Probabilistic approach of overtopping's effects on Macro stability in Zwolle Olst

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PREFACE

Before you lies my Thesis "Probabilistic approach of Overtopping's effects on Macro stability in Zwolle Olst''. It investigates the relationship between overtopping and the changes in the selected dike design's stability according to the semi and probabilistic norms. This thesis has been written to fulfill the graduation requirements of the BSc Civil engineering and management program at the University of Twente. I was engaged in researching and writing this thesis from May 2022.

The project has undertaken at the request of Witteveen+Bos, where I undertook a graduation internship. My research question was formulated together with my supervisor, Thomas Naves. The research was a bit challenging, owing to its limitations and available information. However, extensive research allowed me to answer the identified question according to the selected methodology.

I would like to thank my supervisors for their excellent guidance and support during this process, namely, Thomas Naves, Pim Willemsen, and Bart van Es. I would also like to thank all of the respondents, without whose cooperation I would not have been able to conduct this analysis.

Lastly, I would like to thank my parents for their wise counsel and kind words, as they have kept me motivated during this whole research.

I hope you enjoy your reading,

Mostafa Yaghi,

Enschede, July 8, 2022

SUMMARY

As a daily part of our engineering world, engineers are always searching for ways to make our designs easier, which also saves us much time. Therefore, most designs are made according to a semi-probabilistic approach, which is developed by different probabilistic findings and cut down into simple equations that we can use.

The research carries a probabilistic assessment for the dike ring south of Zwolle Olst. It checks whether the used semi-probabilistic norms/rules deliver a safe design or not according to the macro-stability failure mechanism. This assessment has been carried out by first making a design using the semi-probabilistic rules and then assessing them according to the FORM methodology norms, which perfectly suited the limitation of the research.

Summerly, the difference between the two methods is that the semi-probabilistic approach works with fixed variables (deterministic). On the other hand, the probabilistic approach has a mix of both deterministic and stochastic variables. These stochastic variables are put in as a mean and a standard deviation. These differences have also raised speculations about how each approach dealt with certain design aspects—for example, modeling the phreatic line and the calculated overtopping probabilities.

Furthermore, the research investigates how different the design would be according to both approaches, which proves the speculations that have been raised by the probabilistic assessment of the semi-probabilistic approach. Furthermore, the research also enlightens the reader about the limitations that the research had to go through and what could have differed the results if those limitation did not exist.

Eventually, the research has found that the semi-probabilistic approach that is used for the selected dike ring is not safe enough and therefore needs further assessment to check its reliability.

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1 INTRODUCTION

1.1 General Introduction

Different water levels cause a variety of hydrological loads that need to be resisted by dikes. These variations change the behavior of the phreatic line inside the dike, which lowers the reliability of a dike’s design. For this reason, conservative approaches are applied to resist this interaction and assess the reliability of the dike. Therefore, a closer look at this interaction between overtopping and the phreatic line is needed to understand its consequences to the current design standards.

In this course, Witteveen +Bos Is interested in a case located in the IJsseldijk, which is a part of dike reinforcement between Olst and Zwolle. The dike stretch spreads over 28.9km in the east of Zwolle. the selected dike trajectory is called ‘’Duursche Waarden’’ (trajectory number 53-2) with a length of 1400 m, which spreads between 26,1-27,5 km of the whole dike line, (TUN, Technische Uitgangspunten Notitie Waterkeringen, 2021). Figure 1 shows the exact location of the trajectory.

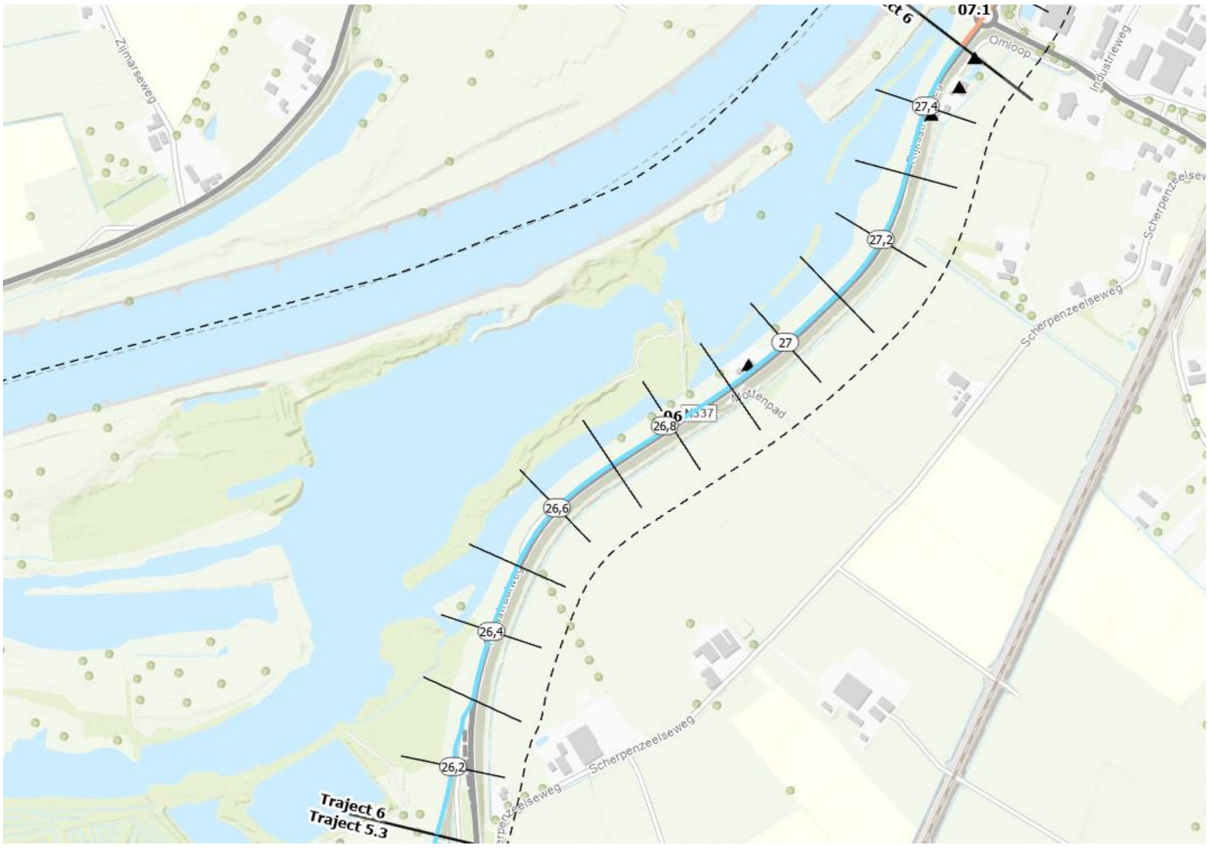


Figure 1 location of the dike trajectory provided from (W+B)

The dike's current design is designed using a semi-probabilistic approach. Therefore, if minimizing the footprint of the dike overtopping is allowed, it would result in a minimal height. However, the adverse effects of overtopping need to be considered when assessing the safety of the dike regarding macro stability. This research strives to better understand the discrepancies/differences between the semi-probabilistic and probabilistic approaches regarding this interaction between the phreatic line and water levels.

The difference between both approaches is that the semi-probabilistic approach works with fixed rules and variables. These rules result from a detailed assessment that could be summarized into fixed rules, which saves much time in calculating the design; therefore, these rules have a margin of uncertainty. On the other hand, the probabilistic approach is a more detailed approach that works with deterministic and stochastic variables. These stochastic variables are put in as a mean and a standard deviation. Therefore, the probabilistic approach has a smaller margin of uncertainty.

The scope of this research is focusing on the differences between the semi-probabilistic and probabilistic approaches, which is going to be done by first designing the semi-probabilistic approach according to its formula and then assessing the approach according to the probabilistic assessment. In this framework, the research will not investigate how these formulas could be improved and will not investigate any hydrological aspects in the dike design, like the modeling of the phreatic line. In short, The research uses pre-determined rules for both approaches. The latter introduces the following research questions:

Main research question:

Does the semi probabilistic approach deliver a reliable design when compared to probabilistic approach?

Research sub-questions:

1- What does the design look like using the semi probabilistic approach?

2- what is the probability function of the main variables in the probabilistic approach? And how sensitive is the safety factor to the different deterministic and stochastic variables?

3- How reliable is the design according to the probabilistic approach?

4- What are the discrepancies between the current design (semi-probabilistic) and the probabilistic design? And how could the semi-probabilistic approach be improved using the findings of previous question?

Research structure

The research structure is as follows first, the semi-probabilistic design with its norms and assumptions has been modeled and explained (question 1, sections 2 & 3). Secondly, there has been a research about the available stochastic variables for the probabilistic approach (question 2, section 4). After that, the probabilistic norms and assessment are explained, where the semi-design is also checked (question 3, section 5). Lastly, the discrepancies between the two approaches are explained along with speculations about different aspects of both approaches (question 4, section 6).

1.2 Questions starting points

In this section the general starting points that apply to all question are written here along with an introduction about the used software in this research.

1.2.1 D-stability software:

D-stability is a software developed by Deltares that can calculate the safety factors of a dike design according to its load, ground profile characteristics, phreatic line positioning, water levels, and sliding surface. Lastly, the software is capable of performing calculations with either fixed or probabilistic input, which are used in this research. (Deltares, 2019)

Methods in the D-stability software:

The method of Uplift Van is used for this research because it is more suitable for situations with and without uplift failure (opbarst) or heave failure (opdrijven) according to (TUN, Technish uitgangspunten notitie waterkeringen, 2021), which may happen because of the existence of the ditch in the landward side.
On that note, D-stability produces a safety factor that can be used to assess the dike stability. On that note, the needed safety factor is determined according to the methodology mentioned in the section 2.1.2.

1.2.2 Ground profile

The general ground profile has been taken from (IJsselwerk, 2022), which indicates the following ground profile, Table 1.1.

Table 1.1 General ground layer formation

Formation	Lithological features	Indication depth [m, NAP]
Antropogeen	sand	5.9 − 7
Echteld	clay	5.6 − 5.9
Antropogeen	sand	2 − 5.6
Echteld	clay	0.3 − 2
Nieuwkoop	peat	0 − 0.2
Boxtel	sand	−5 − 0

Dike geometry & standard D-stability model without reinforcement:

Using the previous table for the ground profile. The standard model is to be seen at the following figure, Figure 2. The geometry of this dike has been provided by Witteveen+Bos.

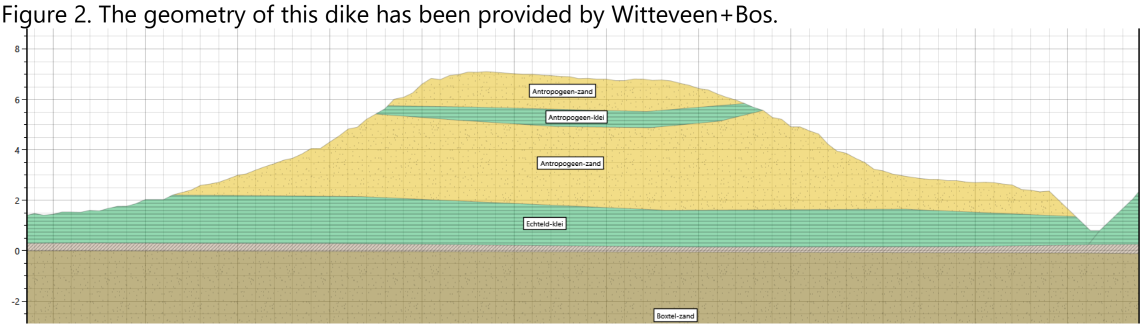


Figure 2 Dike geometry and ground profile (current situation)

State POP points in the first stage of D stability model.

State POP points have been defined in the model. These points determine the over consolidation ratio of the materials in the model. These points have been defined in the following locations, Figure 3.

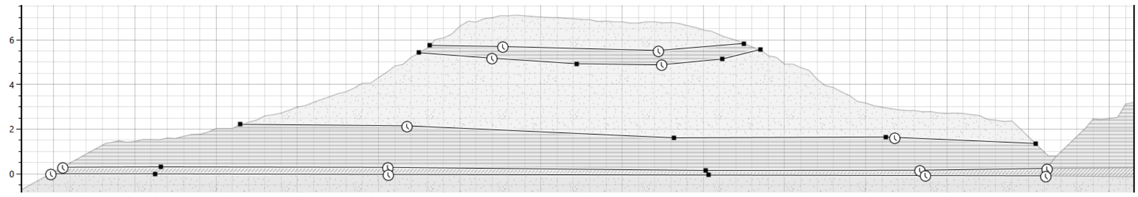


Figure 3 State points locations

The location of these points was defined around clay layers with only one rule. The layer should have about 2 or 4 points, depending on how long the layer is. The latter is dependent on the dike design's change in geometry; that is why they are located around the clay and peat layers in this case.

The previous rule was assumed because inputting many POP points would make the probabilistic calculations take too much time; therefore, the number of points had to be limited.

1.2.3 Loads settings

For the situations with reinforcement but without overtopping , a load has been applied on top of the dike, which has the following properties:

Table 1.2 load settings

variable	value

variable	value
starting point [x point]	91.3 (m)
end point [x point]	93.6 (m)
magnitude	10 $kN/m2$
Angle of distribution	30 (deg)

This applies a layer consolidation percentages settings to the materials of the dike, these settings are to be found in section 9.1.

1.2.4 Hydra-NL program and methodology

Hydra-NL is a probabilistic software that calculates the statistics of the hydraulic loads (water level, wave conditions, wave overtopping) for assessing the primary dikes and structures in the Netherlands. It is consistent with the assessment and design instrumentation to achieve the probabilistic approach (BOI), (HelpdeskWater, 2017)

This program can calculate different things, like water level, hydraulic load, and overtopping criterion. For this calculation, only the failure probability of hydraulic load of an overtopping criterion of $(q \geq 1\ l/m/s)$ is required of the year 2075. For this purpose, the mean of the failure probabilities for the years 2050 and 2100 is calculated since only these two years are available in the program.

On that note, Hydra-NL trajectories are made of multiple points along the whole trajectory. Each one of those points has a different failure probability for the hydraulic load. Therefore, the point with the highest probability is chosen as a representative point, Figure 8 . The result of this point is chosen for the calculations of both the semi and probabilistic approaches.
The way the program is used is not mentioned in this report, but could be found in the following reference, (Duits, 2020).

Starting points for Hydra-NL:

Hydra-NL outer slope model.

In order to calculate the probability of overtopping of the dike trajectory. A standard outer slope has been defined in the Hydra-NL, Figure 4. In this model the height of the dike ring has been set to be 7 m+Nap, which is equal to the average height of the dike (TUN, Technische Uitgangspunten Notitie Waterkeringen, 2021). This is also the same outer slope that is to be found in figure 2.

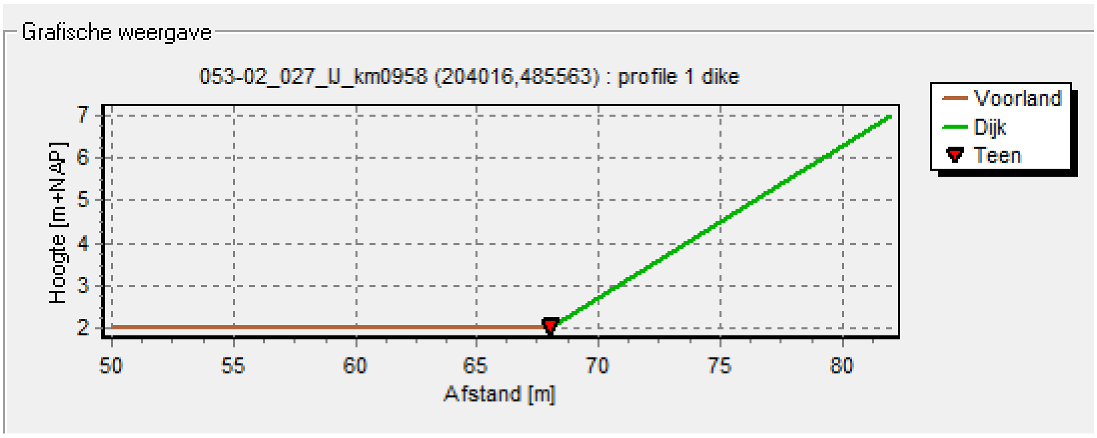


Figure 4 Hydra-NL outer slope model

1.2.5 Determination of the phreatic line and hydraulic head in the D-stability model

Phreatic line

In this semi-approach, the value of the accepted overtopping, materials of the dike, and ground layers determine the shape of the phreatic line inside the dike.

If the overtopping value is less than $1\ l/s/m$,then the phreatic line is determined according to the guidelines mentioned in (TAW, 2004). However, if this criterion is over $1\ l/s/m$ then a set of rules are used, which are determined by the team of W+B. These rules are mentioned in (TUN, Technish uitgangspunten notitie waterkeringen, 2021) and are not to be found in an official technical report, as these rules are the result of a hydrological study that has been done in Witteveen+Bos. These rules define the shape of the phreatic line in overtopping conditions depending on the surrounding environment, (TUN, Technish uitgangspunten notitie waterkeringen, 2021).

