is possible that a probabilistic approach is more suitable for one dike type than for another. For example, the change in parameters can have little effect on one dike but more effect on another. A situation like this has occurred during this research. Initially, the cross-section that was going to be studied had a thick (80 cm) clay covering on the outer side of the dike and a thinner (30 cm) clay covering on the crest and inner slope of the dike. However, less infiltration occurred due to the lower hydraulic conductivity of clay and thus the phreatic line was not much affected by wave overtopping. Also, a significant amount of water remained in the clay covering, instead of infiltrating into the core of the dike, this can be seen in Figure 27. Therefore, it was decided to exclude the thin clay covering on the crest and inner slope from the model. This affected the model results because more infiltration occurred and thus the location of the phreatic line was higher.

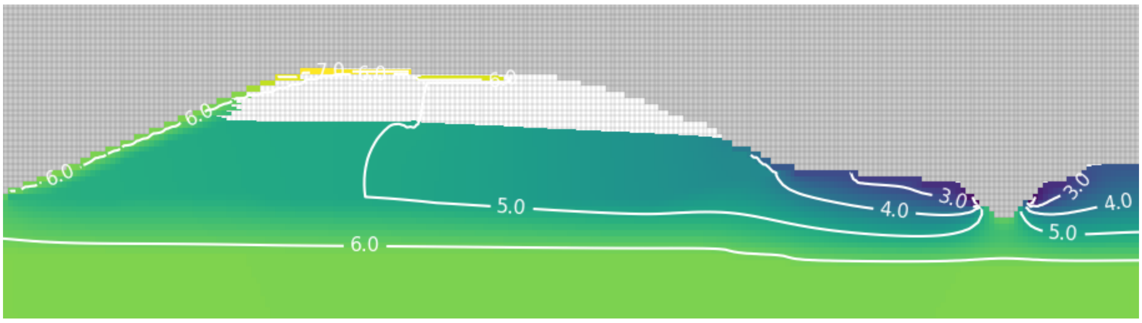


Figure 27, Phreatic line of the dike with thin clay covering on the crest and inner slope

### Infiltration Capacity

In this study, wave overtopping is modelled as a layer of water on the dike with a resistance towards the dike body. This resistance factor was obtained through calibration in combination with the infiltration capacity. For this calibration, an average value for the infiltration capacity was used because only a range with possible infiltration capacities was found in literature. This is not the most ideal method since it is not known if this average infiltration capacity matches the infiltration capacity of the studied dike. If the actual infiltration capacity of the dike is higher than the average, less infiltration will be modelled than the amount of infiltration that would occur in reality and vice versa. Therefore, the most ideal method to determine the infiltration capacity would be to obtain this value through field infiltration tests. On the other hand, the uncertainty in the value for the resistance factor is mitigated by defining a wide range of possible resistance factors in the distribution from Figure 42.

### Flow in the Unsaturated Zone

Within this study, the simplification was made to exclude flow in the unsaturated zone because it is difficult to model flow through the unsaturated zone accurately. Namely, because this process takes a significant amount of time. Besides, additional parameters have to be specified, which could increase the uncertainty of the model. This simplification has the consequence that the phreatic line rises quicker because the water that is added to the phreatic line is not delayed as a result of flow through the unsaturated zone. The quicker rise eventually results in a higher phreatic line.

### High Water Level Event

In the model, one high water level was used for the entire wave overtopping duration of 6 hours. This is not realistic since in reality the water levels differ throughout a high water level event, as was discussed in 3.1.2. Therefore, a more realistic approach would be to include multiple water levels, based on the water level course. And to determine the significant wave height, wave overtopping discharge and percentage of time in which infiltration occurs based on the water level course as well. This would result in a lower duration of infiltration and thus a lower phreatic line. The use of one high water level instead of multiple water levels from a high water level course has as a consequence that more infiltration occurs. This is because it is not realistic for the highest water level to occur for 6 hours.

### Saturated Cells in MODFLOW

During the analysis of the model results some very high phreatic lines occurred. After further looking into this it was concluded that the saturation of cells acts oddly when both the resistance factor and hydraulic conductivity of the sand core are low. The odd saturation of cells can be seen in Figure 28. This causes the coordinates of the phreatic line to be generated incorrectly. Which resulted in the phreatic line to be located at the ground level on the right side of the dike. Therefore, this is considered to be a limitation of the model. Additionally, these very high phreatic lines are excluded from the results since these high phreatic lines are caused by a limitation.

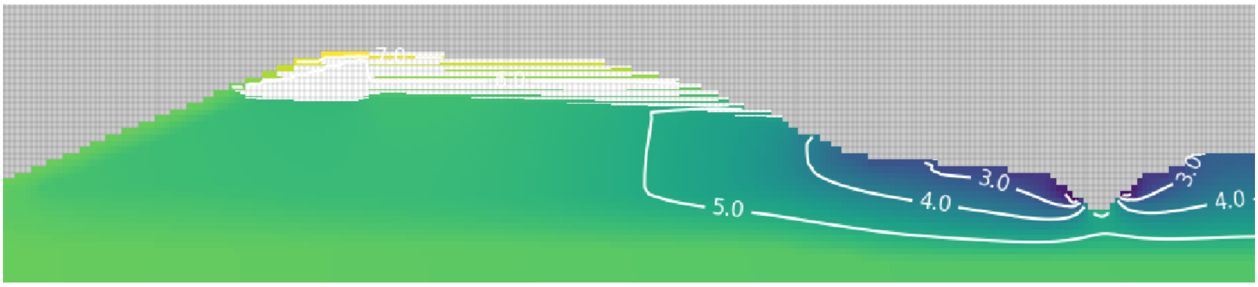


Figure 28, Limitation in saturation of cells in the model

# 8 CONCLUSION

### What variables are important when determining the phreatic line?

Three types of variables are identified; soil parameters, water levels and parameters related to wave overtopping. Herein, the parameters related to water levels and wave overtopping are modelled deterministically for one recurrence time because also one recurrence time is used to assess failure mechanisms in the Netherlands. On the other hand, the specific yield, infiltration capacity and hydraulic conductivity of the clay layer, sand core and clay covering are modelled stochastically because the model is the most sensitive to these parameters.

### Which methods are there to determine the phreatic line and which method is the most suitable?

In this section, four groundwater flow models that could be used to determine the phreatic line are identified. Eventually, based on three criteria; applicability, accessibility and suitability for a probabilistic approach, MODFLOW is selected as the most suitable model. These advantages make MODFLOW the most suitable model:

- MODFLOW can be used in combination with a scripting tool and the programme has a relatively short simulation duration. This means that MODFLOW is very suitable for a probabilistic analysis.
- MODFLOW is more accessible than other models.
- MODFLOW is considered an international standard for groundwater modelling.

### How can the most suitable method be applied to express the phreatic line in a probability or confidence interval?

In order to express the phreatic line in a confidence interval or probability MODFLOW is used. In this model, the defined variables from sub-question 1 are used as input and the stochastic parameters are determined based on the sensitivity analysis. A Monte Carlo simulation is herein used as a probabilistic approach. The results from the model are 76 phreatic lines. These 76 phreatic lines can be used to express the phreatic line in a level of confidence, herein is assumed that the highest phreatic line is the worst-case scenario. A Python code is used to determine the level of confidence of the phreatic line. This code sorts the y coordinates from low to high for each x coordinate. Subsequently, the code extracts the y coordinate that is higher or equal to the pre-defined percentage (for example 90%) of the possible y coordinates. This results in the coordinates of the phreatic line with a 90% level of confidence. These coordinates can be used to plot the phreatic line with a 90% level of confidence in combination with the range of possible phreatic lines. The 90% level of confidence indicates that it can be said with 90% confidence that the actual phreatic line is located at or below the phreatic line with the 90% level of confidence.

