ASSESSMENT OF MACROSTABILITY

The level of detail of the soil layers in a cross-section for both probabilistic and semi-probabilistic calculation methods

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Preface

This thesis is the final part of my Bachelor Civil Engineering at the University of Twente. The thesis was carried out at Witteveen+Bos. I have worked around 3 or 4 days a week at Witteveen + Bos in Deventer. During my time at Witteveen+Bos, I also have vistited the offices in Utrecht and Rotterdam.

First I would like to thank the group Waterkeringen for their input in my thesis. Everyone was open for questions and helpfull. I really appreciated, that I could be at the meetings from Waterkeringen Deventer but also from the other locations together. I would especially like to thank David Barmentloo for supervising me. I really liked the way the thesis went and the discussions we have had were very helpfull. Last but not least, I want to thank Weiqiu Chen for her supervision. Her feedback about my writing was very helpfull.

I hope you will enjoy reading this bachelor thesis.

Hilbert Buijs

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Parameter, figure and table list

PARAMETER	SYMBOL	UNIT
SHEAR STRENGTH RATIO	S	-
STRENGTH INCREASE COMPONENT	m	-
PRE-OVERBURDEN PRESSURE	POP	kN/m^2
COHESION	c	kN/m^2
SHEAR STRENGTH	τ	kN/m^2
NORMAL STRESS	σ_n	kN/m^2
FRICTION ANGLE	θ	-
UNDRAINED SHEAR STRENGTH	S_u	kN/m^2
IN-SITU EFFECTIVE VERTICAL STRESS	$\sigma'_{v,i}$	kN/m^2
EFFECTIVE STRESS	σ'	kN/m^2
STRESS	σ	kN/m^2
PORE WATERPRESSURE	u	kN/m^2
OVER-CONSOLIDATION RATIO	OCR	kN/m^2
FAILURE PROBABILITY	f_p	$Year^{-1}$
RELIABILITY INDEX/BÉTA	β	-
SATURATED BÉTA	β_{sat}	-
UNSATURATED BÉTA	β_{unsat}	-
PROBABILITY OF OVERTOPPING	$P_{overtopping}$	-
STANDARD NORMAL DISTRIBUTION	ϕ	-
MODEL FACTOR	Y_d	-
DRIVING MOMENT	M_D	kNm
RESISTING MOMENT	M_R	kNm
FACTOR OF SAFETY	FoS/ γ_n	-
RANDOM VARIABLE	X	-
MEAN	μ	-
INFLUENCE FACTOR	α	-
STANDARD DEVIATION	σ	-

1. Introduction

The Netherlands is a unique country. Large parts of the Netherlands are below sea level, which makes the Netherlands vulnerable for floodings. The floodings are caused by the sea and the rivers like the Ijssel, Rijn and the Waal. To prevent floodings, dikes have been built in the past. However dikes are no guarantee for preventing floodings. The recent floodings in Limburg are a good example. The failure of a dike can occur on different locations and have different causes. The different causes of a dike to fail are called failure mechanisms. Dikes should be designed in a way that they can safely prevent a flooding with a certain return period which can be considered as the probability of its occurrence per year. Different regions in the Netherlands have different norms for their probability of flooding. In Figure 1, the norms for the probabilities of floodings are given. As visible in Figure 1, is there a large difference between the norms for different regions.

Figure 1: Flooding probabilities for the Netherlands (Informatiehuis Water, 2022)

Dutch governmental institutions have made manuals for the different failure mechanisms for which the dike should be checked and to make sure that the dike is sufficiently safe and thus meets the norms. The main law for dike safety document in the Netherlands is waterlaw. The 'Wettelijk Beoordelings Instrumentarium or WBI for the assessment of primary flood defences. Additionally, the method to calculate the hydraulic load is included (Rijksoverheid, 2017). There are other manuals like the 'schematiserings handleiding' that add to the WBI and support the procedure for the assessment.

The case in the thesis is a dike section of dikering 15 located at the Hollandsche Ijssel. This dike section needs reinforcement, because the dike does not meet the norms for failuremechanisms like overtopping and macrostability. It was not achievable to reinforce the total dikesection of 19 km of at once and therefore 10 km of the dike section is chosen for this reinforcement project. This reinforcement of the dike section is the project Krachtige IJssseldijken Krimpenerwaard or KIJK. For the reinforcement project KIJK multiple soil investigations have been executed. Project Overstijgende Verkenning Macrostabiliteit (i.e. Project Overstijgende Verkenning Macrostabiliteit) has also conducted soil investigations at the same dike section. POV-M is a project that targets to make new innovations applicable for the reinforcements of the dike for macrostability. The experiments executed by POV-M also include laboratory investigations (Rozing & Schweckendiek, 2016). The difference between the soil investigations is the location of the investigation. During the soil investigations of POV-M one small part of the dike is investigated in a high level of detail. For KIJK less samples have been taken, however the samples are spread over multiple locations.

2. Theoretical Framework

In this chapter, the theory that is used in this research is explained. With the help of the theory explained in this section about macrostability, a methodology is proposed to answer the research questions from Chapter 3.

2.1 Macrostability

As mentioned in the introduction, there are a lot of different failure mechanisms like overtopping, piping, macrostability and erosion. Macrostability is the failure of the dike due to slipping of the soil caused by a force larger than the resistance of the shear strength of the soil along a slipping plane, see Figure 2.

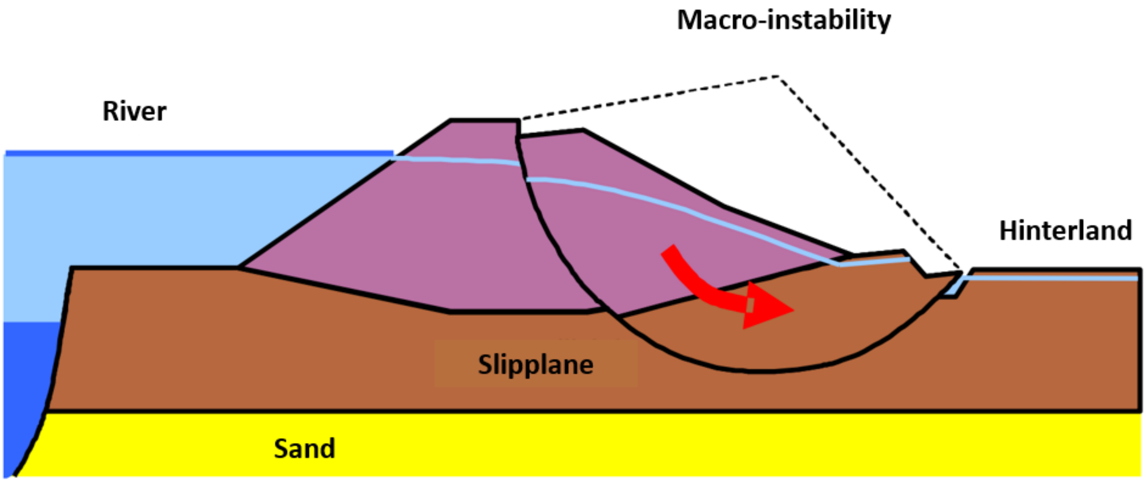


Figure 2: Macrostability (Rijkswaterstaat; Water Verkeer en Leefomgeving, 2021) (Translated to English)

There are three different locations where macro-instability can happen (i.e., the dike landward slope, the waterside slope and the foreshore). The thesis will focus on macrostability of the inner slope, see Figure 2. The moment created by a certain load is larger than the moment of resistance. This is also the defenition of the Factor of Safety or in Dutch 'stabiliteits factor', see Equation 1.

Equation 1: Factor of Safety

$$FoS = \frac{M_R}{M_S}$$

Where:
FoS = Factor of Safety [-]
M_R = Resisting moment [kNm]
M_S = Driving moment [kNm]

The shear strength of the soil contributes to the resisting moment and to the slipplane. The shear strength of soil is created by the friction of soil particles sliding over each other and the cohesion between the particles themselves. If the soil is saturated, the soil will slip faster due to a lower friction. Therefor, the waterlevel in the dike or the phreatic line is important for macrostability. To calculate the shear stress in soil and the slipplane, three different methods are used i.e., the Spencer method, Uplift Van method and the Bishop method. In Table 1, the different methods are displayed with their characteristics.

Table 1: Macrostability methods

Method	Equilibrium	Slipsurface	Method	Downsides	Benefits
Spencer	Forces and momentum	(Non-)circular	Slices method	Computation time	Friction between slices is taken into account
Bishop	Momentum equilibrium	Circular	Slices method	No horizontal force equilibrium	Easy calculations
Uplift Van	Horizontal force equilibrium and momentum equilibrium	(Non-)circular	Slices method		Computation time

2.2 Shear strength

This section about the shear strength of the soil consists of two parts. First, two methods for the calculation of the shear strength are addressed. Second, the soil state is explained. This settlement is used for the calculation of the shear strength in the first part of this section.

Methods

The shear strength of the soil is important for the macrostability of a dike. The shear strength can be determined in two different ways. The Mohr-Coulomb method and the critical stress state mechanics or CSSM using the Stress History and Normalized Soil Engineering Property or SHANEP. There are also two types of strength, the drained strength and the undrained strength.

The law of Mohr-Coulomb states that the shear stress has a linear relationship with the normal stress. This is also visible in Equation 2.

Equation 2: Law of Mohr-Coulomb

$$\tau = c + \sigma_n \tan\theta$$

Where:
τ = Shear strength [kN/m^2]
c = Cohesion [kN/m^2]
σ_n = Normal stress [kN/m^2]
θ = Friction angle [degrees]

The other method for soil shear strength is the Stress History and Normalized Soil Engineering Property or SHANSEP. SHANSEP considers the history of the soil. Consolidation of the soil increases the strength of the soil. The Mohr-Coulomb method does not consider this increase in strength. The SHANSEP method leads to Equation 3. This method is used in the Critical Soil State Mechanics or CSSM.

Equation 3: Undrained SHANEP

$$S_u = \sigma'_{v,i} * S * OCR^m$$

Where:
S_u = Undrained shear strength [kN/m^2]
$\sigma'_{v,i}$ = In-situ effective vertical stress [kN/m^2]
S = Shear strength ratio [-]
OCR = Over-Consolidation Ratio [-]
m = Strength increase component [-]

The benefit is that consolidation of the soil is considered. Another benefit is that strength parameters S and m can be estimated from the same sample in a statistical test. There are also downsides. The value of the strength parameter can differ from the value of the theory, due to limited data. In the schematization of the soil have the local stress situation and the level of over consolidation to be estimated. To conclude the SHANEP method is now more used than the Mohr-Coulomb method, while the SHANEP method gives a better indication of the shear strength.

Equation 4: Effective stress

$$\sigma' = \sigma - u$$

Where:
σ'= effective stress [kN/m^2]
σ = stress [kN/m^2]
u = pore water pressure [kN/m^2]

As mentioned in Equation 3 is the effective stress important for the shear strength. With Equation 4, the effective stress can be calculated. In this equation is also visible that the waterpressure decreases the effective stress. This results in that saturated soil slips easier.

Soil state

Besides soil strength parameter S and m, there is another parameter to quantify the soil state. The most commonly used parameter for this is the POP or pre-overburden pressure. The POP is expressed as a load per squard meter (kN/m^2). Dikes are frequently heightened and the loads are not removed, therefor the POP of the dike is not very high compared to the hinterland. In the hinterland the soil subsidence increases the POP. The difference between POP and OCR is that OCR is the ratio between the pressure and the POP is the difference, see Equation 5 and Equation 6 .

Equation 5: Overconsolidation Ratio

$$OCR = \frac{\sigma'_p}{\sigma'_{yy}}$$

Equation 6: Pre-Overburden Pressure

$$POP = \left|\sigma'_p - \sigma'_{yy}\right|$$

Where:
POP = Pre-Overburden Pressure[kN/m^2]
σ'_p = Pressure in the past [kN/m^2]
σ'_{yy} = Current pressure [kN/m^2]

There are two different soil characteristics regarding water in soil. There is drained soil and undrained soil. The drainage of the soil is caused by the soil type, geological formation and the rate of loading. If the soil is drained, the water can easily drain out of the soil. In undrained condition the pore water is unable to drain out of the soil and increases the pore pressure. If the pore pressure increases the effective stress decreases. For the macrostability calculations in D-stability, the low permeability layers are modelled as undrained layers and the aquifer layer is modelled as drained layers.

2.3 Schematization

A key step in the calculation of the failure probability of the dike for macrostability is the schematization. There are several parts in the schematization, these are:

- Geometry of the dike
- Waterlevel of the hinterland
- Mechanic properties of the soil
- Water pressure in the sand layer and the cover layer
- Soil build-up
- Waterlevel
- Phreatic line

2.4 Probabilistic and semi-probabilistic calculations

There are two main methods for calculation of macrostability. The probabilistic calculations and the semi-probabilistic calculations are visible in Figure 4, where in green the similarities and in red the differences are visible. The parameters in a probabilistic calculation are based on a distribution of values of the parameters. Therefore, the mean and standard deviation of each soil layer are the input for calculations. The mean and the standard deviation of these parameters are obtained during the soil investigation. The output of the calculations is a conditional probability of failure. With the help of the occurrence of the waterlevel, the failure probability per year is calculated, see Figure 3. For assessing the dike-stability the probability of failure is checked with the acceptable probability of failure to see whether the dike is sufficient for macrostability.

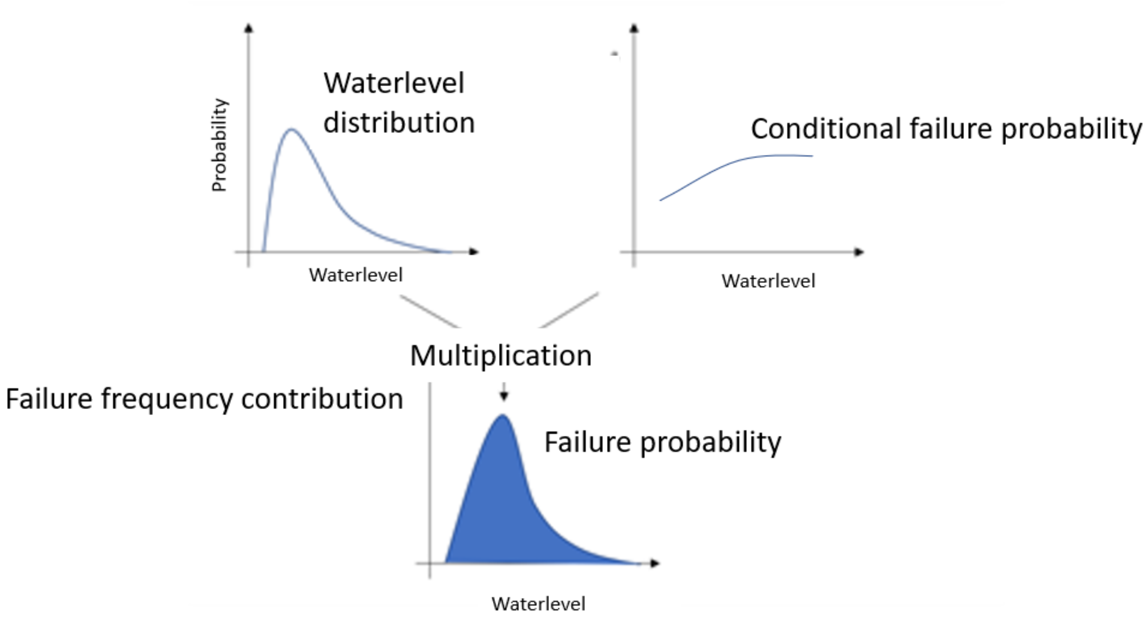


Figure 3: Failure probability

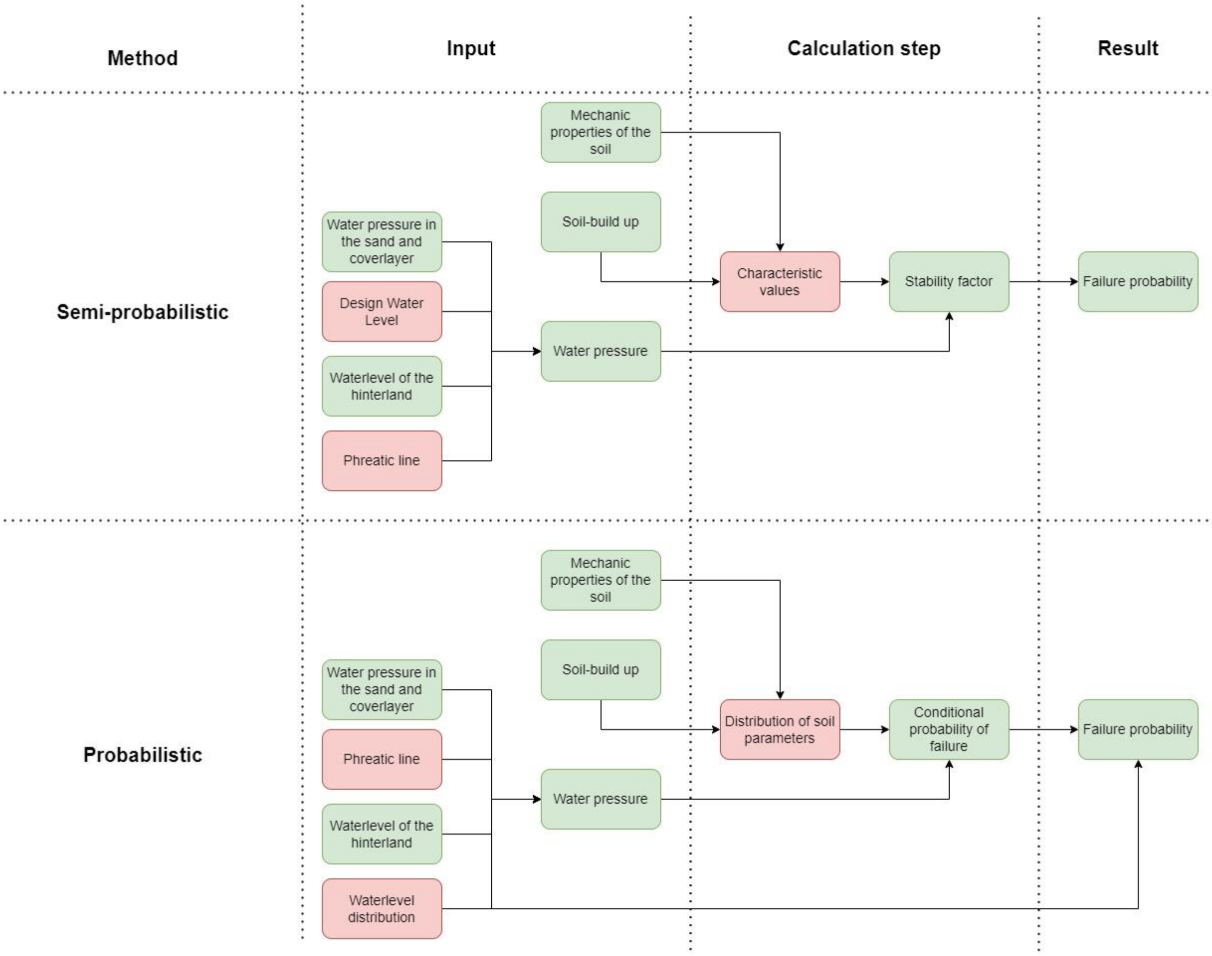


Figure 4: Schematization of macrostability methods

Another difference in Figure 4 is the waterlevel. The waterlevel with the same occurrence as the norm of the dike section is used in semi-probabilistic calculations. For the probabilistic calculations a distribution of the waterlevel is used, for an example see Appendix C. The use of different waterlevels also results in different phreatic lines. So for probabilistic calculations the phreatic line varies with the waterlevel, while semi-probabilistic calculations consider only one waterlevel and one phreatic line. In contradiction to the probabilistic calculations, semi-probabilistic calculations use characteristic values instead of a distribution, see Figure 4.

