A study of the effect of the slope angle of a green dike on the failure of the grass revetment due to wave impact

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Preface

This report is the result of my research that I executed at Sweco the past five months. With the completion of my thesis, I complete my master Civil Engineering and Management at the University of Twente.

Without several people, it was not possible to execute this study. I would like to thank Jos van Zuylen for the opportunity of doing this research at Sweco and the good guidance during my research. I would also thank Jord Warmink and Vera van Bergeijk for their guidance from the University of Twente and the valuable feedback. Furthermore, I am grateful to Suzanne Hulscher for her feedback and ideas during the meetings. I would also thank the people of the department "Waterbouw" of Sweco for the nice time during my research. Additionally, I would like to thank Myrte Wennen for her support during my research and the feedback on the report. Finally, I would like to thank my family, friends and fellow students who supported me during my study and my student life.

In enjoyed doing my research on the resistance of a grass revetment against wave impact. I hope this report inspires people to continue with my research and to implement my results in the engineering of green dikes.

Martijn Peters

De Bilt, January 2020

Summary

Over the past years, nature, biodiversity and climate change have played an increasingly large role in flood protection projects in the Netherlands. One of these flood protection projects is the "Wide Green Dike" at the Dollard. A wide green dike is a wide dike with a grass cover on the entire waterside slope. The dike, in comparison to most sea dikes, does not contain a hard revetment to deal with the incoming waves. Unfortunately, it is uncertain under which exact storm circumstances the seaside grass revetment fails. The assessment of the strength of the grass revetment against wave impact is captured in the "Wettelijk Beoordelingsinstrumentarium" (WBI), but the slope angle is not included although it has an important effect on the revetment strength. Therefore, the objective of this research was to determine the effect of the slope angle on the duration until failure of the grass revetment due to wave impact, also termed resistance-duration.

The "Wide Green Dike" at the Dollard is a demonstration project and has an estimated slope of 1:7. For this project, it is necessary to obtain knowledge about resistance-duration of the revetment on a gentle slope. Next to computation of the relation between the slope angle and the resistance-duration, the return period of the storm when the revetment fails for the case was studied.

Results of executed experiments were gathered with a literature study and were used to establish the relation between the slope angle and the resistance-duration. The results of the experiments with different slope angles were compared with the predicted resistance-duration curves of the WBI and the Wave Impact Pressure Erosion (WIPE) model. A linear negative correlation between slope angle and resistance-duration described this relation the most accurately. This means that a grass revetment on a slope of 1:6 has twice the resistance-duration compared to a revetment on a slope of 1:3 with similar wave conditions.

With the found relation, the resistance-duration curves for slopes between 1:3 and 1:8 were generated. The resistance-duration curves were applied on the case of the project "The Wide Green Dike" at the Dollard. For different storm conditions with a specific return period, the frequency of the storm to occur, the moment of failure was calculated. This resulted in a return period of 90 years for a slope of 1:7, while the WBI, that does not take the slope angle into account, predicts a return period of less than 10 years. The slope angle thus substantially reduces the probability of failure for the grass revetment in case of a gentle slope.

Finally, a sensitivity analysis was conducted. Different grass parameters were changed to determine the effect of the uncertainty of the quality of the grass on the resistance-duration. The resistance-duration was very sensitive for the root tensile strength, which describes the force that breaks the roots. The tensile strength depends on the type of grass and the maintenance of the grass revetment. However, this aspects is only included in the WIPE model and not in the WBI for the safety assessment. It is advised to further study the tensile strength and to implement this parameter in the WBI model.

From this research, the primary recommendation is to implement the found relation between the slope angle and the resistance-duration in the safety assessment, because it does have a large impact on the assessment of the grass revetment. Additionally, this study found that waves below 0.5 meter do not cause damage to the dike and will not result in failure. The WBI suggests a threshold value of 0.25 meter, but the results from this study indicate that an increase of this threshold value to 0.5 meter is reliable.

Contents

Chapter 1

Introduction

Over the past years, nature, biodiversity and climate change have played an increasingly large role in flood protection projects in the Netherlands [Van Loon-Steensma and Vellinga, 2019]. A recent view on the map of the Netherlands in the future shows a large increase in the amount of nature [Baptist et al., 2019]. In a response to this development, wide dikes that consist of only natural materials instead of shallow dikes with a cover of stone or asphalt were proposed. The use of these wide green dikes increases space for nature and agriculture and provide an adjustable flood protection in times of climate change. These values are captured in a project of a green dike in the north of the Netherlands [Stuurgroep E&E, 2016].

1.1 Background

In the north of the Netherlands, a few dikes with only a grass cover already exist. One of these green dikes is part of the coastal flood defense line at the Dollard, but the dike does not meet the safety standards of the future. Therefore, a demonstration project is being set up, which is called the "Wide Green Dike". The project is part of the multi-annual program of the region that combines ecological improvement and reinforcement of the flood defense structures [Stuurgroep E&E, 2016]. Due to the gentle slope of the dike, it can be easily raised when the sea level rises. This adaptive design also results in space for nature and agriculture. The combination of the adaptability of the dike and the contribution to ecological improvement fits well in tackling current views on challenges in flood protection [Baptist et al., 2019].

Figure 1.1: Cross section of a traditional dike and a wide green dike [Van Loon-Steensma and Vellinga, 2019].

Unfortunately, most dikes in the coastal area have a hard revetment in the wave impact zone as is shown in Figure 1.1. Where normal sea dikes have a hard revetment to deal with incoming waves, the green dike has a grass revetment that has to withstand the waves. The incoming waves cause pressure on the slope of the dike, which is referred to as wave impact. The pressure penetrates into the soil which results in an overpressure after the wave attack (Figure 1.2) [Van Hoven, 2015a]. This might cause damage to the revetment and can even torn the top layer apart.

This research focuses on the strength of the grass revetment against the incoming waves. This process is one of the challenges at the demonstration project at the Dollard located close to the German border (Figure 1.3). Waves in the Dollard can reach heights of more than 1.5 meter [Van

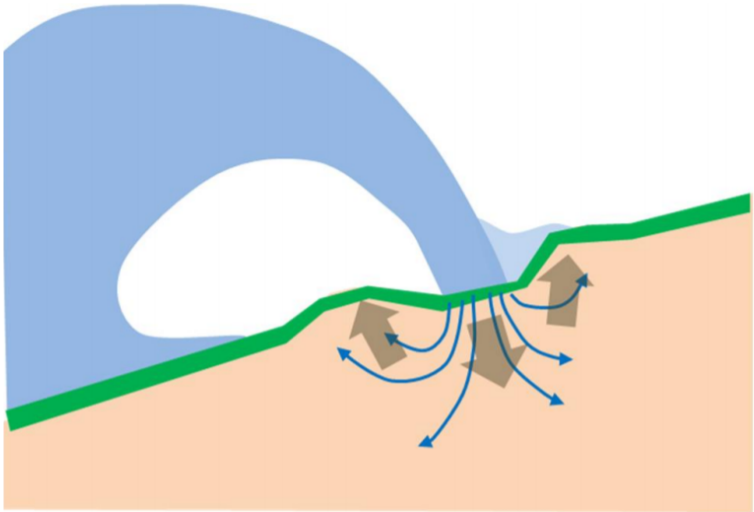

Figure 1.2: Schematisation of wave impact with groundwater flow (blue arrows) and soil movement (brown arrows) [Van Hoven, 2015a].

Loon-Steensma et al., 2014]. However, grass revetments are often not resistant to waves that exceed heights of 1 meter, according to the Dutch safety standards [Klerk and Jongejan, 2016]. To overcome this, the designed green dike contains a thick clay layer, that offers enough protection against the wave attacks during the storm after failure of the grass revetment.

Failure of the grass revetment does not necessarily lead to failure of the dike. The dike fails only when the clay layer is also eroded. The grass revetment fails when the layer with the majority of the roots is eroded. This is determined to be the top 20 cm [Van Hoven, 2015a]. The strength of the grass, which affects the duration until failure of the grass revetment, is important for the safety assessment of the dike.

Figure 1.3: Location of case "Wide Green Dike" (trajectory of project indicated with dark red line).

The assessment of the resistance of the dike to wave impact is captured in the "Wettelijk Beoordelingsinstrumentarium" (WBI) 2017 [De Waal, 2016]. The WBI contains the methods to determine whether a flood defense system meets the Dutch safety standards. A dike is tested on several failure mechanisms which are present in Figure 1.4.

The failure of the grass revetment on the waterside slope due to erosion (Dutch: Grasbekleding erosie Buitentalud (GEBU)) exists of two sub-mechanisms, namely failure due to wave run-up and failure due to wave impact [Klerk and Jongejan, 2016]. However, only erosion due to wave impact is relevant in the case of a grass revetment, since van Hoven et al. [2015] have shown that this is dominant over erosion due to wave run-up when the slope is completely covered with grass.

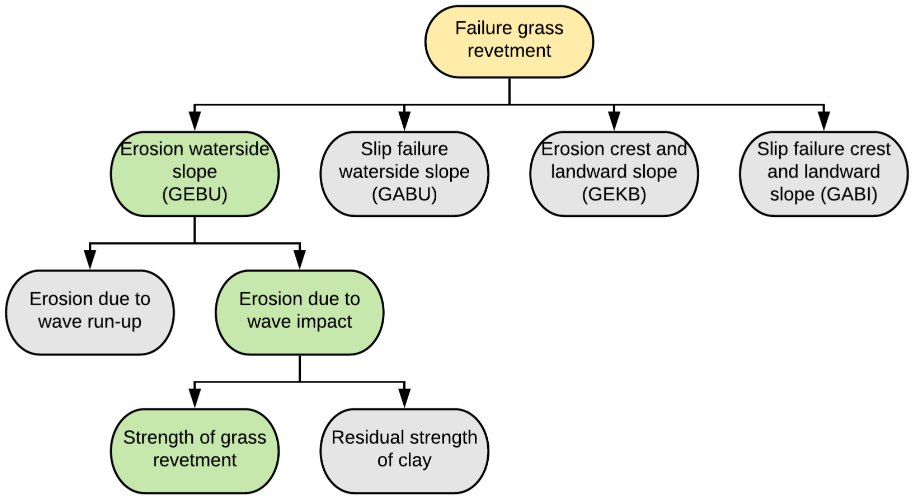

Figure 1.4: Failure tree grass revetment according to WBI 2017 (adapted from [Van Hoven, 2015b]). The green part indicates the focus of this study.

The assessment of erosion due to wave impact exists of two parts. First, the resistance of the top layer, which is the grass revetment in this study, is assessed. Secondly, the residual strength of the clay beneath the top layer is assessed. The resistance of the grass revetment, is assessed by the resistance-duration. Resistance-duration is the duration that the grass revetment can withstand incoming waves and depends on the height of the waves [Ministerie van Infrastructuur en Milieu, 2016]. When the storm duration is longer than the resistance-duration, the grass revetment fails and the residual strength of the clay has to be calculated.

The grass on top of clay increases the erosion resistance of the clay layer due to the tension strength of the roots of the grass [Muijs, 1999]. The strength of the roots and the root density are important for the erosion process while the erosion-resistance of the soil does not significantly contribute to the erosion resistance of the grass revetment [Wu, 1995, Verheij et al., 1997, Van Loon-Steensma et al., 2014, Van Hoven, 2015a]. In the assessment of the strength of the grass revetment for wave impact (WBI), the density of the grass is included. In the WBI, a distinction between open sods and closed sods is made to assess the resistance-duration [Ministerie van Infrastructuur en Milieu, 2018]. Closed sods, which means high density of roots, is the most common type. In the field, the distinction between closed sods and open sods is made based on visual inspection [Ministerie van Infrastructuur en Milieu, 2018].

Next to the quality of the grass, the slope angle also has an effect on the resistance-duration of the revetment [TAW, 1984]. A gentle slope leads to less wave impact, partly due to the damping effect [Verheij et al., 1997, Führböter and Sparboom, 1988]. The damping effect is the effect that the wave impact is reduced due to a layer of water that is still present on the slope due to the previous wave attack. When the slope of the dike is less steep, it takes more time before all the water from the wave has ran down the slope. Thus, a thicker layer of water is still on the slope when the next wave attacks. Next to the damping effect, a gentle slope, in comparison to a steep slope, has the effect that less soil is flushed away by incoming waves and influences the initial impact of the wave on the slope [Kruse, 2010]. The slope angle also affects the way a wave breaks, which results in a variety of pressures on a slope [Führböter, 1986]. The experiments by Burger [1984], with a gentle slope of 1:8, confirm that a gentle slope increases the resistance-duration of the grass revetment [Verheij and Kruse, 1998].

1.2 Problem definition

The effect of the slope angle is not included in the WBI since this has not been systematically studied [Verheij and Kruse, 1998]. The WBI handles all slopes as a slope of 1:3, because the assessment is based on experiments with a slope of 1:3 and 1:4. As was mentioned before, the slope angle does affect the resistance-duration substantially. Although a wide green dike with a slope of around 1:7 is rejected according to the WBI, it might be safe due to its gentle slope.

In the past decades, limited experiments on the resistance of a grass revetment have been executed. A short overview of the different experiments is shown in Table 1.1. From a selection of these experiments, the resistance-duration curves for the safety assessment (WBI) were generated [Klein Breteler, 2009]. Global observations of the slope angle were made, but this did not lead to a clear relation between slope angle and resistance-duration for the assessment.

In another study, a Wave Impact Pressure Erosion (WIPE) method was established [Mous, 2010]. This method describes the initiation of erosion of grass revetments on the waterside slope by wave impact pressures. The WIPE method was based on several physical principles and was calibrated on the experiments of EroGRASS. This model contains more parameters than the WBI model which only exists of a few empirical parameters. This is described in more detail in Chapter 2.

Table 1.1: Summary of experiments of waves on a grass revetment.

Name	Reference	Slope [-]	Wave height [m]
Burger	[Burger, 1984]	1:8	1.0 - 1.8
EroGRASS	[Piontkowitz and Christensen, 2012]	1:4	0.5 - 0.9
Scheldegoot*	[Kruse, 2010]	1:3	0.3
Smith*	[Smith, 1994]	1:4	0.7 - 1.4
Van Steeg	[Van Steeg, 2014]	1:3	0.5 - 1.1
TUD*	[Wolffenbuttel, 1989]	1:1.5	0.2 - 0.4

*used for development WBI

Next to these experiments, multiple experiments on wave impact without grass were performed. From these experiments, relations between slope angle and wave impact were concluded. However, these relations do not describe the relation between the slope angle and the resistance-duration of grass revetments. Thus, the relation between the slope angle and resistance-duration of grass revetments is not implemented in the WBI, while this probably influences the safety and therefore the assessment of the green dike.

When the strength of the grass revetment is higher, which means that the resistance-duration is longer, it is safe to have less residual strength of the clay layer for the same storm scenario. When it can be proven that the resistance-duration of the grass revetment is higher due to the slope angle, a lot of clay can be saved.

The return period of the storm when the grass revetment is damaged provides information about the maintenance of the revetment. This leads to a better prediction of the maintenance and therefore a more accurate consideration of the design of the dike. Thus, the durability of the grass revetment until failure is important for the residual strength of the clay. The durability of the grass revetment until it is damaged is valuable for maintenance purposes.