### How does this derived phreatic line fit into the safety philosophy for the design of a flood defence?

The main conclusions from this chapter are that it is a realistic possibility to include the probabilistic approach in the current safety philosophy because the model can be used to determine the phreatic line both with and without wave overtopping. This would be an alternative approach to the phreatic line than using schematizations. The probabilistic aspect of the model has as advantage that it gives an insight into the range of possible phreatic lines. It therefore also gives an insight into the effect of changing variables on the phreatic line. This makes it possible to apply the probabilistic part of the model in practice. Namely, to use it in a fully probabilistic assessment of the macro-instability failure mechanism. Additionally, another application would be to use the probabilistic approach to the phreatic line if the uncertainty of some parameters is high. The probabilistic phreatic line would provide an insight into the uncertainty due to unknown parameter values and this uncertainty can be mitigated by using a high level of confidence.

### Main Question: How can the phreatic line be expressed in a probability or confidence interval?

All in all, the sub-questions provide an answer to the main question of this research. Therefore, the probabilistic approach used in this study is proposed as a method to determine the phreatic line in a probability or confidence interval. A summary of this proposed method can be found in Appendix VI. In the final sub-question, the advantages of this probabilistic method and the insights this method can give are discussed.

# 9 RECOMMENDATIONS

In this research, a probabilistic method is proposed to determine the phreatic line with and without wave overtopping. This method provides an alternative view on how the phreatic line is currently determined. Furthermore, the probabilistic method provides insight into how changing variables affect the phreatic line, which can be used in combination with the level of confidence to mitigate the effects of uncertain or changing variables. However, in combination with the points mentioned in the discussion, further research could enhance this probabilistic method.

### Macro-Instability

The detailed analysis of the phreatic line that was recommended by Yaghi (2022) is done in this study. In the current probabilistic approach for STBI, one phreatic line is used throughout the entire analysis. Therefore, a recommendation for further research would be to implement the probabilistic phreatic line from this research into the probabilistic approach for STBI. Herein, different levels of the phreatic line could be used to calculate the failure probability and safety factor for macro-instability probabilistically. This would result in an improved assessment of the STBI failure mechanism since the phreatic line plays an important role in this assessment.

### Other Dikes

As previously mentioned in the discussion, this research is a case study on a particular dike cross-section. Therefore, it is not known if the used approach also works on for example a clay dike. Different soil types can affect the phreatic line due to the difference in soil parameters. In order to use the probabilistic approach on a larger scale, the approach should also work on other dike types. Therefore, further research could look into how to implement the probabilistic approach on other dike types. Consequently, if the probabilistic approach is applied to multiple types of dikes in a research it would also become clear if the approach is applicable on a larger scale.

### Level of Confidence

In this research, the probabilistic phreatic line is expressed in a level of confidence. However, it lies outside of the scope of the research to determine what level of confidence is safe to use for the assessment of failure mechanisms. Additionally, it is difficult to recommend a level of confidence to be used based only on this research since the used approach is relatively new and only one dike-section is studied. Therefore, further research could look into what level of confidence for the phreatic line is most optimal to use for assessing flood defences.

### Stochastic Soil Parameters

In this research distributions for some variables were defined in order to model these variables stochastically. If the probabilistic approach would be implemented on a large scale, it would be useful to have standard distributions for the soil parameters. This would save a significant amount of time in comparison to when the soil parameters have to be defined for each dike section separately. Therefore, further research could look into the possibility of standard stochastic distributions for soil parameters and how to define these distributions.

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## DETERMINISTIC SOIL PARAMETER DERIVATION

**Hydraulic Conductivities:**

In order to determine the hydraulic conductivities of the different soil layers of the cross-section, soil samples have to be used. Two representative soil samples were chosen from the case study area (DINOloket, 2023), these will be used to determine the hydraulic conductivities. The soil samples can be seen in Figure 29. In the soil samples, the lithostratigraphy (geological formations) and soil types are displayed.

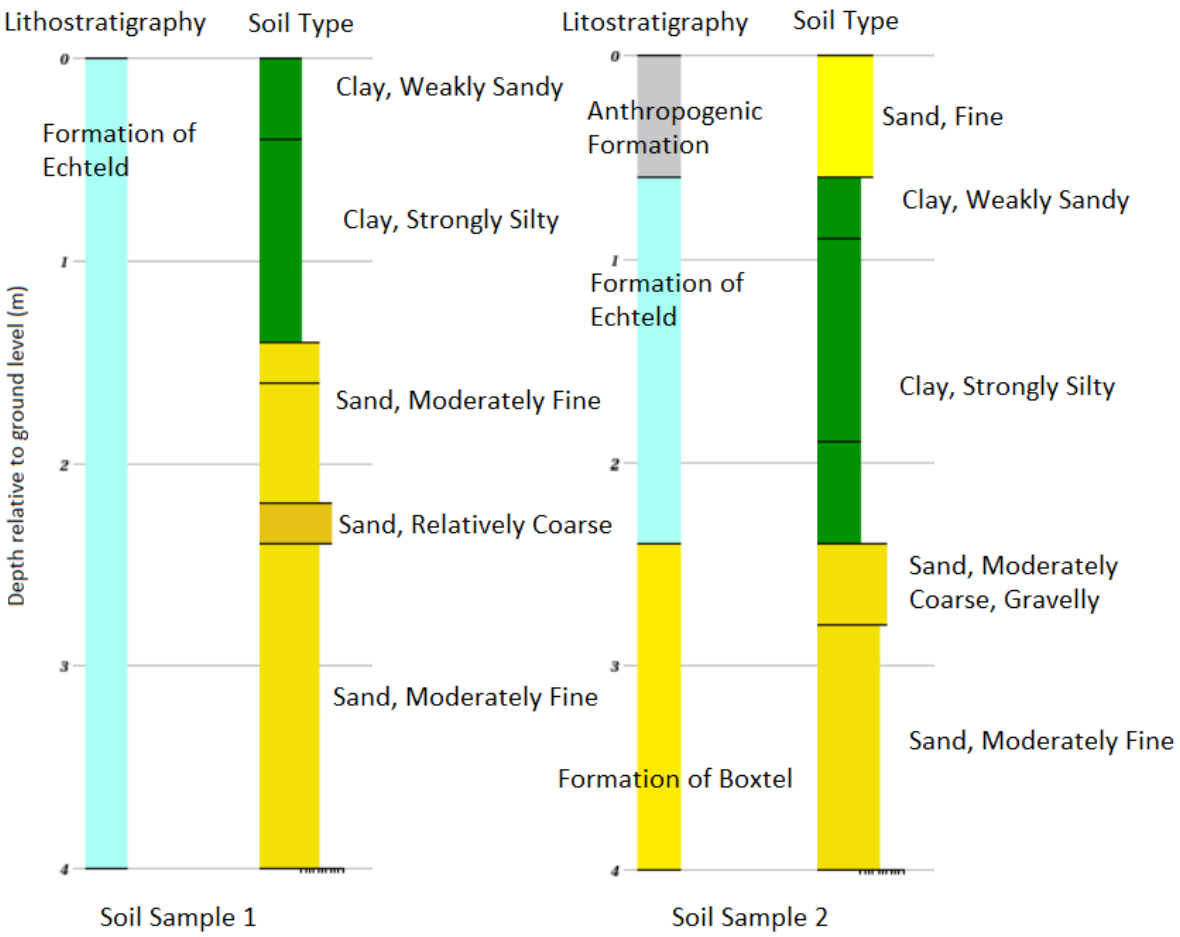


Figure 29, Representative soil samples from the case study area (DINOloket, 2023)

For the first layer of the cross-section, which is the deep sand layer, the grain sizes differ from moderately fine to relatively coarse. This could mean that the hydraulic conductivity of this layer is between 3 and 30 m/d (Bot, 2011), which is a large range. Luckily, permeability tests are available for this soil layer (Klop & van Meekeren, 2021). Based on these measurements the hydraulic conductivity of the deep sand layer is assumed to be 15 m/d.