Failure probability

For the semi-probabilistic calculations a safety factor can be calculated. With Equation 7 giving the formula to translate the factor of safety provided by the semi-probabilistic calculations into a failure probabilit. The formula is based on the model used for the calculations, which can be Spencer, Bishop or Uplift Van. With a normal distribution the failure probability for the dike section can be calculated and checked with the norms to see whether the dike is sufficiently safe. For probabilistic calculations the output is a reliability-index. The reliability index can be rewritten into a failure probability with Equation 8.

Equation 7: Probability of failure

$$P_f = \phi(-\frac{\left(\frac{FoS}{\gamma_d}\right) - 0.41}{0.15})$$

Where:
P_f = Probability of failure [1/year]
ϕ = Standard normal distribution [-]
FoS = Factor of Safety/stability factor [-]
Y_d = Model factor [-]

Equation 8: Probabilistic probability of failure

$$P_f = \phi(-\beta)$$

Where:
P_f = Probability of failure [1/year]
ϕ = Standard normal distribution [-]
β = Reliability index [-]

Form-calculation

For probabilistic calculations is a FORM-calculation very common to calculate the reliability index. A FORM-calculation is an iterative process. The first estimate is the mean value in D-stability. After the itteration process, the variables have converged (Jonkman, Steenbergen, Morales-Nápoles, Vrouwenvelder, & Vrijling). With these variables the alpha values can be calculated. These alpha values indicate the failure frequency contribution of a single parameter.

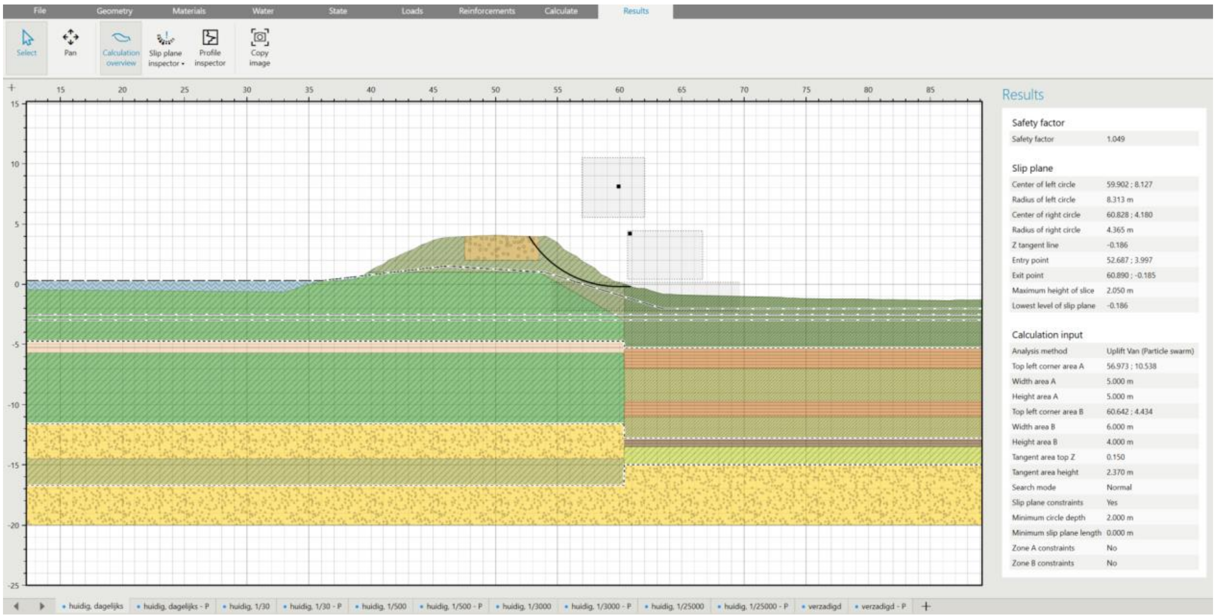
$$X_i = \mu_i - \alpha_i * \beta * \sigma_i$$

Where:
X = random variable [-]
μ = Mean [-]
α = Influence factor [-]
β = Reliabilty index [-]
σ = Standard deviation [-]

The sum of all the alpha values squared is according to the theory equal to 1 (Jonkman, Steenbergen, Morales-Nápoles, Vrouwenvelder, & Vrijling). With this theory the failure frequency contributions of different parameters per soil layer can be compared between different schematizations. A FORM-calculation is often chosen above a full probabilistic calculation, because full probabilistic calculations require a lot of computation time.

2.5 D-stability

Deltares developed the D-stabililty software to calculate failure probability of macrostability of a 2-D cross-section of a dike. Different methods can be used for calculations, as mentioned in Table 1. D-stability can perform both probabilistic and semi-probabilistic calculations. The input for D-stability is the same as the input for the calculation methods, see Figure 4. The output of the model is the slip plane, but also other parameters can be calculated. The output is the stability factor for semi-probabilistic calculations and the conditional failiure probability for probabilistic calculation. A visualisation of D-stability is in Figure 5, where the black line represents the slipplane of this specific cross-section.



Results

Safety factor	
Safety factor	1.049

Slip plane	
Center of left circle	59.902 ; 8.127
Radius of left circle	8.313 m
Center of right circle	60.828 ; 4.180
Radius of right circle	4.365 m
Z tangent line	-0.186
Entry point	52.687 ; 3.997
Exit point	60.890 ; -0.185
Maximum height of slice	2.050 m
Lowest level of slip plane	-0.186

Calculation input	
Analysis method	Uplift Van (Particle swarm)
Top left corner area A	56.973 ; 10.538
Width area A	5.000 m
Height area A	5.000 m
Top left corner area B	60.642 ; 4.434
Width area B	6.000 m
Height area B	4.000 m
Tangent area top Z	0.150
Tangent area height	2.370 m
Search mode	Normal
Slip plane constraints	Yes
Minimum circle depth	2.000 m
Minimum slip plane length	0.000 m
Zone A constraints	No
Zone B constraints	No

Figure 5: Cross-section in D-stability

Modelfactor

The modelfactor is a factor to compensate for the uncertainties in a model. The modelfactor is a value that is used as stochastic threshold for the calculations. In Equation 7 is also the modelfactor used and thus is the uncertainty of the model taken into account. The modelfactor adresses the following uncertainties (Duinen, 2015):

- Uncertainty in the slipplane.
    - Circle slipplane or rectangular slipplane vs reality
    - Horizontal force equilibrium
- Uncertainty in 2D while reality is in 3D
- Spatial variability of shear strength parameters that is averaged
- Uncertainty in shear force along the slipplane

2.6 Derivation of the semi-probabilistic rule

The derivation of the semi-probabilistic rule is a calibration between the safety factor and the probability of failure. To obtain the relationship between the safety factor and the failure probabilty 34 different dike cross-sections in the Netherlands have been used for the calibration (Kanning, Huber, Krogt Mvd, & Teixeira, 2015). The result of the calibration is Equation 9.

Equation 9: Relationship SF and Beta

$$\gamma_n = 0.15 * \beta + 0.41$$

Where:
Y_n = safety factor [-]
β = reliability index [-]

In Figure 6, the cases are presented together with the WBI-fit. The black line in Figure 6 represents Equation 9. This gives the relationship between the reliability index and the safety factor. As mentioned before, the semi-probabilistic method is in general more conservative than the probabilistic method. This is visible in Figure 6, because the black line is in most cases above the reliability index from a case. This means that the WBI-fit is more conservative and thus the semi-probabilistic calculations as well. Therefor, the probabilistic calculations can be usefull, if the dike is not sufficient according to the norms.

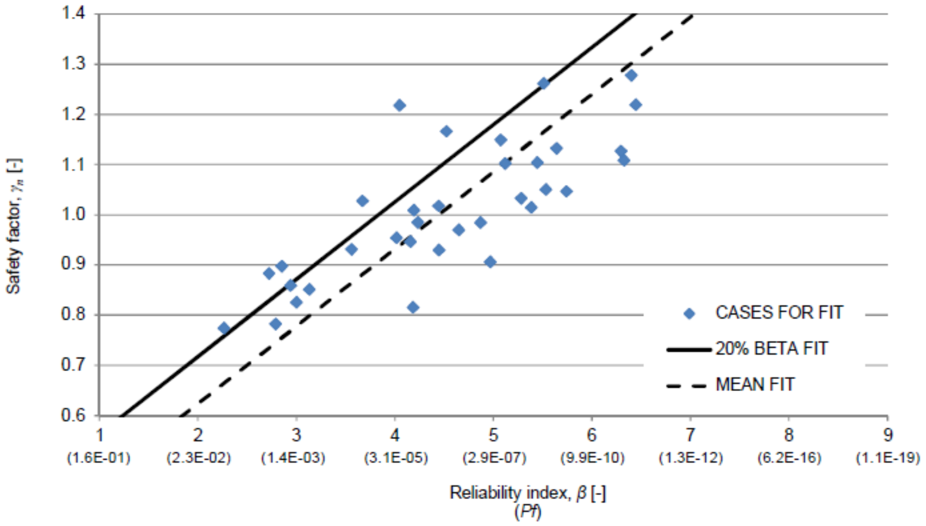


Figure 6: WBI-fit (Kanning, Huber, Krogt Mvd, & Teixeira, 2015)

2.6 Problem statement

In this section the problem is stated, from this problem statement the benefit for Witteveen+Bos is explained. Witteveen + Bos is also the company that commissioned the project.

The problem statement

The schematization step is very important for calculating the failure probability of a dike. As mentioned, there are two methods for calculating the failure probability. There is a large variability in how detailed the schematization is done, which results in a difference within the output of the two methods. The variability is based on soil investigations and an experts opinion. However, soil layers that are 0.5 m thick are often neglected in the cross-section. This makes the soil schematizations more arbitrair, resulting in that one expert might consider one layer of clay as clay, while another expert it considers at clay with plants and clay with shells for example.

Involved parties

Witteveen+Bos is the party that commissioned the project. The result of the project is relevant for themThe data used is from a current dike project, which is already in the constructing phase. This means that for the project KIJK the information cannot be used. Currently there is a gap between probabilistic and semi-probabilistic calculations. This has resulted in that dikes were sufficiently safe for probabilistic calculations, but not for semi-probabilistic calculations. Therefor people living close to the dikes might disagree with the reinforcements of the dike. If the results of this report show that the dike is not sufficiently safe, people might appeal to the reinforcement of the dike. For Witteveen+Bos it is important to understand the difference in detailed or rougher schematization of a dike. This is where the project is focused on.

3. Research objective and research questions

3.1 Research objective

The objective of this research is to quantify the effects on the failure probability of the different level of detail for schematization of the number of soil layers for macrostability of a dike. This means that for both semi-probabilistic and probabilistic calculations the effects of different levels of detail for schematizing the soil layers must be investigated. The next step is to understand if this difference is justifiable, while the semi-probabilistic calculations are based on the probabilistic calculations via a calibration. The hypothesis is that more layers will result in a lower failure probability for probabilistic calculations and that for semi-probabilistic calculations the failure probability will not change.

3.2 Research questions

R.Q.1 What are the effects of choosing a rough or detailed dike lay-out?

First to make clear what the effects are to choose for a rough or detailed dike lay-out for both probabilistic and semi-probabilistic calculations for macrostability. This means that in the detailed dike lay-out there will be more soil layers compared to the rough dike lay-out. It is expected that increasing the number of independent soil layers in a probabilistic calculation has a significant decrease in failure probability on the estimated stability of a dike, while this is not the case for a semi-probabilistic calculation. This expectation is based on the distribution used for probabilistic calculations. The chances for every soil layer to have a relative worse value is smaller, resulting in a higher value for some layers. Therefor the failure probilty is expected to decrease for probabilistic calculations. For semi-probabilistic calculations, all layers make use of a characteristic value and therefor the effect of choosing for a certain level of detail is expected to have less influence compared to the probabilistic calculations. Since this question is based on two different methods, the question can be split up into:

a) What are the effects of choosing a rough or detailed dike lay-out for semi-probabilistic calculations?
b) What are the effects of choosing a rough or detailed dike lay-out for probabilistic calculations?

R.Q.2 How does the result of the first research question relate to the calibration of the semi-probabilistic method?

The last research question is based on the calibration of the semi-probabilistic calculations. First, the difference between the WBI-fit and the results of R.Q. 1a and 1b. For the calibration of the semi-probabilistic method different cases with different schematizations have been used. In research question 1a and 1b are the effects of the number of soillayers on the failure probability determined. There are two options for this.

- The first option is that in case of a large number of soil layers is used for schematizing, the reliability index will be higher. This might influence the calibration and result in an unsafe calibration.
- The other option is that there is no effect in failure probability depending on the number of soillayers for both calculations. In that case there will be no effect on the WBI-fit.

4. Methodology

In this section, the method that is used to answer the research questions is explained. First research question 1a & 1b will be adressed. Large steps of these two research questions are the same, while both questions require the same cross-section. Choosing a dike section is also the first part of the method. The next step is to define the parameters necessary for the model. Following that, the layers are split into multiple sub-soil layers for each scenario and these sub-soil layers have the same parameters. If all scenarios are defined and all necessary input is given, the calculations can start in D-stability. The output of D-stability will be a reliability index or a safety factor, which can be transformed into a failure probability. With the failure probabilities, research questions 1a and 1b can be answered. The calculations are based on a single case and therefor it would be preferred to come up with something general for the last research question. To generalise this case, we have looked at the failure frequency contribution. After the generalisation, the calibration of the semi-probabilistic method can be compared with the results of research question 1a and 1b. The final step for answering research question 2 is to compare the cases of the calibration with the number of soillayers through the slipplane.

4.1 Determination of a cross-section

The first step is to determine a cross-section for the project. In project KIJK different cross-sections are used for their calculations. Every dikesection has its own cross-section and one of these cross-sections will be the case of this thesis. The choice of the cross-section is based on three different things. The first criteria is the reliabiltity index. The cross-section should be unsafe. This will show if a dike can be sufficient according to the norms if more layers are schematized. This criterium is chosen, because an already sufficient dike will already result in an even more safe dike according to the hypothesis. For this criterium the calculation results of Witteveen+Bos from project KIJK will be used. The second criterium is the question of how general the dike is. A more generic dike will most probably be closer to another dike and thus can be said with more certainty that the effects of schematizing the soil in more detail results in a lower failure probability if that is the result. Meaning that the result of this certain case will be less of an outlier and could be applied to other dike sections. The last criteria is that there have to be large soil layers. These large parts can be more easily split up in different layers of soil. While if there are already small layers of peat and clay following each up, the layers can neither be combined nor be split up in more layers. These criteria resulted in the choosing of the following cross-section, which is visible in Figure 7 (for a better visualization see Appendix A). This cross-section had a very deep slipplane in the calculations from Witteveen+Bos, resulting in a possibility to have more relevant slipplanes in the different schematizations.

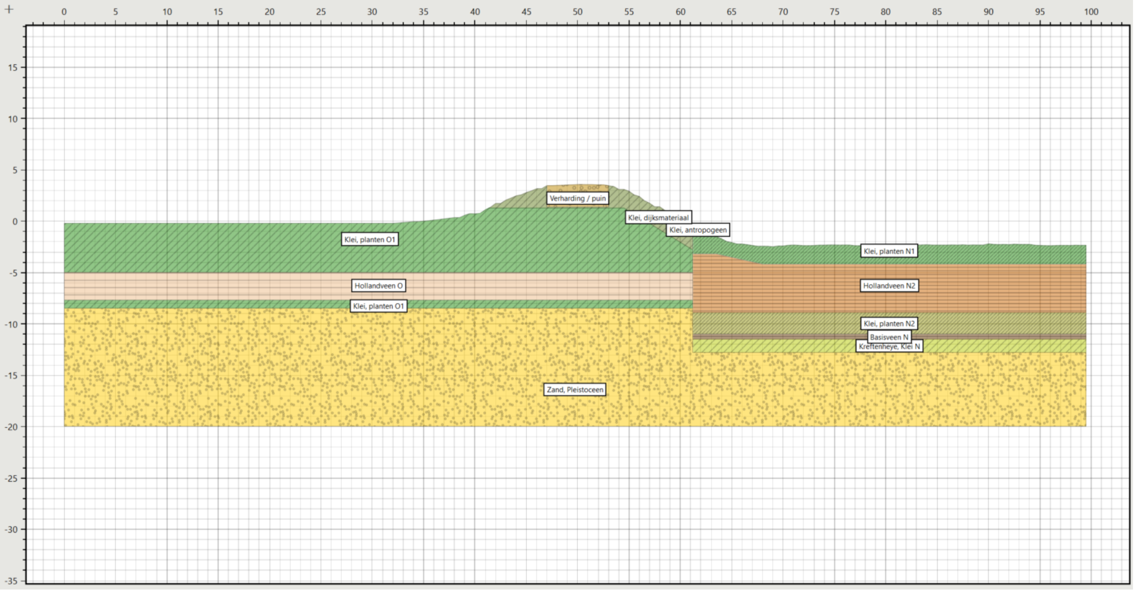


Figure 7: Cross-section of the dike (Distance in meters)

4.2 Parameters

In the parameter section different parameters are explained. First the shear strength ratio and the strength increase component are presented from soil investigations from KIJK and POV-M. The second part consists of the Pre-Overburden Pressure and the unit weight from the soil investigation of KIJK. In the last part, the phreatic line is explained.

Shear strength ratio and strength increase component

As mentioned in the introducion, two projects have been investigating the soil at the Hollandsche Ijssel. These projects are KIJK and POV-M. For each project different soil investigations have been conducted, both resulting in different parameters. The parameters from POV-M are visible in Table 2,

Table 3 and Table 4 and the parameters from KIJK are visible in Table 5, Table 6 and Table 7. For the calculations both soil investigations will be used, to check whether different input parameters result in the same trend over the different scenario`s.

Table 2: Soil parameters POV-M (where M_{avg} is the average strength increase component, S_{avg} is the average shear strength ratio, φ_{avg} is the average friction angle and c_{avg} is the average cohesion.)

Soil-type	m_{avg}	S_{avg}	ϕ_{avg}	c'_{avg}
Hollandpeat	0.881	0.384	29.3	7.48
Clay with shells	0.918	0.317	31.3	7.32
Clay with plant residues				
Clay antropogeen				
Clay kreftenheye	0.8	0.25	-	-
Sand antropogeen	-	-	32.5	0
Sand kreftenheye	-	-	35	0

Table 3: Soil Parameters POV-M (where $M_{st.dev}$ is the standard deviation of the strength increase component, $S_{st.dev}$ is the standard deviation of the shear strength ratio, $\varphi_{st.dev}$ is the standard deviation of the friction angle and $c_{std.dev}$ is the standard deviation of the cohesion.)