1.3 Research objective

The goal of the research is to define the relation between the slope angle and resistance-duration of the grass revetment in the wave impact zone. The following research questions are used to reach the final research goal.

1. How can experiments on grass erosion due to wave impact with different slope angles be compared?

2. Which relation between slope angle and resistance-duration describes the empirical data the most accurately?

3. What is the effect of the slope angle on the failure probability?

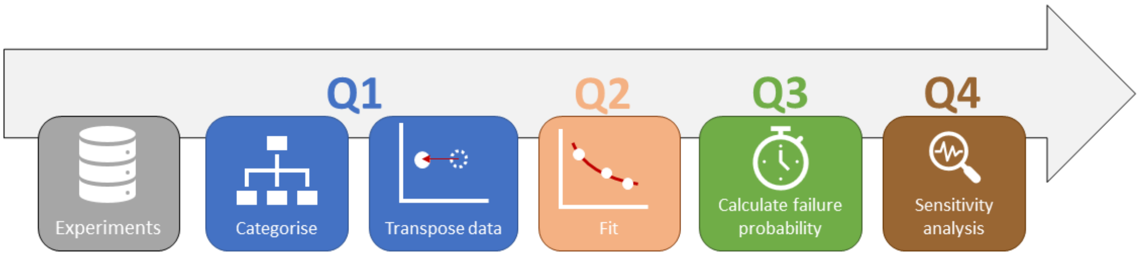

Figure 1.5: The steps of this research linked to the four research questions.

4. How is the resistance-duration affected by grass quality parameters?

The global method to reach the research objective is shown in Figure 1.5. First, the data from different experiments was gathered and categorised based on the quality of the grass. Secondly, the effect of the slope angle was computed from the results of the experiments to compare the different experiments. To answer the second research question, resistance-duration curves were simulated with the WBI and WIPE model and were fitted on the data from the experiments. Question 3 was specifically executed for the "Wide Green Dike" case, because the wave characteristics were needed to calculate the failure probability of the grass revetment. The quality of the grass is hard to determine in the field, thus it is important to know what the effect of the variety on the resistance of the revetment is. To study this, a sensitivity analysis of the grass parameters was executed.

1.4 Case description

For the area Eems-Dollard, a multi-annual program was set up [Stuurgroep E&E, 2016]. The wide green dike is part of this program. In this paragraph, a short technical description of this project is given.

The dike between Kerkhovenpolder and the German border (Figure 1.3) does not meet the safety requirements in the future. Before the complete dike is reinforced, a demonstration project is set up to test the design of the wide green dike. The wide green dike will be constructed for 1 km in Groningen near Germany as a demonstration project. Eventually, the concept of a wide green dike may be applied on the complete dike between Kerkhovenpolder and Germany, since the current dike is not meeting the safety standards of the future. The final design for the complete trajectory depends on the experiences of the demonstration project.

The design of the wide green dike is not yet chosen, thus a temporary design is assumed in this study. The design year of this project is 2073 including climate change scenario W+ [KNMI, 2015]. Climate scenario W+ is the most extreme climate scenario and corresponds to a sea level rise of around 60 cm for the year 2073 relative to 2014 [KNMI, 2015]. The dike has an average foreland of around 300 meter with a height of 2.45 meter + NAP. This means that under normal conditions, the waves do not reach the dike. Figure 1.6 shows the waterside slope of the temporary design of the dike with a slope of 1:7 with a berm at 3.55 m + NAP.

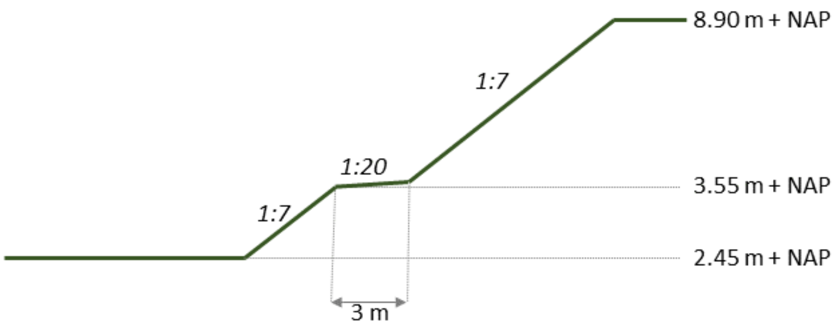

Figure 1.6: Cross-section waterside slope of the dike.

1.5 Report outline

Chapter 2	**Experiments and models**	This chapter contains the background theory of the research. First multiple experiments on wave impact on a grass revetment, that were executed, are discussed. Secondly, the WBI and WIPE model are explained.
Chapter 3	**Method**	The main focus of Chapter 3 is the methodology of the research. The method is generally explained and is followed by a detailed description per research question.
Chapter 4	**Results**	Chapter 4 concerns the presentation of the results. It has a similar structure as the methodology and follows the steps described in the flowchart of Chapter 3
Chapter 5	**Discussion**	In Chapter 5, contains a discussion of the results of the research. Firstly, the discussion elaborates on assumptions made during the study and the effect of this assumptions. Secondly, the two models (WBI and WIPE) will be compared. Finally, a discussion on the limitations of the research is presented.
Chapter 6	**Conclusion**	In the final chapter, the research objective and questions are answered and the major conclusions are given. The conclusion is followed by recommendations for further research and implementation of the results in the safety assessment.

Chapter 2

Experiments and models

2.1 Experiments

Different experiments were executed to gather data and knowledge on the resistance-duration of a grass revetment on wave impact. A literature study of these experiments is executed and a summary of relevant experiments is given in this section. In the end an overview is given of all the data that is used.

Burger

Around 1984, tests with a green dike with a slope of 1:8 were executed in the Delta Flume [Burger, 1984]. The goal of this research was to test the feasibility of a green dike in the northern part of Friesland. On top of the sand core, a clay layer of 0.3 m above the stormwater level and 1 m below the stormwater level was applied. The wave impact occurs just below the stormwater level, which was the reason for the variation in the thickness of the layer. The clay of the top layer of the experiments was characterised as sandy clay (dry density of around 14.8 kN/m^3). The maximum root depth of the grass revetment was 0.4 meter. However, the root intensity decreased over depth, thus the added strength due to the roots at a depth of 0.4 meter was lower than just below the surface as can be seen in Figure 2.1. Three tests with the same dike sample were executed and the important conclusions of the research are presented below.

1. **Tide test:** In this test, a storm of 29 hours with a significant wave height of 1.57 meter including a tide was simulated. Erosion of 0.5 to 1 cm of the top layer was measured already after the first hours. Parts of the roots of the grass revetment were visible and formed a dense layer. This layer prevented the underlying layers from eroding. Except this small damage to the grass revetment, no significant damage was measured during this test.

2. **Damage developing test:** In the second test, a waterside slope with four initiated holes of 7 cm in the top layer was tested. Two of the four holes were located at the location of waves breaking and the most load was expected, thus just below the stormwater level. For 8 hours, waves were simulated with a significant wave height of 1.57 meter and a wave period of 5.26 seconds. After 6, 7 and 8 hours the developing of the damage of the layers was determined. The first signs of damage development were observed after 5.5 hours. After 8 hours, the depth had increased from 7 cm to around 40 cm and the width of the holes had also significantly increased. The depth of the holes was similar as the thickness of the grass sod and therefore no significant damage of the underlying clay layer was observed.

3. **Long-term test:** The last test was a long-term test of 18 hours in total with a lower significant wave height of 1.03 meter and a wave period of 5.2 seconds. After 18 hours, the dense layer of clay and roots that was formed during the tide test, was torn apart. However, this effect did not lead to erosion of the clay layers.

The two major reasons for the low erosion rate were the gentle slope of 1:8 and the deep roots of the grass. Additionally, is has to be stated that the influence of wave direction was excluded in this experiment. All wave attacks were perpendicular situated from the revetment, which resulted in the highest impact.

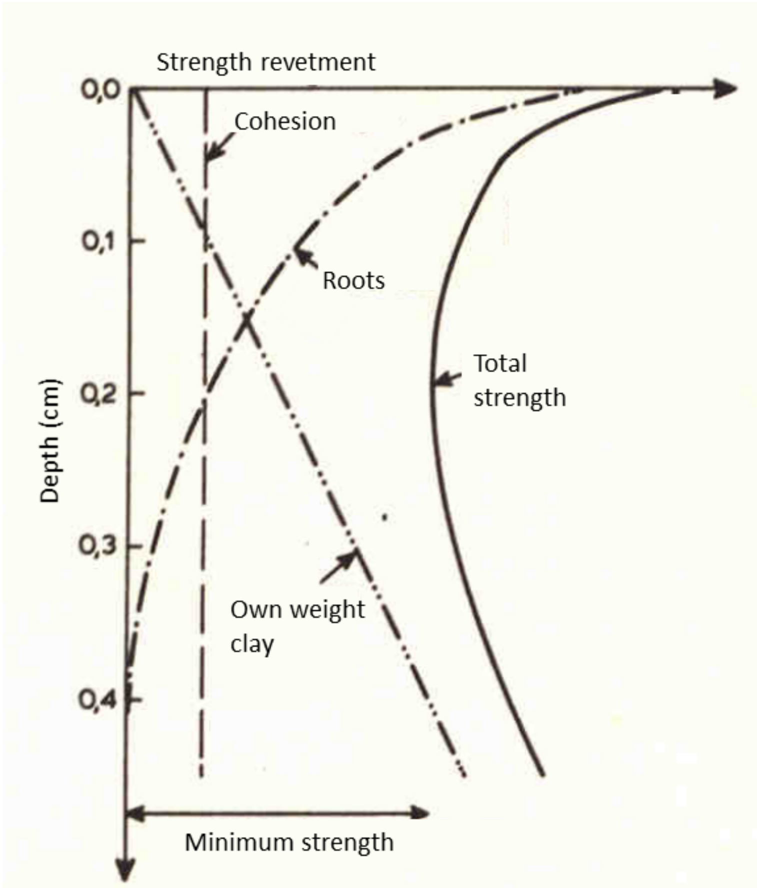

Figure 2.1: The strength of the grass revetment due to cohesion, roots and own weight over the depth (adapted from [Burger, 1984]).

Germany and Emmapolder

Next to the experiments, dikes around the Wadden Sea were damaged in the storm of 1962 [Kruse, 2010]. With a significant wave height of around 1.5 meter, the grass revetments of multiple dikes were torn apart. The grass revetment of the Emmapolderdike, with a slope of 1:4, failed in 3 hours. The grass revetment of the dike in Germany, with a slope of around 1:3, failed in around 2 hours. The information about the failure is very limited and the erosion depth is therefore not known. Also the exact damage after the storm and the quality of the grass revetment before the storm is not exactly known. However, there are indications that the grass quality was poor and there were multiple open spots before the storm occured [Kruse, 2010]. The revetment was probably damaged by driftwood which had an effect on the overall resistance-duration of the revetment.

TUD

Soil with vegetation from five river basins was used in a Delta Flume at the Technical University of Delft test to gain knowledge on the erosion sensitivity of river dikes [Wolffenbuttel, 1989]. In this experiment, steep slopes (slope angle between 1:1.5 and 1:3) and low wave heights (around 0.25 meter) were used. The results from the test was with a high root density (closed sods) and soil was firm, no erosion occurred. While poor grass on sandy and loose soil resulted in an eroded grass revetment in a few hours [Kruse, 2010]. The two major conclusions were that the grass quality is very important when the sand fraction is high and the shape of the erosion over time is linear.

Smith

Around 1994, tests with a clay layer with grass revetment were executed in the Delta Flume [Smith, 1994]. One of the goals of this experiment was to measure the erosion rate of a grass revetment and analyse the processes to increase the fundamental knowledge. Similar to the experiments by

Burger, the used grass revetment was existing grass of a sea dike in the northern part of Friesland. This time, the slope was 1:4. The quality of the grass was recorded by Sprangers [1992] and was qualified as good.

Two tests were executed to measure erosion of the grass revetment with multiple wave characteristics. The first test (Wave height (H_s) of 1.35 m and the wave period (T) of 4.7 s) took 17 hours in total and erosion was detected after 9 hours. Two holes were formed 1 m and 0.5 m below mean water level with a depth of respectively 15 cm and 11 cm during the test. The duration of the second test ($H_s = 0.76$ m and $T = 3.4$ s) was longer, because no damage was observed. Only bare spots were originated, but the roots were still present and the strength of the clay with the roots was remained.

EroGRASS

In the Large Wave Flume of the Coastal Research Center in Hannover, Germany, experiments on wave impact on grass revetments on a slope of 1:4 were executed [Piontkowitz and Christensen, 2012]. The reason for a 1:4 slope was research on wave impact without the damping effect. The Root Area Ratio that was used was $8*10^{-4}$ which is similar to good grass quality. Significant wave heights between 0.5 and 0.9 m were used to determine whether erosion occurred or not. Instead of starting with initial damage in the grass revetment, this experiment started with no cracks. From the results, it can be concluded that the significant wave height of 0.5 meter will probably not result in erosion. This was also concluded based on the results of Van Steeg [2014]. When erosion occurred, it mostly happened just above the Mean Water Level (MWL). In most of the cases the erosion was located at the side of the flume close to the wall and is therefore not representative for an actual sea dike, since the grass revetment was not completely connected to the wall. The observed depth was between 7 cm and 10 cm. This was the total depth and is therefore not the erosion depth rate. However, the order of magnitude is in line with other experiments. With the knowledge from this experiment the Wave Impact Pressure Erosion (WIPE) method was established and calibrated [Mous, 2010]. The WIPE model is described in Chapter 2.3.

Scheldegoot

Soil with different vegetation was tested in the Scheldegoot with a slope of 1:3 [Kruse, 2010]. In the Scheldegoot, the revetment was tested with a wave height of 0.31 meter. Fragmented vegetation, which means that there were only a few spots with vegetation, on loose soil was eroded in 1 hour. Soil with very poor quality of the sods, was slightly damaged after 10 hours. Only the top 10 mm was damaged and no further erosion was observed for the following 50 hours. Soil with good quality of the sods did not erode at all in the test of 60 hours.

Van Steeg

Multiple experiments were performed to determine the wave impact on a grass revetment with different grass qualities and significant wave heights on a slope of 1:3 [Klein Breteler, 2015]. Besides the Delta Flume, a wave impact generator was used in this research. The wave impact generator is a tank that can be situated on a slope of a dike and releases a certain amount of water on the slope. The wave impact generator represents a load that corresponds to a significant wave height of 0.6 to 0.7 m [Van Steeg et al., 2014].

The grass used for the test in the Delta Flume, was abstracted from real existing dikes at Oostbierum and Harculo (the Netherlands) where the wave impact generator tests were performed either. In this experiment an initial damage of 20 cm deep was created. The depth of erosion over time is presented in Figure 2.2. An important side note of this experiment is that the grass quality was not equal for every test due to the maintenance of the grass after removing it from the existing dikes. This resulted in a higher erosion rate during an experiment with a significant wave height of 0.7 m than during the experiment with a higher wave height. This can be seen in the results of the experiments in Figure 2.2A. With a significant wave height of 0.5 meter, the erosion is barely visible. The erosion rate in the cases with a higher significant wave height is hard to determine, since there is no clear trend line. It has to be noted that the experiment in the Delta Flume was executed with multiple blocks of grass, which resulted in weak spots between the blocks which was also observed in the experiments of EroGRASS [Van Steeg, 2014].