In the soil samples can be seen that the grain sizes of the clay are relatively large because it is sandy/silty clay. The hydraulic conductivity of sandy clay is 0.05 m/day (Bot, 2011). Therefore, this value will be used as the hydraulic conductivity for the clay layer.

The formation of the sand core of the dike is anthropogenic (de Jager, 2022). In the second soil sample, it can be seen that the sand of this anthropogenic formation in the case study area is fine. According to Bot (2011), the hydraulic conductivity of fine sand is between 1 and 10 m/d. Therefore, a hydraulic conductivity of 5 m/d will be assigned to this soil layer.

Finally, the fourth layer, which is the thick clay covering on the outer slope of the dike. This covering of clay consists of relatively heavy clay, this is done to prevent erosion as a result of waves crashing on the dike (IJsselwerken Zwolle-Olst, 2021). The hydraulic conductivity of relatively heavy clay is 0.01 m/day. Therefore, this value will be used.

### Specific Storage:

The value for the specific storage can be calculated with Equation 7, as this was also discussed in section 3.1.1. The specific storage has to be calculated for clay and sand separately since some of the variables differ. The input values and the values for the specific storage can be seen in Table 6.

$$S_s = \rho_w g(m_v + n\beta)$$

Equation 7, Formula for the specific storage (TAW, 2004)

Table 6, Calculation of the specific storage

| Parameter | Value for Clay | Value for Sand | Source |
|---|---|---|---|
| $\rho_w$ (kg/m$^3$) | 1000 | 1000 | (USGS, 2018) |
| g (m/s$^2$) | 9.81 | 9.81 | (Engineering ToolBox, 2003) |
| $m_v$ (m$^2$/N) | 5.5E-07 | 5.5E-08 | (TAW, 2004) (Average value was taken) |
| n (-) | 0.42 | 0.41 | (Todd & Mays, 2005) |
| β (m$^2$/N) | 5E-10 | 5E-10 | (TAW, 2004) |
| $S_s$ (L$^{-1}$) | 5.40E-03 | 5.42E-04 | |

## II MODFLOW 6 AND USED PACKAGED IN THE MODEL

Within MODFLOW 6 there are 2 types of hydrological models: the groundwater flow model (GWF) and the groundwater transport model (GWT) (USGS, 2022b). For this research, the groundwater flow model will be used. The GWF model makes use of the control-volume-finite-difference (CVFD) method.

The CVFD method makes use of a mathematical method based on Darcy's law. First, the mathematical model will be explained in order to understand the CVFD method. Three-dimensional groundwater flow through porous earth material can be described by Equation 8 (Darcy, 1856).

$$q = -K\Delta h = -\begin{pmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & o & K_{zz} \end{pmatrix} \Delta h$$

Equation 8, Formula for t Three-dimensional groundwater flow through porous earth material (Darcy, 1856)

Where, q is a vector of specific discharge (L/T), $K_{xx}$, $K_{yy}$ and $K_{zz}$ are hydraulic conductivities in x, y and z directions and Δh is the head gradient vector. This formula combined with a water balance on a small volume leads to a partial differential equation (Langevin, et al., 2017). This partial-differential equation describes the distribution of hydraulic head and can be seen in Equation 9.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + Q'_s = SS\frac{\partial h}{\partial t},$$

Equation 9, Partial-differential equation that describes the distribution of hydraulic head (Langevin, et al., 2017)

Where $Q'_s$ is a volumetric flux unit per volume, this represents sinks and sources of water (Langevin, et al., 2017). A positive $Q'_s$ represents flow into the system and a negative $Q'_s$ represents flow out of the system. SS is the specific storage ($L^{-1}$) of the system and t is time (T). A mathematical representation of a groundwater flow system is represented when Equation 9 is combined with the specification of initial head conditions and specification of head and flow conditions at the boundary of the groundwater system.

It is rarely possible to find analytical solutions for Equation 9, with an exception for very simple systems (Langevin, et al., 2017). Therefore, numerical methods should be used to calculate approximate solutions. One of these numerical methods is the CVFD method. In this method, the continuous Equation 9 is replaced by a finite set of discrete points. Additionally, the partial derivatives are replaced by calculated terms from the head difference at the discrete points. The outcome of this method is a value for the head at specific times and points. These values are an approximation of the head distribution over time from Equation 9.

The GWF model is structured in cells. Within each cell is a point for which the head is calculated, this point is called a node (Langevin, et al., 2017). All the cells and the connections between the cells is called the model grid. When cells are connected, groundwater flow can occur between these cells under the influence of the hydraulic gradient. Furthermore, the GWF model is divided into packages. A package simulates a certain aspect of the model. For example, the Lake package simulates the effect of lakes. In the model used for this research, several packages were used. An overview of the used packages and their functions can be seen in Table 7.

Table 7, Used packages and their functions (Langevin, et al., 2017)

| Package | Function |
|---|---|
| Discretization (DIS) | This package is used to calculate the surface area and volumes of cells and the geometric properties of connections between cells. |
| Initial Conditions (IC) | This package reads the initial head values (starting values) for a simulation. |
| Node Property Flow (NPF) | The NPF package calculates the flow and hydraulic conductance between adjacent cells. Additionally, it manages drying and wetting of cells. |

| Package | Function |
|---|---|
| Storage (STO) | This package calculates the change in groundwater storage over different time steps. |
| Specified Head (CHD) | The CHD package assigns a constant head value to selected cells. |
| River (RIV) | The river package is used to simulate water flow between surface water and groundwater features. |
| General-Head Boundary (GHB) | The function of this package is to simulate flow out or into a cell from an external source. |
| Drain (DRN) | This package simulates the removal of water from the groundwater systems based on the differences in head. |
| Output Control (OC) | This package indicates what types of data and the time steps for which this data has to be saved. |

Some of the packages needed to be assigned to specific locations in the cross-section, an overview of this can be seen in Figure 30. Firstly, the GHB package is used to model wave overtopping. This package is added from just above the water level to the inner toe of the dike. The DRN package has been added from the point just above the water level to the end of the model, except for the location of the water level in the ditch. When the pressure in the soil near the drain is higher than the pressure outside the dike, groundwater will be drained from the system. It can be seen that the RIV package has been added to two locations in the model. Firstly, the package has been added to the outer side of the dike until the height of the water level. Secondly, the package has been added to the ditch. The water level in this ditch is 1.6 m+NAP in the summer and 1.35 m+NAP in the winter (data provided by Witteveen+Bos). Therefore, a water level of 1.5 m+NAP was assigned to the ditch. This value is chosen because only steps of 0.25 could be used due to the cell size. Finally, the CHD package was used to assign a constant value for the head at the left border of the deep sand layer. This value is assumed to have the same value as the water level.