The difference between the two models is that one without overtopping conditions; therefore, the phreatic line goes under the starting point (C1) in the following figure. On the other hand. the other one models with overtopping conditions, which shows that the phreatic line gets heightened above the water level point (A), which makes sure that the dike is saturated. Figure 6

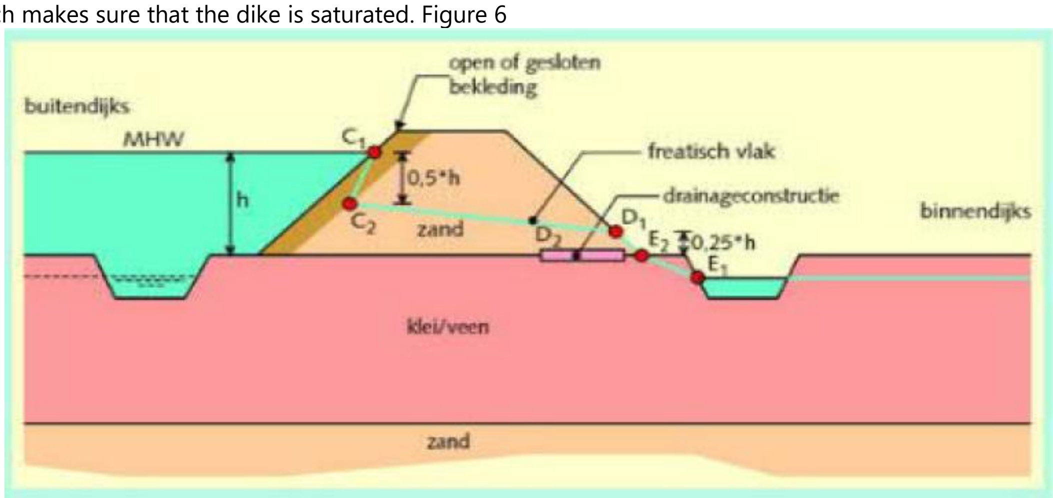


Figure 5 phreatic line model without overtopping

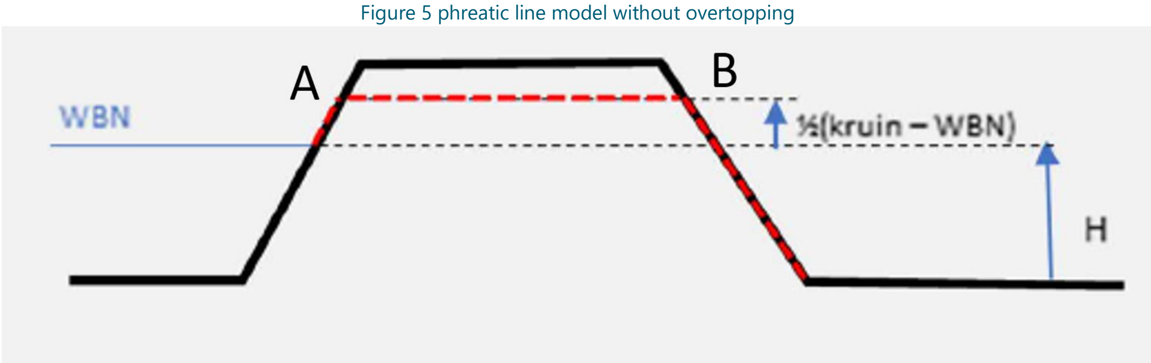


Figure 6 phreatic line shape with overtopping

Hydraulic head (stijghoogte):

For the pressure to be calculated in the D-stability model, the hydraulic head needed to be determined and modeled in the software as a second water headline. This correlates with water reference lines determined/modeled around the clay layers. Including these lines helps the software model the water pressure along the layers correctly. Summarily, The Hydraulic head or piezometric head is a specific measurement of liquid pressure above a vertical datum. (Linquip, 2020)

Following this, a formula of the hydraulic head has been provided in (TUN, Technish uitgangspunten notitie waterkeringen, 2021), which is:

$$n_{opdr} = \frac{\sum_{i=1}^{n} \gamma_i d_{i_i}}{\gamma_w(\phi_z - h_{sand})} \quad (eq. 1)$$

Where:

n_opdr	pressure safety, which is pre-determined to be either 1.2 or 1. (1.2 is for uplift and 1 for the burst mechanisms). 1 is eventually used.	$[-]$
γ_i	volumetric weight	$kN/m2$
d_i	thickness of layers of the ditch (thickness of this layers is dependent on the shape of the slope as defined in (TUN, Technish uitgangspunten notitie waterkeringen, 2021))	m
γ_w	volumetric wight of water	$kN/m2$
ϕ_z	hydraulic head	$m + NAP$
h_{sand}	height of the sand layer	$m + NAP$

1.2.6 Ground material properties

The semi probabilistic has made use of the materials properties that has been provided (IJsselwerk, 2022), which can be found in the following Tabel 1.3.

Tabel 1.3 Semi probabilistic model ground materials properties.

	Antropogeen-sand	Antropogeen-clay	Echteld-clay	Nieuwkoop-peat	Boxtel-sand	reinforcement-clay
Unit weight (kN/m2) above water	18.2	18.5	16.4	10.8	19.7	18.5
Unit weight (kN/m2) under water	19.2	18.5	16.4	10.8	19.7	18.5
Cohesion (kN/m2) above water	0	20	10	-	0	15
Frictional angle (deg)	31.3	0	0	-	31.3	0
Dilatancy angle (deg)	0	0	0	-	0	0
shear strength ratio (-)	-	0.29	0.29	0.39	-	0.29
Strength increase exponent (-)	-	0.83	0.83	0.83	-	0.83

OCR:

Most OCR points had an OCR of **1.5** above water and an OCR of **1.4** underwater. However, for the OCR points around the pear layer, The above water OCR is **1.4** and **2** for underwater. (IJsselwerk, 2022)

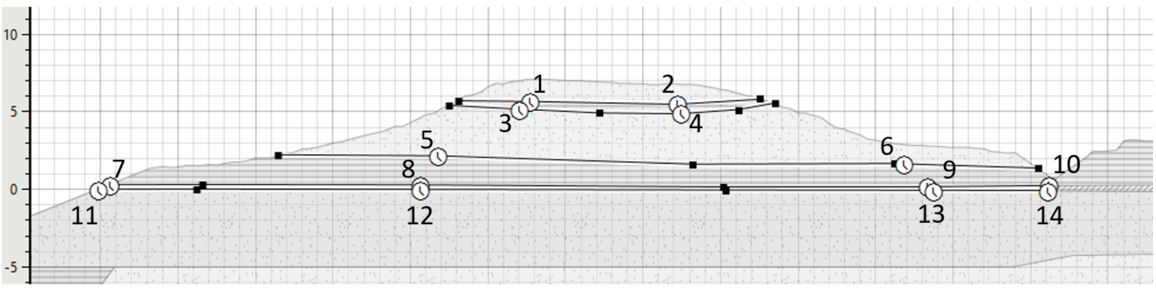


Figure 7 OCR points numbering

2 SEMI-PROBABILISTIC APPROACH

Question: How does the design look like using the semi probabilistic approach?

2.1 Methodology

In the following section, the semi-probabilistic rules are explained with all the included assumptions in this research. Each assumption is also provided with enough reasoning that led to its selection. The Following methodology is taken from the KRP memo provided by Witteveen+Bos, (KPR, 2018).

2.1.1 Dike geometry and ground profile of the dike section

First of all, a dike geometry model has been provided from Witteveen+Bos, along with a ground profile that provides information about the whole trajectory (Drens Overijsselse Delta , 2022). As mentioned above the trajectory has a length of 1400m.

One profile (doorsnede) will be studied for the whole trajectory. A location is chosen with a high probability of overtopping. The profile selection is further based on the dike section with the most sand layer in the dike's body, as sand is the weakest against overtopping. The rest of the dike section (the underground layers) is based on the most common dike layers depending on their location, either in front of, underneath, or behind the dike. All information has been taken from (IJsselwerk, 2022) provided by Witteveen+Bos.

2.1.2 Methods of safety factor.

As the name of the research suggests, the failure mechanism that is researched is Macro-stability. In order to calculate whether the design is safe enough or not, the method of Uplift Van is going to be used, which should be used when heave failure happens (opbarsten) according to (TUN, Technische Uitgangspunten Notitie Waterkeringen, 2021)

For the calculations of the safety factor. There are two conditions that the research has dealt, with overtopping and without overtopping. This is important as these conditions change the behavior of the phreatic line, which is elaborated on in section 1.2.5.

Safety factor with an overtopping criteria < 1 l/m/s

For the situation where $q < 1\ l/m/s$ the required safety factors is calculated according the formulas mentioned in (OI2014v4, 2014). The required safety factor for dikes with no overtopping is calculated following this Tabel 2.1. This table shows different factors that the research rely on, namely, material factor, damage and schematization factor. These factor make up for the uncertainty that the design might have according to the name of each factor. However, this research will only have different damage factor, which is explained below.

Tabel 2.1 safety factor of the conditions without overtopping

factor	
Damage factor	$Y_n = 0.15 * \beta_{eis,dsn} + 0.41$
Model factor Uplift-Van	1.06
Material factor	1.0
Schematization factor	1.05
Safety factor	$SF = Y_n * 1.11 * 1.0 * 1.05$

1 To calculate the damage factor, the failure probability for macro stability at a cross sectional level $P_{eis,dsn,stbi}$ need to be determined, based on the maximum allowable flood probability, the failure probability factor macro instability and the length effect, which is a standard procedure according to the (OI2014v4)

$$P_{eis,dsn,stbi} = f_{stbi} * Pmax/\ (1 + a * L/b) \qquad (eq.2)$$

$$\beta_{eis,dsn} = -\phi^{-1}(P_{eis,dsn,stbi}) \qquad (eq.3)$$

#Look below for the explanation of the variables;

Safety factor with an overtopping criteria > 1 l/m/s

As mentioned, the damage factor differs between conditions with and without overtopping. The following section explains the difference and how it is calculated.

Table 2.2 factors to calculate the safety factor for overtopping situation

factor	
Model van Uplift-Van	1.06
Material factor	1.0
Damage factor	$Y_n = 0.15 * \beta_{T,stbi,q} + 0.41$
schematization factor	1.05
Safety Factor	$SF = 1.06 * 1 * Y_n * 1.05$

Step 1 is the same step mentioned for the damage factor without overtopping.

2 Calculate the probability of exceeding 1 $l/s/m$ for the considered dike profile (done via HydraNL)

3 Determine the failure probability for macro stability given significant wave overtopping by dividing the failure probability from step 1 by the exceedance probability from step 2.

$$P_{T,stbi,q} = P_{eis,dsn,stbi}/P(q \geq 1\ (l/s/m)) \qquad (eq.4)$$

$$\beta_{T,stbi,q} = -\phi^{-1}(P_{T,stbi,q}) \qquad (eq.5)$$

Where:

$P_{eis,dsn,stbi}$	failure probability for macro instability at cross section level (per year)
$Pmax$	Maximal allowable flooding chance = (1/3000) (TUN, Technish uitgangspunten notitie waterkeringen, 2021)
f_{stbi}	Failure probability factor for macro instability, default value = 0.04
a	Fraction of the trajectory length that is sensitive to the considered failure mechanism, default value in OI2014v4: a = 0.033
b	Length of independent, equivalent dike sections, default value: b = 50m
L	Trajectory length (m) 1400m.
$P(q)$	overtopping probability
$P_{T,stbi,q}$	Failure probability for macro-instability given significant overtopping at cross-sectional level (-)
$\beta_{T,stbi,q}$	Required reliability index for a cross-section at significant wave overtopping (-)
$\beta_{eis,dsn}$	Required reliability index for a cross-section without significant wave overtopping (-)
ϕ^{-1}	Inverse of the standard normal distribution function

As mentioned in step number 2, $P(q \geq 1\ (l/s/m))$ needs to be calculated using a probabilistic program called HydraNL

2.2 Results:

2.2.1 Overtopping probability and safety factor for the model without overtopping

According to the methodology that has been used for the situation without overtopping, the following results has been found:

Tabel 2.3 results of the criteria without overtopping

$P_{eis,dsn,stbi}$	$1/114430$
$\beta_{eis,dsn}(without\ overtopping)$	$4.35(-)$
$Y_n withoutOvertoppig$	1.06
SF	1.23

2.2.2 Overtopping probability and safety factor for the model with overtopping

A database is uploaded to the Hydra-NL program. This database is provided by Witteveen + Bos (but could also be available via the Helpdesk of Rijkswaterstaat). This database has points of the whole dike trajectory, Figure 8. Furthermore, the database is used to calculate the overtopping probability for the year 2075. However, it is only possible to calculate the probability for the years 2050 and 2100. Therefore, the overtopping probability of the year 2075 of each point is the mean of the probabilities of the years 2050 and 2100. This has also been mentioned in the starting points section 1.2.4.

In this course, the result of the highest probability is used to assess the model, which is found in the red box in Figure 8. This has led to the results of (point 20), which has the highest probability of the while dike ring.

The overtopping probability of the year 2075 is $P(q \geq 1\ (l/s/m)) =$ 1/1187.6 $year^{-1}$. Therefore, following the equations (2),(4) and (5). The reliability index $\beta = 2.4$, which, resulted in a safety factor of 0.85 $(-)$ for the model with overtopping characteristics.
Lastly, the program performed a calculation for the expected water level that might occur in $1/3000\ year - 1$, The corresponding value is to be found in the following Table 2.4.

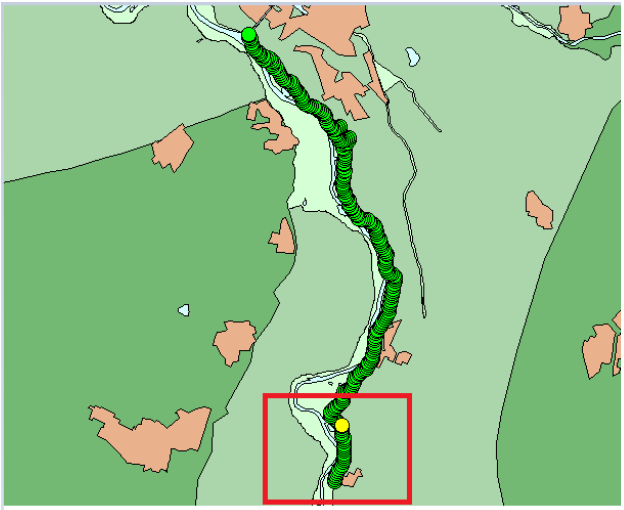


Figure 8 Dike trajectory in the Hydra-NL software

Table 2.4 Results overtopping probability and reliability index

$P(q \geq 1\ (l/s/m))$	$1/1187.6\ year^{-1}$
$\beta_{T,stbi,q}\ (with\ overtopping)$	$2.4\ (-)$
WL	$6.2m + Nap\ \left(\frac{1}{3000}\right)$
$P_{T,stbi,q}$	$1/108$
$Y_n with\ overtoppig$	0.77
$SF_{withOvertopping}$	$0.85(-)$

2.2.3 Hydraulic head

As aforementioned, the hydraulic head results are to be found in the following table.

Table 2.5 Hydraulic head results

variable	result
$\sum Y_i d_i$	$18.66\ kN/m^2$
h_{sand}	$0.09\ m + Nap$
n	$1\ (-)$
ϕ_z	$1.776\ m + Nap$

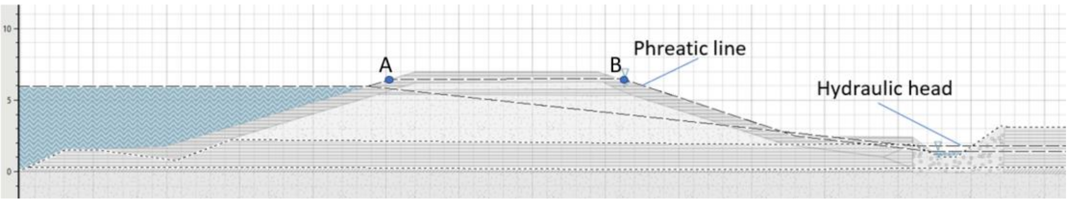
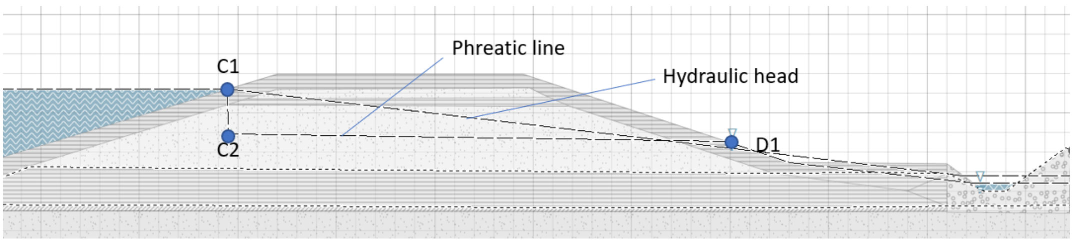
2.2.4 D-Stability model

Reinforcement had to be added to the standard design; this is done by adding a layer of 80cm of reinforcement clay. Therefore, an inner slope had to be defined for the dike's design. This is also modeled by using a water level that has a probability of $1/3000\ \ year^{-1}$ according the database of Hydra-NL, which is $6.2\ m + Nap$.

After that, an iteration process was done by changing the inner slope of the dike until the resulted safety factor was equal to the required overtopping conditions safety factor (0.85) with overtopping .

The iteration began with a slope equal to the inner slope of the starting points 1:4. However, the design had a greater SF than the required 0.85 (-). Therefore, two inner slopes were modeled to test the results, which are designs with an inner slope of 1:3,25 and 1:3. Eventually, it is concluded that a dike with an inner slope equal to 1:3 satisfies the stability factor requirement which is to be seen the following figures. Figure 9, Figure 10 and Figure 11. Table 2.7.

Table 2.6 D stability model with ground layers

Sf -	Model
0.889	 Figure 9 D stability model with overtopping point A has a z coordinate of 6.6 m+Nap point B has a z coordinate of 6.6 m+Nap
1.450	 Figure 10 D stability model w/o overtopping Point C2 has a z coordinate of 3.9 m+Nap Point D1 has a z coordinate of 3.55 m+Nap

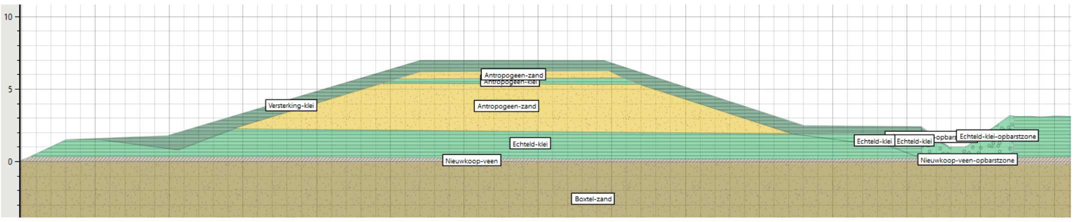
Sf -	Model
–	 Figure 11 D stability model with ground layers with a legend (the legend could be used for all other figures as well.  *#Note: top layer is reinforced clay, the rest is the same as the standard profile in the starting points#*

Table 2.7 Safety factors of the model with 1:3 slope

slope	SF with overtopping	SF without overtopping	hydraulic head
1: 3	0.889	1.450	hydraulic head= 1.77 m+Nap
1: 4	1.043	1.370	hydraulic head= 1.77 m+Nap
1: 3.25	1.149	1.393	hydraulic head= 1.77 m+Nap

2.3 Question results summary

The previous question has shown how the semi-probabilistic approach was developed according to the methodology used in the question and the starting points mentioned in section 2. Furthermore, the question gave answers on how the criteria for the semi-probabilistic design have been developed, which eventually led to a design with an inner slope of 1:3. Furthermore, the question also determined the weakest ground profile for the dike, which has been added to the standard model in figure 2, where sand is the dominant layer in the main dike body.