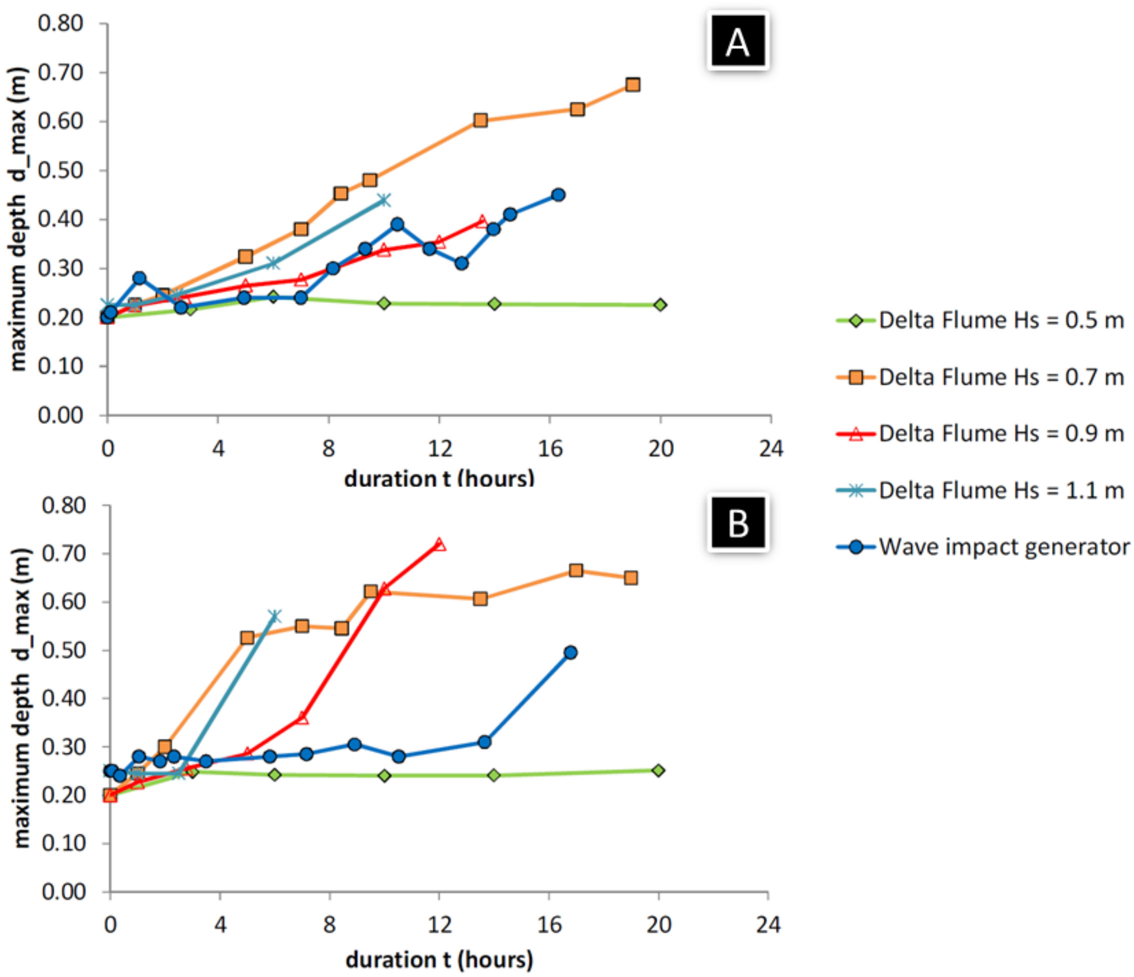

Figure 2.2: Maximum erosion depth (d_{max}) as function of time (t) for different significant wave heights (H_s) with grass from Oosterbierum (A) and Harculo (B) [Klein Breteler, 2015].

Overview

From the mentioned experiments and observations, resistance-duration values were extracted. Both duration before failure, or the maximum time of the experiment when there is no failure, and duration until observed failure of the grass revetment are bundled in Table 2.1. To refer to a specific observation point, all the data points are named with a code. The colouring of the table indicates for every data point whether the revetment failed (red) or not (green) which is also presented in the final column.

Additionally, the type of wave breaking is calculated for all experiments. As was mentioned before, the wave impact depends on the breaking of the waves [Mous, 2010]. Plunging waves is the breaker type that results in the highest wave impact due to its short release of energy [Führböter and Sparboom, 1988]. In all cases the breaking of the wave was calculated and had a breaking parameter close to 1, which means that the waves were plunging waves [Heineke and Verhagen, 2007]. The breaking parameter is calculated by the slope angle and the wave steepness. Only for the Scheldegoot and the experiences at Germany and Emmapolder, the type of wave is unknown. Since the rest of the experiments all had plunging breakers and it results in the highest wave impact, this type of breaking is assumed for the rest of this study.

Table 2.1: Summary of points where the grass revetment failed (red) or did not fail (green) during an experiment.

Name	Code	Slope	Significant wave height	Resistance-duration	Fail
Burger	Bu1	1:8	1.57 m	9.5 h	Yes
	Bu2	1:8	1.57 m	8.0 h	No
	Bu3	1:8	1.03 m	18.0 h	No
	Bu4	1:8	1.75 m	5.0 h	No
Germany	Du	1:3	1.50 m	2.0 h	Yes
Emmapolder	Em	1:4	1.50 m	3.0 h	Yes
EroGRASS	Er1	1:4	0.50 m	11.0 h	No
	Er2	1:4	0.80 m	1.5 h	No
	Er3	1:4	0.90 m	11.5 h	Yes
Scheldegoot	Sch1	1:3	0.31 m	60.0 h	No
	Sch2	1:3	0.31 m	60.0 h	No
Smith	Sm1	1:4	1.35 m	9.0 h	Yes
	Sm2	1:4	1.35 m	6.0 h	No
	Sm3	1:4	0.76 m	20.0 h	No
Van Steeg	St1	1:3	0.50 m	20.0 h	No
	St2	1:3	0.65 m	15.0 h	Yes
	St3	1:3	0.65 m	14.0 h	No
	St4	1:3	0.90 m	13.0 h	Yes
	St5	1:3	0.90 m	12.0 h	No
	St6	1:3	1.10 m	10.0 h	Yes
	St7	1:3	1.10 m	6.0 h	No
	St8	1:3	0.50 m	20.0 h	No
	St9	1:3	0.65 m	17.0 h	Yes
	St10	1:3	0.65 m	14.0 h	No
	St11	1:3	0.90 m	10.0 h	Yes
	St12	1:3	0.90 m	7.0 h	No
	St13	1:3	1.10 m	6.0 h	Yes
	St14	1:3	1.10 m	3.0 h	No
TUD	TU1	1:1.5	0.29 m	264.0 h	No
	TU2	1:1.5	0.25 m	264.0 h	No
	TU3	1:1.5	0.25 m	168.0 h	No
	TU4	1:1.5	0.35 m	7.0 h	Yes
	TU5	1:1.5	0.22 m	168.0 h	No

2.2 WBI model

The used Dutch safety assessment for different failure mechanisms is described in the WBI. The assessment exists of three different levels: elementary assessment, detailed assessment and the customised assessment [Ministerie van Infrastructuur en Milieu, 2016]. The elementary assessment is a simple assessment based on three characteristics; wave height, whether the sod is open or closed and whether the core of the dike exists of clay [Ministerie van Infrastructuur en Milieu, 2016]. The detailed assessment is an assessment where based on the resistance-duration that is described below. The customised assessment can be executed when the revetment is rejected by the detailed assessment, but the revetment can meet the requirements with additional calculations customised to the case.

The detailed assessment is based on the resistance-duration curve [Ministerie van Infrastructuur en Milieu, 2016]. The resistance-duration curve describes the relation between the wave height and the maximum duration the grass revetment can resist. This curve is shown in Figure 2.3. While the load duration is shorter than the resistance-duration, the grass revetment will withstand the wave attacks.

The resistance-duration curve was generated based on experiments and therefore mostly consists of empirical parameters [Van Hoven and De Waal, 2015]. In the model, there is no clear distinction between load and strength, but the failure criterion is defined as load duration to failure. The

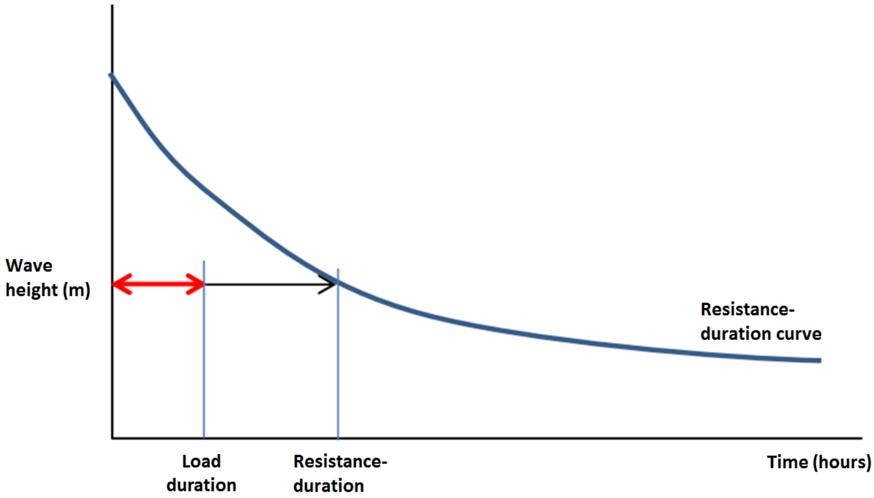

Figure 2.3: Resistance-duration curve that shows the failure criterion for a grass revetment against incoming waves (adopted from [Ministerie van Infrastructuur en Milieu, 2016]).

relation between the strength duration of the top layer (grass revetment) and the wave height is presented in equation 2.2.1 [Van Meurs and Kruse, 2017].

$$H_s = ae^{b*t_{s,top}} + c \tag{2.2.1}$$

Where:

H_s : Significant wave height [m]

$t_{s,top}$: Time to failure of grass revetment [h]

a : Empirical parameter [m]

b : Empirical parameter [h^{-1}]

c : Threshold wave height [m]

The upper limit of the significant wave height ($H_{s,max}$) is found at $t_{s,top} = 0$ and the lower limit ($H_{s,min}$) is found at $t_{s,top} \to \infty$. Equation 2.2.1 can be rewritten to the time to failure of the grass revetment. The rewritten equation with the limits is presented in equation 2.2.2. The values of the empirical parameters are presented in Table 2.2. Next to the distinction between open and closed sods, there is also a value for different failure probabilities.

$$\begin{aligned} &\text{if } H_s \geq H_{s,max} \text{ or } a = 0 && \text{then } t_{s,top} = t_{s,top,min} \\ &\text{elseif } H_s \leq H_{s,min} && \text{then } t_{s,top} = t_{s,top,max} \\ &\text{else } t_{s,top} = \frac{1}{b}\ln(\frac{H_s - c}{a}) \end{aligned} \tag{2.2.2}$$

Where:

$H_{s,max} = a + c$

$H_{s,min} = c$

$t_{s,top,min}$: Minimum value for the strength duration of the top layer [h]

$t_{s,top,max}$: Maximum value for the strength duration of the top layer [h]

Equation 2.2.2 shows the time until failure. Failure is defined as when the top layer of 20 cm is eroded [Van Hoven, 2015a]. When this part is eroded, the grass and the majority of the roots are eroded. This part of the revetment is the part which gives the additional strength to a clay dike. Therefore, this failure definition is used in this entire research.

During a storm, the wave heights vary. To assess the grass revetment for wave impact, the failure fraction is calculated for the different wave heights. The failure fraction is calculated with

Table 2.2: Values of parameters of WBI model for different failure probabilities [Klerk and Jongejan, 2016]

	closed			open		
	50%	5%	+/- 0%	50%	5%	+/- 0%
a	1,82	1	0,5	1,4	0,8	0,4
b	-0,035	-0,035	-0,035	-0,07	-0,07	-0,07
c	0,25	0,25	0,25	0,25	0,25	0,25

equation 2.2.3 [Ministerie van Infrastructuur en Milieu, 2016]. The failure fraction is calculated for all the different time steps with the wave height. When the sum of all calculated failure fractions per time step is more than 1, it means that the revetment failed.

$$F_{frac} = \frac{\Delta t}{t_{s,top}} \tag{2.2.3}$$

Where:

F_{frac} : Failure fraction [-]

Δt : Time step [h]

2.3 WIPE model

In contrast to the WBI model, the WIPE model by Mous [2010] is a combination of multiple physical models and was calibrated on the experiments of Erograss. For every wave, the uplift pressure (p_{up}) caused by wave impact is compared to the strength of the grass revetment. There are two types of strength defined for the calculation of the erosion of the grass revetment. The fracture resistance (σ_f), which indicates when the cracks grow, and the critical uplift strength (p_c), which indicates the maximum allowed uplift pressure before the block is torn apart. Figure 2.4 shows the failure criteria of the WIPE model. When the uplift pressure is higher than the total strength of the revetment, defined as the critical uplift pressure, block erosion occurs. Block erosion is the type of erosion where a block of the grass revetment is torn apart from the slope. In this section the details of the strength are discussed after the explanation of determining the load.

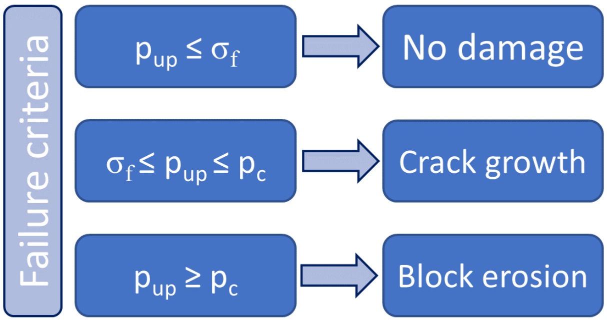

Figure 2.4: Failure criteria of the WIPE model with the uplift pressure (p_{up}) compared to the fracture resistance (σ_f) and the critical uplift strength (p_c) (adapted from [Mous, 2010]).

2.3.1 Load

The WIPE model calculates the effect of every wave impact on the revetment. The storm is simulated as a series of waves. The first step is to calculate the impact pressure of every wave and the second step is to translate the impact pressure to uplift pressure.