Soil-type	$M_{st.dev}$	$S_{st.dev}$	$\Phi_{st.dev}$	$c'_{st.dev}$
Hollandpeat	0.017	0.021	-	-
Clay with shells	0.021	0.023	-	-
Clay with plant residues				
Clay antropogeen				
Clay kreftenheye	-	-	-	-
Sand antropogeen	-	-	-	-
Sand kreftenheye	-	-	-	-

Table 4: Soil parameters POV-M (where M_{char} is the characteristic strength increase component, S_{char} is the characteristic shear strength ratio, φ_{char} is the characteristic friction angle and c_{char} is the characteristic cohesion.)

Soil-type	M_{char}	S_{char}	Φ_{char}	C_{char}
Hollandpeat	0.863	0.36	28.4	0.41
Clay with shells	0.893	0.29	31.3	0
Clay with plant residues				
Clay antropocene				
Clay kreftenheye	0.73	0.21	-	-
Sand antropocene	-	-	30	-
Sand kreftenheye	-	-	32.5	-
Debris	-	-	32.5	-

Table 5: Soil parameters KIJK (where Mavg is the average strength increase component, Savg is the average shear strength ratio, φavg is the average friction angle and cavg is the average cohesion.)

Soil-type	m_{avg}	S_{avg}	ϕ_{avg}	c'_{avg}
Hollandpeat/Basispeat	0.847	0.387	-	-
Clay with plant residues	0.88	0.316	-	-
Clay antropocene	0.906	0.354	34	-
Clay kreftenheye	0.88	0.316	-	-
Sand Pleistoceen	-	-	35	-

Table 6: Soil Parameters KIJK (where $M_{st.dev}$ is the standard deviation of the strength increase component, $S_{st.dev}$ is the standard deviation of the shear strength ratio, $\varphi_{st.dev}$ is the standard deviation of the friction angle and $c_{std.dev}$ is the standard deviation of the cohesion.)

Soil-type	$M_{st.dev}$	$S_{st.dev}$	$\Phi_{st.dev}$	$c'_{st.dev}$
Hollandpeat/Basispeat	0.019	0.02	-	-
Clay with plant residues	0.01	0.022	-	-
Clay antropocene	0.02	0.016	2.2	-
Clay kreftenheye	0.01	0.022	-	-
Sand Pleistoceen	-	-	1.5	-

Table 7: Soil parameters KIJK (where M_{char} is the characteristic strength increase component, S_{char} is the characteristic shear strength ratio, φ_{char} is the characteristic friction angle and c_{char} is the characteristic cohesion.)

Soil-type	M_{char}	S_{char}	Φ_{char}	C_{char}
Hollandpeat/Basispeat	0.83	0.37	-	-
Clay with plant residues	0.87	0.3	-	-
Clay antropocene	0.89	0.34	31.3	0
Clay kreftenheye	0.87	0.3	-	-
Sand Pleistoceen	-	-	32.5	-

POP and unit weight

Except for the shear strength ratio and strength increase component there are other parameters that are necessary input for the calculations. These are the unit weigth and the Pre-Overburden Pressure or POP. To estimate the effect of only the number of soil layers, other factors like the unit weight and POP are kept constant. Additionally, the differences between the POP and unit weight from KIJK and POV-M were negligible. The POP and unit weight used for the calculations in D-stability is given in Table 8.

Table 8: POP and Unit weight parameters KIJK (O= for soillayers under the dike, N=Next to the dike)

Soillayer	POP [kN/m^2]			Unit weight above phreatic level [kN/m^3]	Unit weight below phreatic level [kN/m^3]
	Characteristic value	Mean	Standard deviation		
Debris	-	-	-	19	20
Clay dikematerial	7	14	5.486	18.5	18.5
Klei with plant residues O	15	25	7.292	16.05	16.05
Clay with plant residues N1	24.9	50.628	20.3	14.2	14.2
Clay with plant residues N2	25	50.628	20.3	14.8	14.8
Hollandpeat O	1	11	16.72	10.85	10.85
Hollandpeat N	24.9	50.628	20.3	10.5	10.5
Clay antropocene	10	22	9.777	18.5	18.5
Clay kreftenheye	25	50.628	20.3	17.2	17.2
Basispeat	25	50.628	20.3	11.55	11.55
Sand pleistoceen	-	-	-	18	20

Phreatic line

The last input is the phreatic line. The phreatic line is the waterlevel in the soil or in this case the dike. The phreatic line can be made with Waternetcreator. However, they did groundwater monitoring in observation pipes and used standards for the determination of the phreatic line in project KIJK. The phreatic line changes for diferent waterlevel, so for each waterlevel a different phreatic line is used. For a visualization of a phreatic line, see Figure 9. The other phreatic lines are given in Appendix E Other groundwater related lines (headline and reference lines are also given in Appendix E. The reference line is used for determination of the waterpressure in a model. The reference line indicate from which level a phreatic line is considered in the calculations. This is visible in Figure 8, where around -5 m the waterpressure decreases. This decrease is caused by the waterpressure from the sandlayer beneath the dike. The reference lines are used for the calculation of the waterpressure from the sand and the waterpressure from the waterlevel in the dike. There is also a light green area visible in Figure 8, in that area only the phreatic line is relevant and the headlines with the waterpressure of the sand are not relevant.

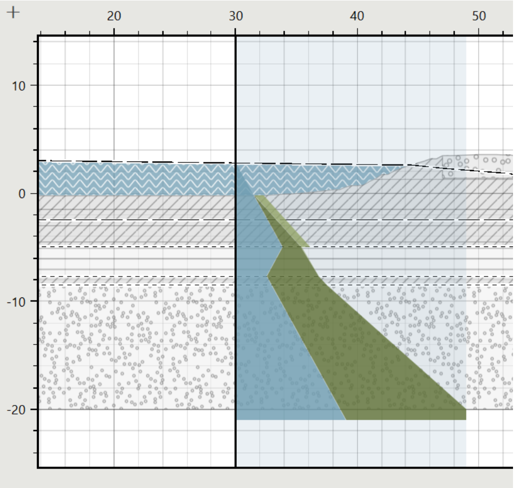


Figure 8: Effective stress in the soil

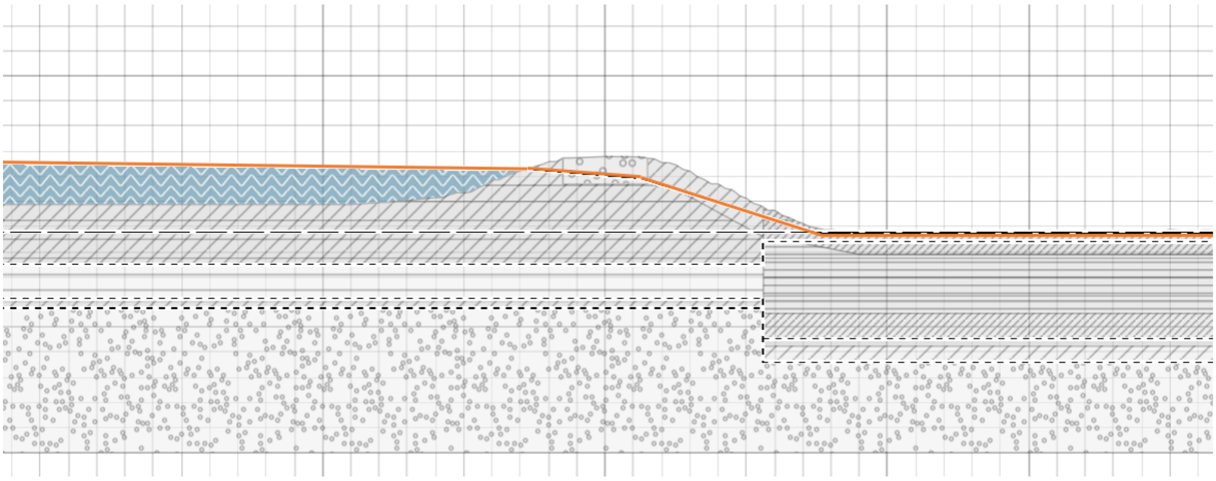


Figure 9: Phreatic line in orange

4.3 Sub-soil layers

To estimate the effect of multiple su-soillayers on the failure probability, the cross-sections have been split up into multiple layers with the same soil parameters. The layers have been divided into sections of 0.5 meter, 1 meter, 1,5 meter, 2 meter and 2,5 meter thick, see Figure 10. In addition to these schematizations also the standard cross-section (1 layer as shown in Figure 10) is calculated as well as the soil layers split into half. These schematizations result in an example like Figure 11. In Apendix A the cross-sections of the different schematizations are presented. Only the layers which crosses the slipplanes have been split up, because this was the only scenario that the 0.5 thick layers were able to run for variation in the POP.[1] Each soillayer has to be a different soillayer with a different name in D-

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[1] For the calculations with both splitting of S and m with the POP 0.5 meter thick layers were not possible, and 1.0 meter was possible if the foreland was shortened with 30 meters. These adjustments were necessary for the calculations.

stability otherwise only the POP is varied. This means that for every layer, a soil type with the same S and m values has to be made in D-stability.

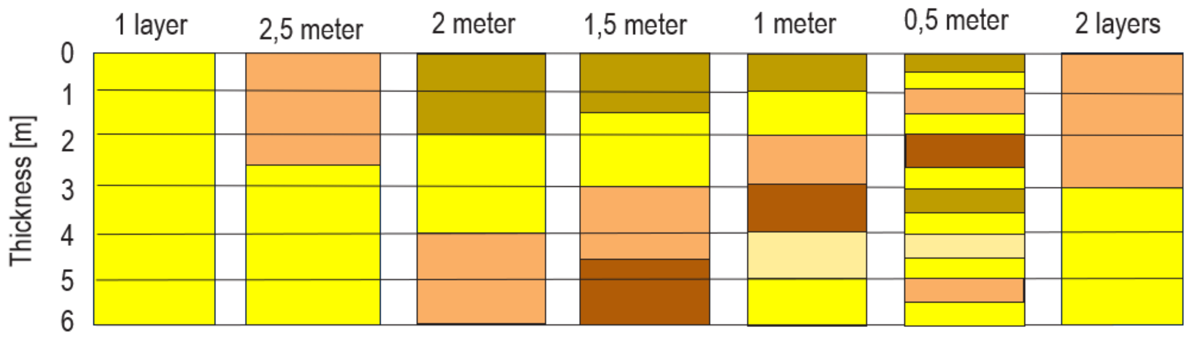

Figure 10: Splitting of a soil layer

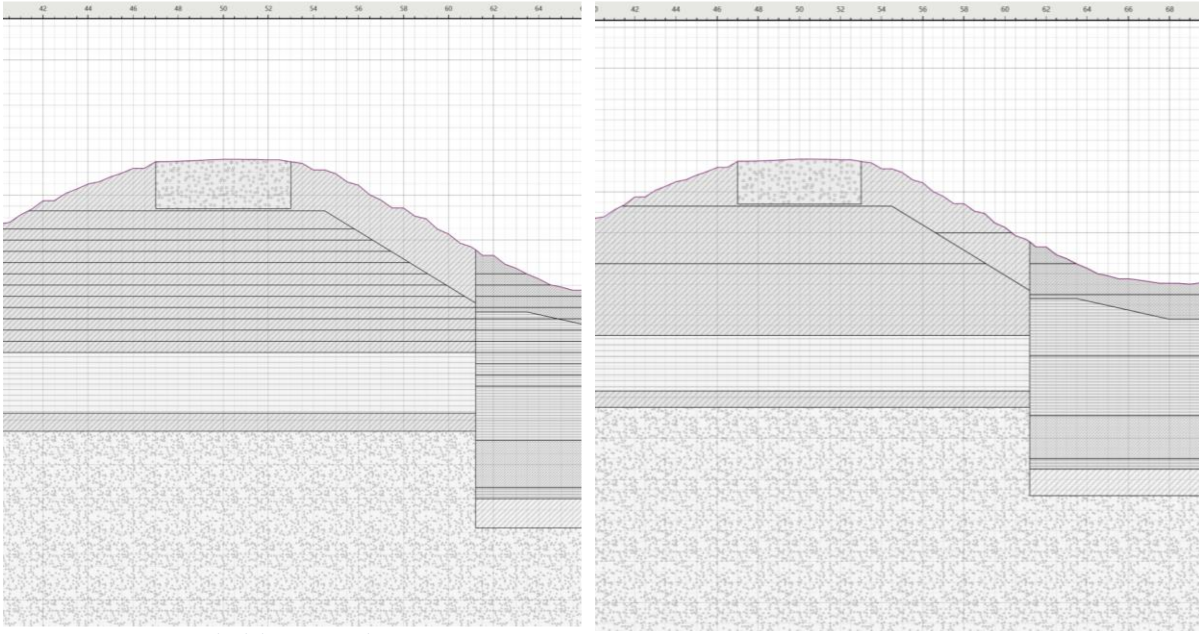

Figure 11: 0.5 meter thick layers vs 2 layers

4.4 Semi-probabilistic calculations

The next step is to calculate the safety factor for each cross-section. The input for the calculations are the parameters mentioned in Chapter 4.2nd the cross-sections of Appendix A. The water level with a frequency of 1/3000 years is used for the semi-probabilistic, since 1/3000 is the norm. The last step is to assign a modelfactor and the deviation of the modelfactor, for this a method have to be chosen. The method Uplift Van is used, see Table 1. There is expected that the choice for the method will not have a large effect on the results (Kanning, Huber, Krogt Mvd, & Teixeira, 2015). With these input parameters D-stability is able to calculate a safety factor. Using Equation 7, the faillure probability for the semi-probabilistic calculation is calculated. The result of the calculations is given in Chapter 5.

4.5 Probabilistic calculations

In the theoretical framework is mentioned, that the fragility curve is based on different waterlevels. These waterlevels are the daily waterlevel, 1/30 years, 1/500 years for 2050, 1/3000 years for 2050, 1/25000 years for 2050 and for a fully saturated dike. The frequency of 1/30 years is used, while this waterlevel is the same as for which the pumping stations become active. Another necessary waterlevel is the saturated dike. The saturation is taken into account in the fragility curve and is therefor a usefull datapoint. The frequencies of the daily, 1/500 and 1/25000 are usefull datapoints in between the necessary frequencies.

D-stability

The following step is to perform the probabilistic calculations in D-stability. For this a FORM-calculation is used, to start the calculation the determined slipplanes of the semi-probabilistic calculations are required. A full probabilistic calculation would take too much time compared to the benefit of a more accurate result. A FORM-calculation is less accurate, but takes less time. Therefor first semi-probabilistic calculations are used for calculations in D-stability to determine the slipplane. For the semi-probabilistic calculations the characteristic values of S, m and POP are used from POV-M and KIJK. With the slipplane known, only a modelfactor has to be added. In case of using the method Uplift Van a modelfactor of 1.06 and a standard deviation of 0.033 are used. In the following step the FORM method is used to determine the failure probability. This calculation is a probabilistic calculation, so the average and standard deviation of the shear strength ratio, strength increase component and POP are used for the calculations, see chapter 4.2. Different probabilistic calculations have been processed. The different combinations are presented in Table 9. The semi-probabilistic calculations for the determination of the slipplane use the same source of the parameters as the probabilistic calculations. The difference between POV-M (1) and POV-M (2) in Table 9 is that for POV-M (2) also the shear strength ratio and strength increase component are split up for each sub-soil layer instead of only the POP for POV-M (1). So for POV-M(1)the S and m is constant for each soil layer.

Table 9: Different calculations

		Parameters				Varied per sub-soil layer
		POP	S and m	Phreatic line	Unit weight	
Calculation	KIJK	KIJK	KIJK	KIJK	KIJK	POP
	POV-M (1)	KIJK	POV-M	KIJK	KIJK	POP
	POV-M (2)	KIJK	POV-M	KIJK	KIJK	POP+S+m

Fragility curve

The values of the examined cross-section for the probabilistic calculations are presented in Table 10. The reliability indices are used to generate an fragility curve. For this curve also the probability of wave overtopping is taken into account. With the input parameters listed in Table 10 and the probability of wave overtopping, a fragility curve can be made, see for an example Figure 12.

Table 10: Reliability index KIJK parameters (per year)

		Frequency					
		Daily	1/30	1/500	1/3000	1/25000	saturated
meter	0.5	3.219	2.786	2.753	2.754	2.701	1.805
	1	3.032	2.532	2.533	2.502	2.47	1.607
	1.5	2.917	2.388	2.397	2.361	2.327	1.506
	2	2.654	2.46	2.421	2.431	2.397	1.559
	2.5	2.742	2.202	2.191	2.173	2.141	1.386
layer	1	2.319	2.112	2.106	2.084	2.05	1.324
	2	2.755	2.219	2.205	2.188	2.156	1.392

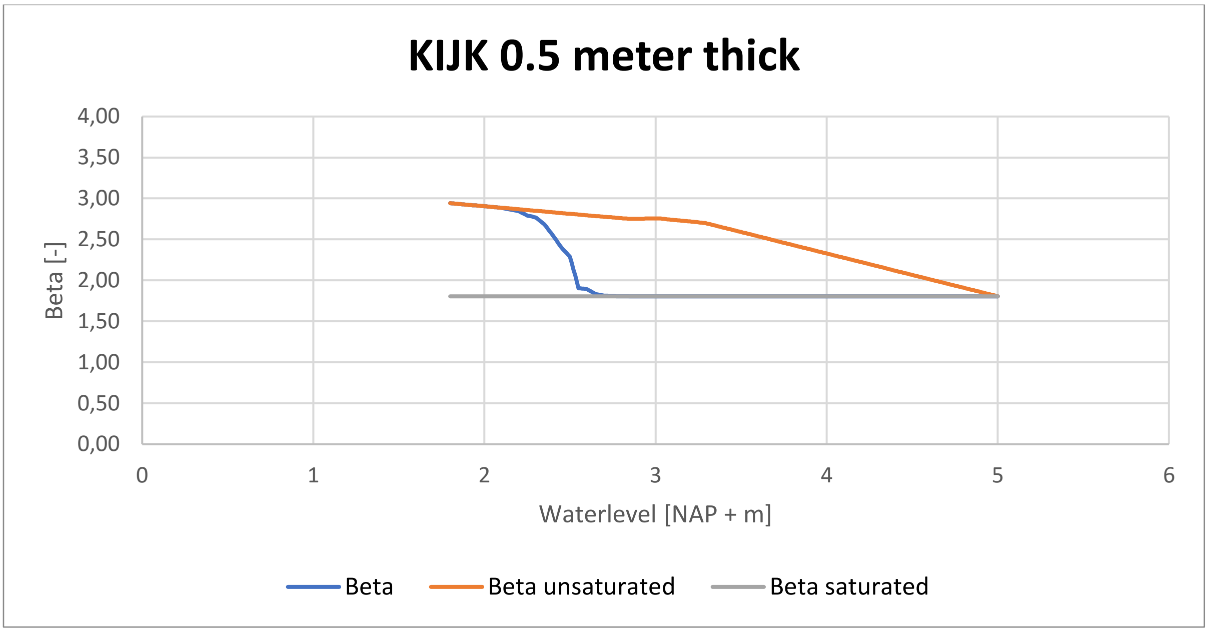

Figure 12: Fragility curve (beta is the reliabilty index depending on the waterlevel)

With the fragility curve and the data of the probability of a certain waterlevel (see Appendix C) the final failure probability can be calculated. From the data of certain return periods a gumbel distribution of the waterlevel is made. In Figure 12, the wave overtopping is used in the calculations. In orange the reliability index from the different waterlevels is interpolated to get a curve. The orange reliability index represents the scenario in which the dike will not have overflow and therefor not be saturated. In grey the saturated reliability index is given, this means that the dike is already fully saturated at the lowest waterlevel. In Appendix B the probability of wave overtopping is given. At the point that there is a probability of overflow the saturated reliability index is taken into account with respect to the probability of wave overtopping, see Equation 10.