3 VARIABLES PROBABILITY FUNCTIONS AND SENSITIVITY ANALYSIS

Question 2: what is the probability function of the main variables in the probabilistic approach? And how sensitive is the safety factor to the different deterministic and stochastic variables?

3.1 Methodology

In this question, different references will be used to collect the available information about the stochastic variables in the project. These variables are primarily mentioned in (IJsselwerk, 2022), which is a combination of previous knowledge of Witteveen +Bos and laboratory research of the ground profile of the dike ring. However, The POP stochastic variables had to be calculated according to the mentioned method below. Eventually, a sensitivity analysis is done to investigate how sensitive the semi-probabilistic design is to some variations in the design. Most of the Sensitivity analysis is be done to the design with an inner slope of 1:3, which satisfies the semi-probabilistic norms and is expected to satisfy the probabilistic norms.

3.1.1 Stochastic and deterministic variables

The main difference between the probabilistic and the semi-probabilistic approach is the fact that some variables need to be inputted as probability functions. These probability functions are expressed as a mathematical probability function with both the mean and standard deviation. Therefore, during the calculations of the probabilistic approach, randomized algorithms are used to get values that are mostly likely to occur.
On the other hand, the semi probabilistic approach use fixed values that are already determined according to different rules and assumptions.

This question, however, is limited to the available knowledge of the variables at the moment because of the limitation of the available information. There are only five variables that are inputted as stochastic variables, while all the other variables are left as deterministic values (6 variables). The following table shows an overview of the variables that are used in this research whether deterministically or stochastically. Table 3.1.

Furthermore, the variable water level has been inputted differently in this research. Even though it is a stochastic variable, it was only possible to model the variable deterministically due to the limitation of the D-stability software. In this course, multiple water levels have been inputted, and the result is shown in a fragility curve. More is explained about this aspect in question 3 section 4.3.1. Furthermore, this variable affects the schematization of both the phreatic and hydraulic-head lines. Therefore, the scenarios in this research have been modelled deterministically according to the mentioned rules in section 1.2.5.

Table 3.1 stochastic and deterministic variables (IJsselwerk, 2022)

variable	stochastic	deterministic	scenario
Unit weight sand		■	
Cohesion sand		■	
Frictional angle sand	■		
Dilatancy angle sand		■	
Unit weight clay		■	
Cohesion clay		■	
Shear strength ratio peat	■		
Shear strength ratio clay	■		
Strength increase component		■	
water level ***	■		

variable	stochastic	deterministic	scenario
Phreatic line ***			■
hydraulic head ***			■
POP	■		

*# variables with *** are connected to each other. In other words, the water level is the stochastic variable and the phreatic line and the hydraulic head change accordingly, forming different scenarios#*

3.1.2 State POP points stochastic variables

Eventually, the POP points has been modified manually to obtain the mean and standard deviation values of the POP points, which, needed to be calculated via D-stability according to the following equation.

$$m_{POP} = \frac{State\ POP\ value}{1.5} * 1.9 \qquad (eq. 6)$$

Where :

- $State\ point\ value$ is the value that has been automatically determined via D-stability using the values in Table 3.4.
- 1.5 is the characteristic lower limit of value of the OCR. (IJsselwerk, 2022)
- 1.9 is the mean OCR value. (IJsselwerk, 2022)

Following that, the standard deviation of each point is calculated through trial and error, which uses the following equation to find the resulted standard deviation implemented in D-stability.

$$\sigma^2 = \ln\left(1 + \left(\frac{v}{m_{pop} - c}\right)^2\right) \quad (eq. 7)$$

Where:
v is the variance
c is the given shift that belongs to a log normal distribution, which is usually equal to 0.

3.2 Sensitivity analysis of different variables

A sensitivity analysis has been done to investigate the effects of different slopes, hydraulic head, and phreatic lines on the safety factor of the model. Therefore, three design variants were selected, the first variant is with an inner slope of 1:3, and the second and third have inner slopes of 1:3.25 and 1:4, respectively. These designs were chosen according to the methods mentioned in section 2.2.4.
This analysis will also show if there is a correlation between the position of the ditch to the inner slope, as a greater slope will result in a greater distance between the two.

D-Stability calculation grids settings:

In order to use the Uplift-van method for the sensitivity analysis, three aspects need to be inputted into the software, two swarm grids, and a tangent plane. The two swarm planes are areas where the software will search for the center points of the circles that will intersect and therefore form a slip plane to calculate the safety factor of each model (Uplift Van method). This is done to minimize the randomness of the results, as the software is built on random-based algorithms. Therefore, this grids settings ensure consistency in the results. The previous settings have been defined manually and then fixed for the aforementioned reasons.

Table 3.2 Grids settings

Grid	x	z	h	w
Right Swarm	106.151	9.552	5	10
Left Swarm	96.112	19.34	10	10
Tangent line	NaN	5	5.5	NaN

Phreatic line

A sensitivity analysis has been done to investigate the effects of the phreatic line on the safety factor. This is done by lowering the phreatic line of the model with overtopping and heightening it for the model without overtopping . This analysis has been done by doing the following:

1- for the model without overtopping: the position of both points C2 and D1 from Figure 5 are heightened according to the relation mentioned in the same Figure 5. Which is, point C2 gets heightened 2 times as much as D1.
Thereafter, point C2 was fixed to the water level height, while D1 was heightened even more. The reason behind fixing C2 is to keep the model in a condition where overtopping is not occurring according the phreatic line shape.

2- for situations with overtopping : point A was fixed, and only point B was lowered using arbitrary choices while keeping it on the inner slope. Table 3.8

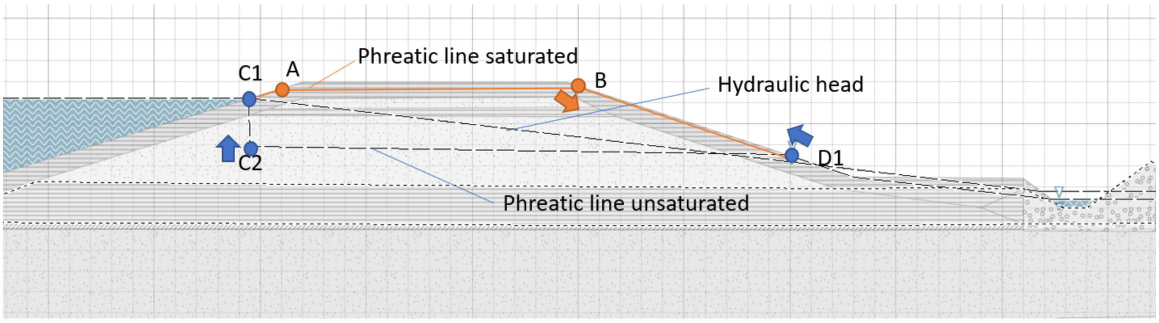


Figure 12 illustration phreatic line S.A. concept

Horizontal positioning of point B

A sensitivity analysis has also been done to the positioning of point B with conditions with overtopping. The point of this analysis is to test how sensitive the design is to the positioning of point B in the situation with overtopping.

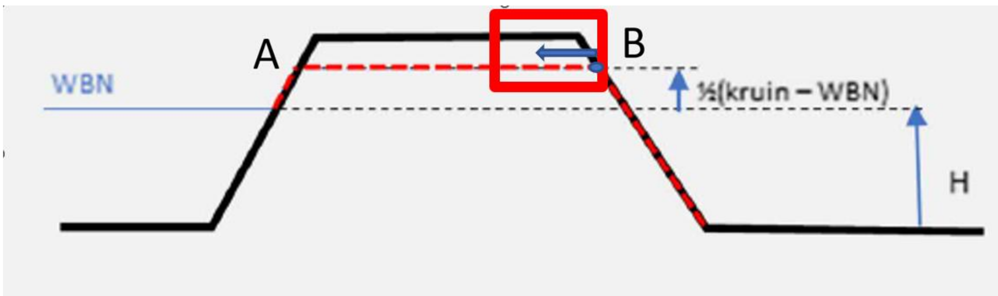


Figure 13 Overtopping phreatic line point B sensitivity analysis

Hydraulic head

This analysis has also been done to the model with the inner slope of 1:3 to investigate the effect of the hydraulic head on the safety factor. Therefore, the following hydraulic heads were chosen, 1.776, 2.4, and 3 m+Nap.
The 2.4 m+Nap is equal to the vertical height of the top layer on the landward side of the dike, and 3 is an arbitrary choice. These changes have also been done while changing the characteristics of the ditch materials.

Ditch materials

A ditch is to be found on the landward side. However, the ditch's material selection indicates uplift failure in the area. This failure happens when the inner slope slides and fills the ditch in front of it, Figure 14.

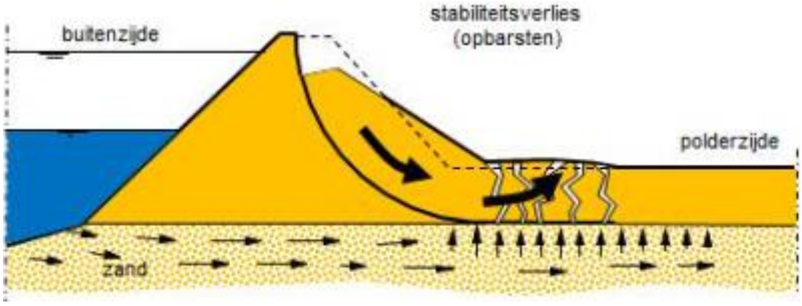


Figure 14 uplift failure (opbarsten)

This implies changing the properties in the ditch's materials in D-stability, which resulted in having a cohesion of $0\ kN/m^2$ for the clay materials types and a shear strength ratio of $0\ (-)$ for the peat layer. Therefore, the same sensitivity analysis has been done using normal types of the same materials and their counterparts.

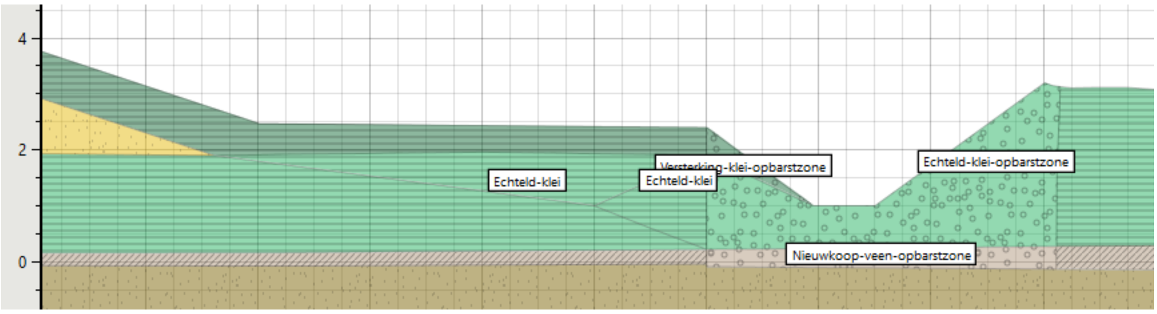


Figure 15 ditch material types

3.3 Results

3.3.1 Statistics of the stochastic variables:

All of the ground statistics belong to a log normal distribution, which have the statistical variables showed in the following tables, Table 3.3 and Table 3.4. Furthermore, the (POP) points of the state points in the daily (dagelijks) stage are also shown in Figure 16.

Table 3.3 mean and standard deviation of the stochastic variables (IJsselwerk, 2022)

Variable	Mean	Standard deviation
Frictional angle sand (deg)	32.9	1.6
shear strength ratio peat (-)	0.44	0.05
Shear strength ratio clay (-)	0.35	0.06
Model factor	1.005	0.033

State POP points stochastic variables:

The mentioned methodology in section 3.1.2 resulted in the following values for the POP points. These points are numbered from 1 to 14 as the following figure shows. This numbering has been selected manually for easier referencing.

Table 3.4 states point POP statistics

State Point	Mean	Standard Deviation
1	15.926	2.207
2	14.614	2.031
3	20.897	2.9

State Point	Mean	Standard Deviation
4	21.893	3.03
5	33.218	4.603
6	14.564	2.019
7	0	0
8	40.095	5.556
9	21.098	2.098
10	2.69	0.374
11	0	0
12	32.389	4.488
13	16.798	2.326
14	2.5	0.34

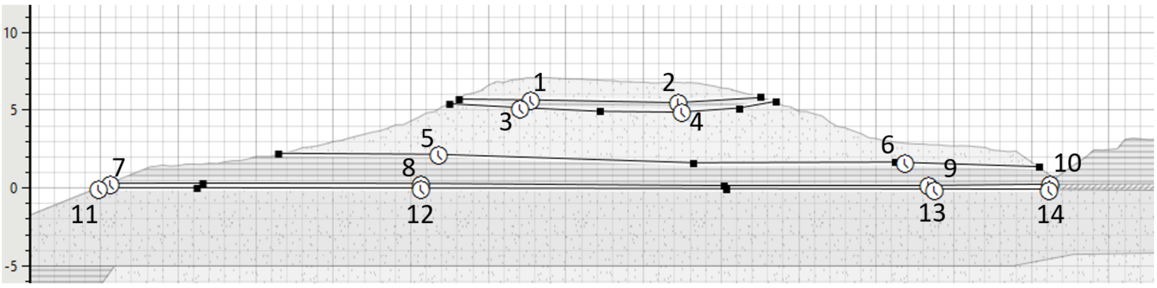


Figure 16 State POP points

3.3.2 Hydraulic head and uplift materials sensitivity

The following table shows the results of the sensitivity analysis that has been done to the dike. The following results shows how sensitive the dike to the hydraulic head and uplift materials.

Table 3.5 sensitivity analysis of the hydraulic head and uplift materials

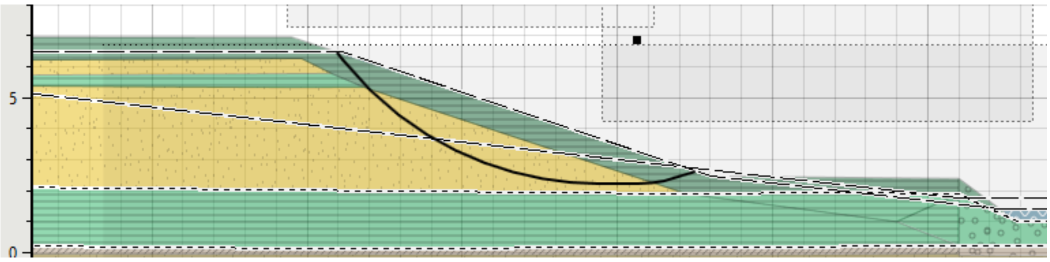
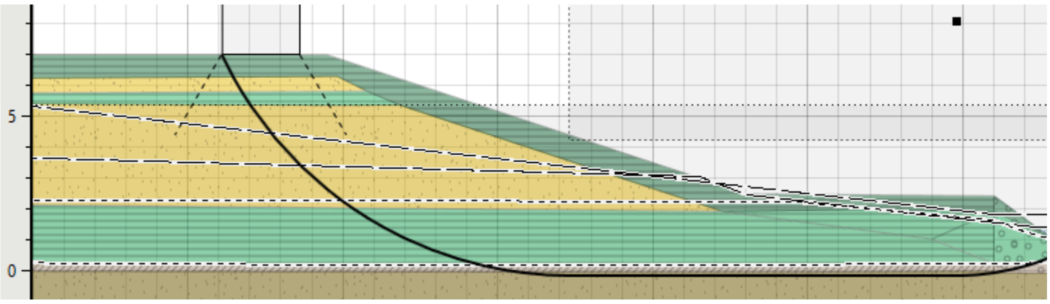
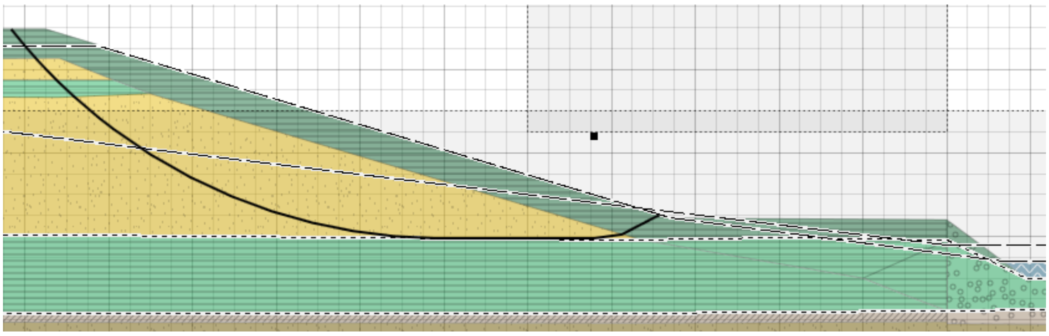
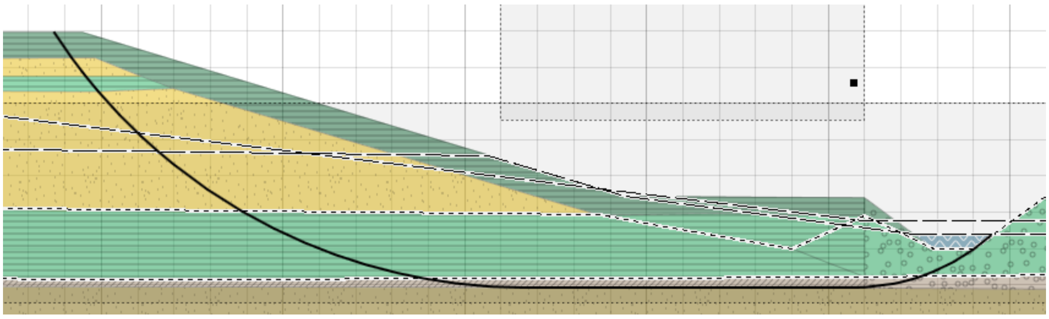
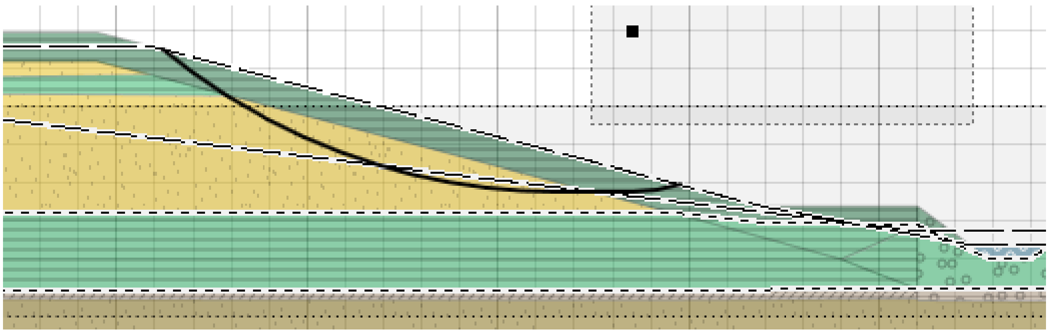
with overtopping	without overtopping	changes
0.889	1.392	hydraulic head= 1.77 m+Nap
0.889	1.461	w/o uplift materials
0.889	1.317	hydraulic head = 2.4 m+Nap
0.889	1.336	w/o uplift materials
0.903	1.194	hydraulic head = 3 m+Nap
0.903	1.202	w/o uplift materials

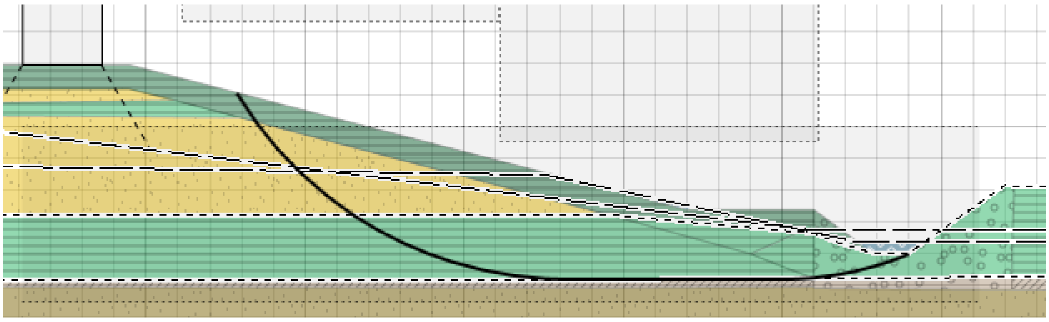
The previous table shows that materials with 0 cohesion and shear strength ratio slightly lower the safety factor. Furthermore, the analysis shows that only the situation without overtopping is sensitive to the uplift materials. This is because of the results slip plane that extends to the ditch materials, Figures 17-22.