The maximum impact pressure can be calculated with equation 2.3.1 [De Looff et al., 2006] based on Führböter and Sparboom [1988]. The maximum impact pressure depends on the impact factor that is empirical determined. The impact factor is ranomly sampled from the probability distribution as is shown in Figure 2.5 [TAW, 2002].

$$
\begin{aligned}
&p_{max} = \rho_w * g * q * H_s \\
&\text{Where:} \\
&p_{max} : \text{Maximum wave impact } [\text{kN/m}^2] \\
&\rho_w : \text{Density of water } [\text{g/cm}^3] \\
&g : \text{Gravitational acceleration } [\text{m/s}^2] \\
&q : \text{Impact factor, dimensionless stochastic parameter } [\text{-}] \\
&H_s : \text{Significant wave height } [\text{m}]
\end{aligned} \tag{2.3.1}
$$

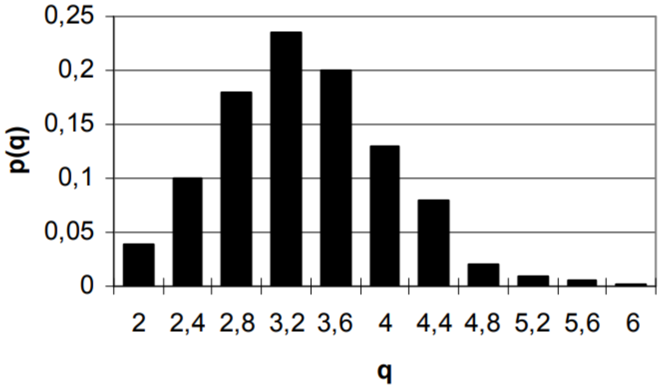

Figure 2.5: Probability density (p) of the factor of impact (q) for a dike with a slope angle of 1:4 [TAW, 2002].

The maximum impact pressure deviates most from the actual measured pressure due to the location of its impact. Figure 2.6 shows the spatial distribution of the wave impact. Equation 2.3.1 is extended with the spatial distribution and is shown as equation 2.3.2 [TAW, 2002]. The probability distribution follows, similar as the wave heights distribution, the Rayleigh distribution. Equation 2.3.2 is only suitable for smooth slopes and is, according to Führböter [1988], reliable for slopes between 1:3 and 1:8.

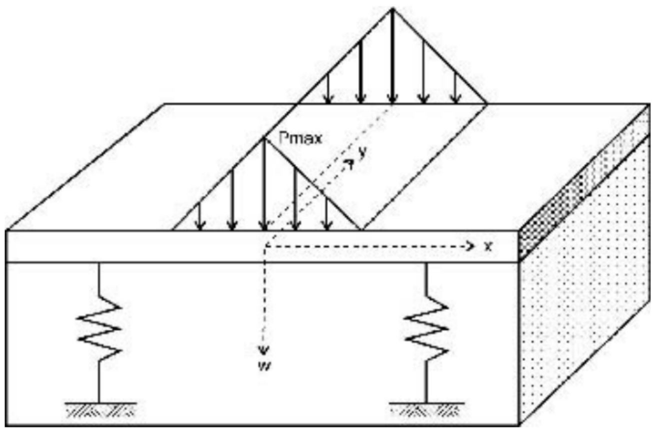

Figure 2.6: Spatial distribution of wave impact on a slope with the pressure indicated by the length of the arrows with the highest pressure indicated by P_{max} [TAW, 2002]

$$p(q) = \frac{1}{\sigma_q \sqrt{2\pi}} e^{-[\frac{(q-q_{avg})^2}{2\sigma_q^2}]}$$

Where:

$p(q)$: Chance of occurrence of impact factor q [-]

σ_q : Parameter probability density function [-]

q_{avg} : Average impact factor [-]

(2.3.2)

The impact pressure can now be calculated with equation 2.3.2 and equation 2.3.1. The uplift pressure, which causes the final block erosion, decreases over depth in the cracks [Müller et al., 2003]. Mous [2010] determined the relation between impact and uplift pressure based on the laboratory experiments by Müller [2003] which is shown in equation 2.3.3. The width of the crack does also have an effect on the pressure reduction, but was not included since there was no model known to predict the width of the crack [Mous, 2010]. Therefore an average pressure reduction coefficient of 5 was chosen.

$$p_{up} = \frac{p_{max}}{1 + \mu d_c}$$

Where:

p_{up} : Uplift pressure [kN/m^2]

μ : Pressure reduction coefficient [m^{-1}]

d_c : Distance in crack [m]

(2.3.3)

2.3.2 Strength

In the WIPE model, the strength of the revetment is calculated with a combination of the root model and turf-element model [Mous, 2010]. The basis is the Mohr-Coulomb equation as is shown in equation 2.3.4. The total soil shear stress is basically calculated by the sum of the cohesion and the normal stress times the resistance of the soil against shear stress (angel of internal friction) [Labuz and Zang, 2012].

$$\tau = c_{soil} + \sigma' tan\phi'$$

Where:

τ : Soil shear stress [N/m^2]

c_{soil} : Cohesion [N/m^2]

σ' : Effective normal stress [N/m^2]

ϕ' : Effective angle of internal friction [°]

(2.3.4)

To apply the Mohr-Coulomb equation to a grass revetment, the root model of Wu [1979] is used. The roots contribution to the shear strength is called the artificial grass cohesion and can be calculated according to equation 2.3.5 [Wu et al., 1979]. The resistance due to the vertical roots is called the normal grass strength and is presented in equation 2.3.6. The root tensile strength depends on the type of grass and the root diameter, but the mean value in case of grass is around 20 MPa [Young, 2005, De Baets et al., 2008].

$$c_{grass} = t_r \frac{A_r}{A}(cos\theta tan\phi + sin\theta)$$

Where:

c_{grass} : Artificial grass cohesion [N/m^2]

t_r : Root tensile strength [N/m^2] (2.3.5)

$\frac{A_r}{A}$: Root Area Ratio (RAR) [-]

θ : Root angle of rotation [°]

$$\sigma_{grass} = t_r \frac{A_r}{A} cos\theta$$

Where: (2.3.6)

σ_{grass} : Normal grass strength [N/m^2]

The term $(\cos\theta \tan\phi + \sin\theta)$ is insensitive to changes of the root angle of rotation and the angle of internal friction and is close to 1.2 for a large range of both parameters [Wu et al., 1979]. Including the contribution of the roots to the shear strength in the Mohr-Coulomb equation, thus combining equation 2.3.4 and 2.3.5, results in equation 2.3.7. This equation is used to calculate the soil shear stress for grass revetments. The effective normal stress can be calculated by the normal stress minus the pore water pressure which is already included in equation 2.3.7.

$$\tau = c_{clay} + c_{grass} + (\sigma - p_w)tan\phi'$$

Where:

c_{clay} : Cohesion of clay [N/m^2] (2.3.7)

σ : Normal stress [N/m^2]

p_w : Pore water pressure [N/m^2]

The turf element method is a balanced force method that combines all forces on a cube with the dimensions $l_x l_y l_x$ [Hoffmans et al., 2010]. Five forces are formulated as can be seen in Figure 2.7. The uplift force is the active force that is caused by wave impact. The forces due to own weight, shear and cohesion are a reaction on this force. The fifth force is the total force at the bottom element. This means that, partially due to roots of the grass revetment, the soil has extra strength from the roots that are connected the underlying soil. The combination of the turf element method and the root model results in equation 2.3.8. With this equation all forces on a cube, that contains clay with grass roots, can be calculated.

$$
\begin{aligned}
&F_p \leq F_w + F_s + F_c + F_g \\
&F_p = p_{up} * l_x l_y \text{ (Uplift force)} \\
&F_w = (1-n)(\rho_s - \rho_w) g * l_x l_y l_z \text{ (Force due to own weight)} \\
&F_s = tan(\phi)(\rho_s - \rho_w) g * (l_x + l_y)(l_z)^2 \text{ (Shear force)} \\
&F_c = (c_{clay,c} + c_{grass,c}) * 2(l_x l_y) l_z + l_x L_y \text{ (Cohesion force)} \\
&F_g = \sigma_{grass,c} z * l_x l_y \text{ (Grass reinforcement)}
\end{aligned}
$$

Where: (2.3.8)

n : Porosity [-]

ρ_s : Soil density [kg/m^3]

ρ_w : Water density [kg/m^3]

$c_{clay,c}$: Critical clay cohesion [kN/m^2]

$c_{grass,c}$: Critical grass cohesion [kN/m^2]

$\sigma_{grass,c}$: Critical normal grass strength [kN/m^2]

2.3.3 Failure criteria

As is mentioned in figure 2.4, there are two different strength forces that are tested against the uplift force due to wave impact.

The fracture strength is calculated per unit area and therefore the depth has to be included in the calculations. The fracture resistance, equation 2.3.9, is calculated by the sum of the gravitational force (F_w), the shear force (F_s) and the grass reinforcement (F_g). When the uplift force

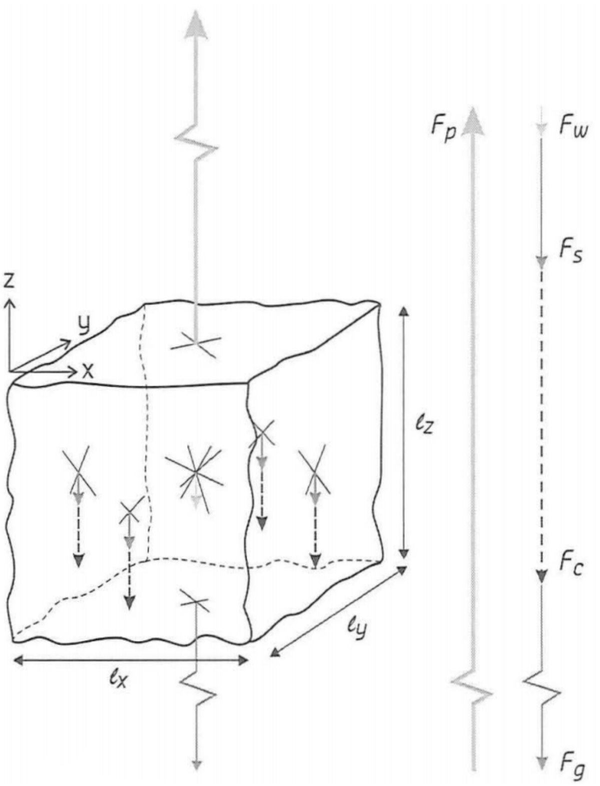

Figure 2.7: The uplift force (F_p) acting on a turf element with the force due to own weight (F_w), the shear force (F_s), the cohesion force (F_c) and the force due to the grass reinforcement (F_g) [Hoffmans et al., 2010].

is higher than the fracture strength, a crack will grow. The block diameter increases due to the growing of the crack which decreases the fracture strength. However, the uplift pressure decreases when the block diameter grows.

$$\sigma_f = (1-n)(\rho_s - \rho_w)gz + \frac{\tan\phi(\rho_s - \rho_w)gz^2}{d_{block}} + \sigma_{grass,c}(z) \tag{2.3.9}$$

Where:

σ_f : Fracture resistance [N/m^2]

z : Depth [m]

d_{block} : Block diameter [m]

When the uplift force is higher than the critical uplift force, block erosion occurs and the revetment fails. The critical uplift force is already given in equation 2.3.8. Similar to the fracture strength, the critical uplift force is calculated per unit area as is shown in equation 2.3.10 [Mous, 2010]. The block erosion occurs at the depth of minimum fracture strength. The fracture strength varies over depth. The force due to own weight and the shear force are positively related with depth, but the density of the grass roots are negatively related with depth. The minimum fracture strength is found at the minimum of the combination of the sum of these three forces. When the crack grows, the critical uplift pressure reduces. Thus, a larger crack will increase the chance on block erosion.

$$p_c = (1-n)(\rho_s - \rho_w)gz_{min} + \frac{tan\phi(\rho_s - \rho_w)gz_{min}^2}{d_{block}} + \frac{2(\int_0^{zmin} c_{grass,c}(z) + c_{clay,c}z_{min})}{d_{block}} + \sigma_{grass,c}(z_{min}) \tag{2.3.10}$$

Where:

p_c : Critical uplift pressure [N/m^2]

z_{min} : Depth of minimum fracture strength [m]

Chapter 3

Methodology

The methodology to answer each research question (of Chapter 1.3) is explained separately. After an outline of the methodology, the methodology of the different research questions are discussed in detail.

Figure 3.1 gives an overview of the methods that were used in this research. First, the data from the experiments, presented in Table 2.1, was categorised. A distinction between open and closed sods was made. The slope angle differed for each experiment and to compare the results of the experiments, the resistance-duration of the results was transposed according to three relations (presented in Table 3.1) to a standard slope of 1:3. After the data was transposed, the experiment could be compared.

The two models, WBI and WIPE model, generate a resistance-duration curve that was fitted on the data by finding the smallest error. From the various fitted resistance-duration curves, the relation that represents the experiments the most accurately was concluded.

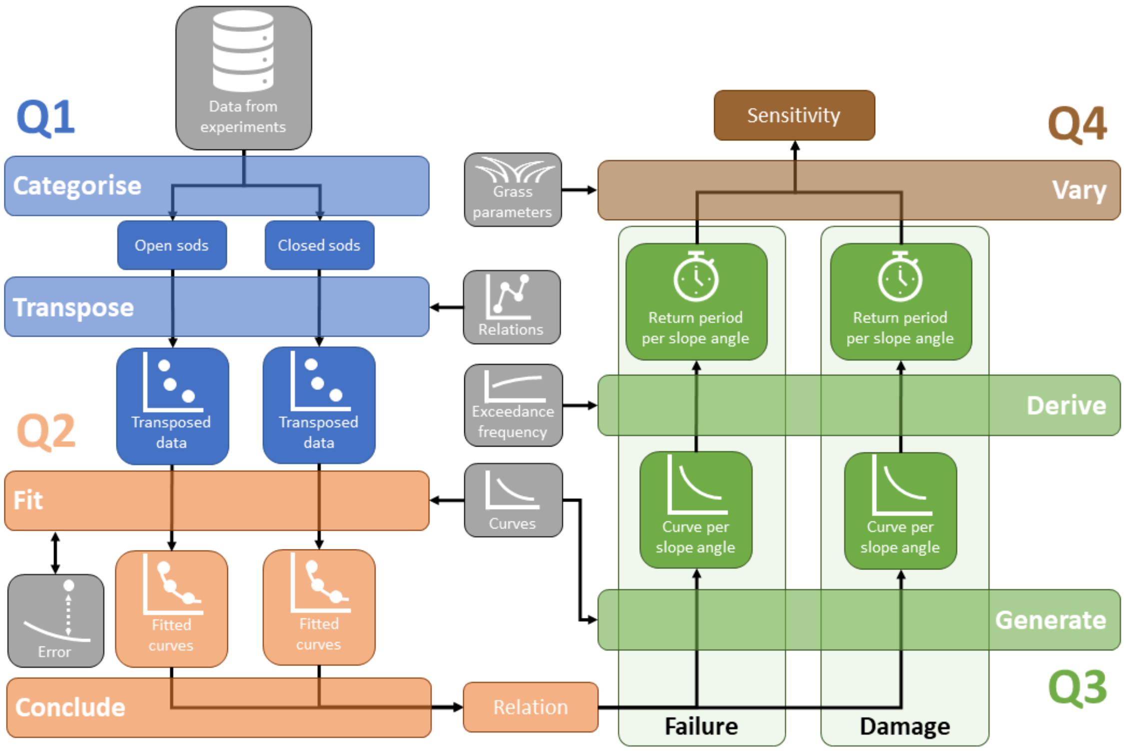

Figure 3.1: Flowchart to answer research question 1 (blue), 2 (orange), 3 (green) and 4 (brown). Relations refer to the relations between slope angle and resistance-duration presented in Table 3.1. The curves are the resistance-duration curves that are generated by the WBI and WIPE model. The exceedance frequency is the frequencies for different wave heights for the Dollard case. The grass parameters are the empirical parameters a and b in the WBI model and the root area ratio and the tensile strength of the roots in the WIPE model.