Equation 10: Beta with overtopping

$$\beta = \beta_{sat} * P_{overtopping} + \beta_{unsat} * (1 - P_{overtopping})$$

Where:
β = Reliability index [-]
β_{sat} = Saturated reliability index [-]
β_{unsat} = Unsaturated reliability index [-]
$P_{overtopping}$ = Probability of overtopping [-]

At the point at which the probability of wave overtopping is 1, the dike is considered fully saturated and the reliability index is the saturated reliability index. The saturated scenario results in the lowest reliability index and thus the highest failure probability. The next step is to multiply the fragility curve in Figure 12 with the gumbel distribution of the waterlevel. This results in the failure frequency given in Figure 13. The area under the blue curve shown in Figure 13 is the failure probability of the specific scenario.

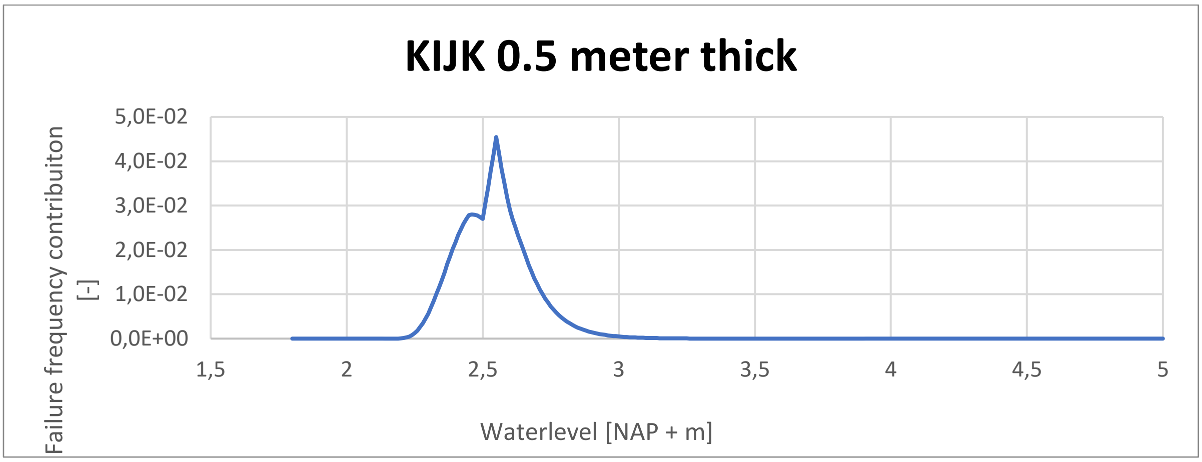

Figure 13: Failure frequency for each waterlevel

4.6 Generalisation

The benefit of a specific case is very low, so in order to make this case applicable to other dikes are there several options. The best option is to look at the importance of each layer for a given waterlevel. If each layer stays equally important for the failure frequency contribution, the number of layers does not affect the failure frequency. The output of the FORM-calculations is a failure probability, but D-stability gives also a alpha value for each soil layer. In the theory of a FORM-calculation, it is mentioned that all alpha`s squared equals one. Therefor all the alpha values of each sub-soil layer should be squared. The alpha squared of each sub-soil layer can be added to each soillayer and than can be checked if the soillayers vary in failure frequency contribution. To see the biggest effect between the alpha`s, the scenario where both S and m and POP were varied each sub-soil layer is used. Another option are a mathematical analysis of the method to calculate the failure probability and mathemetically prove that the failure probability is dependent on the number of layers for the probabilistic calculations. The last option is to do more cases and based on those multiple cases a conclusion can be drawn, whether the analysis shows that probabilistic calculations are dependent on the number of layers. The last two options will take too much time for this thesis and are thus impossible.

4.7 WBI-fit

To see whether the results of research question 1 and 2 match the WBI-fit. The results of research question 1a and 1b are plotted together with the cases that are used for the WBI calibration. This way the result can be analysed. To understand the effects of multiple layers, the cases should be categorised according to the number of soillayers that intersect the slipplane. The next step is to see how much the WBI-fit deviates from the actual calculated factor of safety.

5. Results

In this chapter the results of the methodology is presented. With the results from this chapter the research questions can be answered. First, the results to answer R.Q. 1a will be presented, followed by the results of the methodology for R.Q. 1b. Last, the results for R.Q. 2 will be provided.

5.1 Semi-probabilistic calculations

In the methodology different calculations have been made. These are KIJK-result and 2 with the POV-M parameters. POV-M (1) is the scenario, where only the POP is varied for every sub-soil layer. POV-M is the scenario for which the POP, S and m are varied for every sub soil layer, see also Table 9. In case of the KIJK results, only the POP is varied for every sub-soil layer.

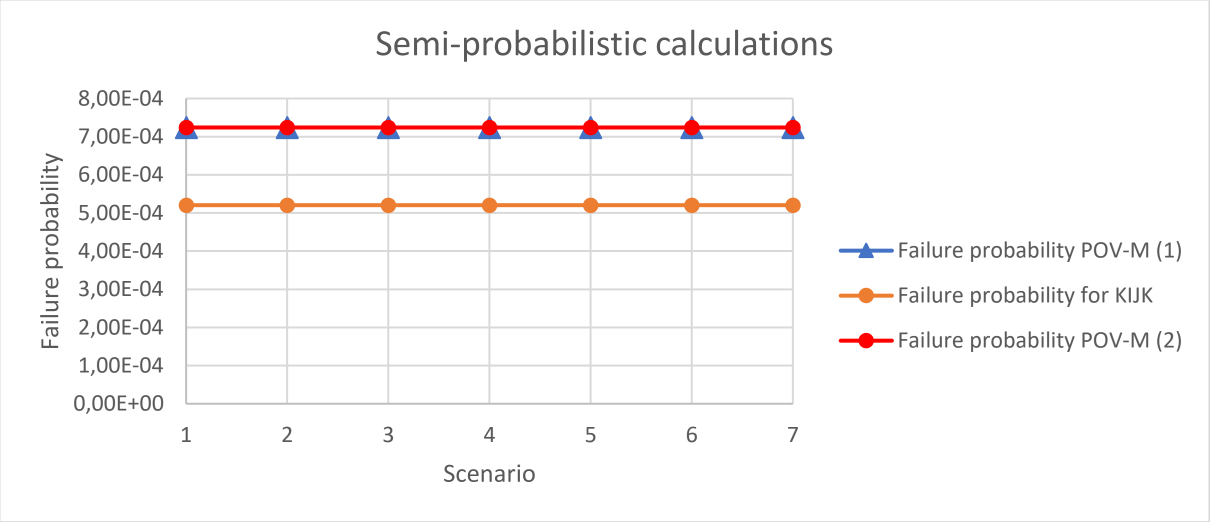

Figure 14: Result semi-probabilistic calculation results

The failure probability for all scenarios calculated using the semi-probabilistic method with different input from POV-M and KIJK is plotted in Figure 9. We can see from Figure 9 that for each soil investigation (POV-M or KIJK), the calculated failure probability using the semi-probabilistic method is the same for all scenarios. The scenario`s are given in Table 11 and for a visualization of the explanation, see Figure 10.

Table 11: Scenario`s

Scenario	Explanation	Soillayers intersect with slipplane
1	0.5 meter thick layers	24
2	1 meter thick layers	14
3	1.5 meter thick layers	12
4	2 meter thick layers	10
5	2,5 meter thick layers	7
6	1 layer	6
7	2 layers	8

5.2 Probabilistic calculations

To answer the second research question, the probabilistic calculations were performed in D-stability. The result of these calculations is shown in Figure 15. In Figure 15, there is a steady increase in failure probability, if less layers are schematized. The only exception for this is scenario 4. The cause for this exception is discussed in Chapter The scenario`s are the same as in Table 11. The same trend for probabilistic calculations can be seen for both the POV-M and KIJK.

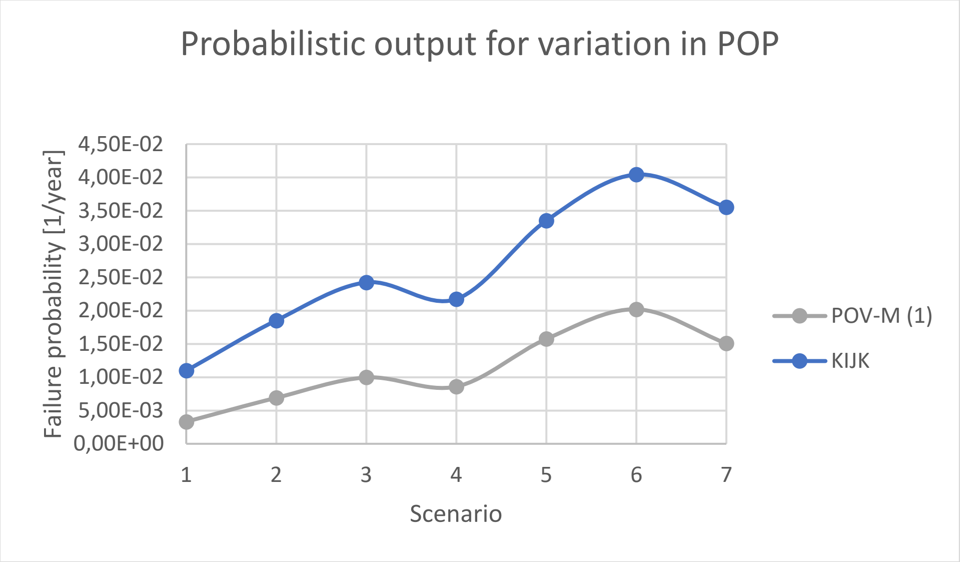

Figure 15: Probabilistic calculation results (scenario`s are explained in Table 11)

In Figure 16, the reliability index is displayed for each scenario. However in stead of the scenario on the x-axis is the number of soillayers intersecting with the slipplane there. In grey all shear strength parameters are varied per layer. In this figure is also visble that the increase in reliability index is larger for POV-M (2) than for POV-M (1). The difference between POV-M (1) and POV-M (2) is that for POV-M (2) the POP, S and m were varied for every sub-soil layer instead of only the POP for POV-M (1). The increase in reliability index means that the failure probability is lower.

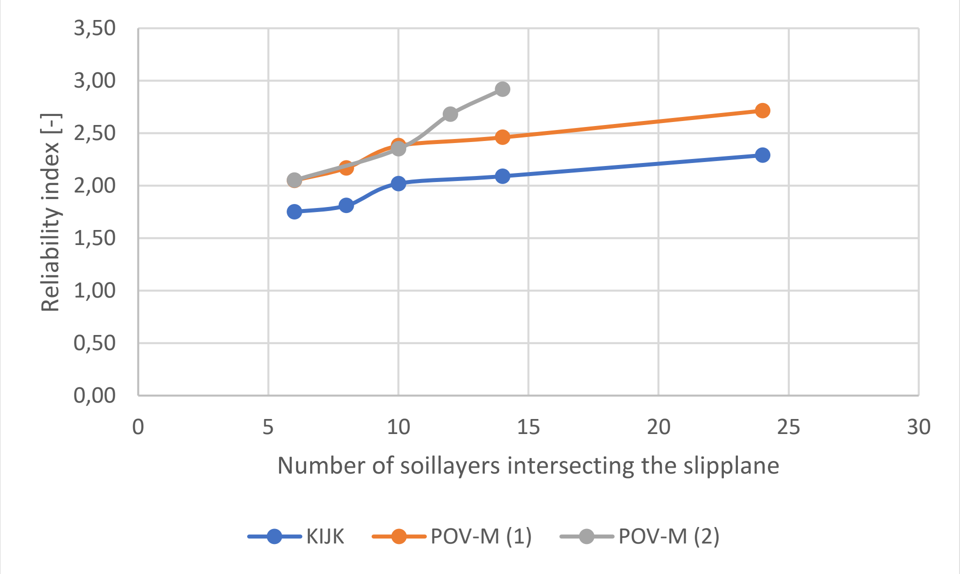

Figure 16: Reliability index vs Number of soillayers

5.3 Alpha values

The alpha values are from the calculations that varied the S, m and POP for each sub-soil layer. The alpha values of the sub-soil layers of one certain soil type are added together, yielding the alpha value for the soil type, see Figure 17. In this figure is clearly visible that there is a large increase in modelfactor, if there are more layers intersecting the slipplane.

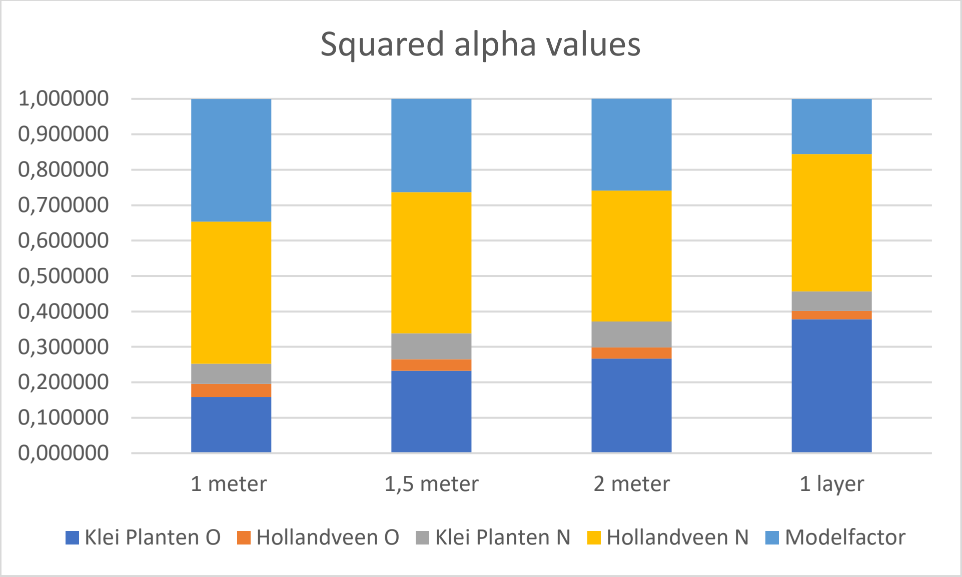

Figure 17: Squared alpha values

The last result of the methodology is the figures in which the WBI-fit is compared to the result of research question 1 and 2. In Figure 18 are the cases displayed from the WBI-fit (Kanning, Huber, Krogt Mvd, & Teixeira, 2015). As visible in this figure are also some cases included from research question 1. In this figure is visible that this specific case was one of the special cases for which the probabilistic calcualtions result in a higher failure probability than the semi-probabilistic calculations. If more layers are schematized, the reliability index increases and the point moves towards the WBI-fit.

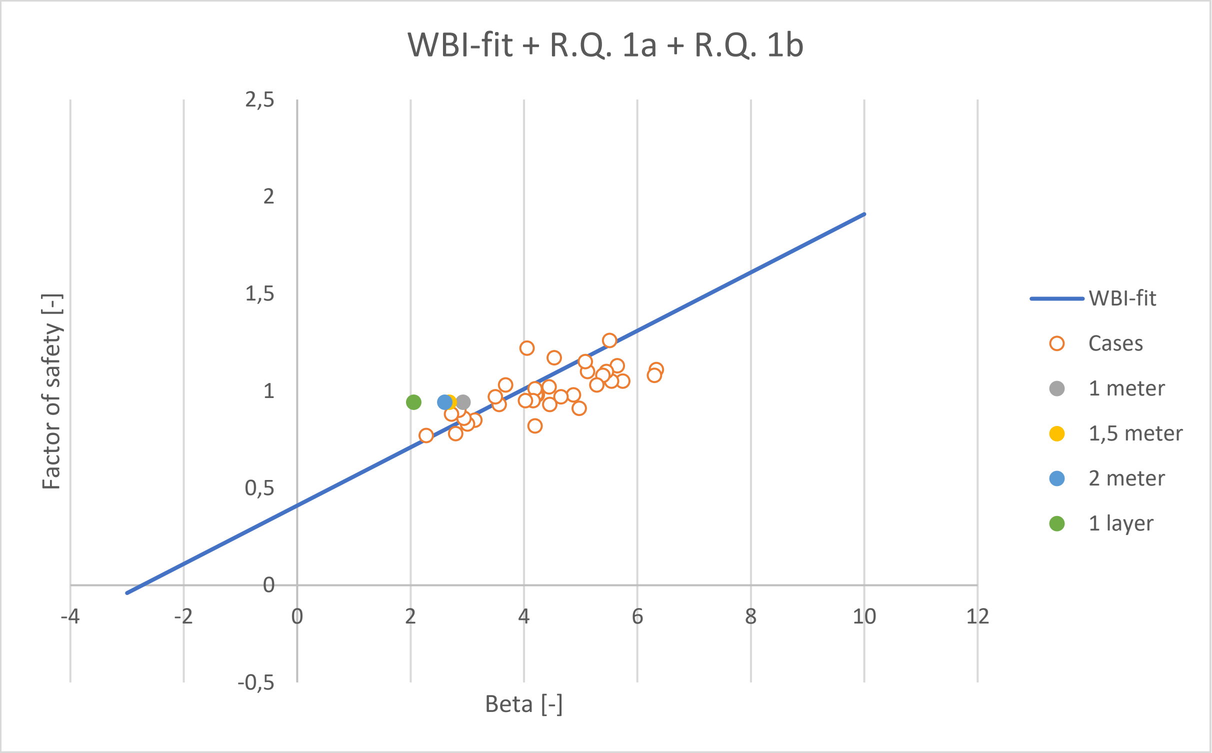

Figure 18: WBI-fit

In Figure 19 is the vertical difference displayed between the WBI-fit and the calculated factor of safety. Some cases were not accepted in the derivation of the semi-probabilistic rule, these are not taken into account for the WBI-fit, however they are presented in Figure 19. They are presented, because they might have had a lot of soil layers intersecting the slipplane and thus have a extreme reliability index and therefor not be used in the calibration. The number of layers were also not visible in Figure 18, but give a more accurate result to compare to the WBI-fit. However, as visible in Figure 19 the schematizations with a high number of soil layers are in line with the other results with no extreme outliers. Again is the same visible that for more layers the difference in factor of safety (calculated-WBI-fit) is smaller.