These figures also show how sensitive the slip plane is to the positioning of the ditch to the inner slope, especially in the situation where overtopping occurs. Summarily The distance between the ditch and the inner slope affects the results of the slip plane.

Table 3.6 Slip plane changes according to the inner slope

SF	Model

SF	Model
0.889	 Figure 17 slip plane position (inner slope 1:3 and with overtopping)
1.45	 Figure 18 slip plane position (inner slope 1:3 w/o overtopping)
1.14	 Figure 19 slip plane position (inner slope 1:3.25 and with overtopping)
1.463	 Figure 20 slip plane positioning (inner slope 1:3.25 w/o overtopping)
1.064	 Figure 21 slip plane positioning (inner slope 1:4 with overtopping)

SF	Model
1.403	 Figure 22 slip plan positioning (inner slope 1:4 w/o overtopping)

3.3.3 Phreatic line sensitivity analysis

As seen below in Table 3.7. The phreatic line plays a major role in the safety factor results. This indicates how important the phreatic line is for the probabilistic approach as it is inputted deterministically according to the water levels. The importance of this aspect is to show how affected the models by the schematization of the phreatic line.

According to the results, the phreatic line is less sensitive when point C2 is below water level (point C1). However, when fixing it to the water level (point C1), results showed a significant effect on the safety factor. This is also to be seen in the standard situation since point A was fixed during the analysis.

Overall, this results shows that that phreatic line in the most important factor when it comes to the safety factor.

Table 3.7 Sensitivity analysis of the phreatic line without overtopping

Safety factor (-)	C1 m+Nap	C2 m+Nap	D1
1.392	6.2	3.9	3.55
1.71	6.2	4.4	3.8
1.352	6.2	4.9	4.05
1.332	6.2	5.4	4.3
1.3	6.2	5.9	4.55
1.242	6.2	6.2	4.8
1.199	6.2	6.2	5.05
1.15	6.2	6.2	5.3
1.029	6.2	6.2	5.55
1.012	6.2	6.2	5.8
0.98	6.2	6.2	6.02
0.955	6.2	6.2	6.2

Table 3.8 S.A. of the phreatic line with overtopping

safety factor (-)	B m+Nap
0.889	6.6
0.906	6.4
0.966	6.2
0.97	6

safety factor (-)	B m+Nap
1.01	5.8
1.0347	5.6

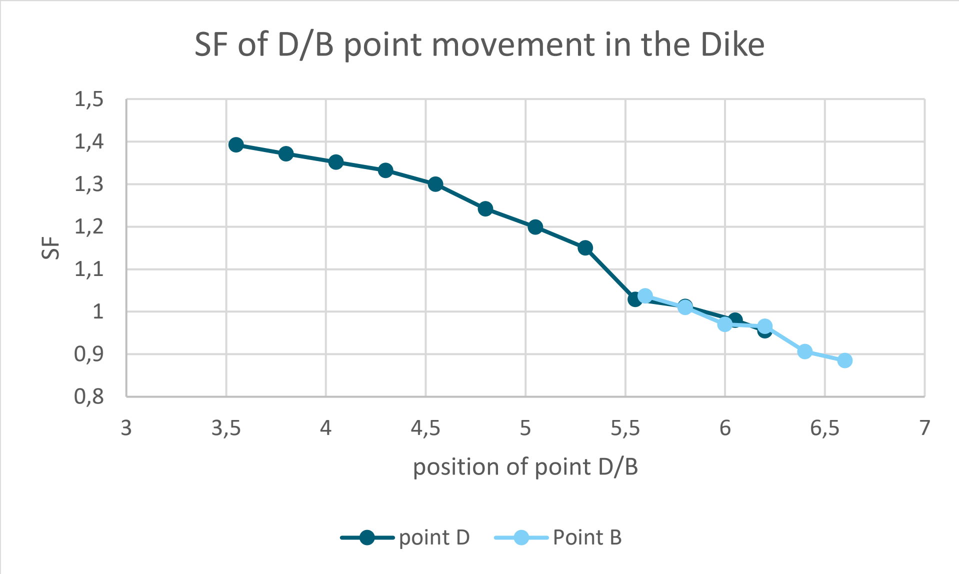


Figure 23 phreatic line sensitivity analysis

Horizontal positioning of point B

The following table shows how sensitive the design is to the position of point B in the condition with overtopping.

Tabel 3.9 sensitivity of the dike design according to the position of point B on the x axis in the D-stability model.

position of B (x-axis)	SF
95.6	0.889
95	0.983
94	1.096
93	1.175

This shows that the design is very sensitive to the positioning of point B, as the safety factor becomes greater when moving B point on the X axis.

3.4 Question results summary

This question has given essential answers to begin the probabilistic approach in question 3. First of all, it showed which variables are going to be handled deterministically and which stochastically Table 3.1. Thereafter, the question also showed the values of the mean and standard deviations of the available variables Table 3.3. It also showed how the statistics of the POP variables are calculated and what they resulted section 3.1.2, Table 3.4.

After that, the question also showed the variables water level, phreatic line, and hydraulic head are connected and how they are modeled in question. Eventually, the question gave answers about how sensitive the design is to the phreatic line and inner slope as they play a significant role in the final safety factor.

4 PROBABILISTIC DESIGN RESULTS

Question 3: How reliable is the design according to the probabilistic approach?

4.1 Methodology

The following question investigates the general rules of the FORM probabilistic analysis. This analysis relies on the results of a fragility curve that uses a reliability index of different scenarios. Therefore, this question shows how interpolation techniques have been done between fragility curves with and without overtopping and how they are related to different scenarios. On that note, the question answers how different scenarios are modeled and what different aspects were modeled in both conditions.

Furthermore, this question shows how the probabilistic assessment calculated both the exceedance probability and the probability of the water levels of the year 2075 and how the results were checked according to different norms. Finally, the question also shows how the minimum reliability index was calculated, to which the probabilistic assessment needs to suffice as a final result.

4.2 FORM Analysis

There are many methods to approach this detailed assessment. However, this research is going to focus on the First-order reliability method. In this framework, it is essential to define the failure probability of the failure mechanism that will be relied upon in this research. This probability is defined when the load behind the structure is greater than the structure's resistance. This is to be expressed in the following form
:

$$Z = R - S \qquad (eq.8)$$

Where Z is the performance function or the limit state function of the failure mechanism, which differentiates the safe and the unsafe zones with respect to R and S. In this framework the equation can be generalized as the following $Z = g(x)$. (Deltares, 2017)
The $g(x)$ In this research is the Uplift-Van method which is being assessed as a safety factor that is calculated via D-stability as question 1 showed in this report.

4.2.1 Fragility curves

Fragility curves give the (conditional) failure probability as a function of the load. In case of instability, the water levels are used on the Y axis, while the reliability index on the X axis where. In this framework, a couple of fragility points are determined to interoperate the structure's instability, between situations with and without overtopping. For each fragility point, a stability model is therefore drawn up for a specific water level and the associated water pressure schematization. Following this, the water level is interpreted as the highest in a high-water situation. The pore pressure schematization usually reflects the uncertainty in the maximum pore pressure response during high water. This leads to the concept of scenarios.

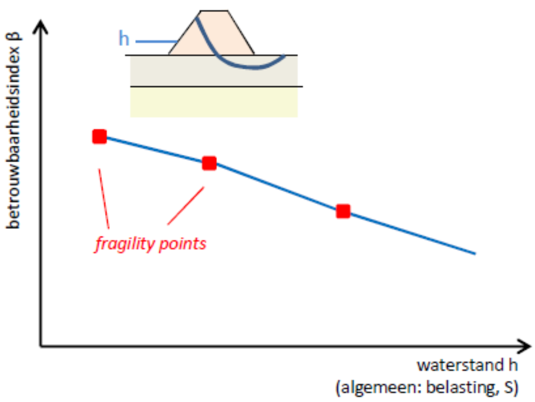


Figure 24 fragility curve method (Deltares, 2017)

4.2.2 Scenarios

In order to assess the probabilistic design of the dike, it is essential to test the design for multiple scenarios, which will expand the domain of possible outcomes of the situations that the dike might experience during its lifecycle. Following this framework, the scenarios are implemented by changing the water level in the model along with the associated phreatic line and hydraulic head on the dike. Therefore, the assessment of the dike has taken a similar approach as mentioned in Figure 25.

Water levels modelling and its relation of the phreatic line

As mentioned in the results of question 2. There is a relation between the water level, the phreatic line, and the hydraulic head since they get affected by the water level. For this purpose, The semi-probabilistic standard model is used for multiple water levels. Each water level has been applied deterministically (along with the resulted phreatic line and the standard hydraulic of 1.776 m+Nap). This resulted in different reliability indices that have been modelled in a fragility curve, as the following figure shows.

Slip planes have been fixed in this analysis according to the grid setting results specified in question 2. As mentioned before, fixing this slip plane brings more consistency to the results of the fragility curve.

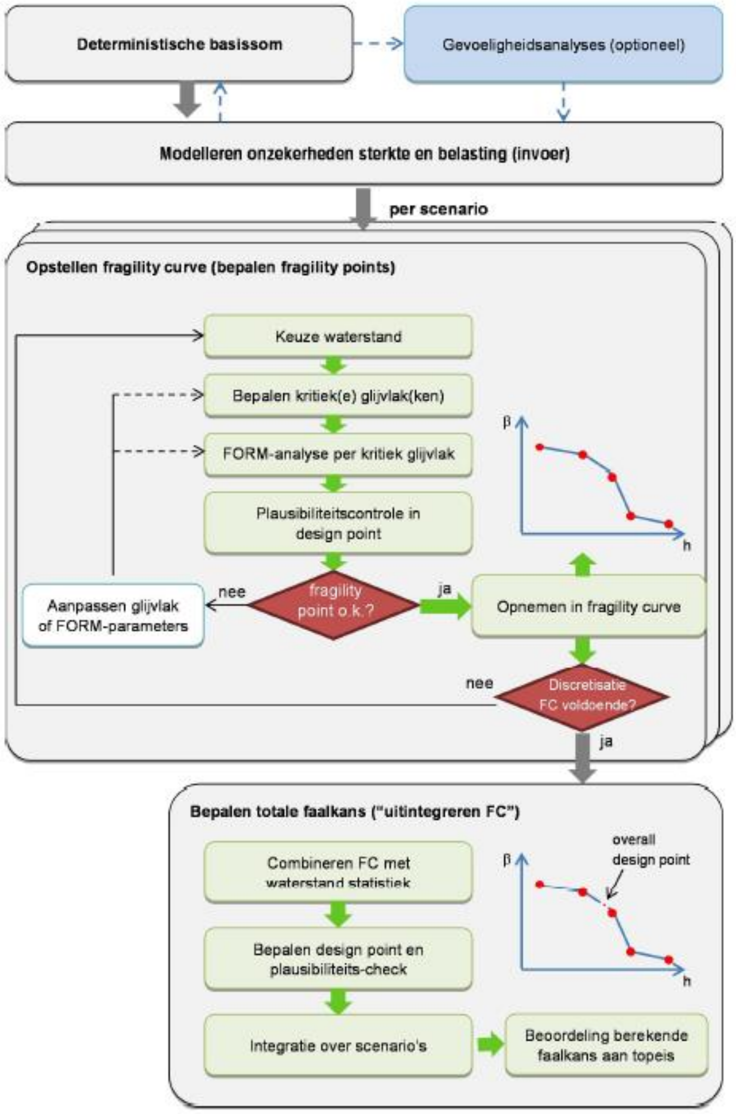


Figure 25 Scenarios methodology (Deltares, 2017)

Interpolation between fragility curves with and without overtopping:

In this research, conditions with and without overtopping are analyzed and determined deterministically via the shape of the phreatic line. In this framework, the result of this analysis will be two fragility curves, where the first one indicates the fragility curve of the overtopping conditions and the second one will be the result of the conditions without overtopping. Therefore, an interpolation process between the resulted curves shows the transition between both conditions. This has been done using an excel sheet that used the following formula, which interpolate between both conditions using the results of the reliability index, which are a result of the failure probability, (KPR, 2018).

$$P(failure|h) = P(failure|h, q \leq qcrit)P(q \leq 1\ (l/s/m)) + P(failure|h, q \leq qcrit)P(q \geq 1\ (l/s/m)) \quad eq. (9)$$

Where
$P(q \geq 1\ (l/s/m))$ is the calculated failure probability via Hydra-NL.
$P(failure|h, q \leq qcrit)$ is the calculated probability according to the interpolation process that relied on Hydra-NL, which is shown as fragility curves in sections 4.3.1 and 4.3.3.

Water levels

All water levels have been modeled with conditions without overtopping, which means that the phreatic line took shape shown in Figure 9. On the other hand, the condition with overtopping is modeled with only one water level, namely 6.2 m+Nap. This is because the probability of failure overtopping conditions will be equal for all the water levels that equal, higher, or lower than 6.2 m+Nap.

After that, the water levels were interpolated using a python script that resulted a CDF function for all the water levels from 2.4 m+Nap to 8 m+Nap (561 water levels). This python script section 9.4 (appendix) uses the found results water levels according to the wind direction and its uncertainty. The results of the Hydra-NL for the years 2050 and 2100 are to be found in section 9.2 and 9.3 (appendix).

Since the study is researching the failure probability of the year 2075, the CDFs of the years 2050 and 2100 were generated and checked separately, and then the average of those two CDFs generated the final water levels' CDF of the year 2075. The latter is then used to check whether the semi-probabilistic approach is safe of not according to the probabilistic one.

Correction water levels according to the required return time:
The CDFs of the water level of the year 2050 and year 2100 have been checked to suffice a minimum return time. This return time has to be equal to the overtopping probability calculated via Hydra -NL, which is 1/1187. This return time has been calculated according to the following equation:

$$retun\ time\ CDF = \frac{1}{\sum \delta WL_{i,i-1} * p(ov)} \geq 1/1187 \quad (eq. 10)$$

Where:
$\delta WL_{i,i-1}$ is the difference between two water levels, which is 0.01 m.
$p(ov)$ probability of overtopping contribution, which is equal to:

$$probability\ of\ occurance\ of\ WL * probability\ of\ overtopping \quad (eq. 11)$$

Water levels exceedance probability

With the output of Hydra-NL calculations, a beta and alpha has been found of the distribution of water level according to the Gumbel distribution, (Detalres, 2016). This is done by using the exceedance probability that has been found for the water levels from Hydra-NL. After that, the exceedance probability of the rest of the water levels was interpolated using the standard form of the Gumbel distribution formula;

$$F(x; \mu, \beta) = e^{-e^{-\frac{x-\mu}{\beta}}} \quad (eq. 12)$$

Where;
μ is the alpha of the distribution.
β is the beta of the distribution.

Minimum reliability index

The minimum reliability index has been calculated by returning the inverse of the normal cumulative distribution of the calculated return time according to a specified mean (=0) and standard deviation (=1). This return time has been calculated in question 1 $P_{eis,dsn,stbi} = 1/144300\ year^{-1}$. Furthermore, this index is multiplied by a 1.05 (schematization factor) to obtain the last results.
When reaching this step, it is then possible to check whether the semi-probabilistic design is safe enough according to the probabilistic assessment. This is to be seen if the resulted reliability index is higher than the minimum index according to the probabilistic assessment.

4.3 Results

4.3.1 Fragility curve

As mentioned before, the results of this analysis are going to be shown in the form of a fragility curve. The following curve shows the reliability of the design starting with a water level of 2.4 m+Nap till a water level of 8 m+Nap with a 0.2 interval between each test.

The modeling of the different scenarios had to have one fixed slip plane for all different water levels for the conditions without overtopping. However, the model with overtopping conditions had to have another tangent plane. These two planes are to be seen in the following; Figure 26 and Figure 27. These two figures also show the modeling o the phreatic line, which is also done according to the phreatic line modelling rules for both conditions (with and without overtopping), which are mentioned in the starting points. On the other hand, all ground materials and the hydraulic head have been fixed for both conditions..