With the relation, resistance-duration curves for slope angles in the range of 1:3 to 1:8 were generated with the WBI and WIPE model. From the exceedance frequency of the wave heights of the Dollard, the return period for failure of the grass revetment was derived. This was done in a similar way for the return period for damage of the revetment with only the WIPE model.

Since the quality and density of the grass revetment have a large impact on the resistance-duration, the sensitivity of parameter that represents the quality was calculated for both models.

The calculations and models were programmed using Python 3.7 and the code can be found in the appendix. In the following paragraphs, the methodology is described in more detail per research question.

3.1 Data comparison

Experiments on wave attack on a grass revetment were executed. Due to the limited data, all the data had to be transposed before the experiments could be analysed and the relation between the different slope angles could be determined.

From the experiments mentioned in the previous chapter, data was extracted. The data consists of wave height, duration and grass quality and provides information on the resistance-duration of the revetment. For every experiment, one or multiple points were generated that show the measured time during a wave attack with the significant wave height and was labelled with the fact whether the revetment had failed or not. An overview of all the data points is already given in Table 2.1. As in the WBI, a distinction between open and closed sods was made, since this is of importance for the resistance-duration of the grass revetment [Klerk and Jongejan, 2016]. The distinction is made based on literature research of the experiments.

After this categorisation, the data was transposed with the relations. The relations are described below and are found in literature of wave impact and clay erosion. It is plausible that one of these relations is applicable for the effect of the slope angle on the resistance-duration of grass. These three different effects of the slope angle are used in this study to remove the effect of the slope angle. Which means that the three possible relations are used to transpose the data with different slope angles to a slope of 1:3 with equation 3.1.1.

$$t_{new} = \frac{t}{\alpha_{new} * \text{relation}} \tag{3.1.1}$$

Where:

t_{new} : Transposed resistance-duration [h]

α_{new} : Slope angle to transpose to [-]

Relation from linear correction factor

Kruse [2010] generated a relation between the slope and the resistance-duration of clay using computer software packages ComFLOW and PLUTO. ComFLOW is used to simulate the flow of liquids close to constructions. The water pressures on the slope were calculated with ComFLOW and was the input for the software PLUTO. With PLUTO, pressure gradients and the movement of the soil was calculated for different slope angles. The pressure and the movement of the soil was generated for a dike with a slope of 1:3 and 1:6 and the resistance-duration curve was calculated as can be seen in Figure 3.2. From these results the relation between the slope and the resistance-duration was established for a clay layer. This relation is referred to as the linear slope angle correction factor and is presented in equation 3.1.2 [Vuik et al., 2018].

$$f_\alpha = \frac{(r_\alpha - 1)/3}{tan(\alpha)} + 2 - r_\alpha \tag{3.1.2}$$

Where:

f_α : Linear slope angle correction factor [-]

r_α : Factor slope angle effect [-]

α : Dike slope angle [°]

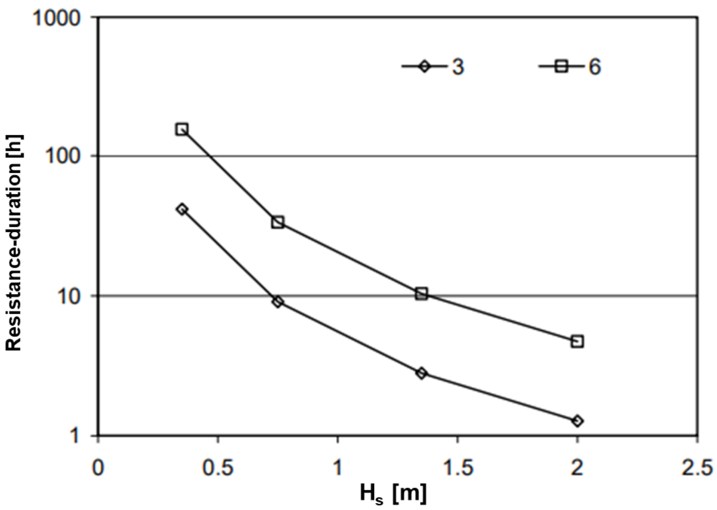

Figure 3.2: Resistance-duration of 1 meter clay layer on a slope with a slope angle of 1:3 and 1:6 (adapted from [Kruse, 2010]).

Relation from maximum wave impact

In the large wave channel in Hannover, a wave impact study with different slopes was executed [Führböter and Sparboom, 1988]. Two prototypes, with an uniform slope of 1:4 and 1:6, were tested in the facility. The dikes were covered with an asphalt layer and the maximum wave impact was measured on the slope surface. Based on the experiment, equation 3.1.3 was established. The relation between the slope angle and the wave impact is the slope.

$$P_{max} = const * \frac{1}{n} * \rho_w * g * H_s \tag{3.1.3}$$

Where:

$const$: Constant based on the probability [-]

n : Slope 1:n [-]

Relation from erosion rate

The effect of the slope angle on the erosion rate was studied by Mourik [2015] . The research was analysing the erosion velocity of clay without grass. With the software called ComFLOW, the pressure on dikes were simulated and compared to the erosion rate of a few experiments. Figure 3.3 shows the relation between the erosion velocity and the slope angle. The plotted trendline is a quadratic function and the function for the erosion velocity is shown in equation 3.1.4.

$$V_e \propto (H_s - 0.5) * tan(\alpha)^2 * t \tag{3.1.4}$$

Where:

$\propto$: in proportion to

V_e : Erosion velocity [m^3/m]

t : Time from the moment that eroding starts [h]

The relation between erosion depth and the erosion velocity was also established by Mourik [2015]. Translating the erosion velocity to erosion depth over time, gave a slightly different relation

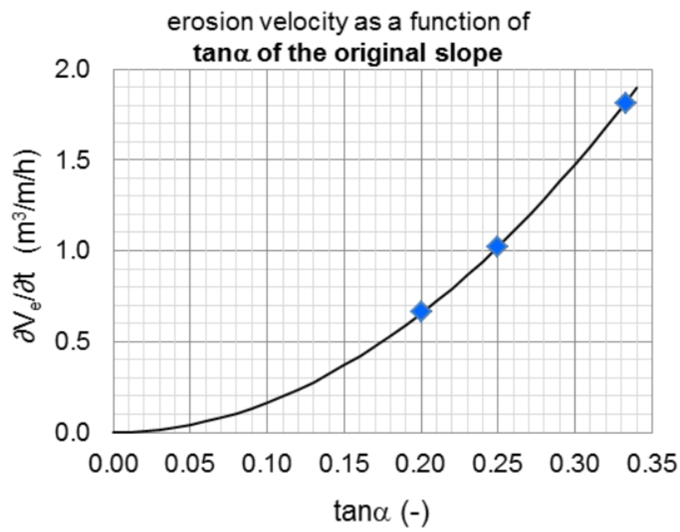

Figure 3.3: Relation erosion velocity over time ($\delta V_e/\delta t$) and slope angle ($\tan\alpha$) [Mourik, 2015].

for the slope angle. The maximum erosion depth can be calculated according to equation 3.1.5.

$$d_e = \sqrt{V_e * tan(\alpha)} - 0.14 \tag{3.1.5}$$

Where:

d_e : Maximum erosion depth [m^3/m]

Combining equation 3.1.4 and 3.1.5 results in the final relation between erosion depth over time and the slope angle. The erosion rate decreases over time due to the development of an erosion terrace [Klein Breteler, 2015]. However, this is not the case for the grass revetment. Equation 3.1.6 was established for grass revetments, which shows how the erosion rate is in proportion to the wave height and slope angle. As can be seen in the equation, the relation between the slope angle and the erosion velocity is to the power of 1.5.

$$R_e \propto (H_s - 0.5) * tan(\alpha)^{1.5} \tag{3.1.6}$$

Where:

R_e : Erosion rate [m/h]

Overview

The three relations are described and are presented in Table 3.1. As was mentioned before, all relations are originally not determined to describe the relation between slope angle and resistance-duration for grass revetment, but it is plausible that one of these relations is applicable for the effect of the slope angle on the resistance-duration of grass. These three relations are used in this study to find the effect of the slope angle on the resistance-duration of the grass revetment.

Table 3.1: Overview of different relations.

	Determined by	Describes	Relation
f_α	Simulations	Slope angle and resistance-duration (clay)	eq. 3.1.2
n	Experiments	Slope angle and wave impact (pressure)	$tan(\alpha)$
R_e	Experiments	Slope angle and erosion rate (clay)	$tan(\alpha)^{1.5}$

3.2 Effect of slope angle

The third step, 'fit', is the step where the resistance-duration curves were generated and fitted on the data. The curves were generated with both the WBI model and the WIPE model. The input values for the WBI model were the values with a probability of 50% and are shown in Table 2.2.

The generation of the resistance-duration curve according to the WIPE model contained more steps. First, the wave impact distribution was determined and all waves were generated according the Rayleigh distribution (equation 2.3.2).

Secondly, the amount of iterations of the model to achieve reliable results was determined. Since the waves were randomly generated according to the distribution, the calculations had to be iterated. The iterations made sure that the randomly simulated peaks did not cause coincidental results. Figure 3.4 shows the results of the WIPE model without iterations and the ideal resistance-duration curve. When more iterations are done and the results are averaged, the results will become closer to the ideal resistance-duration curve. To quantify the number of iterations needed to get close to the ideal resistance-duration curve, the deformation is calculated. The deformation is the absolute difference between the two resistance-duration curves. The absolute difference of the curve between an number of iterations and the number of iterations one step back was calculated. In this way, the effect of more iterations could be determined. Since the input of the experiments was rounded by half an hour, the maximum deformation of the curve was determined to be 0.5 hours. The step size of the amount of iterations was chosen to be 25 (which equals to a run time of 15 minutes) to minimise the probability that the curve deforms significantly after the chosen amount of iterations, but not to overcompensate that results in more iterations. More iterations means that the time to run the model will increase which is not favorable.

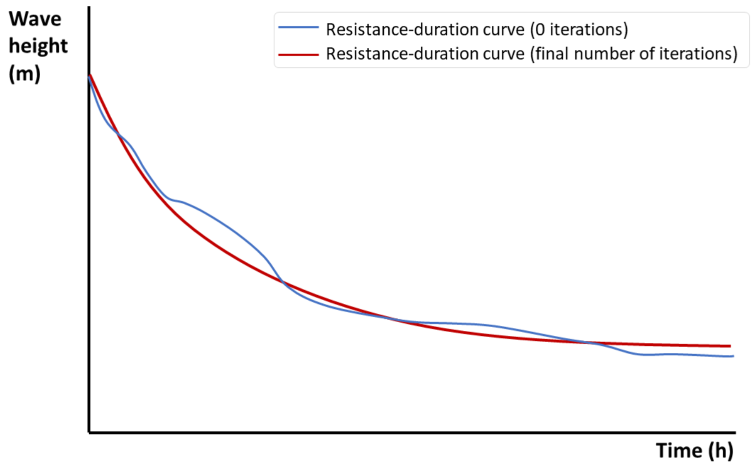

Figure 3.4: Effect of increasing number of iterations of the WIPE model with the red resistance-duration curve as ideal curve.

After these two calculations, the curve was generated by calculating after which number of waves the uplift pressure was higher than the critical uplift pressure (equation 2.3.10) for all wave heights. The complete model is described in Appendix B. The input values for the WIPE model are presented in Table 3.2.

After the generation of the resistance-duration curves, the curves were fitted on data points. The fitting was done by minimising the error between the data and the generated curves using multiple combinations of the calibration parameters in the WBI and WIPE model. For the WBI model, all combinations of the parameter a and b were calculated. The WIPE model needs a significant longer time to run and therefore it was not possible to test all combinations with the small step size as the parameters of the WBI model. The calibration parameter for the soil (α_{soil}) affects the results more than the calibration parameter for the growth of the cracks (α_{crack}) [Mous, 2010]. Therefore, the soil parameter was calibrated first and the parameter for the growth of the crack was calibrated second.

The Mean Absolute Error (MAE) method was chosen to calculate the error as is shown in equation 3.2.1. This method was chosen since it treats all errors equally and does not give more

Table 3.2: Input values of the WIPE model [Mous, 2010].

Parameter	Symbol	Value	Unit
Root area ratio at the surface (closed sods)	RAR_0	0.0008	[-]
Root area ratio at the surface (open sods)	RAR_0	0.0004	[-]
Grass tensile strength	t_r	$20*10^6$	[N/m^2]
Root diameter	d_r	$0.13*10^{-3}$	[m]
Root decay coefficient	β	22.32	[-]
Clay cohesion	c_{clay}	$30*10^3$	[N/m^2]
Critical clay strength [Hoffmans et al., 2010]	$c_{clay,c}$	$3.75*10^3$	[N/m^2]
Aggregate diameter at the surface	d_a	0.004	[m]
Saturated volumetric weight of soil	ρ_s	2000	[kg/m^3]
Volumetric weight of water	ρ_w	1000	[kg/m^3]
Porosity	n	0.4	[-]
Angle of internal friction	ϕ	35	[°]
Pressure reduction factor in cracks	μ	5	[m^{-1}]
Characteristic impact time	t_{imp}	0.350	[s]

Table 3.3: Calibration parameters.

WBI			WIPE		
Parameter	**Interval**	**Step size**	**Parameter**	**Interval**	**Step size**
a	[0, 2.80]	0.01	α_{soil}	[0.5, 4.5]	0.2
b	[-0.1, -0.01]	0.01	α_{crack}	[390, 450]	10

importance to extremely large errors [Chai and Draxler, 2014]. These large errors can originate from inaccuracy of experiments and therefore it is not desirable to give the large errors more weight [Willmott, 2005]. The value of the MAE is the absolute difference between predicted and observed wave height. In this case the difference in wave height with the same resistance-duration value was used to calculate the error as can be seen in Figure 3.5. The error between the resistance-duration values with a same wave height (horizontally) was not effective due to the fact that many points have a low resistance-duration value and therefore do not have a substantial effect on the error. The ideal curve lies between the green points, where the revetment did not fail, and the red points, where the revetment did fail. In order to generate this curve, the error was only calculated when the wave height of the curve was lower than a green point and higher than a red point.