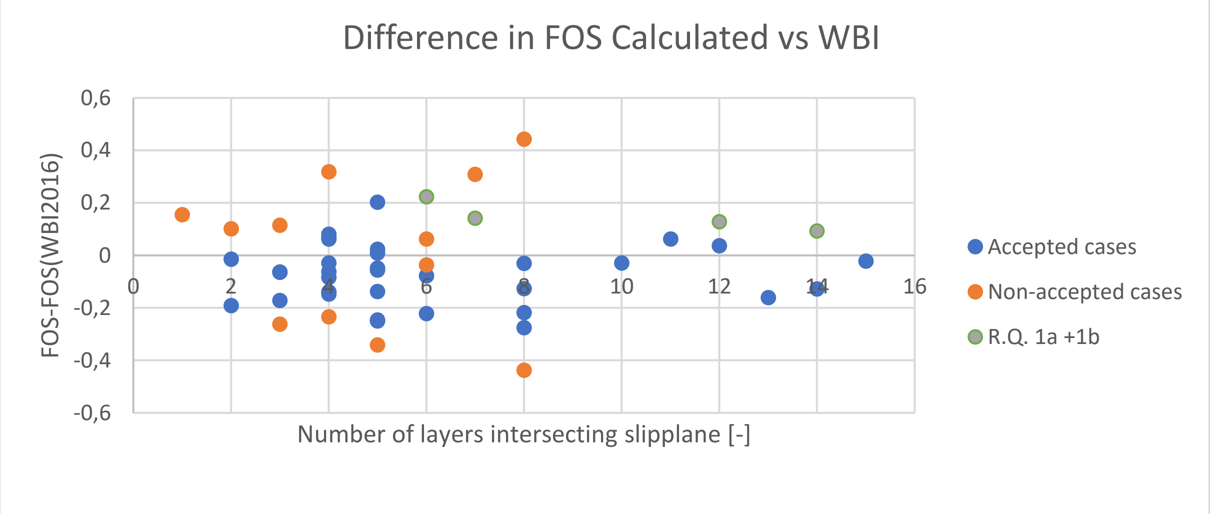

Figure 19: Calculated FOS vs WBI FOS

6. Discussion

The results show that the semi-probabilistic calculations are independent of the number of slipplanes. However, in case of the probabilistic calculations there can be seen a decrease in failure probability. There are several problems that arise. First, the results are based on an individual case and might therefor not be applicable for other cases. The second problem is that in the current model no correlation is assumed between the soillayers. The result of only having POP split up into multiple layers and the S and m values not, is a scenario in which the S and m are fully correlated and the POP is no correlated at all. In reality there is correlation for the parameters at KIJK (Konstantinou, 2017). In practice, there are two possibilities to schematize the soil layers and the soil shear strength parameters. These are full correlation and zero correlation. However full correlation means that for all sub-soil layers the parameters are the same, because there is no variation within the soillayer. So when the parameters are the same, they can be treated as 1 layer instead of 1 layer divided into multiple sub soil layers. The result of this full correlation will be that the failure probability stays equal. To prove this are the semi-probabilistic calculations a good example. Every sub-soil layer had the same characteristic values. The result of the semi-probabilistic calculations was, that the semi-probabilistic calculations with the same characteristic values was not changing dependent on the number of soil layers. The scenario with zero correlation is the result of this thesis. Where is visible that there is a increase in reliability index and decrease in failure probability, if the number of soil layers increase.

Parameters

The third point of discussion is the parameter choices. There were two soil investigation performed, both with a different outcome. The soil investigation of KIJK was a more general soil investigation, thus values characteristic for the whole dike section. However, for POV-M was looked at a specific location. The results show that the different input parameters from both POV-M and KIJK result in the same trend that more layers lead to lower failure probability, which indicate that the variations of the mean and standard deviation of the input parameters may not significantly influence the trend of failure probability changing with the number of sub-soil layers.

Cross-section

The fourth point of discussion is the cross-section. There is a very big jump in the soil layer thickness, see Figure 20 for a red circle. If this jump would have been smoothed, the result will differ. However this would only be necessary, if the output would be the goal. In this case the effect of multiple layers is investigated and while the layers are kept the same over all scenario`s. The smoothening of this jump would make the schematization of the soil more realistic, but would not say anything about the effect of the different calculation methods.

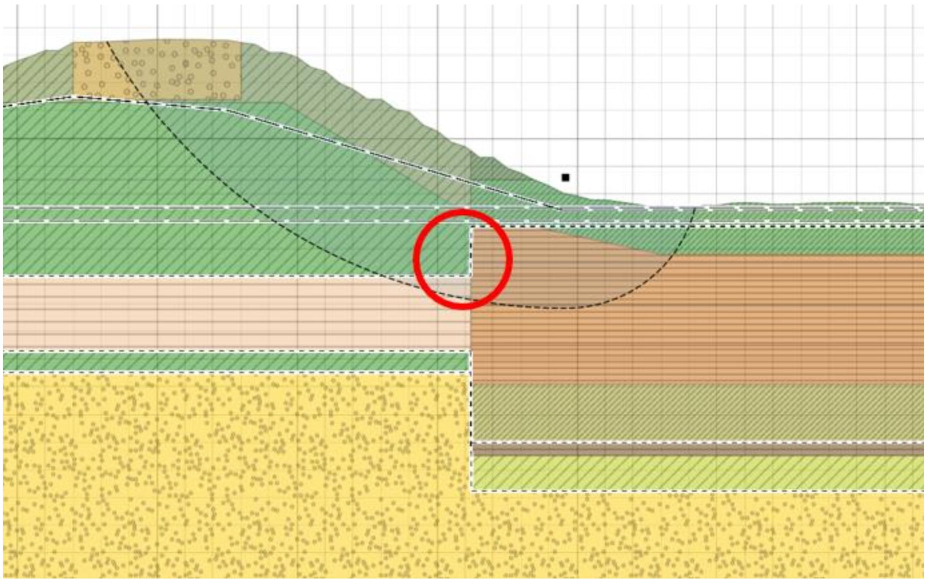

Figure 20: Cross-section jump in thickness

Scenario 4

The sixth point of discussion is the strange outlier in the results, see Figure 15. It can be seen that scenario 4 results in a lower failure probability than the scenario before. This difference is caused by the splitting of the clay with plant residues next to the dike. This section is splitted at 2 different points. Both layers are for 1.5 meter and 2.5 meter thick layers split in 2, but the different locations cause the failure probability to be different. This is also visible in the failure frequency contributions, where this layer is quite important for the failure probability. The effect means that different parts of the slipplane are not equally important, which is again visible in the failure contribution of each layer. The conclusion from this result is that not only the number of layers matter, but also at which location these layers are splitted.

1 layer scenario

Another point for discussion is in Figure 16, where the grey line is equal for the 1 layer case. That makes sense, since they consist of the same parameter distribution. However in the next step the lines are still close, this can be explained with the alpha value`s. As visible in **Fout! Verwijzingsbron niet gevonden.** is the contribution of the POP much higher than the contribution of the shear strength parameters and strength increase exponent. Therefor, The difference for a smaller umber of soillayers is lower compared to the scenario where only the POP was varied.

Overflow

In the probabilistic calculations is the probability of overtopping considered. This overtopping results in a saturated dike and might give an accurate result of the failure probability. However future research might conclude that this method of considering the saturation of the dike is incorrect. The effect of the number of soillayers is independent on the way the saturation is taken into account. In all scenarios, the same method is used and the probability of overflow is the same for every scenario. This means that the difference in failure probability will still exist if another methodology for taking the overflow into account will applied.

Modeluncertainty

The difference between the semi-probabilistic result and the probabilistic results can be explained. D-stability give all the actual values of parameter for each soil layer. Results show that different sub-soil layers have different values and therefor different failure frequency contributions. For the semi-probabilistic calculations every sub-soil layer has the same characteristic value and therefor the number of layers do not have an influence. While the first research question is based on one case, the generalisation has been executed. However there cannot be concluded that in general more layers result in a lower failure probability based on the probabilistic calculations. Due to a change in failure frequency contribution for each layer, there cannot be concluded that the layers stay equally important for every scenario. The model factor increases a lot with the increasing number of sub-soil layers, see Figure 17. The model factor is a factor to define the model uncertainty, so this leads to a following question. Why are more layers resulting in a larger model uncertainty? If the model is exact the model factor should be treated as 1. However the model is not exact and a standard distribution is used to define the uncertainty. The increase in the contribution to the failure probability of the model factor means that result becomes less reliable, while the model uncertainties play a larger role.

7. Conclusion and recommendations

This report answers the research questions. Research question 1a and 1b will be answered first. This research questions were, whether there is an effect in the failure probability for semi-probabilistic and probabilistic calculations depending on the number of soil layers. The second part consists of a conclusion about the correlation. The next part is the answer to research question 2 *How does the result of the first research question relate to the calibration of the semi-probabilistic method?* This section ends with a conclusion and recommendation for further research.

R.Q. 1a and 1b

The research question 1a is about the semi-probabilistic calculation method. In the results no difference in failure probability is concluded. Therefor, the number of layers for a semi-probabilistic calculation has no effect on the failure probability. Research question 1b concerns the probabilistic method. In the results was a decrease visible in the failure probability. In case of 14 layers intersecting the slipplane the difference in failure probability was $1.33*10^{-2}$, when only the POP was varied for each layer. If also the shear strength ratio and strength increase component are varied for each layer, it results in a difference of $1.69*10^{-2}$. Considering only the POP varied but 24 layers intersecting the slipplane results in a difference of $1.84*10^{-2}$ difference in failure probability.

Correlation

In reality there is correlation between the soil strength parameters. In this research, no correlation was assumed. However if only one parameter (POP) was variable for each layer the increase in failure probability was much lower, compared to the scenarios were 3 parameters were variable (POP, S, m). This leads to the following conclusion, that if full correlation is assumed between the sub-soil layers, the line is flat. So there will not be an increase in failure probability, due to the number of soil layers. While full correlation is not the case, the failure probability will be in between no correlation and full correlation. The scenario with one parameter variable is a scenario where full correlation is assumed between S and m and might therefor give an indication of what the reality is.

R.Q.2

Comparison with the WBI calibration resulted into two conclusions. First, there are scenarios that are overestimated and underestimated, both with a high number of soil layers. The case investigated in the first research question is moved more towards the line with an increase in soillayers. Therefore it seems that the calibration has approperiate schematizations used for the calibration. Another reason for this is that on average the number of soil layers is not very high. Which leads to the second conclusion, there were not enough cases with a high number of soillayers that intersected the slipplane to statistically prove that a large number of soillayers result in an overestimation in failure probability compared to the WBI-fit.

Recommendation

A limitation of the current research is that only one case is proven. However, it still proves that there are possibilities for which the number of layers in the schematization affect the failure probability. To understand this phenomena better are two recommendations, which are both possible. The first option is to calculate more cases and check whether these cases also result in a lower failure probability for more sub-soil layers. The benefit of this method is that it will probably be faster and thus cheaper. Another benefit is that the alpha values for each layer can be checked, to see whether there is again an increase in the model factor for schematizations with more layers. The second option is to mathematically prove that the failure probability is dependent on the number of soillayers.

The recommendation for the calibration is that it good enough. The number of soillayers that intersect the slipplane are relatively low. Therefor if the effect can be justified using a mathematical approach or a large number of cases, the calibration will not be affected in a large numbers compared to the uncertainties the model has.

The last recommendation is to understand the effect and benefits of the modelfactor. It represents a large part of the failure frequency contribution, but it should represent the uncertainty in the model. Is this justifiable that it has such a large part in the failure contribution. Especially with van Duinen concluding for another model that it took a large part and also considering that a failure mechanism like piping does not consider a modelfactor.