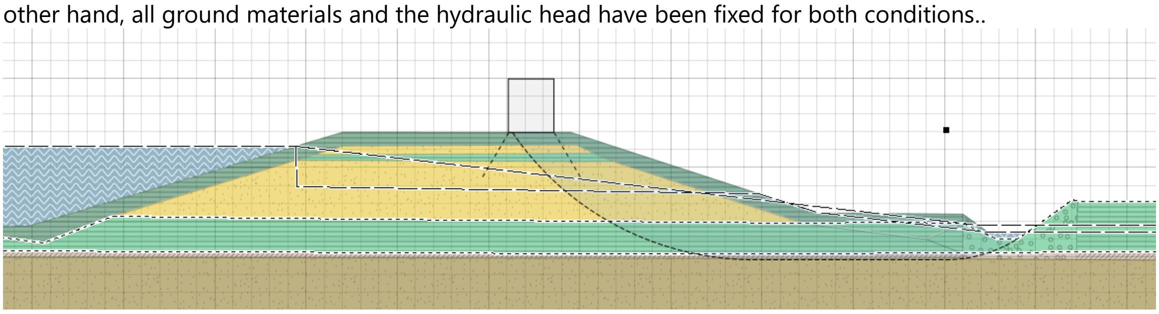


Figure 26 tangent plane without overtopping Beta = 7.053, SF=1.45

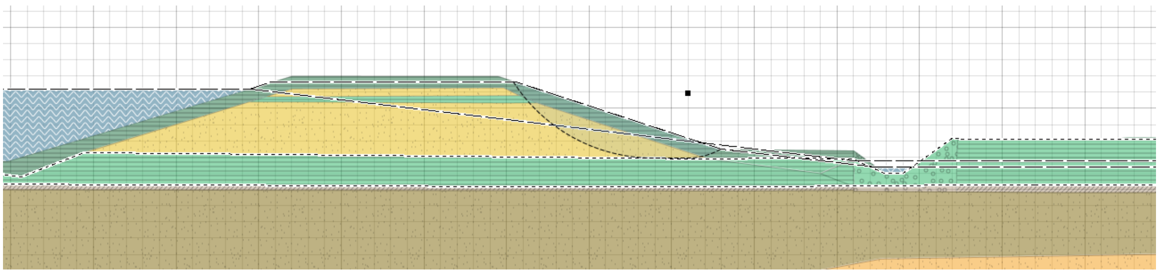


Figure 27 tangent plane with overtopping Beta =-0.5, SF=0.889

Figure 28 shows the results of the different scenarios as they form two fragility curves; the first one (the dark blue curve) shows the results of the conditions without overtopping, which has different results for each water level. However, the other curve (the light blue curve) shows consistent results for all water levels. This is because the result is the same since the whole dike is considered to be saturated for all levels. Therefore, all the different scenarios will have the same reliability index result, which is $-0.5(-)$.

On the other hand, the curve also shows a big difference between conditions with and without overtopping. As the overtopping conditions have a remarkably low reliability index, namely $-0.5\ (-)$ with a failure probability of 70 % . This means that there is almost a 100% chance that the design will fail in overtopping conditions.

This difference between saturated and unsaturated conditions is related to multiple reasons, these reasons are discussed further in the report, namely, section 5.1.2.

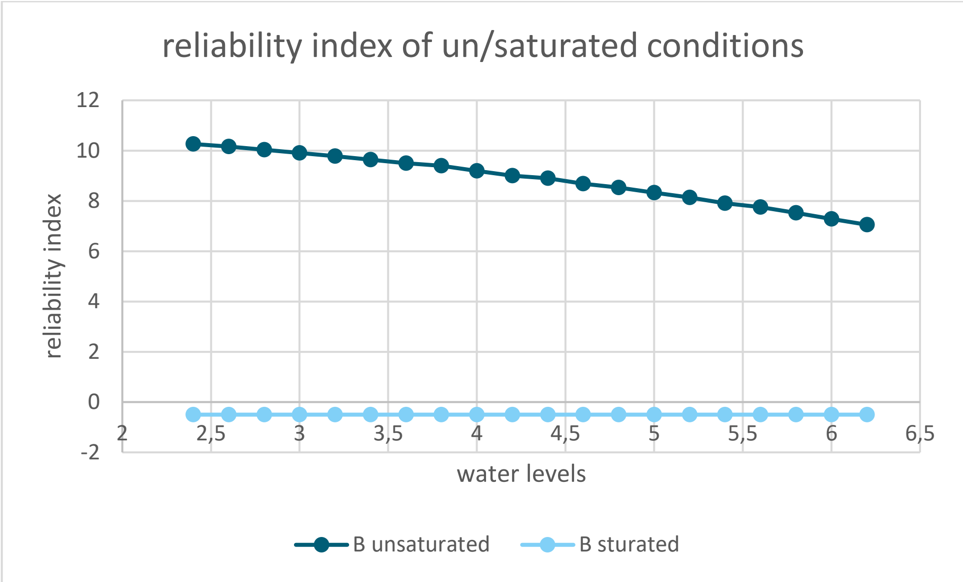


Figure 28 Fragility curve before interpolation

4.3.2 Water levels' CDFs (cumulative distribution functions)

As mentioned in the methodology, the water levels' CDF of the years 2050 and 2100 have been generated using Hydra-NL and interpolated via a python script (as a tool). This resulted in two CDF that unfortunately did not satisfy the failure probability that has been found in Hydra-NL, namely , $P(q \geq 1\ (l/s/m)) = \frac{1}{1187} year^{-1}$.

For that purpose, both CDFs had to be corrected. This correction has been done by adjusting the failure probabilities for higher water levels until the overall failure probability of all water levels is lower than $\frac{1}{1187} year^{-1}$. This correction is a consequence of Hydra-NL output, as it did not provide enough output for the interpolation process to give correct results. This process however, could have been skipped if enough output was provided.

The following figures show the resulted water level CDF without and with correction for the years 2050 and 2100. Lastly, the last figure showed the resulted averaged CDF for the year 2075.

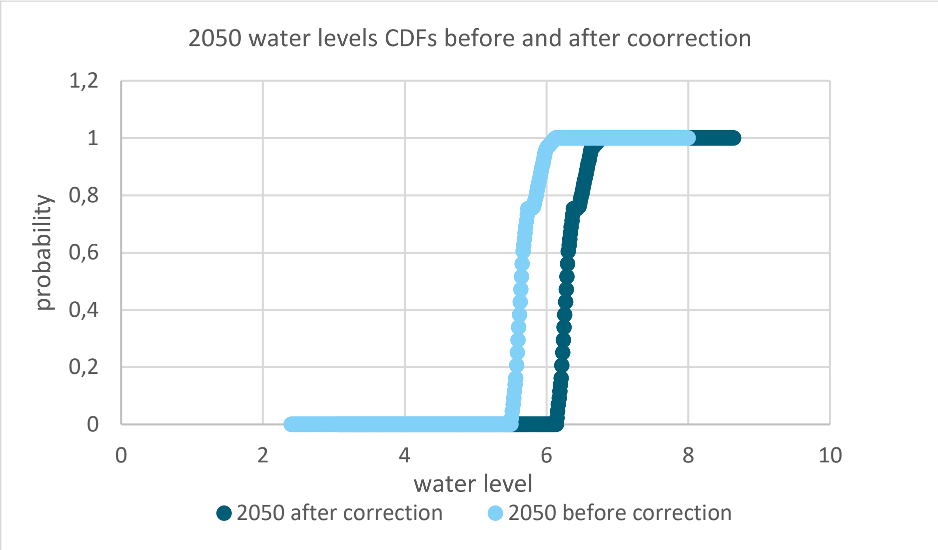


Figure 29 water levels' CDF before and after correction year 2050

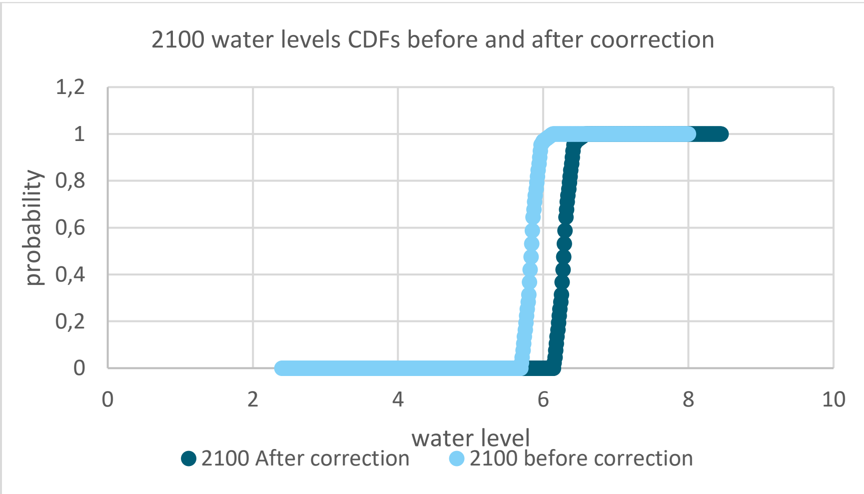


Figure 30 water levels' CDF before and after correction year 2100

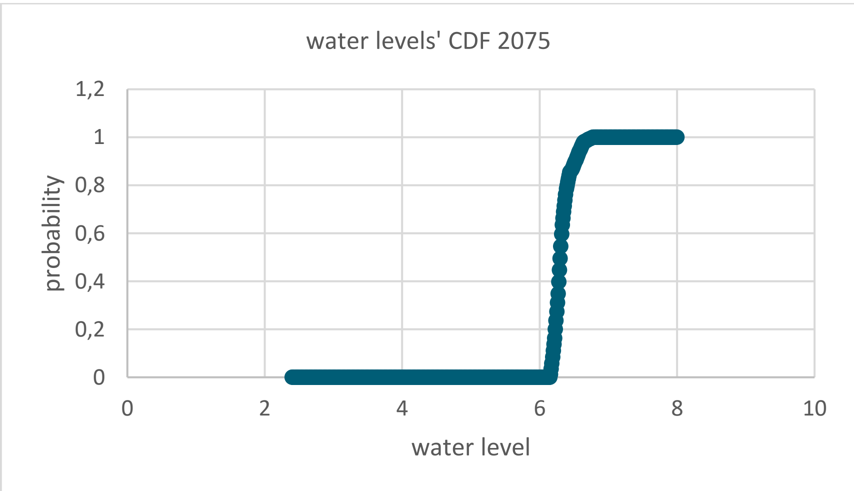


Figure 31 water levels' CDF year 2075

Water exceedance probability:

The water levels probability was interpolated using a Gumbel distribution with an alpha equal to 5.85 and a beta equal to 0.05. This resulted in the following figure for the water level exceedance probability. In this figure, the water level 6.2 m+Nap has an exceedance probability of 1/2700 $year^{-1}$.

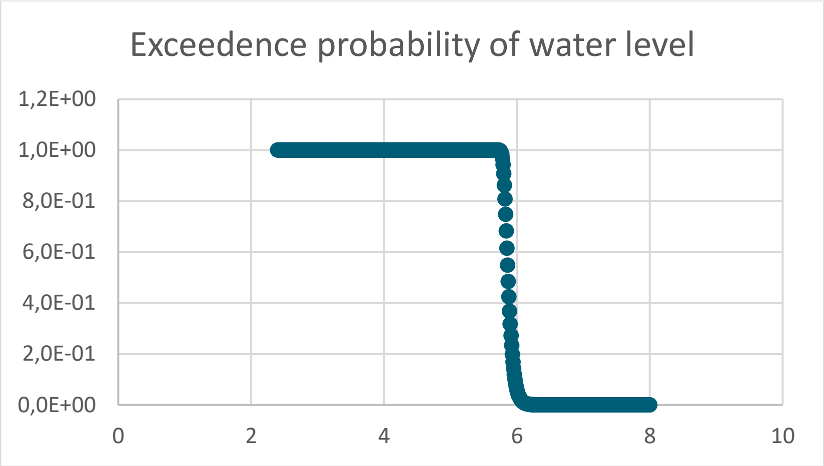


Figure 32 Exceedance probability of water levels

4.3.3 Results probabilistic approach

Fragility curve interpolation results:

After the interpolation mentioned in section 4.3.1. The following figure shows the final results of the fragility curve interpolation between conditions with and without overtopping.

The figure shows that around a water level of about 6.2 m+Nap, the dike's environment will start having a probability of turning into overtopping conditions. This probability, however, has a 100% chance when reaching a water level of 7.8 m+Nap. Figure 33.

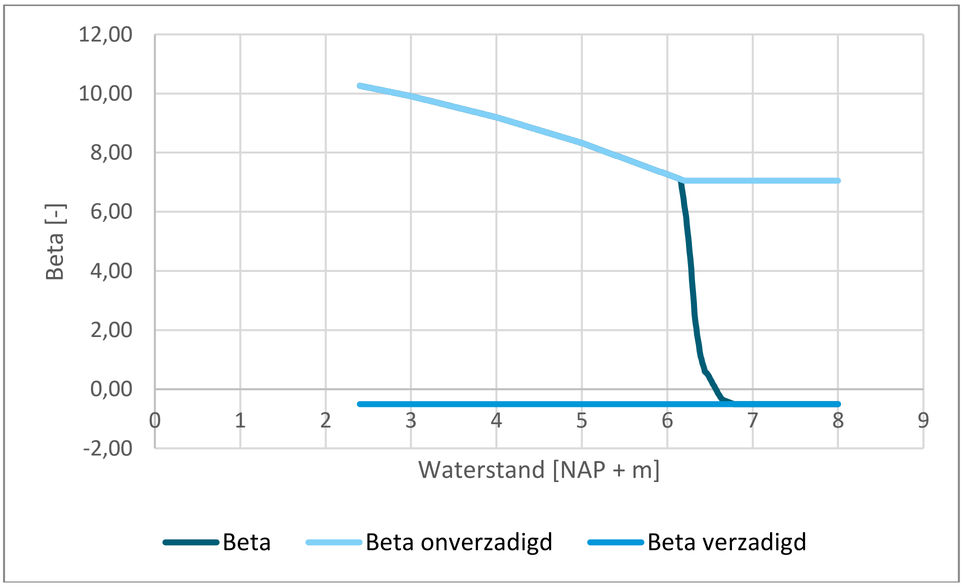


Figure 33 Fragility curve after interpolation

Beta results:

The following table shows that the minimum reliability index is 4.56. This index has to be obtained via the probabilistic assessment of the design that has been defined in question 1 (inner slope 1:3). However, the probabilistic assessment resulted in a beta equal to 4.14, which means that the semi-probabilistic design is not sufficient according to the probabilistic assessment.

Tabel 4.1 resulted reliability indices

	failure probability	Return time	Beta
probabilistic approach	1.74E-05	57555	4.14
required minimum	6.93E-06	144300	4.35
required minimum with schematization factor	2.52E-06	397307	4.56

4.4 Question results summary:

This question showed what the results of the probabilistic assessment looked like. Firstly, the FORM analysis results have been shown in the form of a fragility curve for both conditions with and without overtopping. These fragility curves have also been calculated using a reliability index β, section 4.3.1.
After that the question has investigated the overtopping probability of water levels and probability of exceedance of the same water levels, which are shown in section 4.3.2. These probabilities have been done using interpolation techniques that used the results of Hydra-NL. Eventually, the question gave an answer to the minimum required reliability index for the probabilistic assessment, which the assessment did not satisfy according to Tabel 4.1

5 DISCREPANCIES BETWEEN SEMI AND PROBABILISTIC APPROACH

Question 4: What are the discrepancies between the current design (semi-probabilistic) and the probabilistic design? And how could the semi-probabilistic approach be improved using the findings of previous question?

The following question compares the results of both the semi-probabilistic and probabilistic approaches. The question investigates the results of overtopping failure probability that has been used in both approaches and where the differences come from. Eventually, the question models the design that is suggested according to the probabilistic design and how different it is from the design that the semi probabilistic approach has required.

5.1 Results of the semi probabilistic design reliability

As shown in the final results of question 3. The semi-probabilistic design is not sufficient for the safety norms according to the probabilistic criteria. These results are related to multiple aspects that are going to be discussed below.

5.1.1 Main differences between the two methods

First of all, both approaches have different types of input. The semi-probabilistic approach, used fixed values for the ground characteristics Tabel 1.3, while the probabilistic approach used both deterministic and stochastic values Table 3.1 and Table 3.4. These stochastic values have been inputted according to a laboratory research which specified the mean and standard deviation values for a couple of variables.

The main difference between the two methods is that the semi-probabilistic approach depends on a safety factor criterion, which is 1.23 for the condition without overtopping and 0.85 for the overtopping one. These two factors are the results of different reliability indices, 4.34 for the situation without overtopping and 2.4 with overtopping. On the other hand, the probabilistic approach had to suffice a reliability index criterion which is 4.56.

Tabel 5.1 beta's of different approaches

Beta	Value
semi- without overtopping	4.34
semi- with overtopping	2.4
probabilistic	4.56

These criteria are found according to different approaches. The semi-probabilistic approach was solely dependent on the results of the D-stability safety factors, which gave a translation to which the research considers a design safe or not.

On the other hand, the probabilistic approach results had to be done via a more detailed process that required many interpolation methods between results. These results were also the product of an integration process between Hydra-NL via Excel, python script, and D-stability. Those differences are the product of the following aspect:

5.1.2 Overtopping failure probability

The most important aspect of this analysis is the difference between the overtopping failure probability that has been found in both the semi-probabilistic and probabilistic approach.

As mentioned above, the semi-probabilistic approach had to suffice to two different safety factors. The first one is for the conditions without overtopping and the second for overtopping conditions. The reason behind having two safety factors is because the damage factor is different for the overtopping conditions, which requires the probability of overtopping of the dike profile.

Tabel 5.2 Damage factors of both conditions

condition	value
with overtopping	$Y_n = 0.15 * \beta_{T,stbi,q} + 0.41$
without overtopping	$Y_n = 0.15 * \beta_{eis,dsn} + 0.41$

Semi probabilistic approach:

#NOTE: Figure 33 shows the results of the probabilistic approach, but is also explains show the semi methodology approached the probabilities via Hydra-NL#

First of all, the reliability of the semi-probabilistic approach is included in two parameters:

1- The water level.

2- Damage factor.

The water level that has been chosen for the semi probabilistic approach equal to the norm of the dike, (in this case 1/3000).

Furthermore, the damage factor has been calculated using the norms that have been mentioned in section 2.1.2. For this factor, a distinction is made between the situation with and without overtopping.

This overtopping probability is the product of the exceedance probability of the water levels (Dark Blue curve) and the probability of overtopping (red curve). Both resulted in the area under the (black curve). This area is equal to 1/1187 $year^{-1}$, Figure 34.

Using this probability, the factor for overtopping conditions is calculated, including the overtopping probability, which is 0.85. This is used to choose a design that has the same safety factor, which is the one with an inner slope of 1:3. This slope used the water level that has an occurrence of 1/3000 year^-1 (6.2 m+Nap).