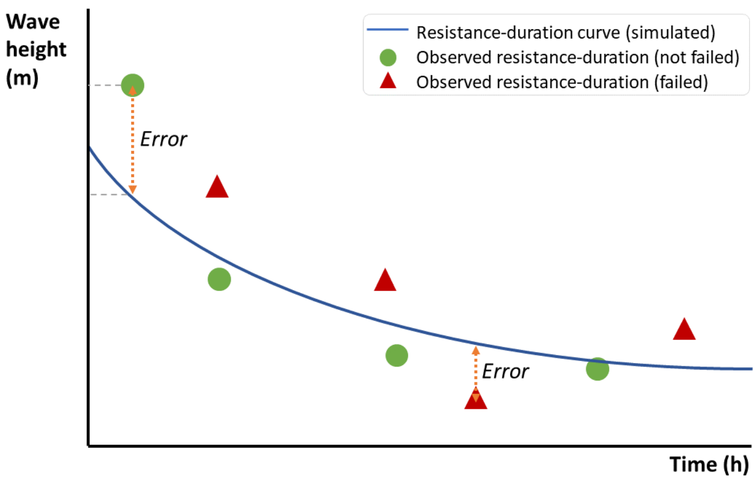

Figure 3.5: Calculation of the error between simulated resistance-duration and resistance-duration points from experiments.

$$MAE = \frac{1}{n_v}\sum_{1}^{n_v}(|Y_t - F_t|)$$

Where:

MAE : Mean Absolute Error [-] (3.2.1)

n_v : Number of values [-]

Y_t : Predicted value [-]

F_t : Measured value [-]

With the calculated error, the resistance-duration curve that reflect the experiments the most accurate was determined.

To conclude which relation leads to the resistance-duration curve that reflects the experiments the most accurate, two reflections were made. First, the smallest error between the resistance-duration curve and the experiments for the different relations was found. Secondly, the experiments with a slope that was not equal to 1:3 were specifically compared to the curve. This was done in a similar way as the calculation of the error as was described before, but the experiments with a slope equals to 1:3 were filtered out. These two reflections were done for both models.

3.3 Durability of grass revetment

For safety and maintenance purposes, the effect of the slope angle on the durability of the grass revetment was made. The durability of the grass revetment is similar as the return period that corresponds to the storm when the revetment fails. The durability of the grass revetment differs per location, because the storm conditions and geometry depend on the location. The case of the wide green dike at the Dollard was used, which was already described in the introduction.

The time until failure, the resistance-duration, was calculated with both the WBI and WIPE model for the previous research question. The resistance-duration curves were generated with the WBI and WIPE model and the translation to the different slopes was done by shifting the curves according to the relation between the slope angle and the resistance-duration. Since the experiments had a slope between 1:3 and 1:8, the resistance-duration curves were generated for this interval. Next to failure of the revetment, the time until the grass revetment is damaged was also studied. With the WIPE model, the time until damage was calculated, which provides information about the frequency of the maintenance of the grass revetment. It was not possible

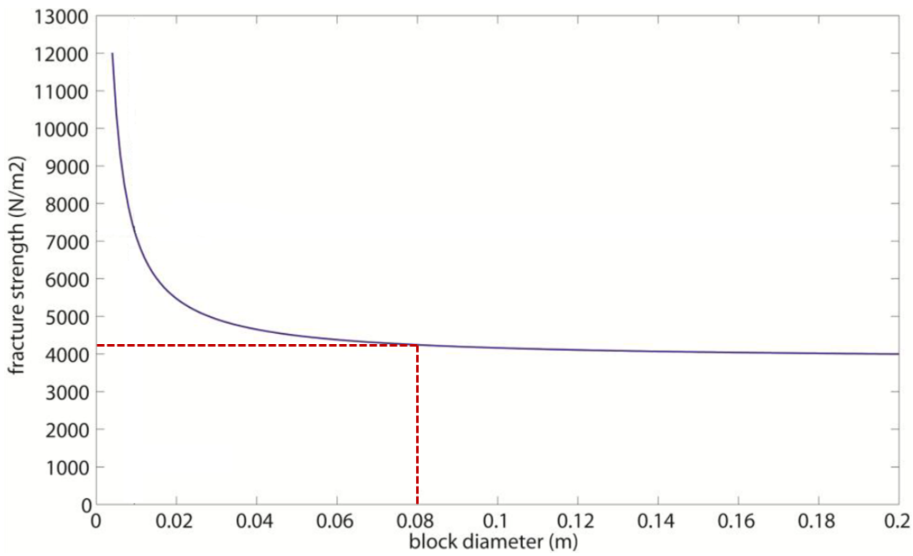

Figure 3.6: The relation between the fracture strength of the grass and the diameter of the block [Mous, 2010]. The red line indicates the diameter of the block from where the fracture strength is almost not decreasing anymore.

to determine precisely when damage of the revetment occurs, thus the damage was defined as the moment that the fracture strength approached the minimum, as can be seen in Figure 3.6. From the relation between the fracture strength and the block diameter, the moment of damage was set to the exceedance of 0.08 meter for the block diameter. Only the damage due to the wave impact was included, thus other factors that might damage the grass revetment were not taken into account. For the time until damage a curve similar to the resistance-duration curve was generated.

The resistance-duration curves were compared to the storm characteristics with a return period for the Dollard case. Figure 3.7 shows how the storms were simulated and compared to the resistance-duration curves. The flowchart was repeated for multiple return periods, with a step size of 10 years, to establish the return period that corresponds to the moment of failure for different slope angles and models. The steps of the flowchart are explained separately below.

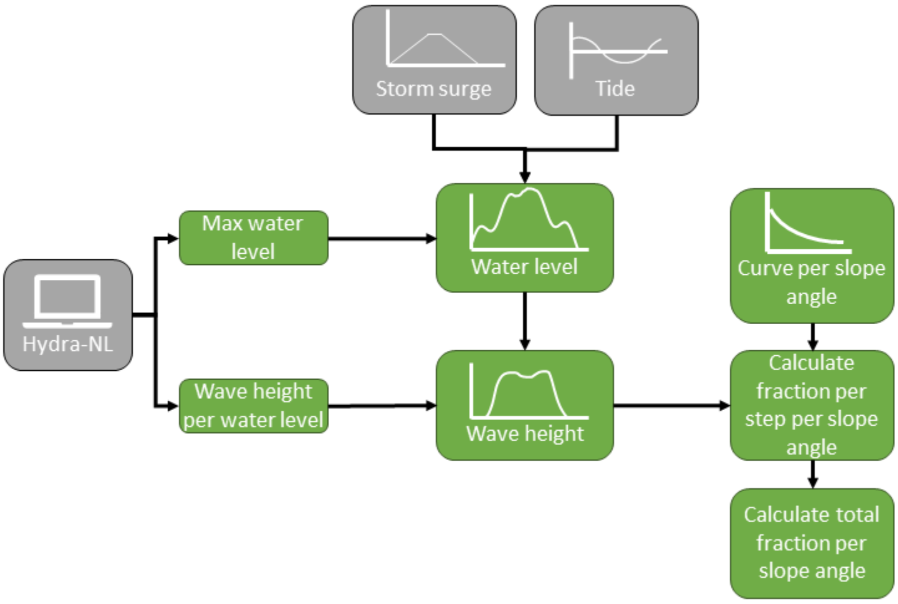

Figure 3.7: Flowchart to answer research question 3, which corresponds to the step 'Derive' in Figure 3.1. The mentioned curves, are the resistance-duration curves generated with the WBI and WIPE model. The fraction is the contribution of the step to failure of the revetment.

First, two scenarios were determined. A scenario without climate change, thus the current situation, and a scenario with climate change. For the scenario with climate change the most extreme scenario (W+ according to the KNMI [Van den Hurk et al., 2006]) for the year 2073 was chosen. This corresponds to a sea level rise of around 60 cm for the year 2073 relative to 2014 [KNMI, 2015]. The year 2073 was chosen for this study, because it is the design year of the green dike at the Dollard, which is 50 years after construction. Secondly, for both scenarios the data of storms with a corresponding return period was abstracted from the software Hydra-NL. Multiple storms with different return period were calculated to find the storm with the shortest return period when the grass revetment fails. Appendix F shows the storms that were used for the calculations.

From the software Hydra-NL, the maximum water level and the corresponding wave height per water level for every return period was abstracted. In the case study a foreland exists at the toe of the dike. This affects the wave heights, thus the geometry of the dike and the foreland was added in Hydra-NL. The details are presented in Appendix E. With information on the maximum water level and the wave heights at the location, a few steps were followed to generate the series of waves of the corresponding storm. To simulate the storm, the water level during the storm was calculated fist. The water level during a storm is the combination of the tide and the storm surge. At the Dollard area, there is a difference of 5.5 hours between the peak of the storm surge and the peak of the tide as is shown in Figure 3.8 for a return period of 100 years. The tide was determined with the data from Rijkswaterstaat [Rijkswaterstaat, 2019]. The tide in the eastern part of the Wadden Sea has an amplitude of 1.35 meter and a period of 12.5 hours. The shape of the storm surge was established according to Klein Breterler et al. [2017] . In the figure, the foreland with a height of 2.45 meter is shown. When the water level is lower than the height of the foreland, no waves will reach the dike. As is visible in the figure, without the storm surge the water will not reach the dike.

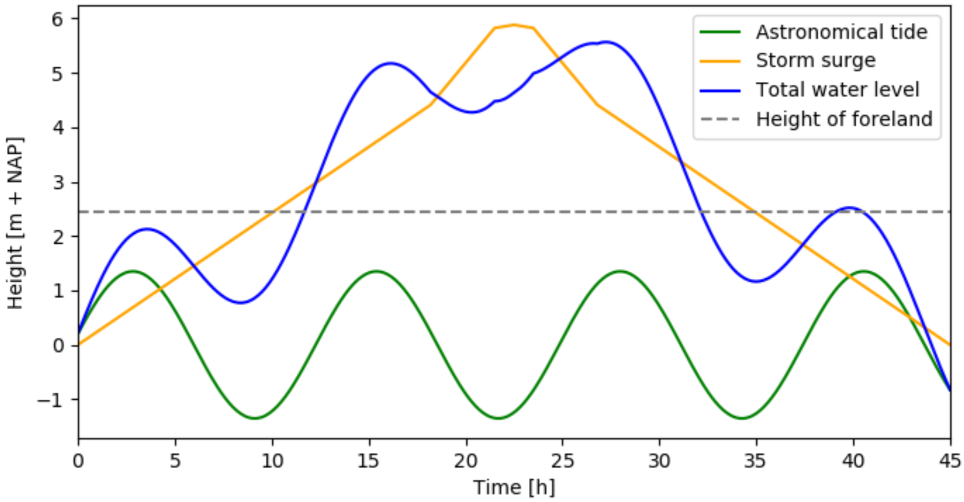

Figure 3.8: Water level during a storm (example of a storm with a return period of 100 years without climate change) which is the result of the tide and storm surge.

The storms for the different return period the maximum water level (shown in Figure 3.8) has to correspond to the maximum water level that was abstracted from Hydra-NL. Thus, for every storm with a return period, the storm surge was adjusted to simulate the water level with the corresponding peak. From the water level during the storm, the wave heights during the storm were simulated as is shown in Figure 3.9. Since the data for 2073 could not be directly computed with the software, the values for the year 2050 and 2100 were calculated and linearly interpolated. For the scenario without climate change, no interpolation was needed

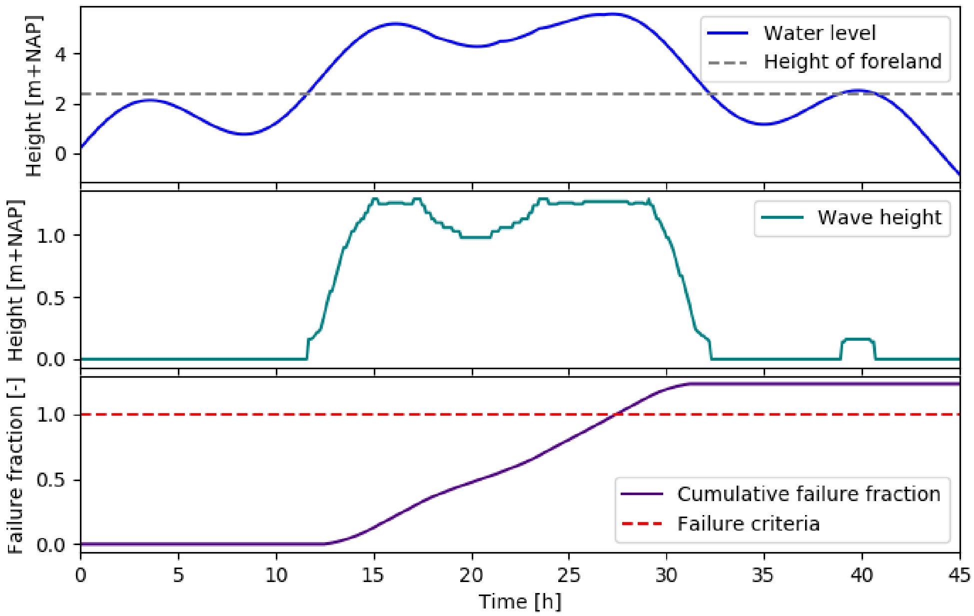

Figure 3.9: Water level during the storm (top figure) with the corresponding wave height at the toe of the dike (middle figure) that results in the failure fraction of the grass revetment with a slope of 1:6 (bottom figure). All figures are from the scenario of 2073 with KNMI climate scenario W+ and a return period of 100 years.

Finally, the wave heights were compared to the resistance-duration curves. Equation 2.2.3 shows the calculation that was done for every time step. Since the simulation of the storms had a time step of 0.1 hours, the failure fraction was calculated with a similar time step. The summation of the failure fractions results in the answer if the grass revetment fails during the storm or not. The bottom figure of Figure 3.9 shows the cumulative failure fraction of that storm for a resistance-duration curve with a slope of 1:6. When the total failure fraction exceeds the value 1, it means that the revetment failed. This was repeated for the different storms until the storm with the shortest return period when the grass revetment failed was found. This was again repeated for the different scenarios (with and without climate change) and the different slope angles.

3.4 Sensitivity of grass parameters

To determine the effect of the grass quality on the resistance-duration, a sensitivity analysis was executed. The grass quality is captured in the parameters a and b in the WBI model. WBI suggests the values for these two parameters in a case of open and closed sods. The grass density varies between these two categories and the tensile strength depends on the type of grass. The sensitivity of the grass parameters gives an indication on the importance of the input. This means that when the parameter is highly sensitive, it is important to determine the value of the parameter precisely.

In the WIPE model, the grass quality is captured in multiple parameters. The two important parameters that are directly affected by the grass quality are the critical tensile strength and the root area ratio. Numerous studies show different values of the critical tensile strength. Hoffmans et al.[2010] suggest a tensile strength of $20*10^6$ N/m^2 while Valk [2009] suggests to use a tensile strength of $45*10^6$ N/m^2. Trükmann et al [2009] advise a mean tensile strength of $38*10^6$ N/m^2 with a standard error of $22*10^6$ N/m^2. Since both values proposed by Valk [2009] and Hoffmans et al. [2010] are included in this range, this range was used. The root area ration interval is established in the Dutch guidelines for assessing primary dikes of 2006. The guidelines suggest a root area ratio of $3*10^{-4}$ for poor grass and $8*10^{-4}$ for good grass [Hoffmans et al., 2010].

Table 3.4 shows the lower and upper boundary values for the parameters to assess the sensitivity. Both models have two parameters that describe the quality of the grass revetment.

Table 3.4: Interval of parameters that describe the quality grass.