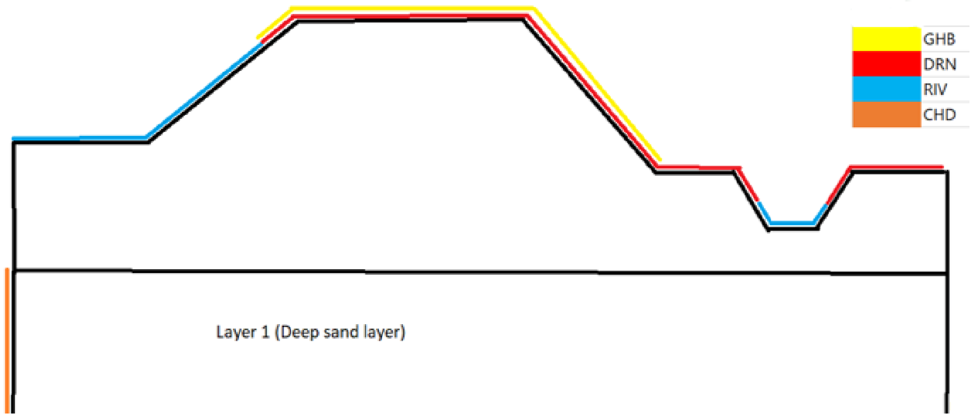


Figure 30, Location of some packages within the cross-section

## III CALCULATION OF THE NECESSARY NUMBER OF SIMULATIONS

In order to perform a reliable simulation study the number of simulations have to be determined. For this, the confidence interval method is used. The formula for this can be seen in Equation 10. In this analysis, the number of simulations is sufficient if the value of the left side of the formula lower is than d (Robinson, 2004). The key performance indicator (KPI), which is the value on which the analysis is conducted, is the y coordinate of the phreatic line at x=89.05.

$$\frac{t_{n-1,1-\frac{a}{2}}\sqrt{\frac{S^2}{n}}}{|\bar{X}|} < d$$

Equation 10, Rewritten formula for the confidence interval method (Robinson, 2004)

Where $t_{n-1,1-a/2}$ is the T-value of n degrees of freedom with α confidence, $S^2$ is the variance of the KPI values, n is the number of simulations, $|\bar{X}|$ is the mean of the KPI values and d is the relative error (Robinson, 2004). For this analysis, the level of confidence is set to 95%. This means that the relative error (d) is 0.025 since (1-0.95)/2 = 0.025.

The results from this analysis can be found in Figure 31, Figure 32 and Table 8. From this can be concluded that 76 simulations are necessary to obtain reliable results.

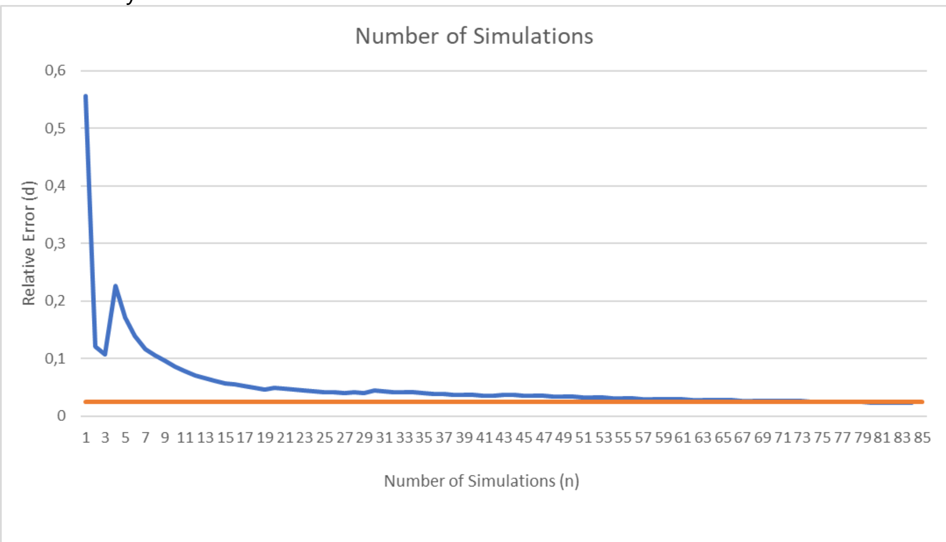


Figure 31, Necessary number of simulations

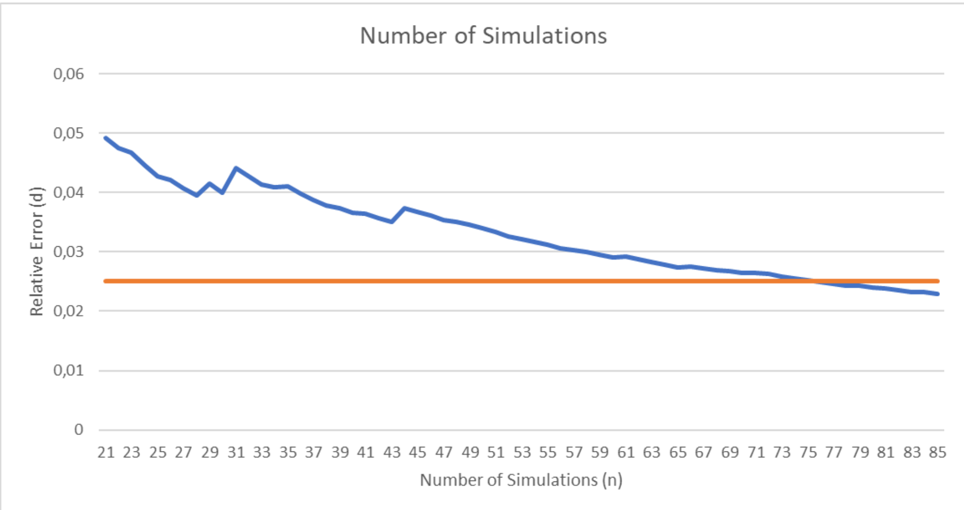


Figure 32, Necessary number of simulations (zoomed in)