Tabel 5.3 required safety factors

condition	SF required
SF with overtopping	0.85
SF without overtopping	1.23

Probabilistic approach:

As mentioned before, the probabilistic approach used a calculation that relied upon interpolation techniques to find both the water statistics and the overtopping probability failure. This analysis began by correcting the water-level CDF so that the return time of both the results of years 2050 and 2100 suffice to 1/1187 $year^{-1}$ (section 4.3.2. After that, the CDF of the water levels of the year 2075 was generated by averaging the corrected CDFs of the years 2050 and 2100 (red curve), Figure 34.

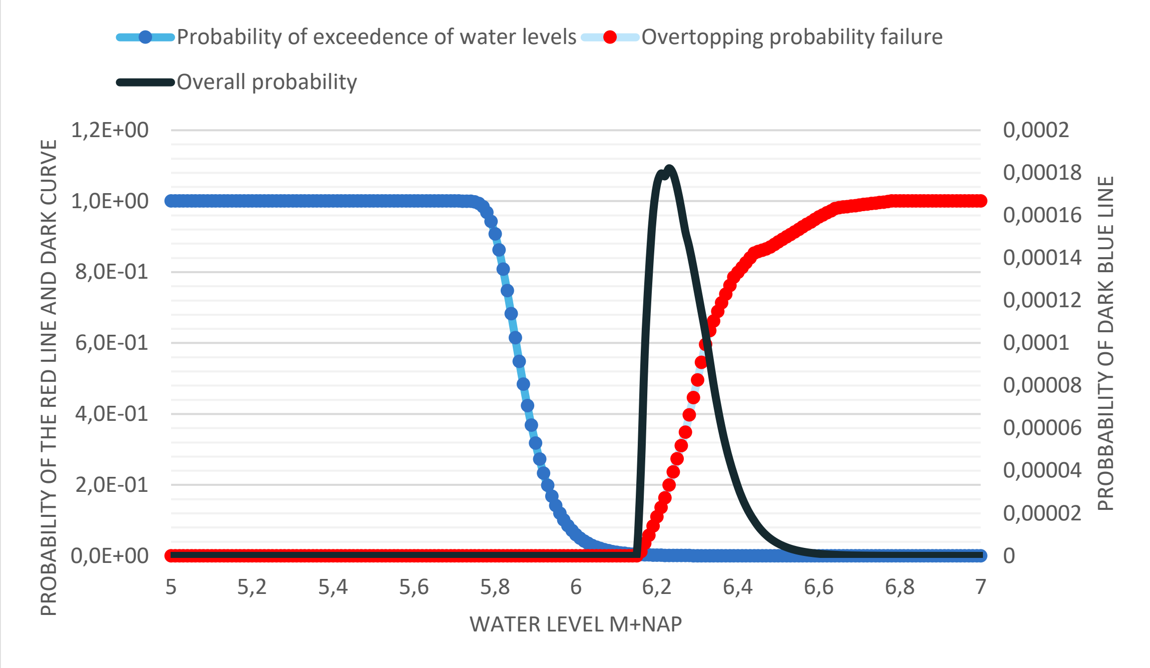


Figure 34 probability functions

Eventually, The excel model integrated the water levels' failure probability with the failure probability of the reliability index function (calculated via D-stability). This integration resulted in the overall failure probability and reliability index values of the probabilistic approach, which is not sufficient according to Tabel 4.1.

Difference

In the **semi-probabilistic** approach, only two scenarios are verified using one water level at a norm condition (1/3000) and the situations with and without overtopping; for both situations, a damage factor has been derived. For the damage factor during overtopping, the overall probability of overtopping has been used, thus including the exceedance probability of water levels.

For the probabilistic approach, the reliability is calculated for each water level separately. For each scenario overtopping probability is considered (excluding exceedance probability of water levels).

So the fundamental difference is that in the **semi-probabilistic** approach, only two situations are calculated, including an overall probability of overtopping (product of the exceedance probability of water levels and overtopping probability). In the **probabilistic** approach, all different scenarios are computed, and for each scenario with the corresponding overtopping probability taken into account.

Results discussion

#Disclaimer: because of a little mistake in the calculations, a water level of 6.2 has been used with an occurrence of 1/3000 instead of 6.28 m+Nap. However, this difference does not change the results of the research. This means that the results are still applicable.#

Because of this difference, The overall probability that has been calculated via Hydra-NL in the semi approach did not match the overtopping probability according to given water levels in the probabilistic approach. The question that needs to be asked here is whether to rely on the overall probability of overtopping (area under black curve) or on the probability of overtopping according to the given water level (red curve). This resulted in a probability of overtopping the water level at 6.2 m+Nap, equal to 1/2.5 $year^{-1}$.

Tabel 5.4 difference in probabilities in both approaches

	value $[year^{-1}$
Overall probability of overtopping	1/1187
Probability of overtopping according to 6.28 m+Nap	1/2.5

This shows how different the results of both curves are from each other, hence the insufficiency of the semi-probabilistic approach.

Improvement on semi approach

Because of this, the safety factor of the overtopping conditions has been recalculated, resulting in a safety factor of 1.14(-). Following the method mentioned in section 2.1.2, the factor required a design with an inner slope of 1:3.25.

Following this reasoning, the probabilistic approach has also been made to the new design to check whether it satisfies the probabilistic conditions and to prove the speculations above. Following Tabel 5.5, the design is too safe and therefore, it is possible to conclude that a design with an inner slope between 1:3 and 1:3.25 would deliver a more reliable design.

Tabel 5.5 results of probabilistic approach of the dike with an inner slope of 1:3.25

	Kans	Terugkeertijd	Beta
Faalkans	1.26E-09	791308353	5.96
Eis	6.93E-06	144300	4.35
Eis met schematiseringsfactor	2.52E-06	397307	4.56

5.2 Question summary results

The last question has shown how different both approaches are. It showed how the semi-probabilistic approach relied on both overtopping probabilities and the exceedance probability of water levels to compute the overall probability of overtopping. On the other hand, the question answered how the probabilistic approach includes the overtopping probability in each scenario separately. Eventually, the question showed what design the probabilistic approach requires in order to satisfy its norms.

6 DISCUSSION

Shallow slip planes in probabilistic analysis for overtopping scenarios

The slip planes that have resulted from the Uplift Van method for situations with overtopping are pretty shallow compared to the slip plane for situations without overtopping. Therefore, the probabilistic assessment only relied on the sand layer as a dominant layer in its calculations. This is different from the situations without overtopping, where multiple ground layers were included in the slip plane.
Therefore, the question that needs to be asked is whether the resulted slip plane is representative enough for the probabilistic assessment or not.

Hydra-NL Output and its results' correction

The failure probability of the water levels is a product of using Hydra-NL results interpolated using a python script. However, Hydra-NL could only show the probability of 9 water levels. Moreover, the python script interpolated these results along 561 water levels, from 2.4 to 8 m+Nap with a 0.1 interval; [2.4 , 8 , 0.1]. This formed the reason behind the correction of the water levels' CDF for the years 2050 and 2100, as the input of Hydra-NL was not enough to have reliable results. However, these results have been corrected and then averaged to get the probability failure of the water levels of 2075.

The reason behind mentioning this is the fact that if Hydra-NL had found more probabilities for more than nine levels, the results could have been different since water level failure probability is directly related to the final probabilistic Beta result, which is found to be not enough for the required minimum Beta for safe design.

Linear relationship between 2050 and 2100 results:

In this framework, the guidelines that have been given for the Hydra-NL analysis assume a linear relationship between the probabilities of the years 2050 and 2100. This makes the resulted probabilities of 2075 (averaged results) questionable, as they might have resulted differently if the program was able to calculate the probabilities of the year itself.

Deterministic input of the phreatic line for probabilistic analysis

The results of the fragility curve have been based on the calculations of the D-stability, where multiple water levels have been modeled along with the resulted phreatic line and hydraulic head. This, however, has been done deterministically and therefore has a margin on uncertainty in it, however, according to the fixed setting that has been taken in this research. The results are consistent. In other words, the results of the condition without overtopping fragility curve do seem logical.
In this course, it is essential to understand how conservative the results are. This means that although this analysis is probabilistic, it has many semi-probabilistic variables. Therefore. this aspect could differ the results a lot as a more stochastic variable would also mean that the results are more reliable.

Damage factor for overtopping conditions

Because of the insufficiency of the semi-probabilistic design according to the probabilistic assessments, there has been little research on the theory used in the semi-probabilistic approach. In this framework, the damage factor that has been used to calculate the safety factors (with overtopping) seems to not sufficient according to the following reference (Detalres, 2016); where it mentions that the calibrated safety format applied to situations without overtopping. This means that the used methodology to calculate the safety factor is only applicable for situations without overtopping, which may explain the low safety factor requirement of 0.85, and therefore the low resulted reliability in the probabilistic approach (with overtopping) as there is a big difference between the reliability indices between the situations with and without overtopping.

7 CONCLUSION

The main question of the research is whether the semi-probabilistic approach provides a safe dike design that could be relied on for the project in Zwolle Olst. In that framework, the research used the FROM method for the probabilistic approach to assess whether the dike's design delivers a safe design or not. The final result could be summarized as the following:
The semi probabilistic approach does not satisfy the safety criteria according to the FORM analysis and therefore the design need to be assessed further to ensure a safe design.

Question 1 has shown how the semi-probabilistic approach was developed according to the methodology used in the question and the starting points mentioned in the beginning of the research. Furthermore, the question gave answers on how the criteria for the semi-probabilistic design have been developed; these criteria turned out to be different and resulted in a safety factor of 1.23 and 0.85 for conditions with and without overtopping, respectively. This eventually led to a design with an inner slope of 1:3. Furthermore, the question gave answers on the ground profile of the dike, which was sand dominant in the main dike body with a little clay layer.

Question 2 formed the starting point for the probabilistic approach is question 3. First, it showed which variables are handled deterministically and stochastically. After that, the question also showed the values of the mean and standard deviations of the available variables. It also showed how the statistics of the POP variables are calculated and what resulted. Summerly, the question is only used the frictional angle of sand, shear strength ratio of clay and peat, and POP state points.
After that, the question also showed that the variables water level, phreatic line, and hydraulic head are connected and need to be modeled deterministically for each water level. Eventually, the question showed that the dike is very sensitive to the modeling phreatic line both vertically and horizontally.

Question 3 showed what the results of the probabilistic assessment looked like. Firstly, it has been found that there is a big difference between the results of the fragility curves for both the conditions with and without overtopping.
After that, the question investigated the overtopping probability of water levels and the probability of exceedance of the same water levels. These probabilities have been done using interpolation techniques that used the results of Hydra-NL. Eventually, the question gave an answer to the minimum required reliability index for the probabilistic assessment, which the assessment did not satisfy. This meant that the selected design in question 1 was not safe enough according to the assessment.

The **last question** has shown how different both approaches are. It showed how the semi-probabilistic approach relied on both overtopping probabilities and the exceedance probability of water levels to compute the overall probability of overtopping. On the other hand, the question answered how the probabilistic approach includes the overtopping probability in each scenario separately. This led to the probabilistic assessment using a water level with a higher probability than the semi-probabilistic approach, namely, 1/1187 for the semi-probabilistic and 1/2.5 for the probabilistic approach. Eventually, the question showed what design does the probabilistic approach requires in order to satisfy to its norms, which is a design that has a slope between 1:3 and 1:3.25.

However, according to the limitation that this research had, It is safe to say that the FORM analysis suited the research and delivered reliable results. In this framework, the research results could be improved using the following recommendations.

7.1 Recommendations

According to the previous discussion, the research could give more accurate results if the following aspects are improved:

1. Modelling of the phreatic line: The modelling of the phreatic line of the overtopping condition is conservative and does not include any dynamic conditions. Therefore, a more detailed analysis of the phreatic line need to be done. This could have resulted in a more accurate assessment according to the probabilistic assessment.

2. It has also been shown the design is really sensitive to the horizontal positioning of point B (of the phreatic line). Therefore, it is highly recommended to find a way to implement this variable stochastically. This could be done by either inserting the position of the point according to a mean and standard deviation or by inserting the variable dynamically using another software than D-stability.

3. Modeling of scenarios: the scenarios were modelled by changing the water levels of the design, and thereby different scenarios were achieved owing to the changes in the phreatic line and the hydraulic head. However, these have been modeled deterministically into a probabilistic approach due to the limitations of D-stability. Therefore, it is highly advised to use a program capable of modeling these aspects stochastically. Such technology might not be available at the moment or might be too complex. However, having such technology might reveal a lot about the behavior of the dike in overtopping conditions. Therefore, a hydrological study about the phreatic line behavior is highly advised for further research.

4. Calculations of the probability of overtopping: The research showed how different approaches handled the failure probabilities. In this framework, both approaches did rely on some results that were calculated via Hydra-NL. However, the assessment did show that the probabilistic calculations of Hydra-NL did not provide enough output. This raises speculations about the reliability of the software, as the difference in results mainly did occur because of calculated overtopping probability.

5. Damage factor calibration for overtopping conditions: As mentioned in the discussion, the methodology used to calculate the damage factor for situations with overtopping is not developed for such situations. Therefore, it is essential to investigate the sensitivity of this damage factor in overtopping conditions and maybe calibrate it so that the results are more reliable. This calibration need to be done for different sections of the dike ring.

6. This research also relied on averaging the results of the years 2050 and 2100, assuming a linear relationship between the results of two years. However, the results could be more accurate if the software could have the option of the year 2075. Hence, enhancing the accuracy of the results. Therefore, having a more detailed assessment of Hydra-NL could differ from the findings of the results.

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9 APPENDENCES

9.1 Layer Consolidation percentages:

Layer consolidation percentages

L 2: Echteld-klei	20	%
L 5: Boxtel-klei	100	%
L 6: Kreftenheye-zand	100	%
L 4: Boxtel-zand	100	%
L 14: Echteld-klei	100	%
L 3: Nieuwkoop-veen	20	%
L 12: Nieuwkoop-veen	100	%
L 15: Nieuwkoop-veen-opbarstzone	100	%
L 17: Versterking-klei-opbarstzone	100	%
L 16: Echteld-klei-opbarstzone	20	%
L 10: Echteld-klei	20	%
L 1: Echteld-klei	20	%
L 13: Echteld-klei	20	%
L 8: Antropogeen-zand	100	%
L 11: Antropogeen-klei	100	%
L 9: Antropogeen-zand	100	%
L 7: Versterking-klei	100	%

9.2 Hydra-NL results of 2050:

```
Hydra-NL            Versienummer: 2.8.2                  mei 2021               Bereken-
ingsresultaten
Naam gebruiker                                            = YAGM
Gebruikersmodus                                           = Ontwerpen
Datum berekening                                          = 23-05-2022 18:36:27

Invoerdatabase                                            = WBI2023_IJsseldelta_53-
2_v00_terBeoordeling.sqlite
Locatie                                                   = 053-02_020_IJ_km0957
  X-coördinaat                                            =  204117 (m)
  Y-coördinaat                                            =  484920 (m)

De golfparameters uit de database zijn in de berekening gebruikt.
Voor de golfbeweging over het voorland is de piekperiode uit de database gebruikt.
```

Profiel = profile 1 dike.prfl
Aanwezige kruinhoogte dijk = 7.00 (m+NAP)
Uitwendige dijknormaal = 0.00 (°N)

Dijkprofielcoördinaten Afstand (m)	Hoogte (m+NAP)	Taludruwheids-factor (-)
68.00	2.00	1.00
82.00	7.00	

Voorlandprofielcoördinaten Afstand (m)	Hoogte (m+NAP)
50.00	2.00
68.00	2.00

Berekeningstype = Hydraulisch belastingniveau
Faalmechanisme = Golfoverslag en overloop
Kritiek overslagdebiet = 1.00 (l/s/m)
De golfoverslag is berekend met versie '19.1.1.8037' van de 'Wave overtopping at dikes'-module

Berekening met statistische onzekerheid.
Berekening met onzekerheid in de waterstand, golfhoogte én golfperioden.
De parameterwaarden van de modelonzekerheid zijn uit de database afkomstig.
Verwachtingswaarde onzekerheid waterstand = 0.00 (m)
Standaarddeviatie onzekerheid waterstand = 0.20 (m)
Aantal gebruikte waarden onzekerheid waterstand = 7
Verwachtingswaarde voor onzekerheid golfhoogte = 1.04 (-)
Standaarddeviatie voor onzekerheid golfhoogte = 0.27 (-)
Aantal gebruikte waarden onzekerheid golfhoogte = 5
Verwachtingswaarde onzekerheid spectrale golfperiode = 0.97 (-)
Standaarddeviatie onzekerheid spectrale golfperiode = 0.13 (-)
Verwachtingswaarde voor onzekerheid piekperiode = 0.97 (-)
Standaarddeviatie voor onzekerheid piekperiode = 0.13 (-)
Aantal gebruikte waarden onzekerheden golfperioden = 5
Correlatiecoëfficiënt modelonz. golfhoogte en periode = 0.00 (-)

Deze berekening is gemaakt voor het scenario W+ voor 2050
en de afvoergolven worden afgetopt boven de afvoer 2845 m^3/s.
Deze berekening is uitgevoerd met statistische gegevens van de IJssel

Berekeningsresultaten

Kruinhoogte: Overschrijdingsfrequentie:
7.000 (m+NAP) 1/ 1622 Illustratiepunten Percentielen

Illustratiepunten bij opgegeven kruinhoogte:

Waarschuwing: Er zijn illustratiepunten berekend in combinatie met aftoppen.
De berekeningsmethode hiervoor is niet geheel correct.
De illustratiepunten zijn daardoor niet altijd betrouwbaar.