	Parameter	Lower boundary	Upper boundary
WBI	a	1.27 m	2.27 m
	b	-0.135 h^{-1}	-0.045 h^{-1}
WIPE	Critical tensile strength	$16*10^6$ N/m^2	$60*10^6$ N/m^2
	Root area ratio	$3*10^{-4}$	$8*10^{-4}$

Table 3.4 shows the parameters with the values that were used in this study to calculate the sensitivity. From these values multiple combinations were determined and presented in Table 3.5. The sensitivity was determined for steep (1:3) and gentle (1:8) slopes for both scenario's: 2023 and 2073.

Table 3.5: Combinations used in the sensitivity analysis with the change with respect to values used in the rest of the study.

		Change	Parameter values
WBI	1	-50% of a	$a = 1.27$ m and $b = -0.09$ h^{-1}
	2	-50% of b	$a = 1.77$ m and $b = -0.045$ h^{-1}
	3	+50% of b	$a = 1.77$ m and $b = -0.135$ h^{-1}
	4	+50% of a	$a = 2.27$ m and $b = -0.09$ h^{-1}
WIPE	1	-20% of tensile strength	$tr = 16*10^6$ N/m^2 and $RAR = 8*10^{-4}$
	2	-62.5% of Root Area Ratio	$tr = 20*10^6$ N/m^2 and $RAR = 3*10^{-4}$
	3	+200% of tensile strength	$tr = 60*10^6$ N/m^2 and $RAR = 8*10^{-4}$

The sensitivity of the grass parameters was determined for two outcomes; the resistance-duration curves and the return period of failure. Firstly, the shift in the resistance-duration curve was computed. Secondly, the difference in the return period when the grass revetment fails was determined. This was done for a slope of 1:3, which is the default output of the WBI model, and for a slope of 1:8. In this way, it becomes clear whether the parameters are more sensitive in cases with a gentle slope compared to a steep slope.

Chapter 4

Results

In this section, the results are shown in the same order as is explained in the previous section in Figure 3.1.

4.1 Data comparison

The first step, categorise, was done based on analysing the reports of the experiments. The quality of the sods is not mentioned directly in literature, but the categorisation was possible based on additional information and pictures made of the grass revetment. Table 4.1 shows the categorised data points.

Table 4.1: Categorisation of observed resistance-duration points that failed (green) and not failed (red).

Closed sods					Open sods				
Code	**Slope**	H_s	$t_{s,top}$	**Fail**	**Code**	**Slope**	H_s	$t_{s,top}$	**Fail**
Er1	1:4	0.50 m	11.0 h	No	Em	1:4	1.50 m	3.0 h	Yes
Er2	1:4	0.80 m	1.5 h	No	Du	1:3	1.50 m	2.0 h	Yes
Er3	1:4	0.90 m	11.5 h	Yes	Sch1	1:3	0.31 m	60.0 h	No
Sch2	1:3	0.31 m	60.0 h	No	TU1	1:1.5	0.29 m	264.0 h	No
TU5	1:1.5	0.22 m	168.0 h	No	TU2	1:1.5	0.25 m	264.0 h	No
St1	1:3	0.50 m	20.0 h	No	TU3	1:1.5	0.25 m	168.0 h	No
St2	1:3	0.65 m	15.0 h	Yes	TU4	1:1.5	0.35 m	7.0 h	Yes
St3	1:3	0.65 m	14.0 h	No	St8	1:3	0.50 m	20.0 h	No
St4	1:3	0.90 m	13.0 h	Yes	St9	1:3	0.65 m	17.0 h	Yes
St5	1:3	0.90 m	12.0 h	No	St10	1:3	0.65 m	14.0 h	No
St6	1:3	1.10 m	10.0 h	Yes	St11	1:3	0.90 m	10.0 h	Yes
St7	1:3	1.10 m	6.0 h	No	St12	1:3	0.90 m	7.0 h	No
Bu1	1:8	1.57 m	9.5 h	Yes	St13	1:3	1.10 m	6.0 h	Yes
Bu2	1:8	1.57 m	8.0 h	No	St14	1:3	1.10 m	3.0 h	No
Bu3	1:8	1.03 m	18.0 h	No					
Bu4	1:8	1.75 m	5.0 h	No					
Sm1	1:4	1.35 m	9.0 h	Yes					
Sm2	1:4	1.35 m	6.0 h	No					
Sm3	1:4	0.76 m	20.0 h	No					

There are two major remarks on the categorised data points. The first remark is that the closed sods data set contains points with different slope angles, while the open sods data set does not contain experiments with a slope more gentle than 1:4. This means that the range of slope angles is smaller for the open sods than for the closed sods. The other remark is that data point TU4 is not in line with all the other data points. While the wave height is low (0.35 meter), the resistance-duration is also really short (7.0 hours). There are three possible explanations for this outlier. The slope is very steep and might have a large effect on the resistance-duration, the grass was very poor or the experiment was not executed properly. Since the other data points with a similar steep slope are in line with the other data points, it is not convincing that the steep slope is the reason for this outlier. To make sure that this data point does not disturb the fitting of the curves in the research, this data point was left out in the rest of this study.

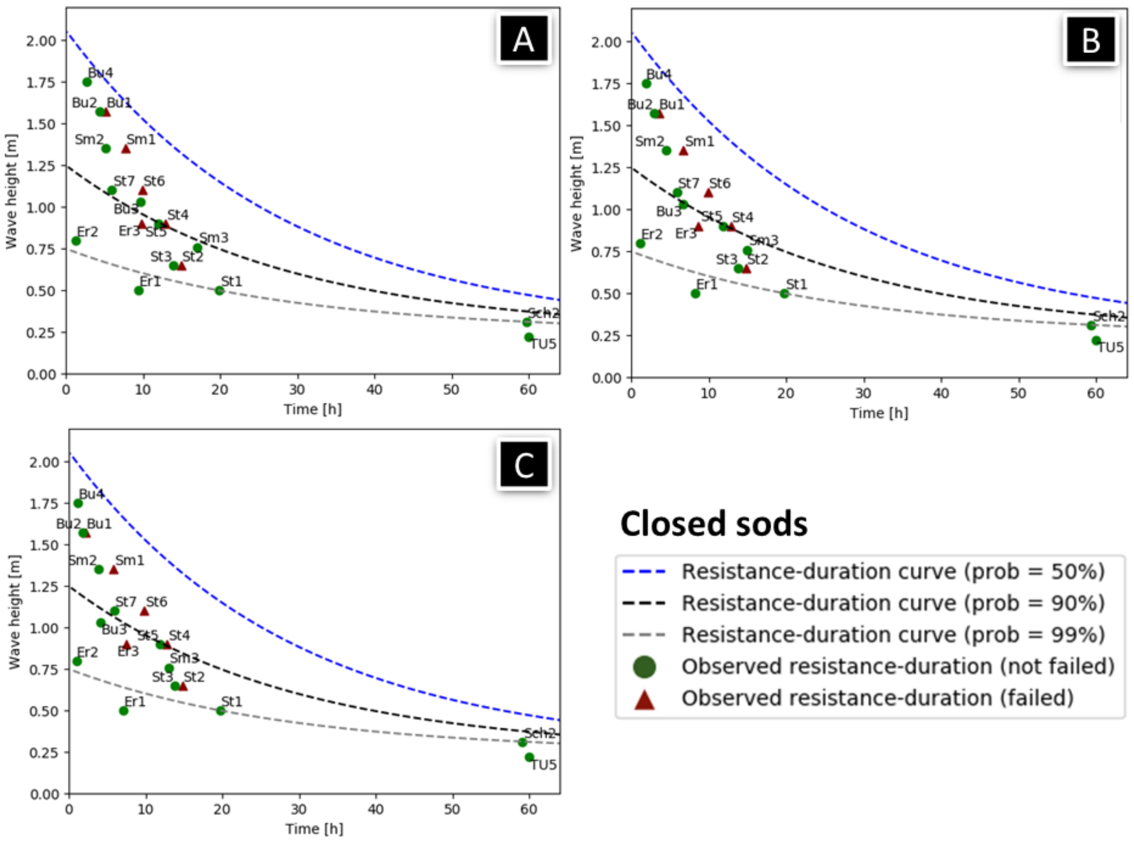

Figure 4.1: Transposed data (equals to a slope of 1:3) for closed sods with plotted resistance-duration curves of the WBI model with different probabilities. A: Relation f_α (eq. 3.1.2), B: Relation n (eq. 3.1.3), C: Relation R_e (eq. 3.1.6).

The second step was to transpose the data points in order to combine and compare the data points with different slope angles. By changing the resistance-duration values according to the three relations, mentioned in the methodology, the data was transposed to a slope angle of 1:3. The data set of the closed sods (Figure 4.1) and the data set of the open sods (Figure 4.2) are visually presented separately according to the three relations. The resistance-duration curves according to the WBI, values from Table 2.2, are plotted in the same figure for visualisation purposes.

The first remark about Figure 4.1 is that all transposed resistance-duration values show a line with the same shape as the resistance-duration curves of the WBI. Although, the curve will probably be steeper in all cases in comparison to the WBI.

The second remark on the results of the closed sods is that the differences between the three relations look small. To show the differences, the transposed values are presented in Table 4.2. It makes sense that the majority of the data points are similar in the figures since most points were from experiments with a slope of 1:3 and did not change. The values from the experiments of Burger change the most, in comparison to the original resistance-duration values, since the slope of that experiment differs the most from a slope of 1:3 (namely 1:8). The transposed values from the experiments of Burger are in line with the other values as can be seen in the figure.

Figure 4.2 does not contain any outliers either. There were no outliers expected since no experiments with a gentle slope are included in this figure. The maximum resistance-duration in the figure is 60 hours, thus the change of the experiments with a resistance-duration higher than 60 hours is not visible. The resistance-duration curves from the WBI seems to reflect the plotted data points very well.

Table 4.2: Transposed resistance-duration to a slope of 1:3 from observed resistance-duration points that failed (green) and not failed (red). Resistance-duration points of experiments on a slope of 1:3 are left out, since the resistance-duration did not change.

Closed sods					
Code	**Slope**	$t_{s,top}$	f_α	n	R_e
Er1	1:4	11.0 h	9.4 h	8.3 h	7.1 h
Er2	1:4	1.5 h	1.3 h	1.1 h	1.0 h
Er3	1:4	11.5 h	9.8 h	8.6 h	7.5 h
TU5	1:1.5	168.0 h	225.9 h	337.7 h	478.7 h
Bu1	1:8	9.5 h	5.1 h	3.6 h	2.2 h
Bu2	1:8	8.0 h	4.3 h	3.0 h	1.8 h
Bu3	1:8	18.0 h	9.7 h	6.8 h	4.1 h
Bu4	1:8	5.0 h	2.7 h	1.9 h	1.1 h
Sm1	1:4	9.0 h	7.7 h	6.8 h	5.8 h
Sm2	1:4	6.0 h	5.1 h	4.5 h	3.9 h
Sm3	1:4	20.0 h	17.1 h	15.0 h	13.0 h
Open sods					
Code	**Slope**	$t_{s,top}$	f_α	n	R_e
Em	1:4	3.0 h	2.6 h	2.3 h	1.9 h
TU1	1:1.5	264.0 h	355.0 h	530.6 h	752.3 h
TU2	1:1.5	264.0 h	355.0 h	530.6 h	752.3 h
TU3	1:1.5	168.0 h	225.9 h	337.7 h	478.7 h

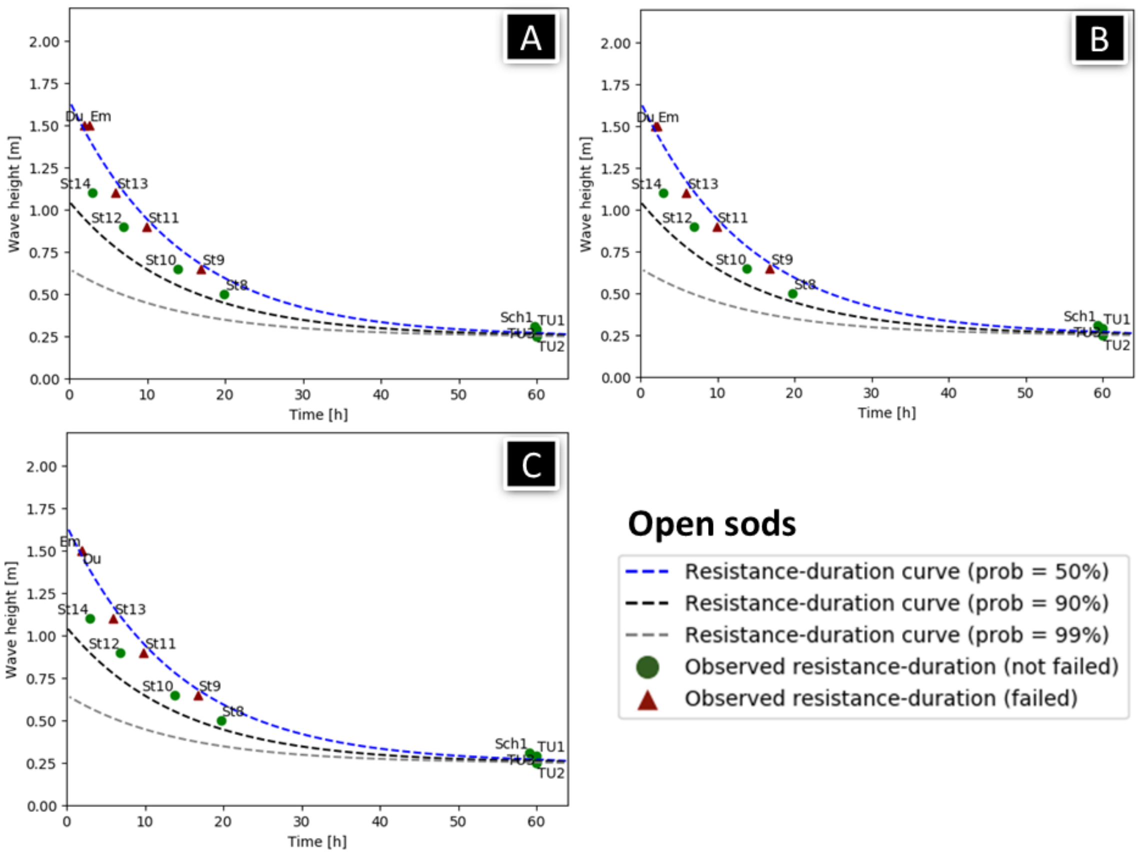

Figure 4.2: Transposed data (equals to a slope of 1:3) for open sods with plotted resistance-duration curves. A: Relation f_α (eq. 3.1.2), B: Relation n (eq. 3.1.3), C: Relation R_e (eq. 3.1.6).

4.2 Effect of slope angle

After the transposing of the data points, curves were generated and fitted on these data points. The curves were generated according to the two different models, WBI and WIPE, and are discussed separately. In the end of this section the results from the two models are compared.

4.2.1 WBI model

The resistance-duration curve generated according to the WBI model and fitted on the data is presented for the closed sods in Figure 4.3 and for the open sods in Figure 4.4. In most cases, the curve is located between the green and red dots after the calibration. Therefore, only small errors were found as can be seen in Table 4.3.