Table 8, Necessary number of simulations

| n | value of the KPI | mean | variance | t-value | error (left side of formula) | Test (if left side is smaller than 0.25) |
|---|---|---|---|---|---|---|
| 1 | 5,023743 | | | | | |
| 2 | 4,602162 | 4,812953 | 0,088865 | 12,7062 | 0,556488 | not enough |
| 3 | 5,004166 | 4,876691 | 0,05662 | 4,302653 | 0,121209 | not enough |
| 4 | 4,363007 | 4,74827 | 0,103714 | 3,182446 | 0,107923 | not enough |
| 5 | 6,75165 | 5,148946 | 0,880492 | 2,776445 | 0,226281 | not enough |
| 6 | 5,029911 | 5,129107 | 0,706755 | 2,570582 | 0,172008 | not enough |
| 7 | 4,916162 | 5,098686 | 0,595441 | 2,446912 | 0,139968 | not enough |
| 8 | 5,25258 | 5,117923 | 0,513338 | 2,364624 | 0,117038 | not enough |
| 9 | 4,604409 | 5,060866 | 0,47847 | 2,306004 | 0,105061 | not enough |
| 10 | 5,763886 | 5,131168 | 0,474731 | 2,262157 | 0,096057 | not enough |
| 11 | 5,263735 | 5,143219 | 0,428855 | 2,228139 | 0,085539 | not enough |
| 12 | 5,026046 | 5,133455 | 0,391013 | 2,200985 | 0,077395 | not enough |
| 13 | 5,532633 | 5,164161 | 0,370685 | 2,178813 | 0,071244 | not enough |
| 14 | 5,25335 | 5,170531 | 0,342739 | 2,160369 | 0,065375 | not enough |
| 15 | 5,511809 | 5,193283 | 0,326023 | 2,144787 | 0,060886 | not enough |
| 16 | 5,531608 | 5,214429 | 0,311442 | 2,13145 | 0,057029 | not enough |
| 17 | 5,774452 | 5,247371 | 0,310425 | 2,119905 | 0,054592 | not enough |
| 18 | 5,015318 | 5,234479 | 0,295157 | 2,109816 | 0,051613 | not enough |
| 19 | 5,264475 | 5,236058 | 0,278806 | 2,100922 | 0,048605 | not enough |
| 20 | 5,513487 | 5,249929 | 0,267981 | 2,093024 | 0,046148 | not enough |
| 21 | 4,125758 | 5,196397 | 0,314761 | 2,085963 | 0,049146 | not enough |
| 22 | 4,76077 | 5,176596 | 0,308398 | 2,079614 | 0,047564 | not enough |
| 23 | 4,596133 | 5,151359 | 0,309029 | 2,073873 | 0,046666 | not enough |
| 24 | 5,256146 | 5,155725 | 0,296051 | 2,068658 | 0,044563 | not enough |
| 25 | 5,313639 | 5,162041 | 0,284713 | 2,063899 | 0,042668 | not enough |
| 26 | 4,555694 | 5,13872 | 0,287465 | 2,059539 | 0,042143 | not enough |
| 27 | 5,510985 | 5,152508 | 0,281541 | 2,055529 | 0,040737 | not enough |
| 28 | 4,807293 | 5,140179 | 0,27537 | 2,051831 | 0,039586 | not enough |
| 29 | 4,019287 | 5,101527 | 0,308859 | 2,048407 | 0,041438 | not enough |
| 30 | 5,291066 | 5,107845 | 0,299407 | 2,04523 | 0,040001 | not enough |
| 31 | 6,843532 | 5,163835 | 0,386607 | 2,042272 | 0,044167 | not enough |
| 32 | 5,10098 | 5,161871 | 0,37426 | 2,039513 | 0,04273 | not enough |
| 33 | 5,017508 | 5,157496 | 0,363196 | 2,036933 | 0,041433 | not enough |
| 34 | 4,543506 | 5,139438 | 0,363277 | 2,034515 | 0,040919 | not enough |
| 35 | 4,294718 | 5,115303 | 0,37298 | 2,032245 | 0,041012 | not enough |
| 36 | 5,25335 | 5,119138 | 0,362853 | 2,030108 | 0,039814 | not enough |
| 37 | 5,28303 | 5,123567 | 0,3535 | 2,028094 | 0,038691 | not enough |
| 38 | 5,515789 | 5,133889 | 0,347994 | 2,026192 | 0,037768 | not enough |
| 39 | 4,524438 | 5,118262 | 0,34836 | 2,024394 | 0,037381 | not enough |
| 40 | 4,81246 | 5,110617 | 0,341766 | 2,022691 | 0,036584 | not enough |
| 41 | 4,40145 | 5,09332 | 0,345488 | 2,021075 | 0,036426 | not enough |
| 42 | 4,781288 | 5,085891 | 0,339379 | 2,019541 | 0,035695 | not enough |
| 43 | 4,7902 | 5,079014 | 0,333332 | 2,018082 | 0,034984 | not enough |
| 44 | 6,847015 | 5,119196 | 0,396622 | 2,016692 | 0,037402 | not enough |
| 45 | 4,765692 | 5,11134 | 0,390385 | 2,015368 | 0,036725 | not enough |
| 46 | 4,767967 | 5,103876 | 0,384273 | 2,014103 | 0,036068 | not enough |
| 47 | 4,887113 | 5,099264 | 0,376919 | 2,012896 | 0,03535 | not enough |
| 48 | 4,524525 | 5,08729 | 0,375781 | 2,011741 | 0,034989 | not enough |

| | | | | | | |
|---|---|---|---|---|---|---|
| 49 | 5,752454 | 5,100865 | 0,376981 | 2,010635 | 0,034574 | not enough |
| 50 | 4,757727 | 5,094002 | 0,371643 | 2,009575 | 0,034011 | not enough |
| 51 | 5,049907 | 5,093137 | 0,364248 | 2,008559 | 0,033328 | not enough |
| 52 | 5,272672 | 5,09659 | 0,357726 | 2,007584 | 0,032671 | not enough |
| 53 | 5,511147 | 5,104412 | 0,354089 | 2,006647 | 0,032132 | not enough |
| 54 | 4,769309 | 5,098206 | 0,349488 | 2,005746 | 0,03165 | not enough |
| 55 | 5,502361 | 5,105555 | 0,345986 | 2,004879 | 0,031145 | not enough |
| 56 | 5,260889 | 5,108328 | 0,340126 | 2,004045 | 0,030574 | not enough |
| 57 | 4,637899 | 5,100075 | 0,337935 | 2,003241 | 0,030244 | not enough |
| 58 | 4,52122 | 5,090095 | 0,337783 | 2,002465 | 0,030022 | not enough |
| 59 | 5,055983 | 5,089517 | 0,331979 | 2,001717 | 0,029502 | not enough |
| 60 | 4,77039 | 5,084198 | 0,32805 | 2,000995 | 0,029102 | not enough |
| 61 | 4,277487 | 5,070973 | 0,333251 | 2,000298 | 0,029156 | not enough |
| 62 | 4,800742 | 5,066615 | 0,328965 | 1,999624 | 0,028748 | not enough |
| 63 | 5,25258 | 5,069566 | 0,324208 | 1,998972 | 0,028286 | not enough |
| 64 | 5,297154 | 5,073123 | 0,319872 | 1,998341 | 0,027848 | not enough |
| 65 | 5,058558 | 5,072898 | 0,314877 | 1,99773 | 0,027409 | not enough |
| 66 | 4,272986 | 5,060779 | 0,319727 | 1,997138 | 0,027467 | not enough |
| 67 | 5,531765 | 5,067808 | 0,318194 | 1,996564 | 0,02715 | not enough |
| 68 | 4,538583 | 5,060026 | 0,317564 | 1,996008 | 0,026957 | not enough |
| 69 | 4,523292 | 5,052247 | 0,317069 | 1,995469 | 0,026774 | not enough |
| 70 | 4,81665 | 5,048881 | 0,313266 | 1,994945 | 0,026433 | not enough |
| 71 | 4,285347 | 5,038127 | 0,317002 | 1,994437 | 0,026452 | not enough |
| 72 | 4,510404 | 5,030798 | 0,316405 | 1,993943 | 0,026274 | not enough |
| 73 | 5,064599 | 5,031261 | 0,312026 | 1,993464 | 0,025904 | not enough |
| 74 | 5,260898 | 5,034364 | 0,308465 | 1,992997 | 0,025559 | not enough |
| 75 | 5,060722 | 5,034715 | 0,304306 | 1,992543 | 0,025209 | not enough |
| 76 | 5,318332 | 5,038447 | 0,301306 | 1,992102 | 0,024895 | enough |
| 77 | 5,061341 | 5,038744 | 0,297349 | 1,991673 | 0,024563 | enough |
| 78 | 4,827401 | 5,036035 | 0,29406 | 1,991254 | 0,024278 | enough |
| 79 | 4,269753 | 5,026335 | 0,297722 | 1,990847 | 0,024315 | enough |
| 80 | 5,00635 | 5,026085 | 0,293959 | 1,99045 | 0,024006 | enough |
| 81 | 4,570732 | 5,020464 | 0,292844 | 1,990063 | 0,023834 | enough |
| 82 | 5,032308 | 5,020608 | 0,289231 | 1,989686 | 0,023537 | enough |
| 83 | 5,083357 | 5,021364 | 0,285751 | 1,989319 | 0,023245 | enough |
| 84 | 4,327765 | 5,013107 | 0,288035 | 1,98896 | 0,023233 | enough |
| 85 | 5,029988 | 5,013306 | 0,284609 | 1,98861 | 0,022953 | enough |