Illustratiepunten bij hydraulisch belastingniveau 7.00 (m+NAP) en terugkeertijd 1622 (jaar)

Locatie = 053-02_020_IJ_km0957 (204117,484920)
Berekeningstype = Hydraulisch belastingniveau, golfoverslag met kritiek overslagdebiet van 1.00 (l/s/m)
Hydraulisch belastingniveau = 7.00 (m+NAP)
Terugkeertijd = 1622 (jaar)
Overschrijdingsfrequentie = 6.17E-04 (per jaar)

Geopende Ramspolkering

r	meerp. m+NAP	q IJssel m^3/s	-- --	windsn. m/s	h,teen m+NAP	Hm0,teen m	Tm-1,0,t s	golfr graden	ov. freq *0.001/whj	ov. freq %
NNO	--	--	--	--	--	--	--	--	0.000	0.0
NO	--	--	--	--	--	--	--	--	0.000	0.0

ONO	--	--	--	--	--	--	--	--	0.000	0.0
O	--	--	--	--	--	--	--	--	0.000	0.0
OZO	--	--	--	--	--	--	--	--	0.000	0.0
ZO	--	--	--	--	--	--	--	--	0.000	0.0
ZZO	--	--	--	--	--	--	--	--	0.000	0.0
Z	--	--	--	--	--	--	--	--	0.000	0.0
ZZW	--	--	--	--	--	--	--	--	0.000	0.0
ZW	--	--	--	--	--	--	--	--	0.000	0.0
WZW	--	--	--	--	--	--	--	--	0.000	0.0
W	--	--	--	--	--	--	--	--	0.000	0.0
WNW	0.25	1850	--	13.4	6.14	0.59	2.52	292.5	0.025	4.1
NW	0.30	1850	--	12.1	6.14	0.54	2.44	315.0	0.033	5.4
NNW	0.35	1850	--	15.0	6.01	0.58	2.47	337.5	0.032	5.2
N	0.35	1850	--	16.0	6.18	0.48	2.21	360.0	0.002	0.3
som									0.093	15.1

Onzekerheidswaarden (let op: deze zijn reeds verwerkt in de weergeven waterstanden/golfparameters)

r	h onz.	f_Hm0	f_Tm-1,0	f_Tp	ov. freq
	m	-	-	-	%
NNO	--	--	--	--	0.0
NO	--	--	--	--	0.0
ONO	--	--	--	--	0.0
O	--	--	--	--	0.0
OZO	--	--	--	--	0.0
ZO	--	--	--	--	0.0
ZZO	--	--	--	--	0.0
Z	--	--	--	--	0.0
ZZW	--	--	--	--	0.0
ZW	--	--	--	--	0.0
WZW	--	--	--	--	0.0
W	--	--	--	--	0.0
WNW	0.34	1.36	1.11	1.11	4.1
NW	0.34	1.36	1.11	1.11	5.4
NNW	0.17	1.36	1.11	1.11	5.2
N	0.34	1.36	1.11	1.11	0.3

Gesloten Ramspolkering

r	meerp.	q IJssel	--	windsn.	h,teen	Hm0,teen	Tm-1,0,t	golfr	ov. freq	ov. freq
	m+NAP	m³/s	--	m/s	m+NAP	m	s	graden	*0.001/whj	%
NNO	--	--	--	--	--	--	--	--	0.000	0.0
NO	--	--	--	--	--	--	--	--	0.000	0.0
ONO	--	--	--	--	--	--	--	--	0.000	0.0
O	--	--	--	--	--	--	--	--	0.000	0.0
OZO	--	--	--	--	--	--	--	--	0.000	0.0
ZO	--	--	--	--	--	--	--	--	0.000	0.0

ZZO	--	--	--	--	--	--	--	--	0.000	0.0
Z	--	--	--	--	--	--	--	--	0.000	0.0
ZZW	--	--	--	--	--	--	--	--	0.000	0.0
ZW	--	--	--	--	--	--	--	--	0.000	0.0
WZW	--	--	--	--	--	--	--	--	0.000	0.0
W	--	--	--	--	--	--	--	--	0.000	0.0
WNW	0.30	1600	--	18.6	5.75	0.80	2.92	292.5	0.220	35.7
NW	0.25	1525	--	17.8	5.68	0.78	2.88	315.0	0.240	38.9
NNW	0.40	1765	--	20.2	6.00	0.60	2.46	337.5	0.060	9.8
N	0.35	1400	--	23.3	5.74	0.69	2.59	360.0	0.004	0.6
som									0.524	84.9

Onzekerheidswaarden (let op: deze zijn reeds verwerkt in de weergeven waterstanden/golfparameters)

r	h onz. m	f_Hm0 -	f_Tm-1,0 -	f_Tp -	ov. freq %
NNO	--	--	--	--	0.0
NO	--	--	--	--	0.0
ONO	--	--	--	--	0.0
O	--	--	--	--	0.0
OZO	--	--	--	--	0.0
ZO	--	--	--	--	0.0
ZZO	--	--	--	--	0.0
Z	--	--	--	--	0.0
ZZW	--	--	--	--	0.0
ZW	--	--	--	--	0.0
WZW	--	--	--	--	0.0
W	--	--	--	--	0.0
WNW	0.17	1.36	1.11	1.11	35.7
NW	0.17	1.36	1.11	1.11	38.9
NNW	0.17	1.04	0.97	0.97	9.8
N	0.17	1.36	1.11	1.11	0.6

Betekenis van de gegevens:

- r = De windrichting
- meerp. = De ruimtelijk gemiddelde waterstand van het IJsselmeer in m+NAP
- q IJssel = De afvoer op de IJssel bij Olst in m^3/s
- q Vecht = De afvoer op de Vecht bij Dalfsen in m^3/s
- windsn. = De potentiële windsnelheid van Schiphol in m/s
- h,teen = De waterstand op de doorgerekende locatie in m+NAP na eventuele transformatie over een voorland
- Hm0,teen = De significante golfhoogte in m na eventuele transformatie over een dam en/of voorland
- Tm-1,0,t = De spectrale golfperiode in s na eventuele transformatie over een voorland
- golfr = De golfrichting in graden t.o.v. Noord na eventuele transformatie over een voorland
- ov.freq = De overschrijdingsfrequentie van het hydraulisch belastingniveau voor de bijbehorende windrichting in gemiddeld aantal keer per winterhalfjaar en als percentage
- h onz. = De verhoging van de waterstand ten gevolge van de onzekerheid in de waterstand in m vóór een eventuele transformatie over een voorland
- f_Hm0 = De vermenigvuldigingsfactor van de golfhoogte als gevolg van de onzekerheid in de golfhoogte vóór een eventuele transformatie over een voorland
- f_Tm-1,0 = De vermenigvuldigingsfactor van de spectrale golfperiode als gevolg van de onzekerheid in de spectrale golfperiode vóór een eventuele transformatie over een voorland
- f_Tp = De vermenigvuldigingsfactor van de piekperiode als gevolg van de onzekerheid in de piekperiode vóór een eventuele transformatie over een voorland

Hoofdillustratiepunten bij hydraulisch belastingniveau 7.00 (m+NAP) en terugkeertijd 1622 (jaar)

	Geopende Ramspolkering (bijdrage aan ov.freq 15.1%)	Gesloten Ramspolkering (bijdrage aan ov.freq 84.9%)
windrichting r (bijdrage aan ov.freq)	NW (5.4%)	NW (38.9%)
IJsselmeerpeil m [m+NAP]	0.30	0.25
IJsselafvoer q te Olst [m³/s]	1850	1525
potentiële windsnelheid u [m/s]	12.1	17.8
lokale waterstand h [m+NAP]	6.14	5.68
significante golfhoogte Hm0 [m]	0.54	0.78
spectrale golfperiode Tm-1,0 [s]	2.44	2.88
golfrichting t.o.v. Noord [graden]	315.0	315.0
onz. lokale waterstand [m]	0.34	0.17
onz. significante golfhoogte [-]	1.36	1.36
onz. spectrale golfperiode [-]	1.11	1.11
onz. piekperiode [-]	1.11	1.11

Percentielen behorende bij de opgegeven terugkeertijden:

Waarschuwing: Er zijn percentielen berekend in combinatie met aftoppen.
De berekeningsmethode hiervoor is niet geheel correct.
De percentielen zijn daardoor niet altijd betrouwbaar.

Percentielen voor hydraulisch belastingniveau 7.00 (m+NAP) en terugkeertijd 1622 (jaar)

Windsnelheidspercentielen bij gegeven windrichting
Windsnelheidspercentielen bij gegeven windrichting en geopende Ramspolkering
Windsnelheidspercentielen bij gegeven windrichting en gesloten Ramspolkering

Locatie = 053-02_020_IJ_km0957 (204117,484920)
Berekeningstype = Hydraulisch belastingniveau, golfoverslag met kritiek overslagdebiet van 1.00 (l/s/m)
Hydraulisch belastingniveau = 7.00 (m+NAP)
Terugkeertijd = 1622 (jaar)
Overschrijdingsfrequentie = 6.17E-04 (per jaar)

Geopende Ramspolkering = 15.1%
Gesloten Ramspolkering = 84.9%

Percentielen van de IJsselafvoer (m³/s)

percentiel	open+dicht	open	dicht
5%	894	1650	808
10%	1190	1728	1128
25%	1497	1835	1447
50%	1746	1964	1694
75%	1927	2140	1879
90%	2103	2419	2038
95%	2236	2646	2144

Percentielen van het meerpeil (m+NAP)

percentiel	open+dicht	open	dicht
5%	-0.08	0.08	-0.10
10%	0.02	0.15	0.01
25%	0.18	0.26	0.16
50%	0.34	0.39	0.32
75%	0.49	0.55	0.48
90%	0.65	0.73	0.64
95%	0.76	0.88	0.73

Percentielen van de windsnelheid (m/s)

percentiel	open+dicht	open	dicht
5%	13.6	11.5	15.4
10%	14.7	12.1	16.3
25%	17.0	13.2	18.1

50%	19.7	14.6	20.5
75%	23.4	16.3	24.1
90%	28.2	17.7	29.1
95%	32.5	18.6	33.5

Locatie = 053-02_020_IJ_km0957 (204117,484920)
Berekeningstype = Hydraulisch belastingniveau, golfoverslag met kritiek overslagdebiet van 1.00 (l/s/m)
Hydraulisch belastingniveau = 7.00 (m+NAP)
Terugkeertijd = 1622 (jaar)
Overschrijdingsfrequentie = 6.17E-04 (per jaar)

Windsnelheidspercentielen (m/s) bij gegeven windrichting en onafhankelijk van de keringsituatie

r	NNO	NO	ONO	O	OZO	ZO	ZZO	Z
percentage	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5%	-----	-----	-----	-----	-----	-----	-----	-----
10%	-----	-----	-----	-----	-----	-----	-----	-----
25%	-----	-----	-----	-----	-----	-----	-----	-----
50%	-----	-----	-----	-----	-----	-----	-----	-----
75%	-----	-----	-----	-----	-----	-----	-----	-----
90%	-----	-----	-----	-----	-----	-----	-----	-----
95%	-----	-----	-----	-----	-----	-----	-----	-----

r	ZZW	ZW	WZW	W	WNW	NW	NNW	N
percentage	0.0%	0.0%	0.0%	0.0%	39.8%	44.3%	15.0%	1.0%
5%	-----	-----	-----	-----	13.8	13.4	13.5	14.8
10%	-----	-----	-----	-----	15.1	14.5	14.7	16.0
25%	-----	-----	-----	-----	17.4	16.7	16.8	18.0
50%	-----	-----	-----	-----	20.0	19.5	19.5	20.6
75%	-----	-----	-----	-----	23.9	22.9	23.3	24.2
90%	-----	-----	-----	-----	29.1	27.4	28.3	28.3
95%	-----	-----	-----	-----	33.9	31.3	32.6	31.3

Windsnelheidspercentielen (m/s) bij gegeven windrichting en een geopende Ramspolkering

r	NNO	NO	ONO	O	OZO	ZO	ZZO	Z
percentage	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5%	-----	-----	-----	-----	-----	-----	-----	-----
10%	-----	-----	-----	-----	-----	-----	-----	-----

```
        25% |     ----- |     ----- |     ----- |     ----- |     ----- |     ----- |
----- |     -----
        50% |     ----- |     ----- |     ----- |     ----- |     ----- |     ----- |
----- |     -----
        75% |     ----- |     ----- |     ----- |     ----- |     ----- |     ----- |
----- |     -----
        90% |     ----- |     ----- |     ----- |     ----- |     ----- |     ----- |
----- |     -----
        95% |     ----- |     ----- |     ----- |     ----- |     ----- |     ----- |
----- |     -----

          r |   ZZW     |   ZW      |   WZW     |   W       |   WNW     |   NW      |
NNW       |   N
------------+-----------+-----------+-----------+-----------+-----------+-----------+----
-------+-----------
 percentage |      0.0% |      0.0% |      0.0% |      0.0% |      4.1% |      5.4% |
5.2% |      0.3%
------------+-----------+-----------+-----------+-----------+-----------+-----------+----
-------+-----------
         5% |     ----- |     ----- |     ----- |     ----- |      11.6 |      11.0 |
12.2 |      13.7
        10% |     ----- |     ----- |     ----- |     ----- |      12.0 |      11.7 |
13.1 |      14.4
        25% |     ----- |     ----- |     ----- |     ----- |      12.9 |      12.7 |
14.4 |      15.8
        50% |     ----- |     ----- |     ----- |     ----- |      14.1 |      13.9 |
15.8 |      17.0
        75% |     ----- |     ----- |     ----- |     ----- |      15.5 |      15.1 |
17.2 |      18.1
        90% |     ----- |     ----- |     ----- |     ----- |      17.2 |      16.6 |
18.0 |      18.7
        95% |     ----- |     ----- |     ----- |     ----- |      19.6 |      18.4 |
18.4 |      18.9
```

Windsnelheidspercentielen (m/s) bij gegeven windrichting en een gesloten Ramspolkering

```
          r |     ----- |   ZW      |   WZW     |   W       |   WNW     |   NW      |
NNW       |   N
------------+-----------+-----------+-----------+-----------+-----------+-----------+----
-------+-----------
 percentage |     ----- |      0.0% |      0.0% |      0.0% |     35.7% |     38.9% |
9.8% |      0.6%
------------+-----------+-----------+-----------+-----------+-----------+-----------+----
-------+-----------
         5% |     ----- |     ----- |     ----- |     ----- |      15.5 |      15.1 |
17.4 |      19.3
        10% |     ----- |     ----- |     ----- |     ----- |      16.3 |      16.0 |
18.2 |      19.7
        25% |     ----- |     ----- |     ----- |     ----- |      18.1 |      17.7 |
19.5 |      20.8
        50% |     ----- |     ----- |     ----- |     ----- |      20.6 |      20.1 |
21.8 |      23.0
        75% |     ----- |     ----- |     ----- |     ----- |      24.4 |      23.5 |
25.4 |      26.1
        90% |     ----- |     ----- |     ----- |     ----- |      29.7 |      28.1 |
30.8 |      30.1
        95% |     ----- |     ----- |     ----- |     ----- |      34.5 |      32.1 |
34.8 |      33.5
```

9.3 Hydra-NL results of 2100:

```
Hydra-NL            Versienummer: 2.8.2               mei 2021              Bereken-
ingsresultaten
Naam gebruiker                                         = YAGM
Gebruikersmodus                                        = Ontwerpen
Datum berekening                                       = 24-05-2022 15:35:36

Invoerdatabase                                         = WBI2023_IJsseldelta_53-
2_v00_terBeoordeling.sqlite
Locatie                                                = 053-02_020_IJ_km0957
  X-coördinaat                                         =  204117 (m)
  Y-coördinaat                                         =  484920 (m)

De golfparameters uit de database zijn in de berekening gebruikt.
Voor de golfbeweging over het voorland is de piekperiode uit de database gebruikt.
```

```
Profiel                                                  = profile 1 dike.prfl
  Aanwezige kruinhoogte dijk                             =         7.00 (m+NAP)
  Uitwendige dijknormaal                                 =         0.00 (°N)

    Dijkprofielcoördinaten   Taludruwheids-
     Afstand     Hoogte      factor
       (m)       (m+NAP)       (-)
       68.00       2.00        1.00
       82.00       7.00

    Voorlandprofielcoördinaten
     Afstand     Hoogte
       (m)       (m+NAP)
       50.00       2.00
       68.00       2.00

Berekeningstype                                          = Hydraulisch belastingniveau
Faalmechanisme                                           = Golfoverslag en overloop
  Kritiek overslagdebiet                                 =         1.00 (l/s/m)
  De golfoverslag is berekend met versie '19.1.1.8037' van de 'Wave overtopping at di-
kes'-module

Berekening met statistische onzekerheid.
Berekening met onzekerheid in de waterstand, golfhoogte én golfperioden.
De parameterwaarden van de modelonzekerheid zijn uit de database afkomstig.
  Verwachtingswaarde onzekerheid waterstand              =         0.00 (m)
  Standaarddeviatie onzekerheid waterstand               =         0.20 (m)
  Aantal gebruikte waarden onzekerheid waterstand        =            7
  Verwachtingswaarde voor onzekerheid golfhoogte         =         1.04 (-)
  Standaarddeviatie voor onzekerheid golfhoogte          =         0.27 (-)
  Aantal gebruikte waarden onzekerheid golfhoogte        =            5
  Verwachtingswaarde onzekerheid spectrale golfperiode   =         0.97 (-)
  Standaarddeviatie onzekerheid spectrale golfperiode    =         0.13 (-)
  Verwachtingswaarde voor onzekerheid piekperiode        =         0.97 (-)
  Standaarddeviatie voor onzekerheid piekperiode         =         0.13 (-)
  Aantal gebruikte waarden onzekerheden golfperioden     =            5
  Correlatiecoëfficiënt modelonz. golfhoogte en periode =         0.00 (-)

Deze berekening is gemaakt voor het scenario W+ voor 2100
  en de afvoergolven worden afgetopt boven de afvoer  2845 m³/s.
Deze berekening is uitgevoerd met statistische gegevens van de IJssel


Berekeningsresultaten

  Kruinhoogte:   Overschrijdingsfrequentie:
   7.000 (m+NAP)         1/     753                          Illustratiepunten   Percen-
tielen

Illustratiepunten bij opgegeven kruinhoogte:

Waarschuwing: Er zijn illustratiepunten berekend in combinatie met aftoppen.
              De berekeningsmethode hiervoor is niet geheel correct.
              De illustratiepunten zijn daardoor niet altijd betrouwbaar.

Illustratiepunten bij hydraulisch belastingniveau  7.00 (m+NAP) en terugkeertijd   753
(jaar)

Locatie                      = 053-02_020_IJ_km0957 (204117,484920)
Berekeningstype              = Hydraulisch belastingniveau, golfoverslag met kritiek
overslagdebiet van  1.00 (l/s/m)
Hydraulisch belastingniveau   =     7.00 (m+NAP)
Terugkeertijd                 =      753 (jaar)
Overschrijdingsfrequentie     = 1.33E-03 (per jaar)

Geopende Ramspolkering

  r       | meerp.  | q IJssel|      -- | windsn. | h,teen   | Hm0,teen| Tm-1,0,t| golfr
| ov. freq   | ov. freq
         | m+NAP   | m³/s    |      -- | m/s     | m+NAP    | m       | s       | graden
| *0.001/whj | %
---------+---------+---------+---------+---------+---------+---------+---------+---------
+------------+---------
  NNO    |      -- |      -- |      -- |      -- |      -- |      -- |      -- |      --
|      0.000 |     0.0
  NO     |      -- |      -- |      -- |      -- |      -- |      -- |      -- |      --
|      0.000 |     0.0
```