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Appendix A Cross-sections

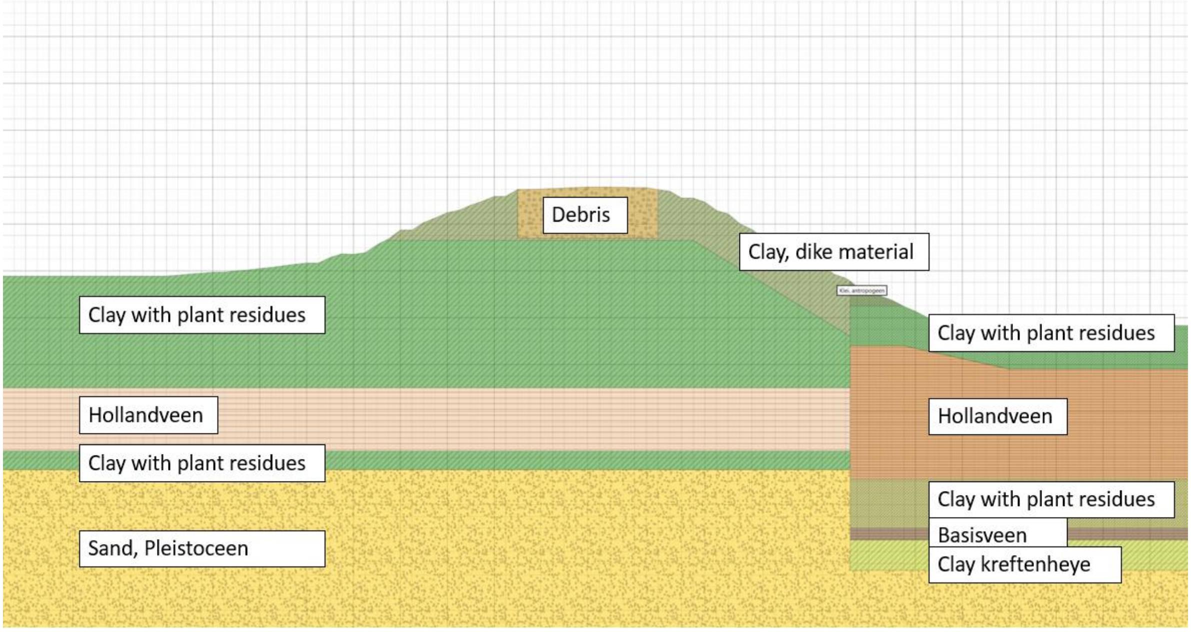


Figure 21: One layer cross-section with the soil layers

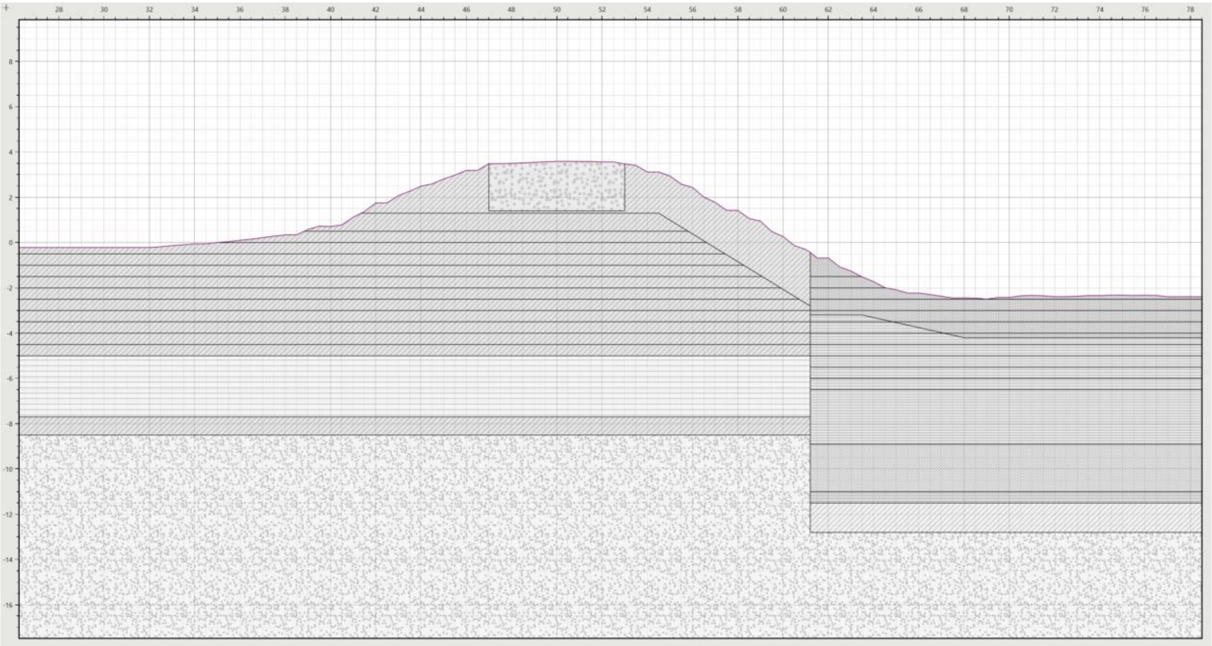


Figure 22: 0.5 meter thick layers

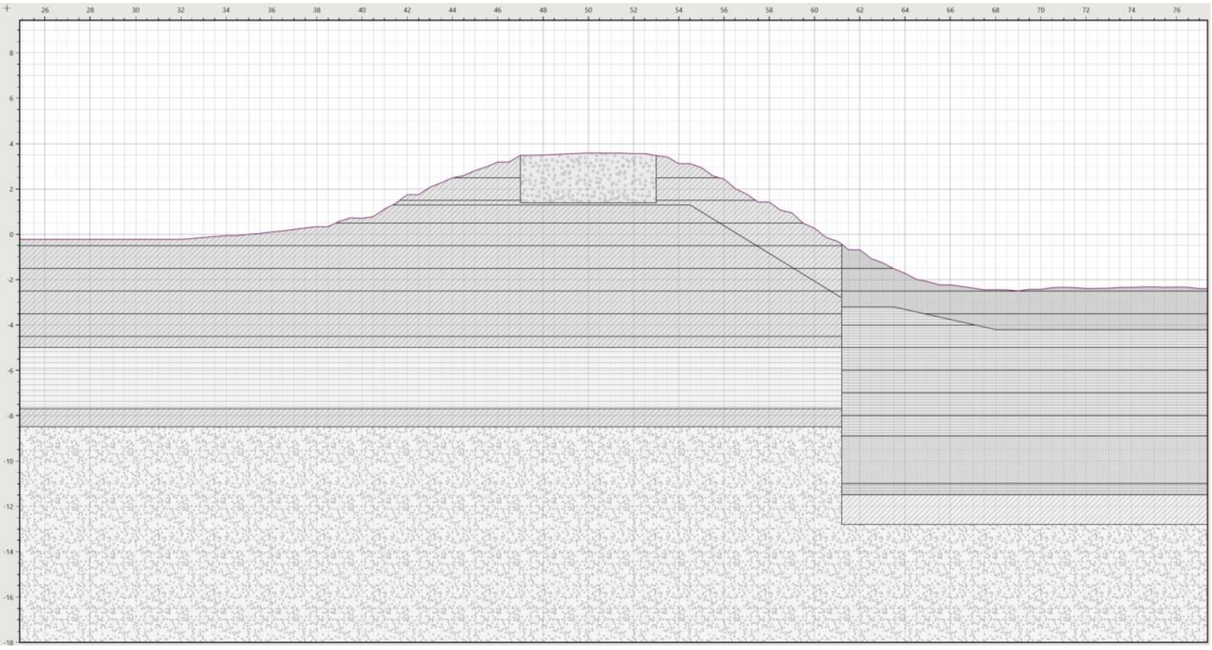


Figure 23: 1 meter thick layers

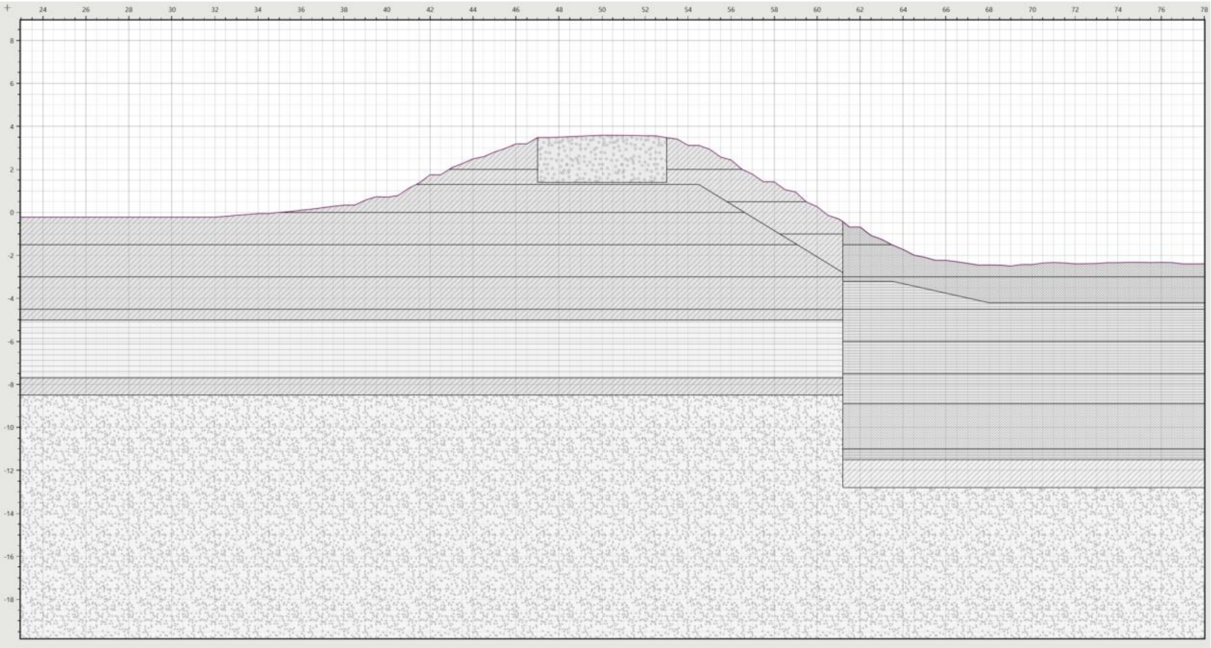


Figure 24: 1.5 meter thick layers

Figure 25: 2 meter thick layers

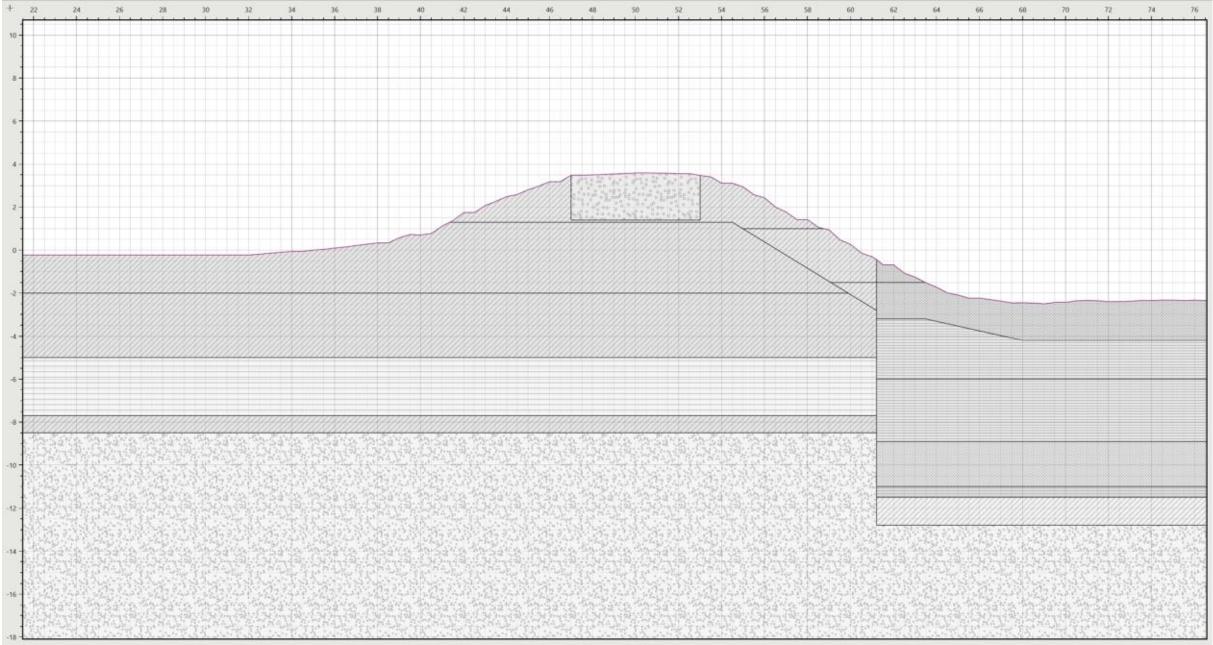


Figure 26: 2.5 meter thick layers

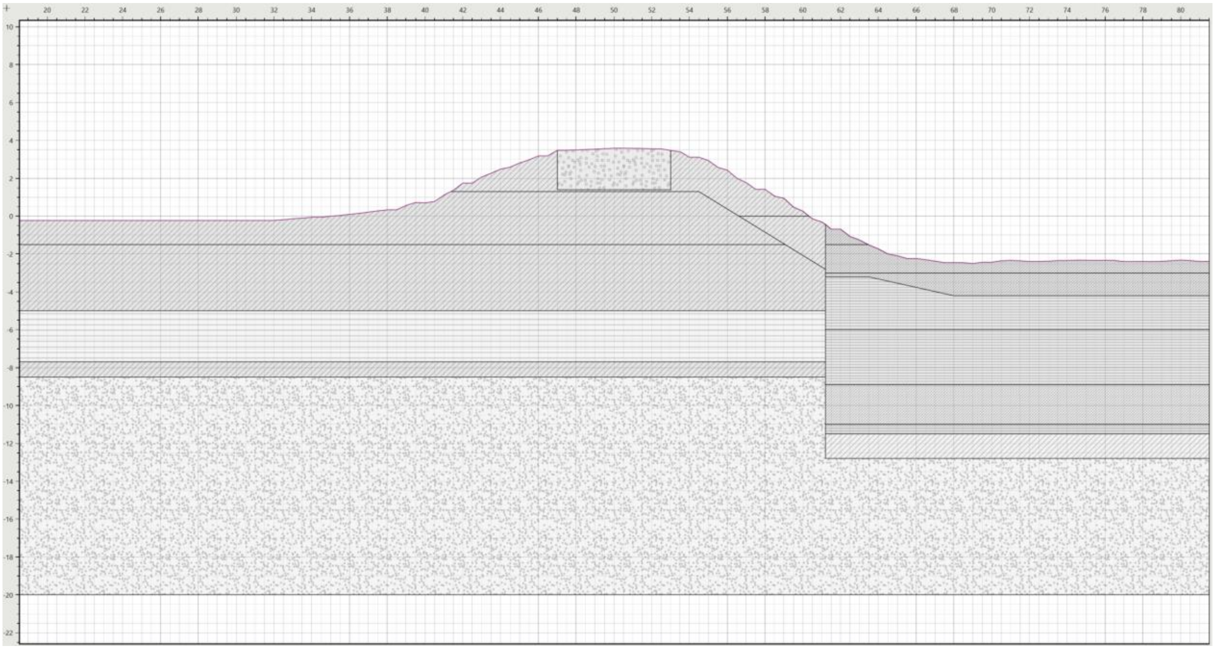
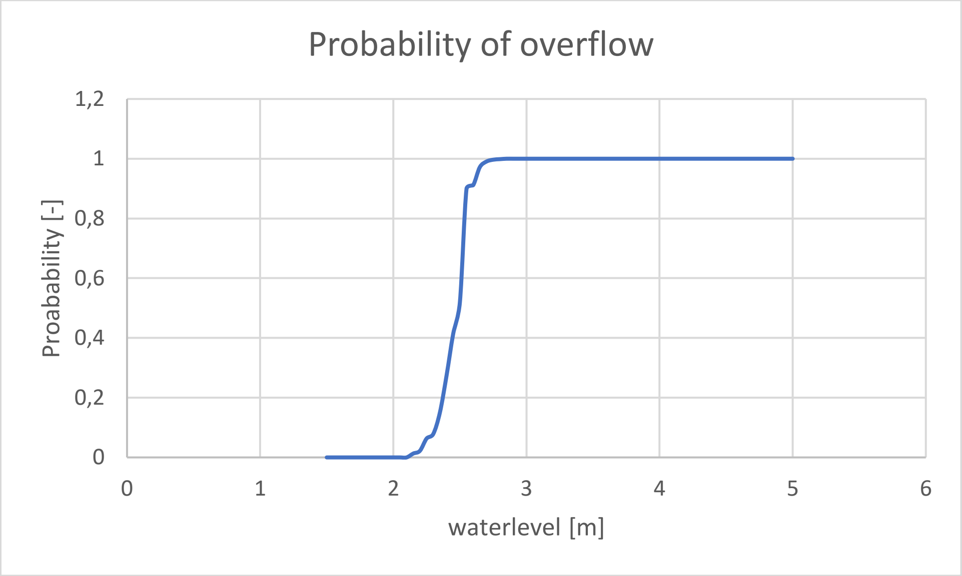


Figure 27: 2 layers

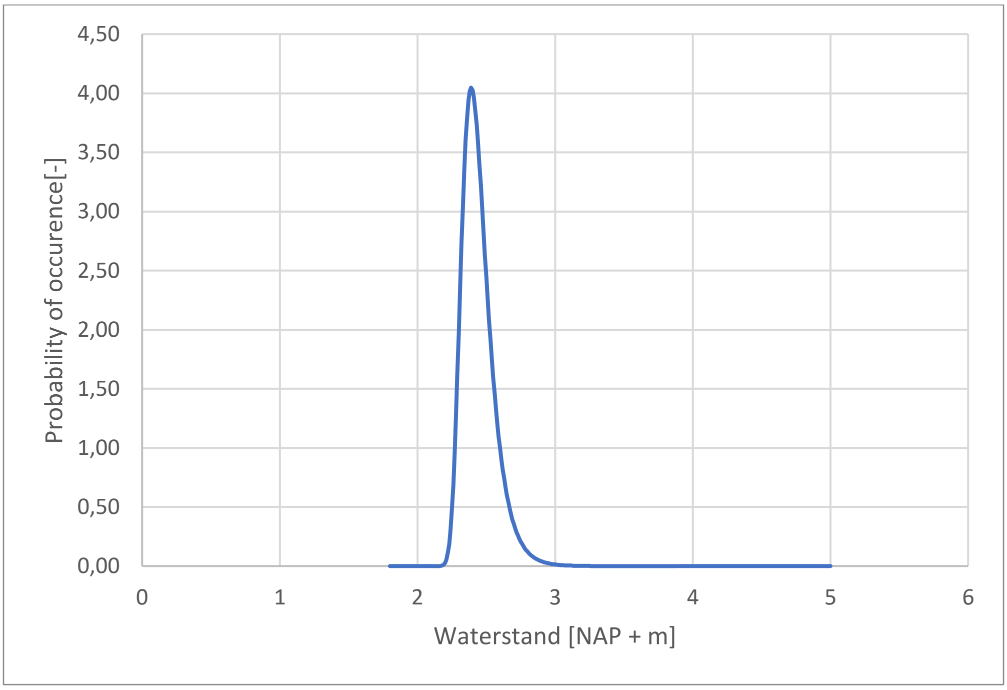
Apendix B Probability of wave overtopping

Table 12: Probability of wave overtopping



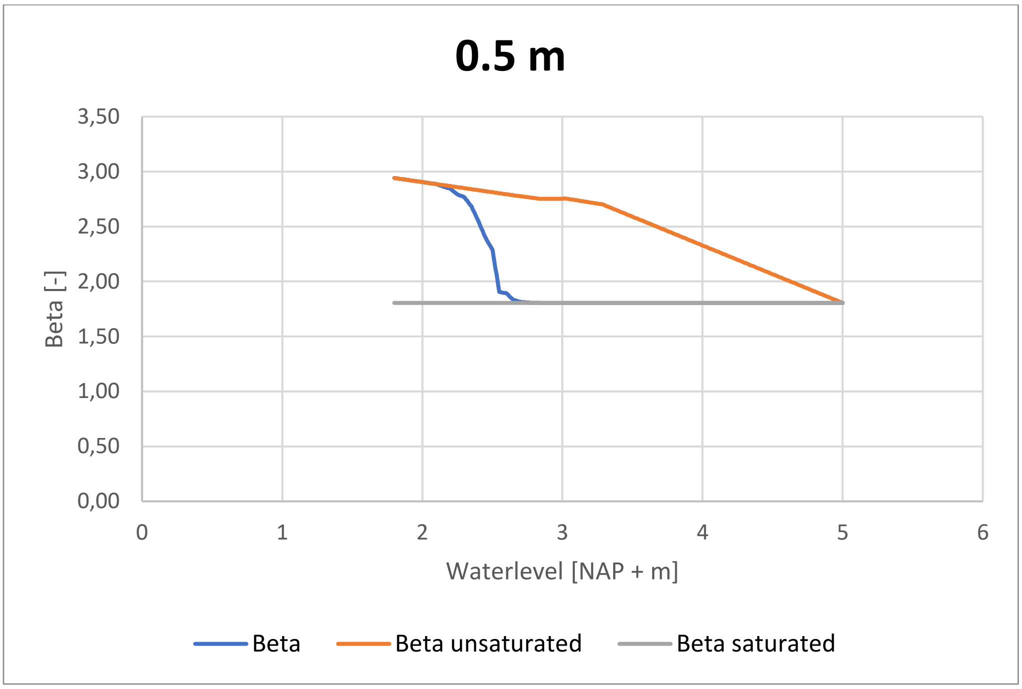
Appendix C Probability of a certain waterlevel