# IV SENSITIVITY OF PARAMETERS

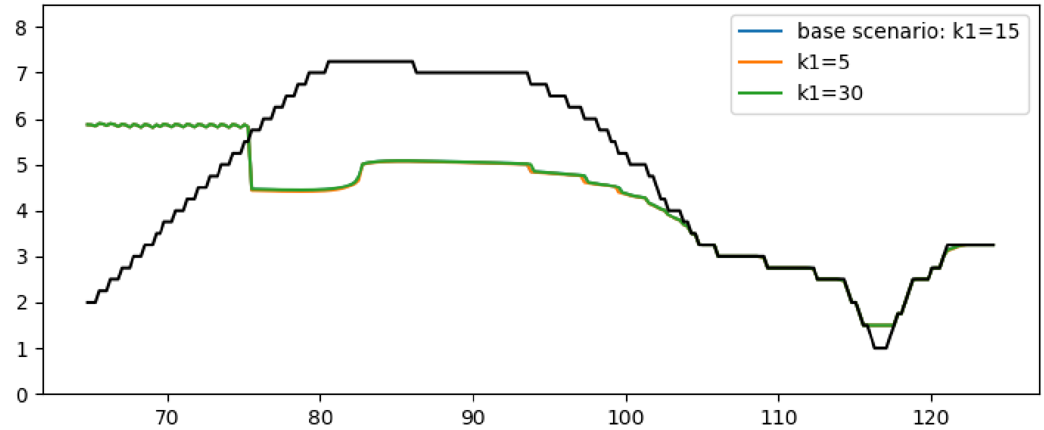


Figure 33, Sensitivity of the hydraulic conductivity of layer 1

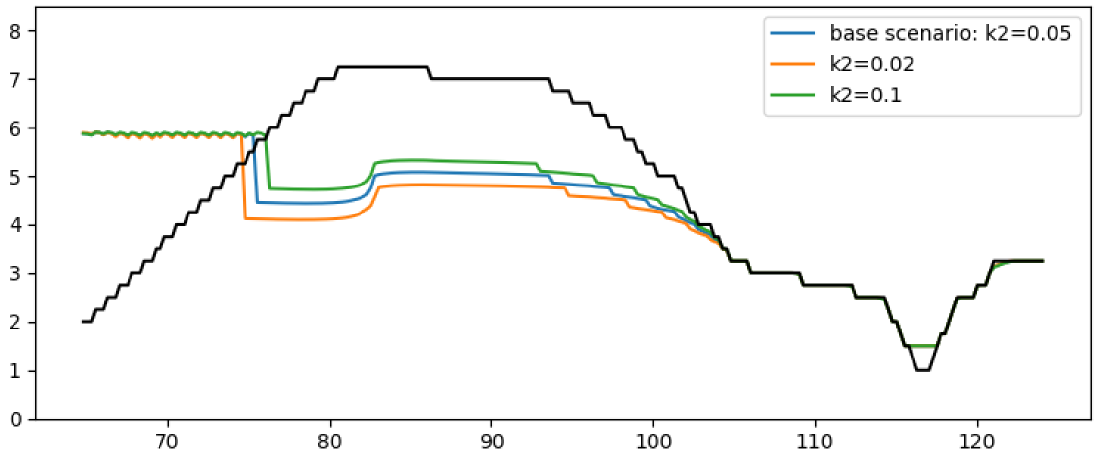


Figure 34, Sensitivity of the hydraulic conductivity of layer 2

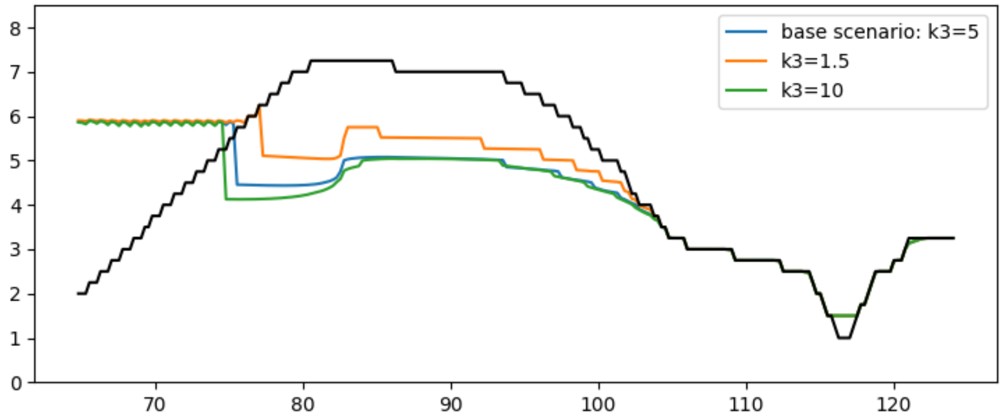


Figure 35, Sensitivity of the hydraulic conductivity of layer 3

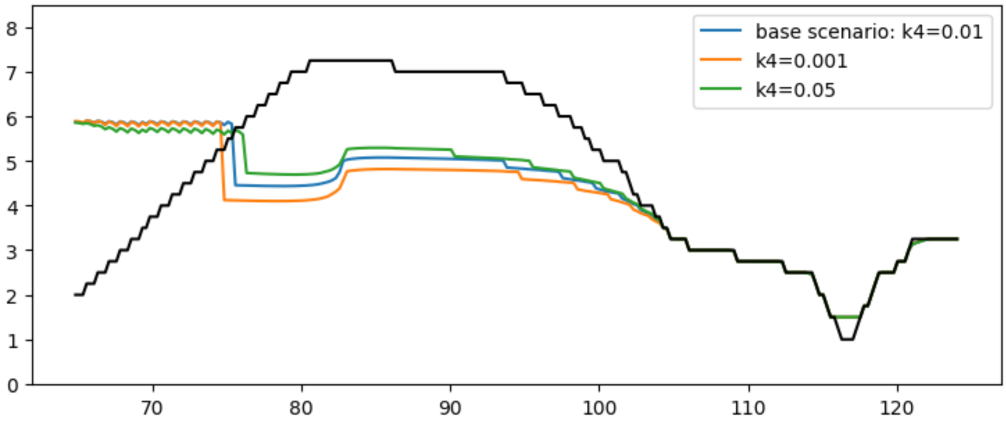


Figure 36, Sensitivity of the hydraulic conductivity of layer 4

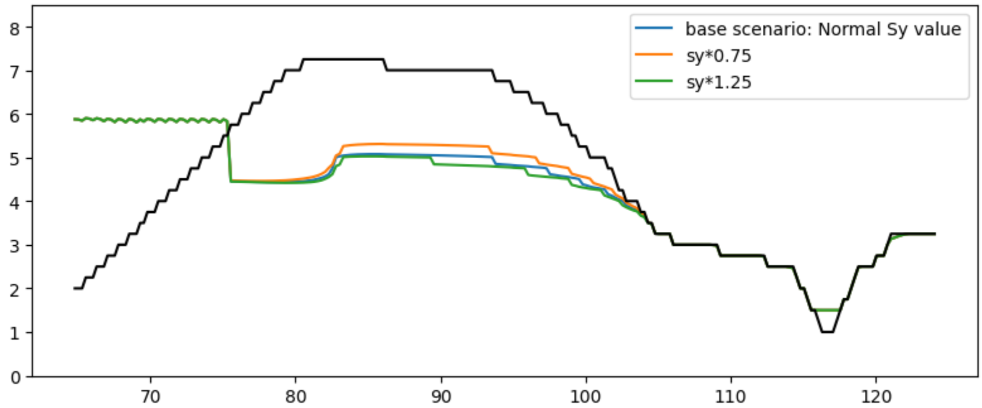


Figure 37, Sensitivity of the specific yield

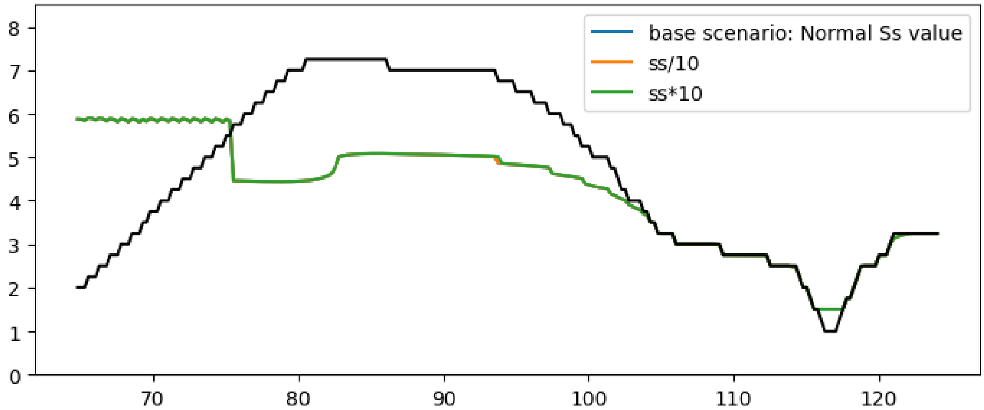


Figure 38, Sensitivity of the specific storage

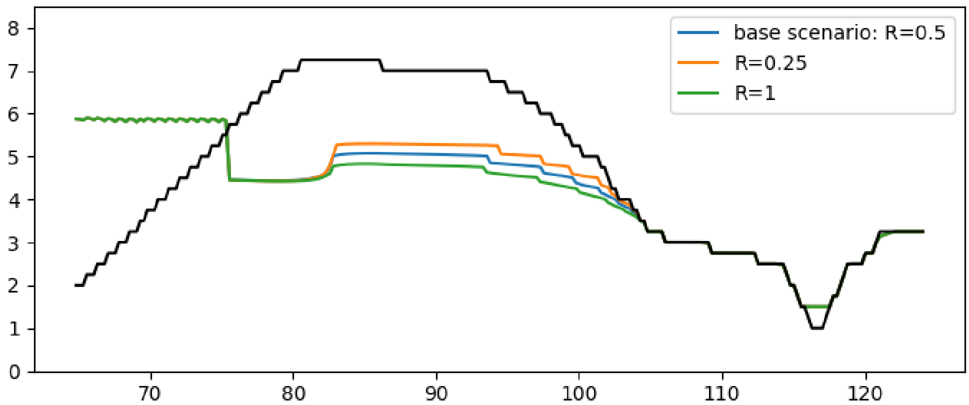


Figure 39, Sensitivity of the resistance factor

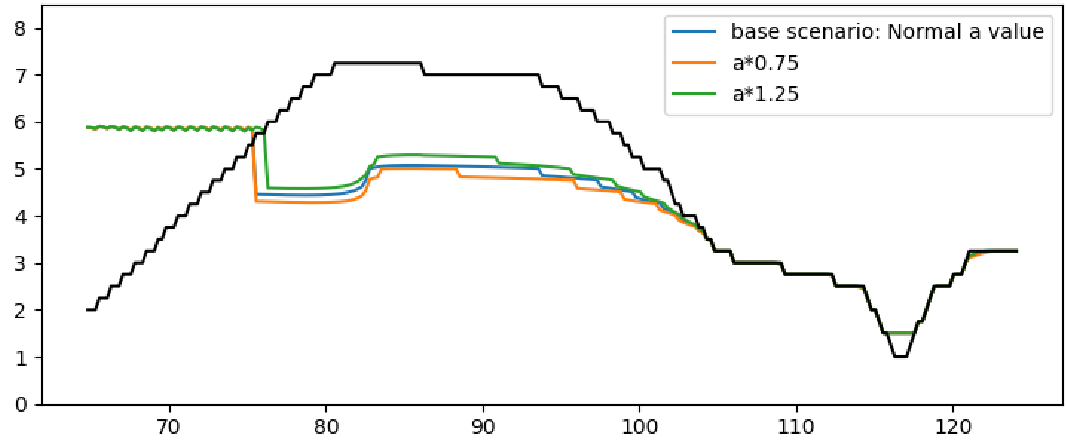


Figure 40, Sensitivity of the hydraulic conductivity anisotropy ratio

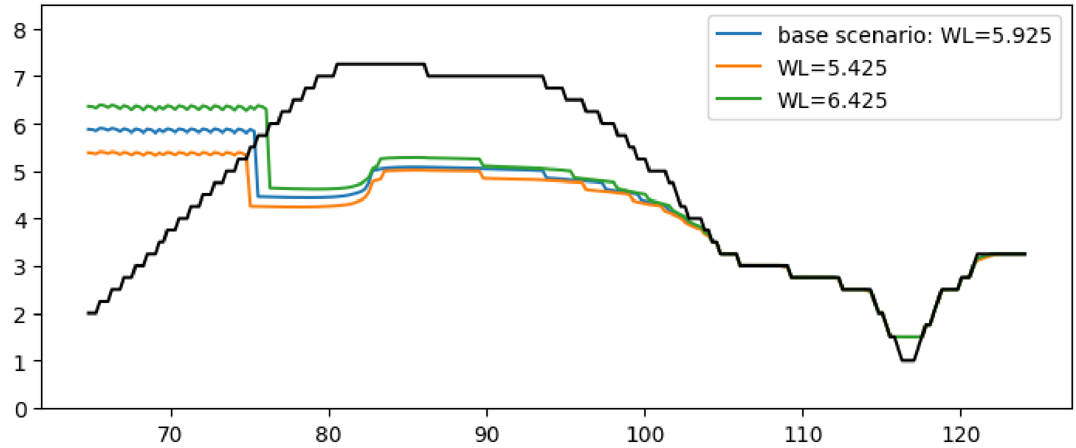


Figure 41, Sensitivity of water levels

# V DISTRIBUTIONS OF STOCHASTIC VARIABLES

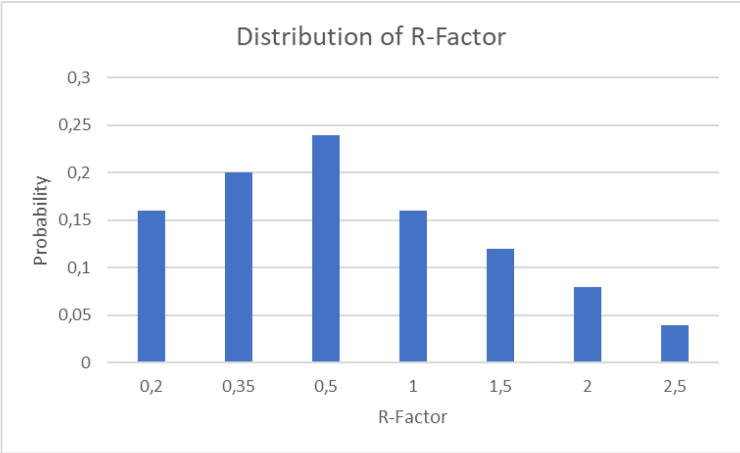


Figure 42, Distribution of the resistance factor

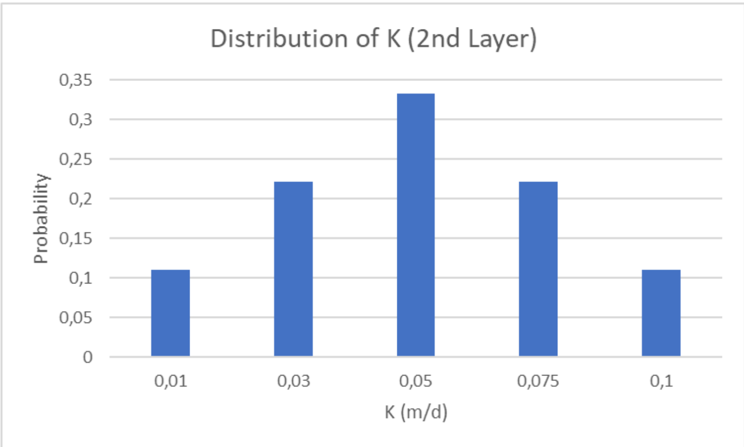


Figure 43, Distribution of the hydraulic conductivity of the second layer

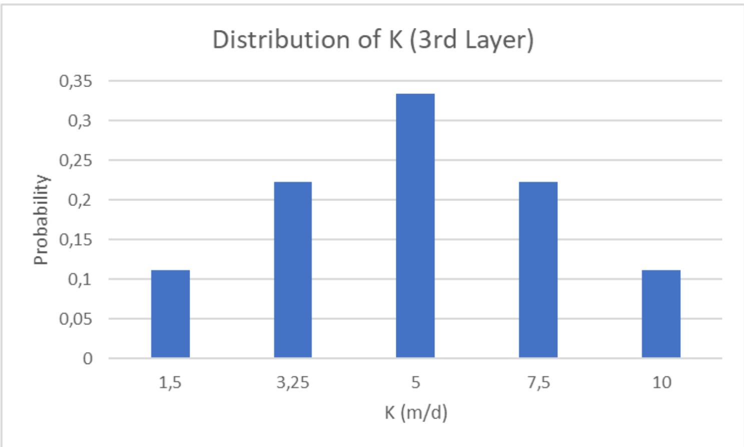


Figure 44, Distribution of the hydraulic conductivity of the third layer

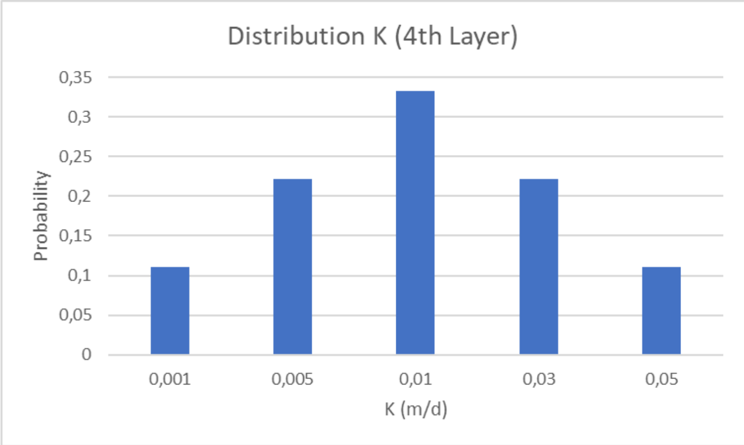


Figure 45, Distribution of the hydraulic conductivity of the fourth layer