ONO	--	--	--	--	--	--	--	--	0.000	0.0
O	--	--	--	--	--	--	--	--	0.000	0.0
OZO	--	--	--	--	--	--	--	--	0.000	0.0
ZO	--	--	--	--	--	--	--	--	0.000	0.0
ZZO	--	--	--	--	--	--	--	--	0.000	0.0
Z	--	--	--	--	--	--	--	--	0.000	0.0
ZZW	--	--	--	--	--	--	--	--	0.000	0.0
ZW	--	--	--	--	--	--	--	--	0.000	0.0
WZW	--	--	--	--	--	--	--	--	0.000	0.0
W	--	--	--	--	--	--	--	--	0.000	0.0
WNW	0.60	1975	--	13.3	6.14	0.59	2.52	292.5	0.046	3.5
NW	0.60	1850	--	12.1	6.14	0.54	2.43	315.0	0.059	4.4
NNW	0.55	1850	--	15.0	6.01	0.58	2.47	337.5	0.062	4.7
N	0.60	1850	--	16.0	6.18	0.48	2.20	360.0	0.006	0.4
som									0.173	13.0

Onzekerheidswaarden (let op: deze zijn reeds verwerkt in de weergeven waterstanden/golfparameters)

r	h onz.	f_Hm0	f_Tm-1,0	f_Tp	ov. freq
	m	-	-	-	%
NNO	--	--	--	--	0.0
NO	--	--	--	--	0.0
ONO	--	--	--	--	0.0
O	--	--	--	--	0.0
OZO	--	--	--	--	0.0
ZO	--	--	--	--	0.0
ZZO	--	--	--	--	0.0
Z	--	--	--	--	0.0
ZZW	--	--	--	--	0.0
ZW	--	--	--	--	0.0
WZW	--	--	--	--	0.0
W	--	--	--	--	0.0
WNW	0.34	1.36	1.11	1.11	3.5
NW	0.34	1.36	1.11	1.11	4.4
NNW	0.17	1.36	1.11	1.11	4.7
N	0.34	1.36	1.11	1.11	0.4

Gesloten Ramspolkering

r	meerp.	q IJssel	--	windsn.	h,teen	Hm0,teen	Tm-1,0,t	golfr	ov. freq	ov. freq
	m+NAP	m³/s	--	m/s	m+NAP	m	s	graden	*0.001/whj	%
NNO	--	--	--	--	--	--	--	--	0.000	0.0
NO	--	--	--	--	--	--	--	--	0.000	0.0
ONO	--	--	--	--	--	--	--	--	0.000	0.0
O	--	--	--	--	--	--	--	--	0.000	0.0
OZO	--	--	--	--	--	--	--	--	0.000	0.0
ZO	--	--	--	--	--	--	--	--	0.000	0.0

ZZO	--	--	--	--	--	--	--	--	0.000	0.0
Z	--	--	--	--	--	--	--	--	0.000	0.0
ZZW	--	--	--	--	--	--	--	--	0.000	0.0
ZW	--	--	--	--	--	--	--	--	0.000	0.0
WZW	--	--	--	--	--	--	--	--	0.000	0.0
W	1.00	2750	--	36.4	7.01	0.00	3.25	270.0	0.000	0.0
WNW	0.60	1817	--	17.7	5.98	0.78	2.50	292.5	0.490	36.9
NW	0.55	1700	--	17.7	5.87	0.78	2.51	315.0	0.520	39.2
NNW	0.55	1675	--	19.1	5.89	0.73	2.39	337.5	0.137	10.3
N	0.40	1400	--	23.2	5.74	0.69	2.59	360.0	0.008	0.6
som									1.155	87.0

Onzekerheidswaarden (let op: deze zijn reeds verwerkt in de weergeven waterstanden/golfparameters)

r	h onz.	f_Hm0	f_Tm-1,0	f_Tp	ov. freq
	m	-	-	-	%
NNO	--	--	--	--	0.0
NO	--	--	--	--	0.0
ONO	--	--	--	--	0.0
O	--	--	--	--	0.0
OZO	--	--	--	--	0.0
ZO	--	--	--	--	0.0
ZZO	--	--	--	--	0.0
Z	--	--	--	--	0.0
ZZW	--	--	--	--	0.0
ZW	--	--	--	--	0.0
WZW	--	--	--	--	0.0
W	0.34	1.04	0.97	0.97	0.0
WNW	0.17	1.36	0.97	0.97	36.9
NW	0.17	1.36	0.97	0.97	39.2
NNW	0.17	1.36	0.97	0.97	10.3
N	0.17	1.36	1.11	1.11	0.6

Betekenis van de gegevens:

- r = De windrichting
- meerp. = De ruimtelijk gemiddelde waterstand van het IJsselmeer in m+NAP
- q IJssel = De afvoer op de IJssel bij Olst in m³/s
- q Vecht = De afvoer op de Vecht bij Dalfsen in m³/s
- windsn. = De potentiële windsnelheid van Schiphol in m/s
- h,teen = De waterstand op de doorgerekende locatie in m+NAP na eventuele transformatie over een voorland
- Hm0,teen = De significante golfhoogte in m na eventuele transformatie over een dam en/of voorland
- Tm-1,0,t = De spectrale golfperiode in s na eventuele transformatie over een voorland
- golfr = De golfrichting in graden t.o.v. Noord na eventuele transformatie over een voorland
- ov.freq = De overschrijdingsfrequentie van het hydraulisch belastingniveau voor de bijbehorende windrichting in gemiddeld aantal keer per winterhalfjaar en als percentage
- h onz. = De verhoging van de waterstand ten gevolge van de onzekerheid in de waterstand in m vóór een eventuele transformatie over een voorland
- f_Hm0 = De vermenigvuldigingsfactor van de golfhoogte als gevolg van de onzekerheid in de golfhoogte vóór een eventuele transformatie over een voorland
- f_Tm-1,0 = De vermenigvuldigingsfactor van de spectrale golfperiode als gevolg van de onzekerheid in de spectrale golfperiode vóór een eventuele transformatie over een voorland
- f_Tp = De vermenigvuldigingsfactor van de piekperiode als gevolg van de onzekerheid in de piekperiode vóór een eventuele transformatie over een voorland

Hoofdillustratiepunten bij hydraulisch belastingniveau 7.00 (m+NAP) en terugkeertijd 753 (jaar)

	Geopende Ramspolkering (bijdrage aan ov.freq 13.0%)	Gesloten Ramspolkering (bijdrage aan ov.freq 87.0%)
windrichting r (bijdrage aan ov.freq)	NNW (4.7%)	NW (39.2%)
IJsselmeerpeil m [m+NAP]	0.55	0.55
IJsselafvoer q te Olst [m³/s]	1850	1700
potentiële windsnelheid u [m/s]	15.0	17.7
lokale waterstand h [m+NAP]	6.01	5.87
significante golfhoogte Hm0 [m]	0.58	0.78
spectrale golfperiode Tm-1,0 [s]	2.47	2.51
golfrichting t.o.v. Noord [graden]	337.5	315.0
onz. lokale waterstand [m]	0.17	0.17
onz. significante golfhoogte [-]	1.36	1.36
onz. spectrale golfperiode [-]	1.11	0.97
onz. piekperiode [-]	1.11	0.97

Percentielen behorende bij de opgegeven terugkeertijden:

Waarschuwing: Er zijn percentielen berekend in combinatie met aftoppen.
De berekeningsmethode hiervoor is niet geheel correct.
De percentielen zijn daardoor niet altijd betrouwbaar.

Percentielen voor hydraulisch belastingniveau 7.00 (m+NAP) en terugkeertijd 753 (jaar)

Windsnelheidspercentielen bij gegeven windrichting
Windsnelheidspercentielen bij gegeven windrichting en geopende Ramspolkering
Windsnelheidspercentielen bij gegeven windrichting en gesloten Ramspolkering

Locatie = 053-02_020_IJ_km0957 (204117,484920)
Berekeningstype = Hydraulisch belastingniveau, golfoverslag met kritiek overslagdebiet van 1.00 (l/s/m)
Hydraulisch belastingniveau = 7.00 (m+NAP)
Terugkeertijd = 753 (jaar)
Overschrijdingsfrequentie = 1.33E-03 (per jaar)

Geopende Ramspolkering = 13.0%
Gesloten Ramspolkering = 87.0%

Percentielen van de IJsselafvoer (m³/s)

percentiel	open+dicht	open	dicht
5%	1055	1703	999
10%	1313	1779	1271
25%	1585	1890	1545
50%	1809	2059	1771
75%	1995	2392	1948
90%	2217	2754	2131
95%	2446	2830	2272

Percentielen van het meerpeil (m+NAP)

percentiel	open+dicht	open	dicht
5%	0.20	0.32	0.19
10%	0.29	0.39	0.28
25%	0.43	0.52	0.41
50%	0.58	0.66	0.57
75%	0.75	0.85	0.73
90%	0.90	1.03	0.88
95%	1.00	1.15	0.97

Percentielen van de windsnelheid (m/s)

percentiel	open+dicht	open	dicht
5%	13.2	11.0	14.8
10%	14.4	11.7	15.7
25%	16.5	12.6	17.5

50%	19.2	14.0	19.8
75%	22.5	15.8	23.1
90%	26.6	17.5	27.3
95%	30.2	18.6	30.9

Locatie = 053-02_020_IJ_km0957 (204117,484920)
Berekeningstype = Hydraulisch belastingniveau, golfoverslag met kritiek overslagdebiet van 1.00 (l/s/m)
Hydraulisch belastingniveau = 7.00 (m+NAP)
Terugkeertijd = 753 (jaar)
Overschrijdingsfrequentie = 1.33E-03 (per jaar)

Windsnelheidspercentielen (m/s) bij gegeven windrichting en onafhankelijk van de keringsituatie

r	NNO	NO	ONO	O	OZO	ZO	ZZO	Z
percentage	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5%	-----	-----	-----	-----	-----	-----	-----	-----
10%	-----	-----	-----	-----	-----	-----	-----	-----
25%	-----	-----	-----	-----	-----	-----	-----	-----
50%	-----	-----	-----	-----	-----	-----	-----	-----
75%	-----	-----	-----	-----	-----	-----	-----	-----
90%	-----	-----	-----	-----	-----	-----	-----	-----
95%	-----	-----	-----	-----	-----	-----	-----	-----

r	ZZW	ZW	WZW	W	WNW	NW	NNW	N
percentage	0.0%	0.0%	0.0%	0.0%	40.3%	43.6%	15.0%	1.0%
5%	-----	-----	-----	-----	13.5	13.0	13.2	14.4
10%	-----	-----	-----	-----	14.6	14.2	14.2	15.5
25%	-----	-----	-----	-----	16.9	16.3	16.3	17.5
50%	-----	-----	-----	-----	19.5	18.9	18.9	20.1
75%	-----	-----	-----	-----	22.9	22.1	22.2	23.4
90%	-----	-----	-----	-----	27.3	26.0	26.5	27.0
95%	-----	-----	-----	-----	31.1	29.3	30.1	29.7

Windsnelheidspercentielen (m/s) bij gegeven windrichting en een geopende Ramspolkering

r	NNO	NO	ONO	O	OZO	ZO	ZZO	Z
percentage	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5%	-----	-----	-----	-----	-----	-----	-----	-----
10%	-----	-----	-----	-----	-----	-----	-----	-----

```
        25% |      ----- |      ----- |      ----- |      ----- |      ----- |      ----- |
----- |      -----
        50% |      ----- |      ----- |      ----- |      ----- |      ----- |      ----- |
----- |      -----
        75% |      ----- |      ----- |      ----- |      ----- |      ----- |      ----- |
----- |      -----
        90% |      ----- |      ----- |      ----- |      ----- |      ----- |      ----- |
----- |      -----
        95% |      ----- |      ----- |      ----- |      ----- |      ----- |      ----- |
----- |      -----

          r |   ZZW      |   ZW       |   WZW      |   W        |   WNW      |   NW       |
NNW      |   N
------------+-----------+-----------+-----------+-----------+-----------+-----------+----
-------+-----------
 percentage |       0.0% |       0.0% |       0.0% |       0.0% |       3.5% |       4.4% |
4.7% |       0.4%
------------+-----------+-----------+-----------+-----------+-----------+-----------+----
-------+-----------
         5% |      ----- |      ----- |      ----- |      ----- |       11.0 |       10.4 |
11.7 |       13.2
        10% |      ----- |      ----- |      ----- |      ----- |       11.6 |       11.1 |
12.5 |       14.1
        25% |      ----- |      ----- |      ----- |      ----- |       12.4 |       12.2 |
13.8 |       15.4
        50% |      ----- |      ----- |      ----- |      ----- |       13.4 |       13.0 |
15.3 |       16.8
        75% |      ----- |      ----- |      ----- |      ----- |       14.9 |       14.4 |
16.6 |       18.0
        90% |      ----- |      ----- |      ----- |      ----- |       17.2 |       16.3 |
17.6 |       18.6
        95% |      ----- |      ----- |      ----- |      ----- |       20.1 |       18.8 |
18.2 |       18.8
```

```
Windsnelheidspercentielen (m/s) bij gegeven windrichting en een gesloten Ramspolkering

          r |      ----- |   ZW       |   WZW      |   W        |   WNW      |   NW       |
NNW      |   N
------------+-----------+-----------+-----------+-----------+-----------+-----------+----
-------+-----------
 percentage |      ----- |       0.0% |       0.0% |       0.0% |      36.9% |      39.2% |
10.3% |       0.6%
------------+-----------+-----------+-----------+-----------+-----------+-----------+----
-------+-----------
         5% |      ----- |      ----- |      ----- |      ----- |       14.8 |       14.5 |
16.3 |       19.1
        10% |      ----- |      ----- |      ----- |      ----- |       15.7 |       15.4 |
17.2 |       19.5
        25% |      ----- |      ----- |      ----- |      ----- |       17.6 |       17.0 |
18.6 |       20.5
        50% |      ----- |      ----- |      ----- |      ----- |       19.9 |       19.4 |
20.7 |       22.5
        75% |      ----- |      ----- |      ----- |      ----- |       23.3 |       22.5 |
23.9 |       25.3
        90% |      ----- |      ----- |      ----- |      ----- |       27.7 |       26.5 |
28.3 |       28.9
        95% |      ----- |      ----- |      ----- |      ----- |       31.6 |       29.8 |
32.2 |       31.7
```

9.4 Python script

```
# -*- coding: utf-8 -*-
"""
Created on Sat Feb 27 16:25:17 2021

@author: ESB
"""
import numpy as np
import matplotlib.pyplot as plt
```

```
import os
from scipy.stats import uniform

from io import StringIO
import pandas as pd

fig, ax = plt.subplots()
legend = []
x = np.arange(2.4, 8.01, 0.01)
cdf = np.zeros((len(x),1))
for folder in os.listdir(os.path.join(os.getcwd(), 'data')):
    profiel = folder.split('_')[1]
    with open(r'data\{}\uitvoer.html'.format(folder)) as f:
        txt = f.read()
    legend.append(profiel+' - 1 l/s/m')
    marker = '\nGeopende'
    semi_structured = [i.split('\nGesloten') for i in txt.split('\nGeopende')]

    tables = []

    for i, tables_unpacked in enumerate(semi_structured[1:-1]):
        for table_unpacked in tables_unpacked:
            items = table_unpacked.split('\nOnzekerheidswaarden')
            string_table = items[0].split("\n",2)[2].replace(
                '-','').replace('+','').replace('\n\n','\n').replace(' ','')
            first_line_table = string_table.split("\n",1)[0] + '\n'
            table = first_line_table+'\n'.join(string_table.split("\n")[2:-2])
            string_onz = items[1].split("\n",2)[2].replace(
                '-','').replace('+','').replace('\n\n','\n').replace(' ','').split('Betekenisvandegegevens:')[0]
            first_line_onz = string_onz.split("\n",1)[0] + '\n'
            onzekerheid = first_line_onz+'\n'.join(string_onz.split("\n")[2:-2])
            tables.append({'table': table, 'onzekerheid': onzekerheid})

    import pandas as pd
    from io import StringIO


    dfs = []

    for table in tables:
        df = pd.read_csv(StringIO(table['table']), sep='|')
        df['honz.'] = pd.read_csv(StringIO(table['onzekerheid']), sep='|')['honz.']
        dfs.append(df)

    for i, sub_df in enumerate(dfs):
        sub_df = sub_df[['h,teen', 'ov.freq.1', 'honz.']].dropna()
        if i == 0:
            df = sub_df
        elif len(sub_df):
            df = df.append(sub_df, ignore_index=True)

    df = df.drop(df[df['ov.freq.1']==0].index)
    df[df['honz.']==0] += 0.001

    p_total = df['ov.freq.1'].sum()
    print(p_total)
```

```
    # p_total = 100
    j = len(legend)-1
    df.reset_index(inplace=True)
    for i, row in df.iterrows():
        mean = row['h,teen'] - row['honz.']
        std  = row['honz.']
        rv = uniform(mean, std)
        if j != 0 and i == 0:
            cdf = np.append(cdf, (rv.cdf(x)*row['ov.freq.1']/p_total).reshape((len(x),1)), axis=1)
        else:
            cdf[:,j] += rv.cdf(x)*row['ov.freq.1']/p_total

# df_statistiek = pd.DataFrame({'h,teen':[], 'kans van voorkomen':[], 'overschreidingskans':[]})

# for h in df['h,teen'].sort_values().unique():
#     prob = df[df['h,teen']==h]['ov.freq.1'].sum()/df['ov.freq.1'].sum()*100
#     df_statistiek = df_statistiek.append({'h,teen':h,
#                         'kans van voorkomen':prob,
#                         'overschreidingskans':df_statistiek['overschreidingskans'].to_list()[-1]+prob if
len(df_statistiek['overschreidingskans']) else prob}, ignore_index=True)

#     df_statistiek.plot(x = 'h,teen', y = 'overschreidingskans', ax=ax)
    # legend.append(folder.split('_')[-1]+' l/s/m')
ax.plot(x,cdf)
# ax.plot(x,np.min(cdf, axis=1))
# legend.append('min line')
plt.legend(legend)
plt.ylim([0,1])
plt.xlim([2.4,8])
plt.xlabel('Waterstand bij teen [NAP + m]')
plt.ylabel('Kans op q $\geq$ 10 l/s/m')

data_output = {'z':x[1:750:1]}
for i in range(len(legend)):
    data_output.update({legend[i]: cdf[1:750:1, i]})

df_output = pd.DataFrame(data_output)
df_output.to_excel('Method Deltares_testrun.xlsx')
```