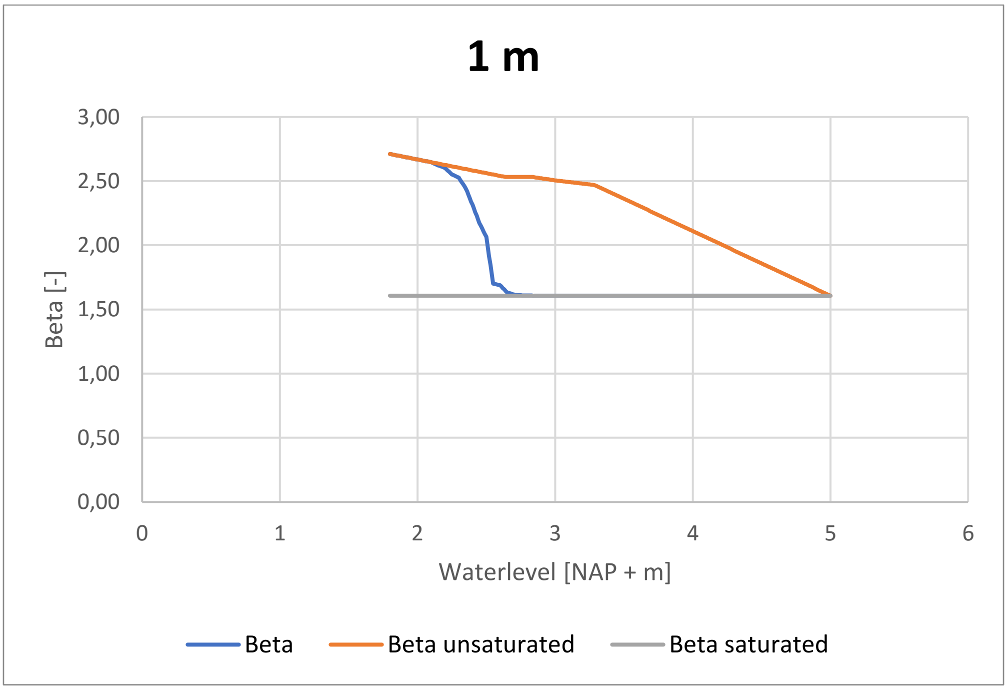
Table 13: Waterlevel occurence

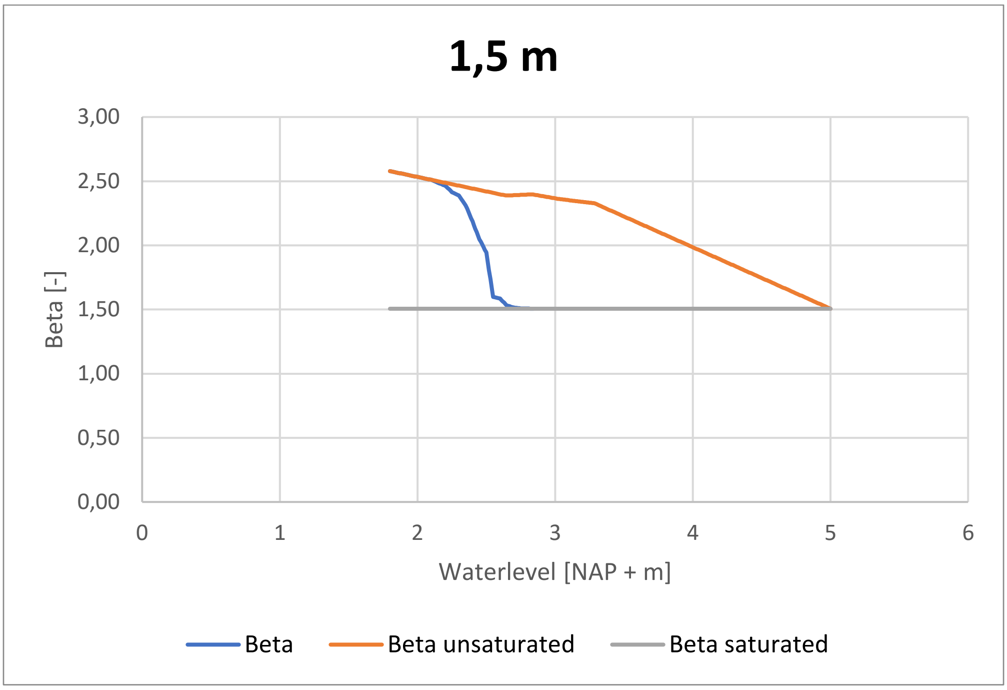


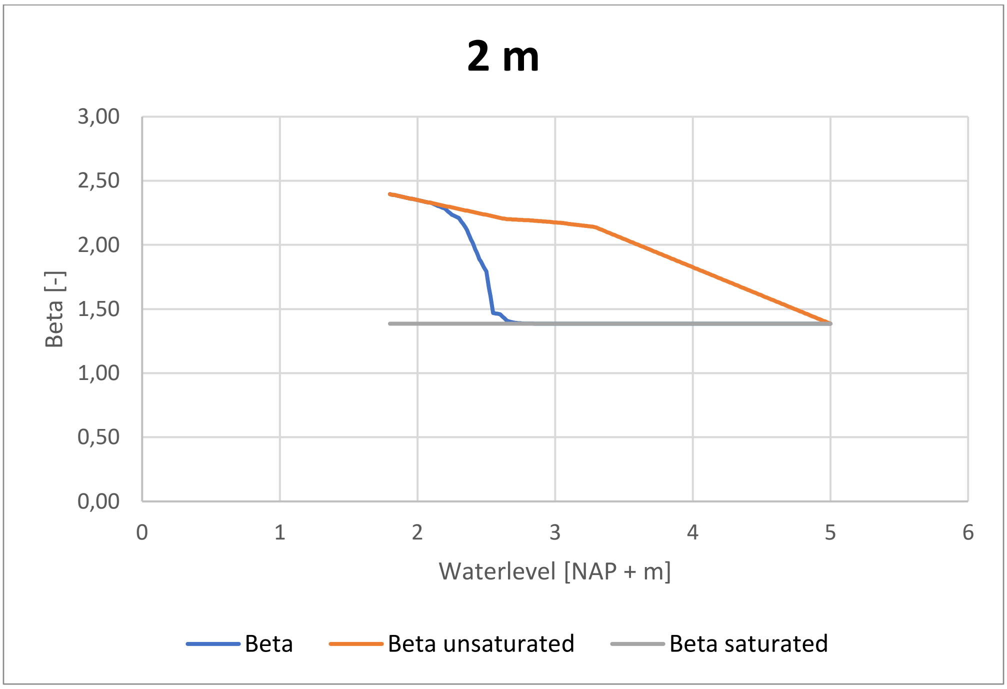
Apendix D Fragility Curves

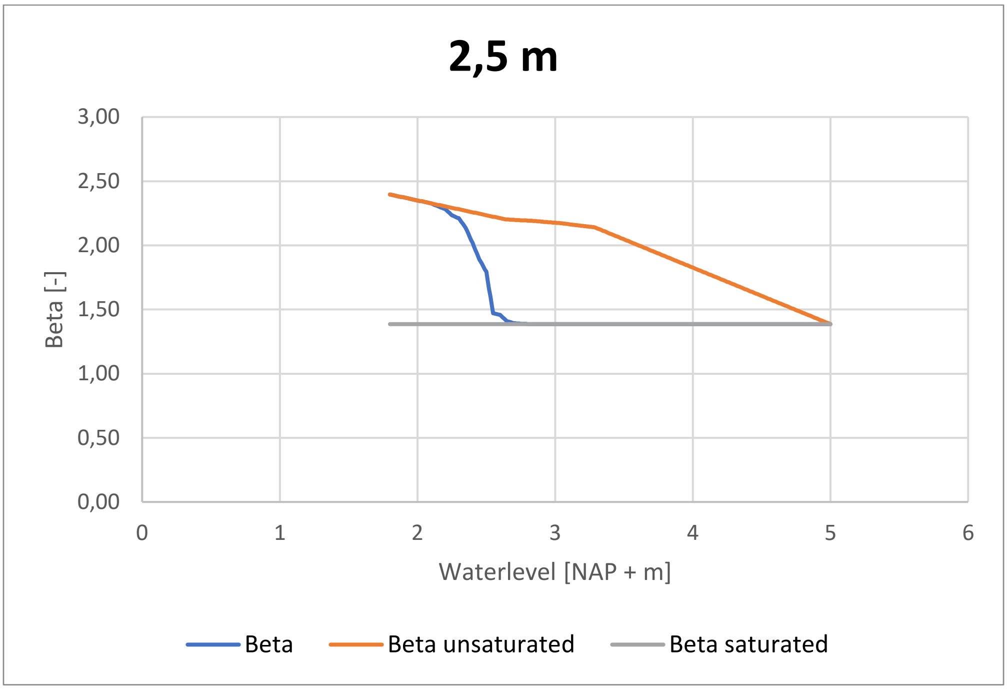
KIJK

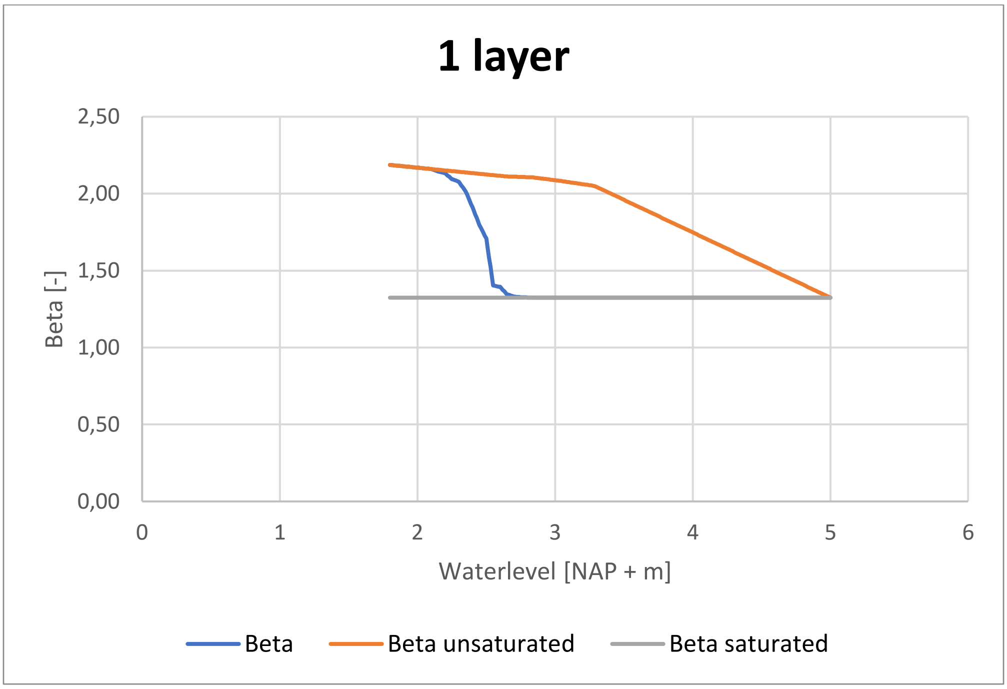


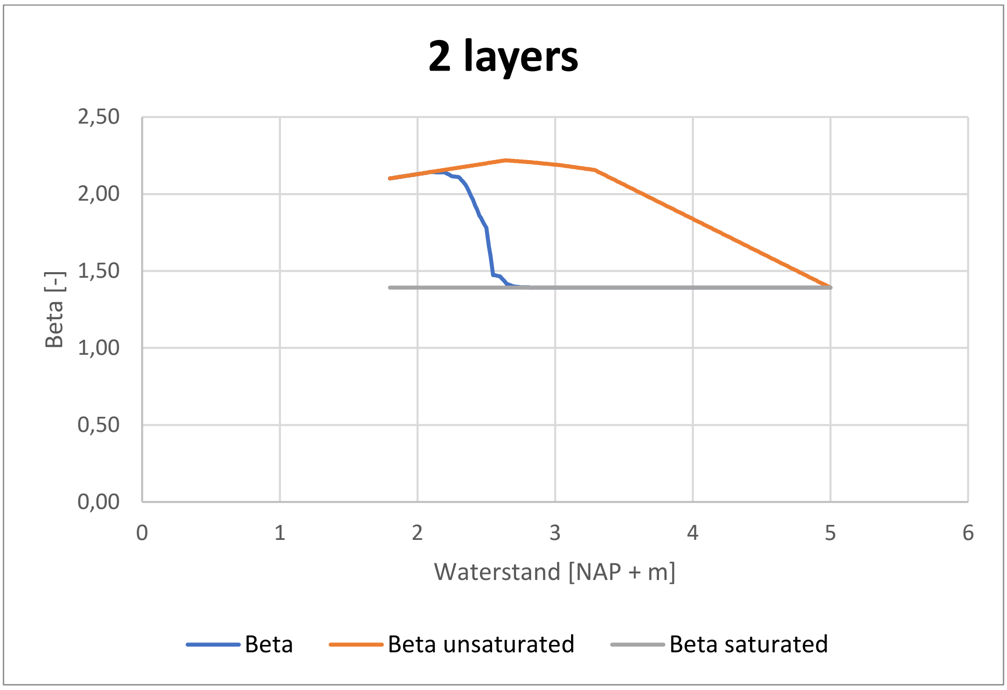



1,5 m
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated

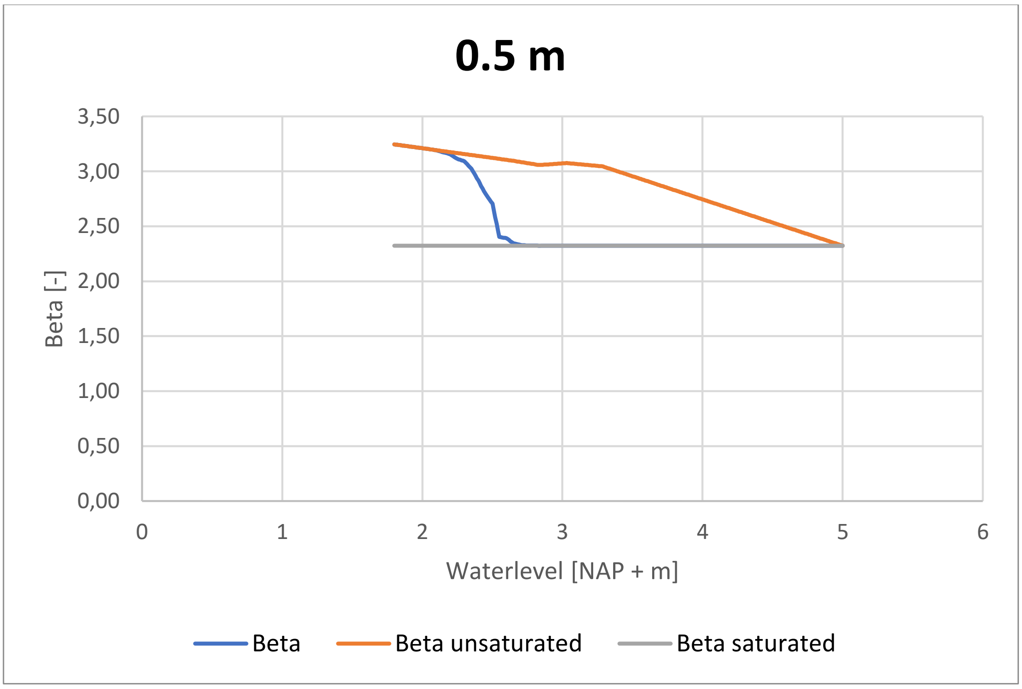

2 m
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated

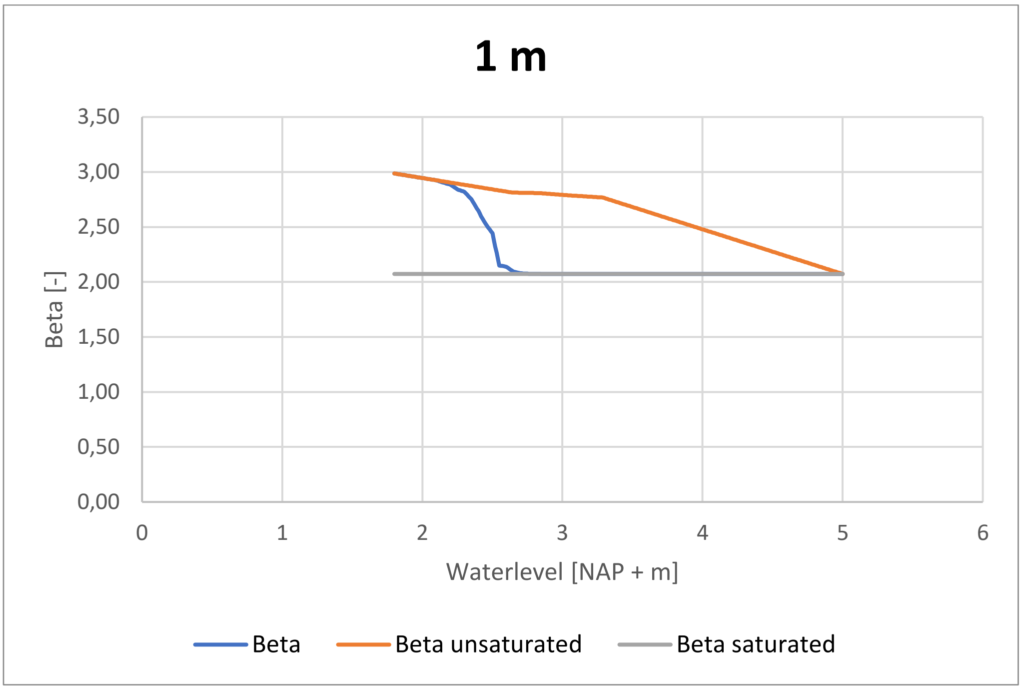

2,5 m
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated

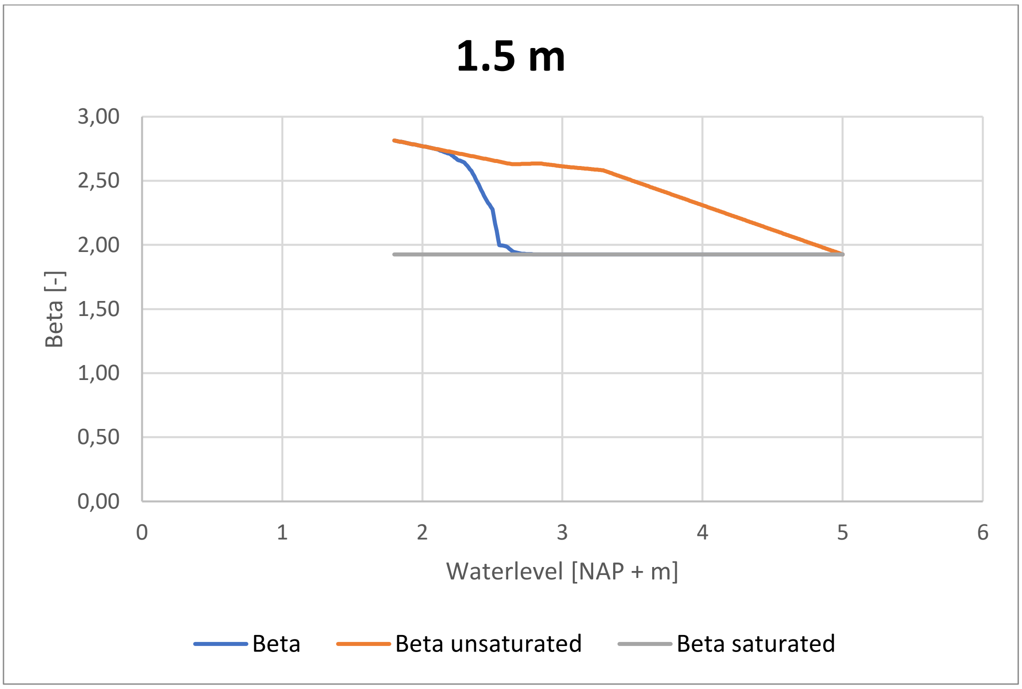

1 layer
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated

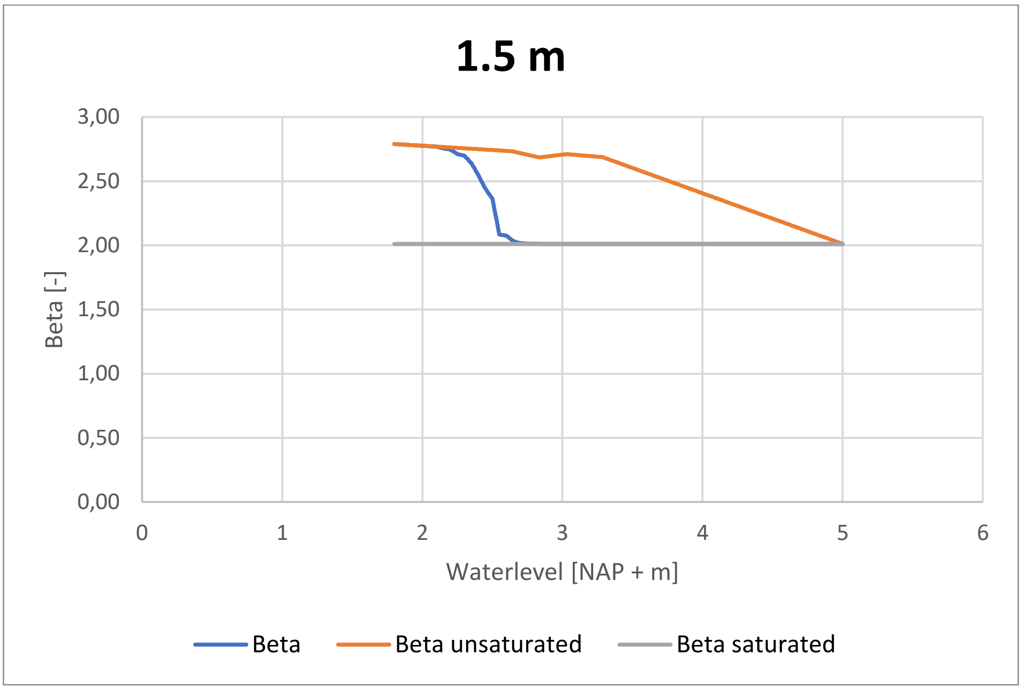

2 layers
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterstand [NAP + m]
Beta
Beta unsaturated
Beta saturated