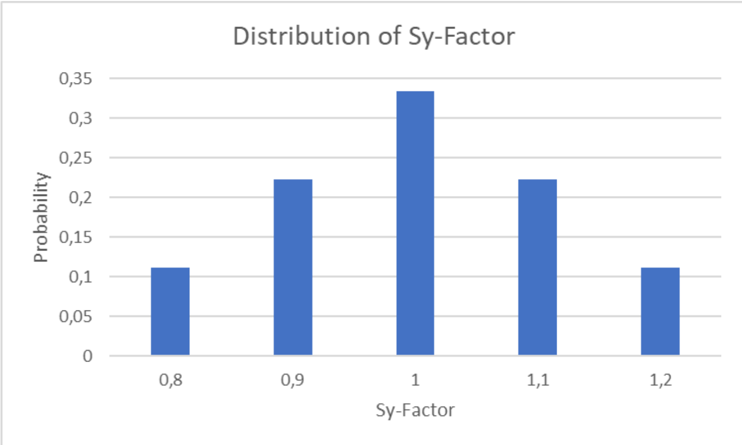


Figure 46, Distribution of the specific yield factor

# VI SUMMARY OF THE PROBABILISTIC APPROACH USED IN THIS RESEARCH

1. Define the soil parameters and by doing so also decide which parameters are going to be modelled stochastic and deterministic. For the stochastic parameters also distributions with possible values for the parameter should be defined.
2. Use Hydra-NL to obtain the water level, significant wave height and wave overtopping discharge for a given recurrence time (Rijksoverheid, 2020). Subsequently, the significant wave height and wave overtopping discharge can be used to determine the percentage of time in which infiltration takes place. Now, the duration of simulation can be calculated. This is used as input for the model, next to the water level.
3. Now the MODFLOW model can be built, this is done by using FloPy to run the MODFLOW model through Python. First, the cross-section with soil types and geometry has to be drawn in QGIS (QGIS, 2023). The QGIS file is then translated into the model grid automatically.
4. Add wave overtopping to the model by adding the GHB package of MODFLOW from just above the water level until the inner toe of the dike. The resistance factor has to be obtained through calibration. For this calibration, the infiltration capacity has to be used. Most ideally, the infiltration capacity is determined using field infiltration tests. Otherwise, the average infiltration capacity can be used in combination with a wide range of possible resistance factors as stochastic input for the model. For the calibration average values for the parameters defined in steps 1 and 2 can be used.
5. A Monte Carlo Simulation will be used as probabilistic approach. This approach has to be implemented in the model as well. Herein 3 steps have to be taken.
   a) Determine the number of simulations necessary to obtain reliable results, preferably with a 95% confidence level.
   b) Implement the time discretization in the model. Important herein is to implement a timestep in which the phreatic line without the effects of wave overtopping is determined. The final time step herein should be equal to the duration of simulation defined in step 2.
   c) Use a Python code to randomly extract values for the stochastic parameters from the defined distributions, in order to have different inputs for each simulation. Subsequently, the input (both stochastic and deterministic) can be added to an Excel sheet, the model extracts the variables from this Excel sheet.
6. Now that the model is constructed, the simulations can be performed in order to obtain the phreatic lines.
7. Define a desired level of confidence for the phreatic line. Based on all the phreatic lines found, the phreatic line with the defined level of confidence is determined by using a Python code.