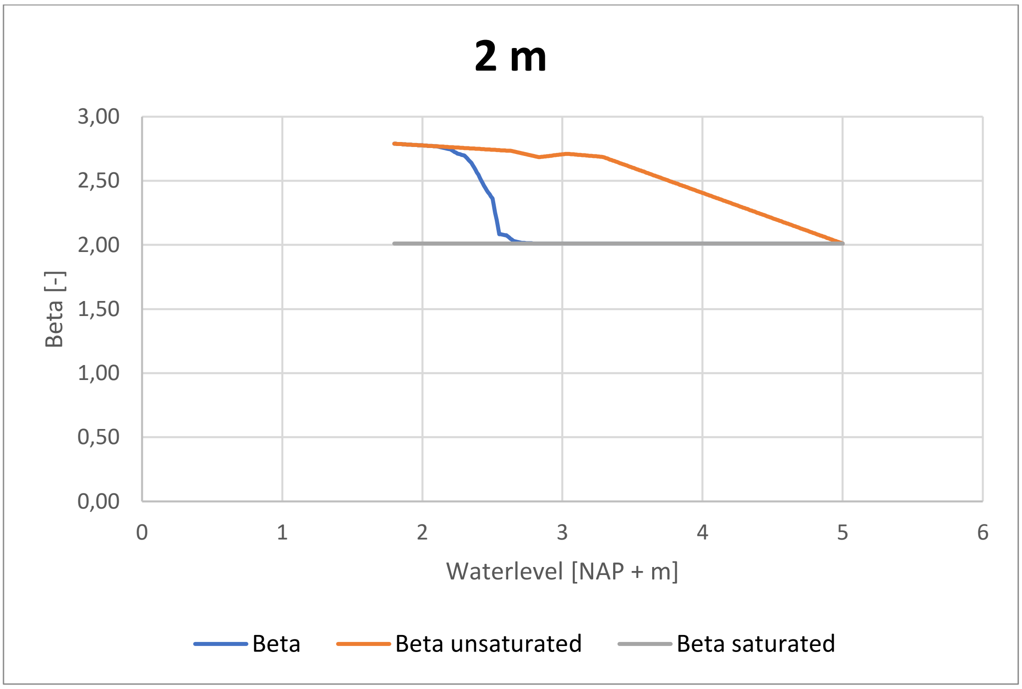
POV-M

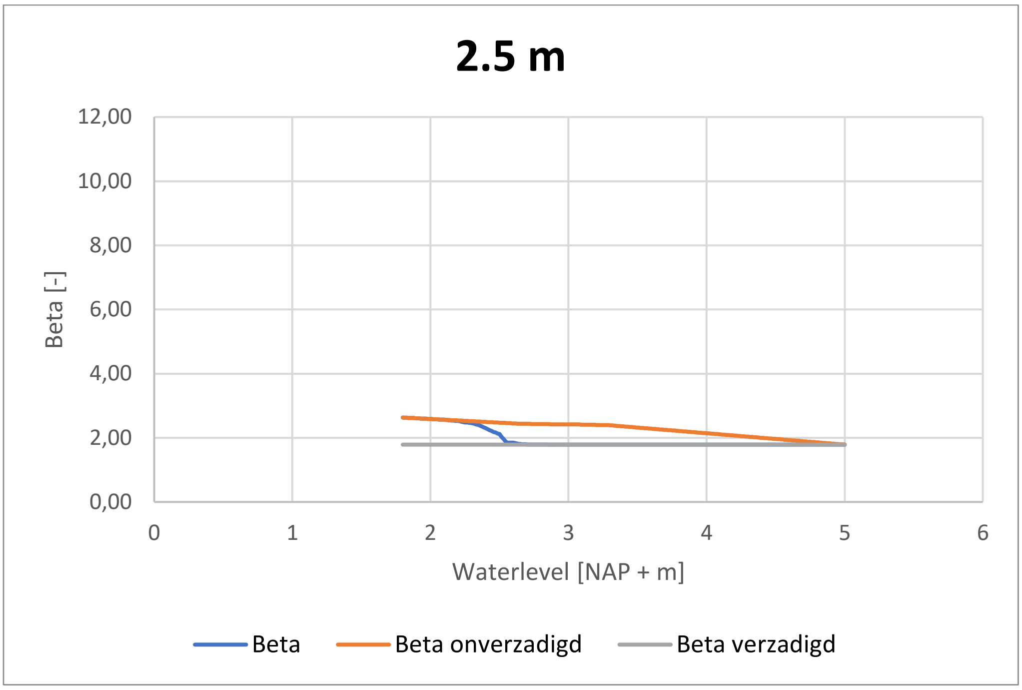

0.5 m
3,50
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated

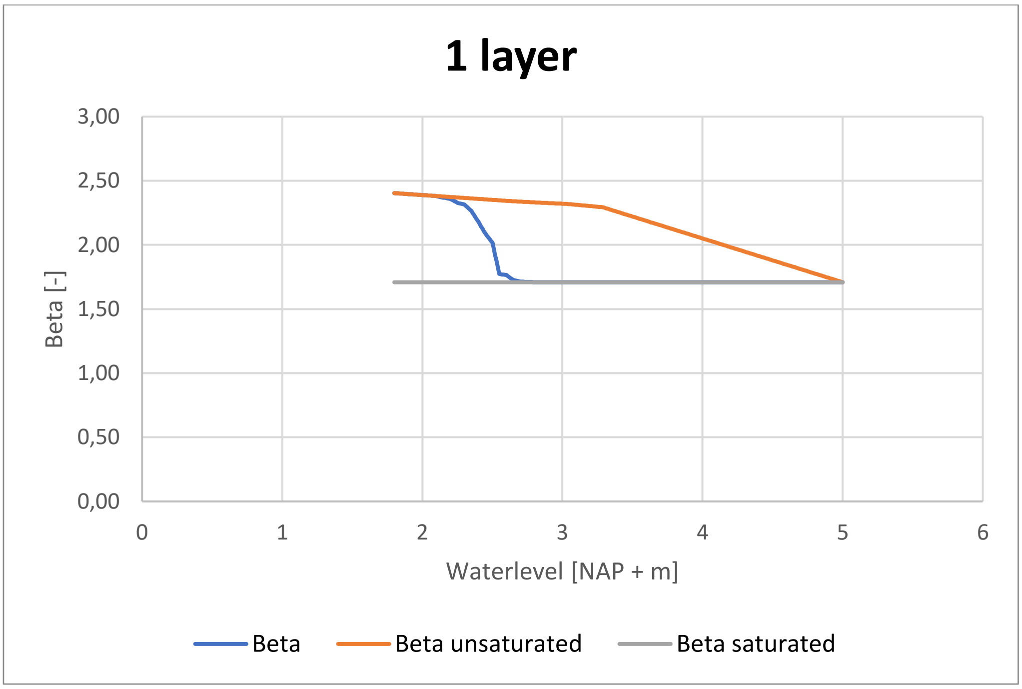

1 m
3,50
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated

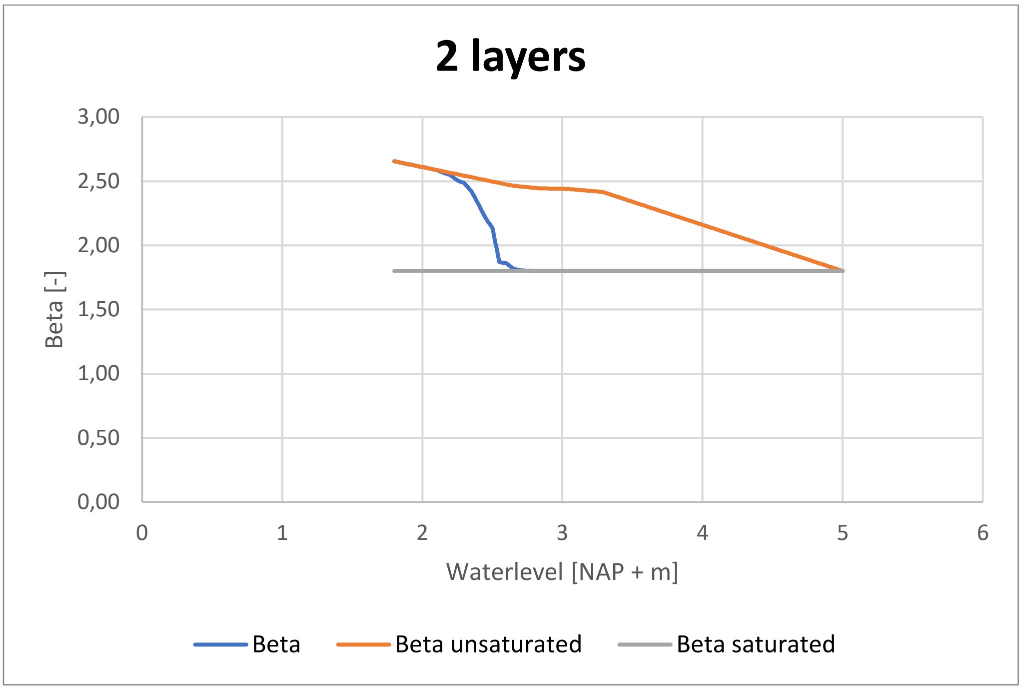

1.5 m
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated


1.5 m
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated

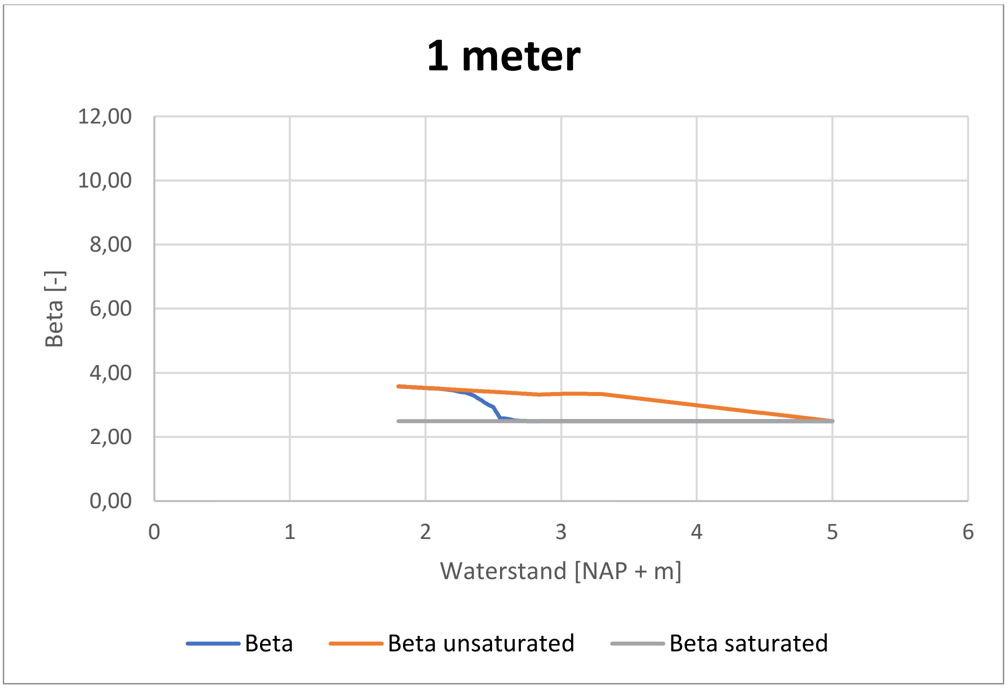

2 m
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated

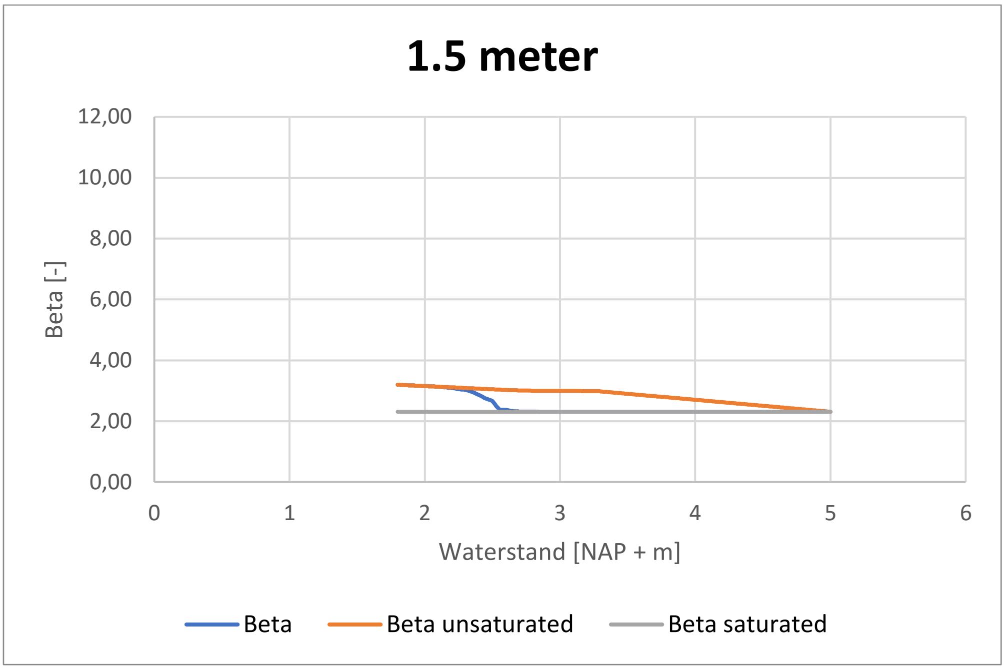

2.5 m
Beta [-]
12,00
10,00
8,00
6,00
4,00
2,00
0,00
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta onverzadigd
Beta verzadigd

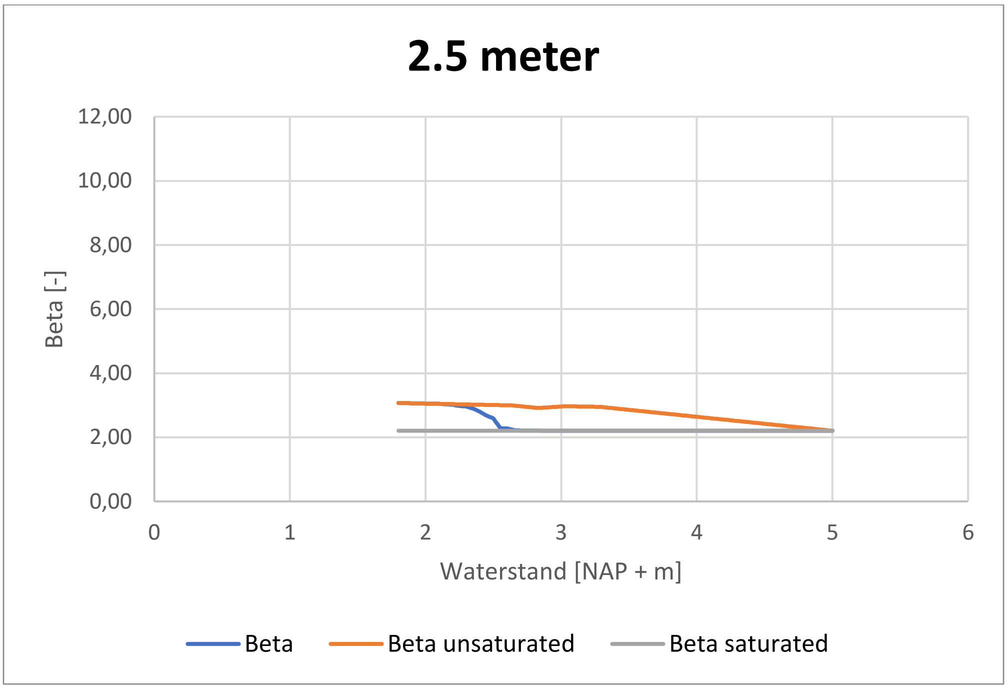

1 layer
Beta [-]
3,00
2,50
2,00
1,50
1,00
0,50
0,00
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated

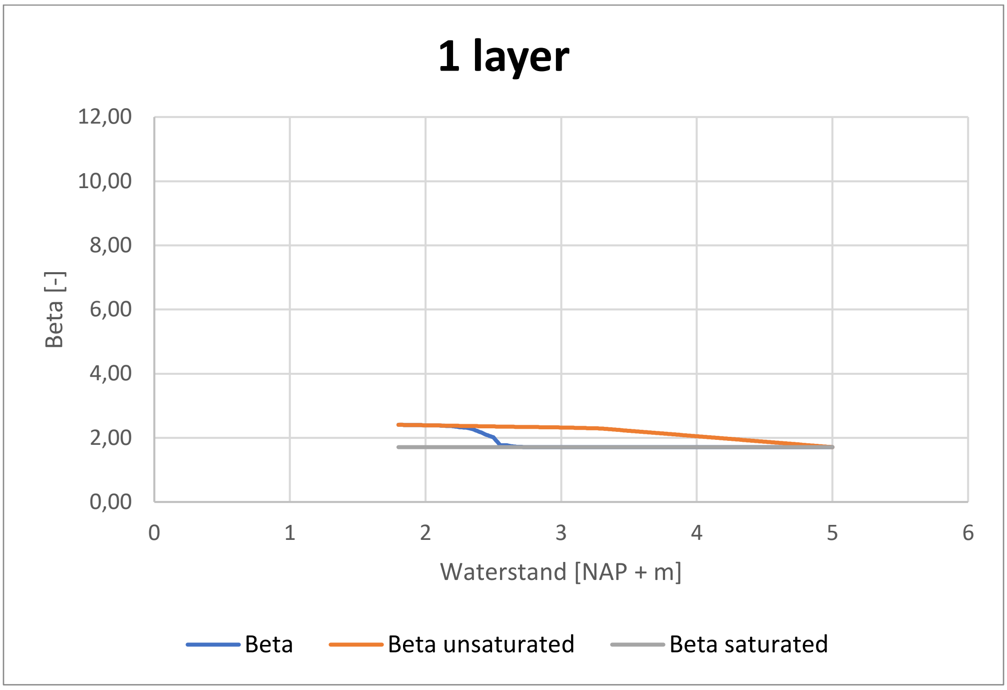

2 layers
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Beta [-]
0
1
2
3
4
5
6
Waterlevel [NAP + m]
Beta
Beta unsaturated
Beta saturated

POV-M (2)


1 meter
12,00
10,00
8,00
6,00
4,00
2,00
0,00
Beta [-]
0
1
2
3
4
5
6
Waterstand [NAP + m]
Beta
Beta unsaturated
Beta saturated


1.5 meter
Beta [-]
12,00
10,00
8,00
6,00
4,00
2,00
0,00
0
1
2
3
4
5
6
Waterstand [NAP + m]
Beta
Beta unsaturated
Beta saturated


2.5 meter
Beta [-]
12,00
10,00
8,00
6,00
4,00
2,00
0,00
0
1
2
3
4
5
6
Waterstand [NAP + m]
Beta
Beta unsaturated
Beta saturated



Appendix E

The same coördinate system as for Appendix A is used. The coördinates are in meters.

Waterlevel	Phreatic line 1	Headline 1	Headline 2
Daily	0;0.3,38.5;0.3,47; 1.5,52.5;1,64.5;-2.59	0;-2.5,99.5;-2.5	0;-3,99.5;-3
1/30	0;3.25,44.5;2.66,47;2.36,52.5;1.86,64.5;-2.29,65.5;-2.53,67.5;-2.59	0;-2.5,99.5;-2.5	0;-3,99.5;-3
1/500	0;3.25,45;2.86,47;2.43,52.5;1.93,64.5;-2.54,65.5;-2.57,67.5;-2.59	0;-2.5,99.5;-2.5	0;-3,99.5;-3
1/3000	0;3.25,45.6;3.05,47;2.5,52.5;2,64.5;-2.29,65.5;-2.53,67.5;-2.59	0;-2.5,99.5;-2.5	0;-3,99.5;-3
1/25000	0;3.25,46.79;3.31,47;2.59,52.5;2.09,64.5;-2.29,65.5;-2.53,67.5;-2.59	0;-2.5,99.5;-2.5	0;-3,99.5;-3
Saturated	The outside of the dike	0;-2.5,99.5;-2.5	-

Reference 1	Reference 2	Reference 3
0;-5,5.5;-5,61.167;-5,61.217;-3.2,65.5;-3.2,99.5;-3.2	61.167;-7.7,61.217;-11	0;-8.5,5.5;-8.5,61.167;-8.5,61.217;-12.8,65.5;-12.8,99.5;-12.8