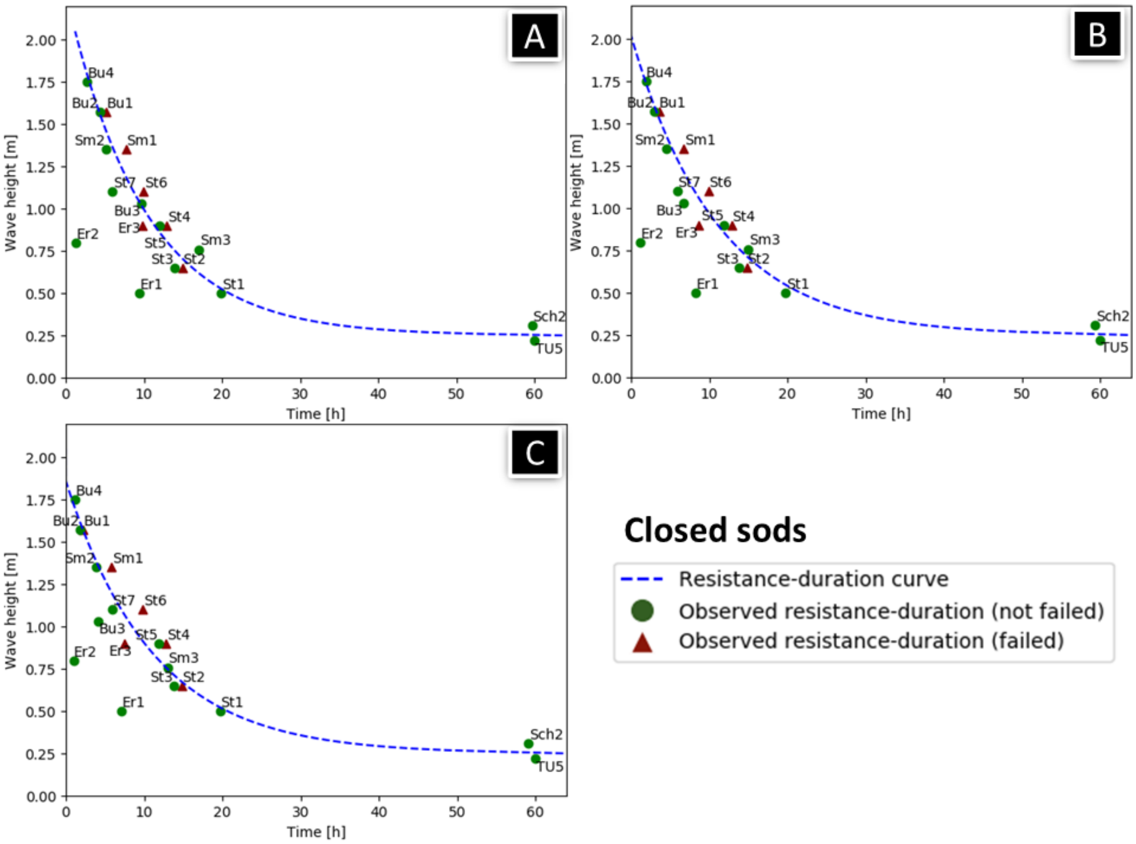

Figure 4.3: Fitted curve of the WBI model for closed sods. A: Relation f_α (eq. 3.1.2), B: Relation n (eq. 3.1.3), C: Relation R_e (eq. 3.1.6).

Comparing the values of the parameters of the fitted curve with the suggested values by WBI with the probability of 50% (comparing Table 2.2 and Table 4.3), result in a few remarks. For the parameter values for the closed sods, the value for parameter a is comparable with the suggested value with a probability of 50%. However, the value for parameter b is lower than suggested. This means that the calibrated resistance-duration curve is steeper than the WBI suggests. Thus, a change in wave height has less effect on the resistance-duration than the WBI implies. In the case of open sods, both parameter values are comparable with the suggested values with a probability of 50%. The expected value for parameter a is slightly higher than was calibrated (1.4 versus approximately 1.0). The curve is mostly between the failed and not failed observations, but is closer to the not failed observations as can be seen in Figure 4.4. Therefore, the calibrated values are justifiable.

The difference in values of the parameters and the errors is small between the various relations. In the case of the closed sods, the relation n resulted in the smallest error. Additionally, the calibrated parameters are close to the suggested values by the WBI with a probability of 50%. For the open sods, the errors are smaller and the values of the parameters are even closer to the suggested values by the WBI. According to the error, the relation R_e describes the observations

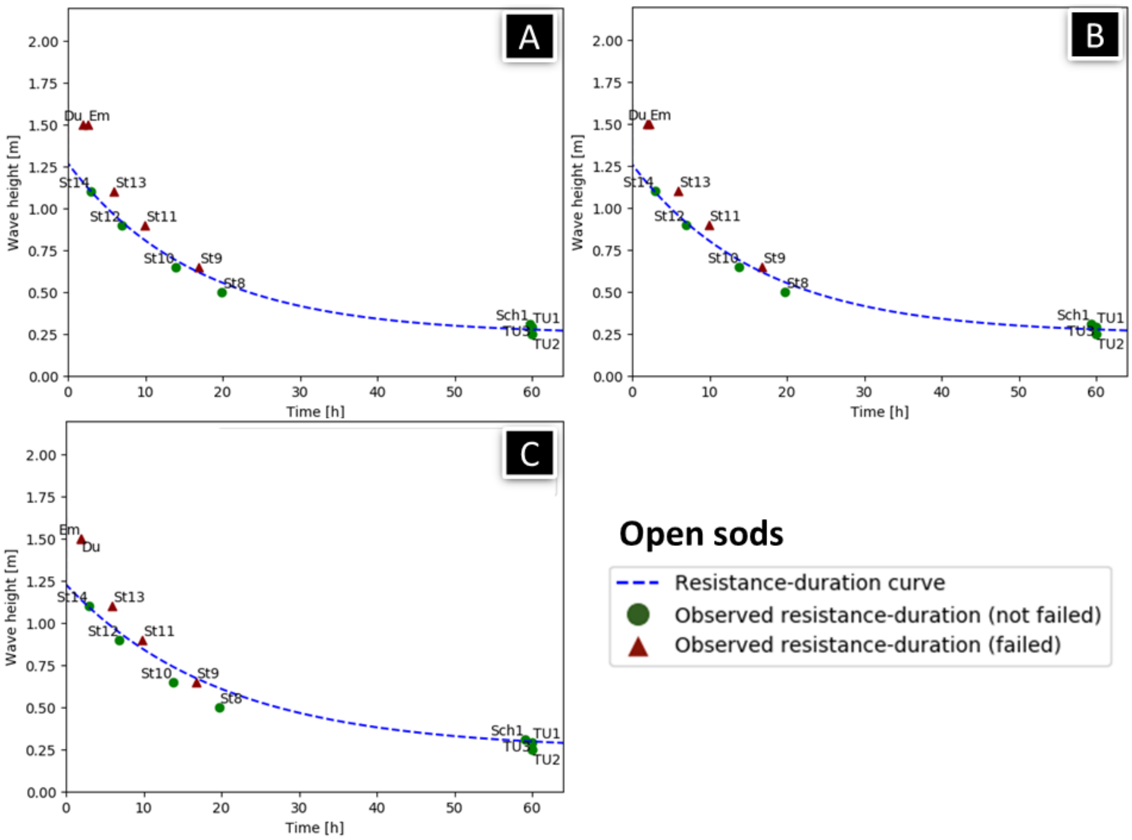

Figure 4.4: Fitted curve of the WBI model for open sods. A: Relation f_α (eq. 3.1.2), B: Relation n (eq. 3.1.3), C: Relation R_e (eq. 3.1.6).

Table 4.3: Results fitting WBI with the Mean Absolute Error (MAE) and the number of points (of the total data points) that contributed to the error.

	Closed sods				Open sods			
	a [m]	b [h^{-1}]	MAE [m]	No. of points	a [m]	b [h^{-1}]	MAE [m]	No. of points
f_α	2.03	-0.1	0.0216	7/19	1.02	-0.06	0.0031	2/13
n	1.77	-0.09	0.0195	5/19	1.01	-0.06	0.0031	3/13
R_e	1.61	-0.09	0.0211	7/19	0.98	-0.05	0.0023	3/13

the most accurately. Visually, the curves of Figure 4.4A and 4.4B are describing the observations more accurately. The error of the plotted curve of Figure 4.4C is smaller due to the observation points with a large resistance-duration. The resistance-duration of point 'Sch1' is smaller due to the relation R_e and is therefore closer to the plotted curve, which gives a lower error.

4.2.2 WIPE model

Before the resistance-duration curves could be generated with the WIPE model, the wave distribution had to be determined. Equation 2.3.2 was used to generate the impact pressure for series of waves. The measured wave impact of the EroGRASS experiments showed that the suggested parameters by Führböter [1988] ($\sigma = 2.2$ and $q_{\text{avg}} = 0.7$) do not generate reliable series of wave impact pressures [Mous, 2010]. Figure 4.5A shows the generated series with a significant wave height of 0.5 meter. During the experiment of EroGRASS, the wave impact was measures and the results are presented in Figure 4.5D with a significant wave height of 0.5 meter. These two figures do not show a similar pattern, therefore the values of the distribution were adjusted.

Führböter [1988] measured the pressure below the surface. Based on the findings of Führböter, the parameters were adjusted ($\sigma = 0.4$ and $q_{\text{avg}} = 0.6$). The generated waves are presented in Figure 4.5B. These values match better with the measurements of EroGRASS, compared to the output presented in 4.5A. However, the wave impact peaks are missing. It is not possible to assess these peaks with the Rayleigh distribution, thus a Gamma distribution was chosen. The Gamma distribution was used to generate the waves of Figure 4.5C and does show more similarities with the measured wave impact. Therefore, the Gamma distribution was chosen to use as input for the WIPE model.

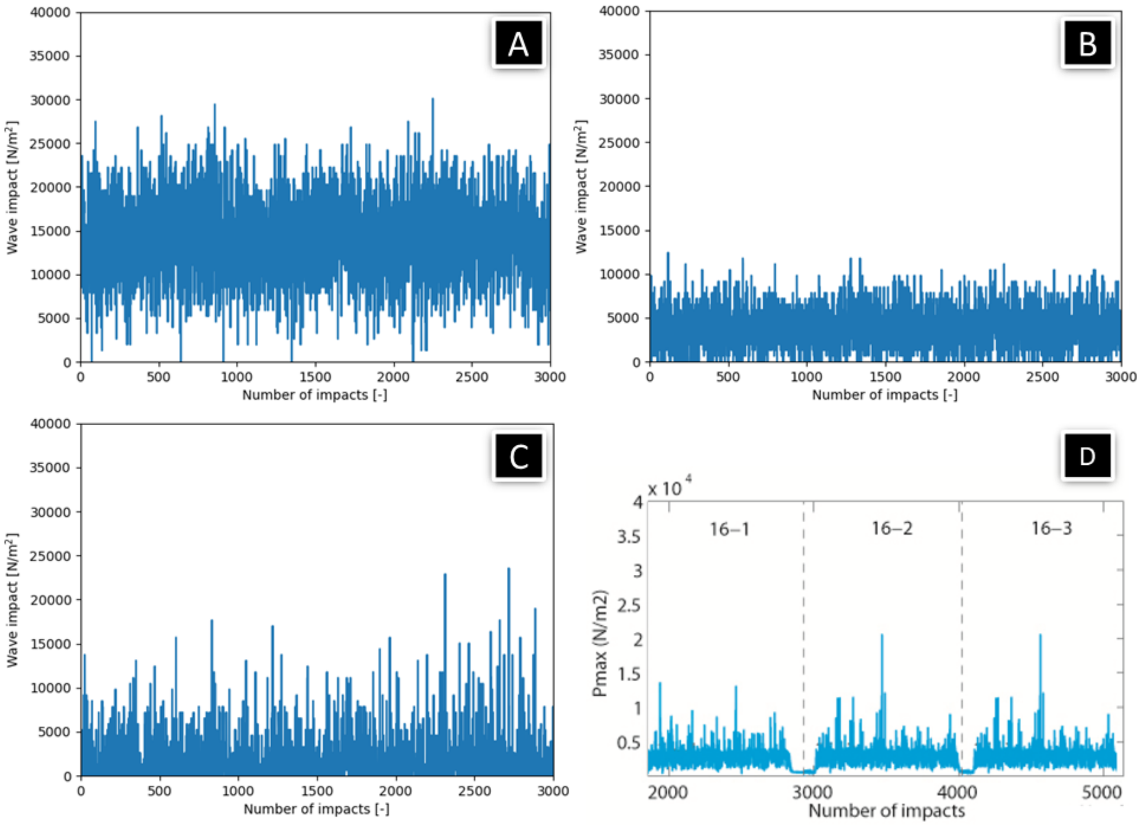

Figure 4.5: Wave impact per wave with H_s=0.5m A: Rayleigh distribution (σ_{std} = 2.2 and q_{avg} = 0.7), B: Rayleigh distribution (σ_{std} = 0.4 and q_{avg} = 0.6), C: Gamma distribution (α = 0.4 and β = 0.6), D: Measured wave impact at experiments of EroGRASS (adjusted from Mous [2010]).

The random waves had to be iterated to compensate for the random distributed wave impact. Iterations of the model were executed and the deformation of the resistance-duration curve was calculated after every step of iterations. Table 4.4 shows the difference of the resistance-duration values after a certain amount of iterations. From 150 iterations, the largest difference in resistance-duration found at one value of the wave height, was below 0.5 h. Since the input of the experiments was rounded by half an hour, the maximum difference of 0.49 hours was chosen to be acceptable. More iterations will increase the reliability, but due to calculation time and the fact that the output of the experiments was rounded by 0.5 hours, 150 iterations were chosen to use for calculation of the resistance-duration curve.

Table 4.4: Differences between iterations.

Iterations	25-50	50-75	75-100	100-125	125-150	150-175	175-200
Mean difference	0.27 h	0.13 h	0.09 h	0.09 h	0.05 h	0.06 h	0.05 h
Max difference	3.29 h	0.98 h	0.74 h	0.92 h	0.55 h	0.49 h	0.30 h

As was mentioned before, the run time of the WIPE model was still high, namely around 1.5 hour per run. The calibration was done in multiple steps and is described in detail in Appendix D. In contrast to the WBI model, it is in favour to use a similar value of the calibration parameters for the closed and open sods. In the WIPE model, the distionction between closed and open sods is made with a different parameter, the Root Area Ratio, while the WBI model does not contain a related parameter. From the calibration can be concluded that the error did not vary substantially in the case of open sods for the different tested relations. However, the error varied for different parameters and different relations in the case of closed sods. Since the relation n resulted in the smallest error, the detailed calibration was done on this parameter. The final values of the parameters were 1.4 for the soil calibration parameter (α_{soil}) and 430 for the crack calibration parameter(α_{crack}). Mous [2010] suggests a value of around 1.35 for the soil calibration parameter and 420 for the crack calibration parameter. This is close to the found values in this research which supports the results of the calibration.

Figure 4.6 and Figure 4.7 show the calibrated curves for the open and closed sods. In Table 4.5 the errors are presented. In case of closed sods, the error between the data transposed according to relation n is the smallest.

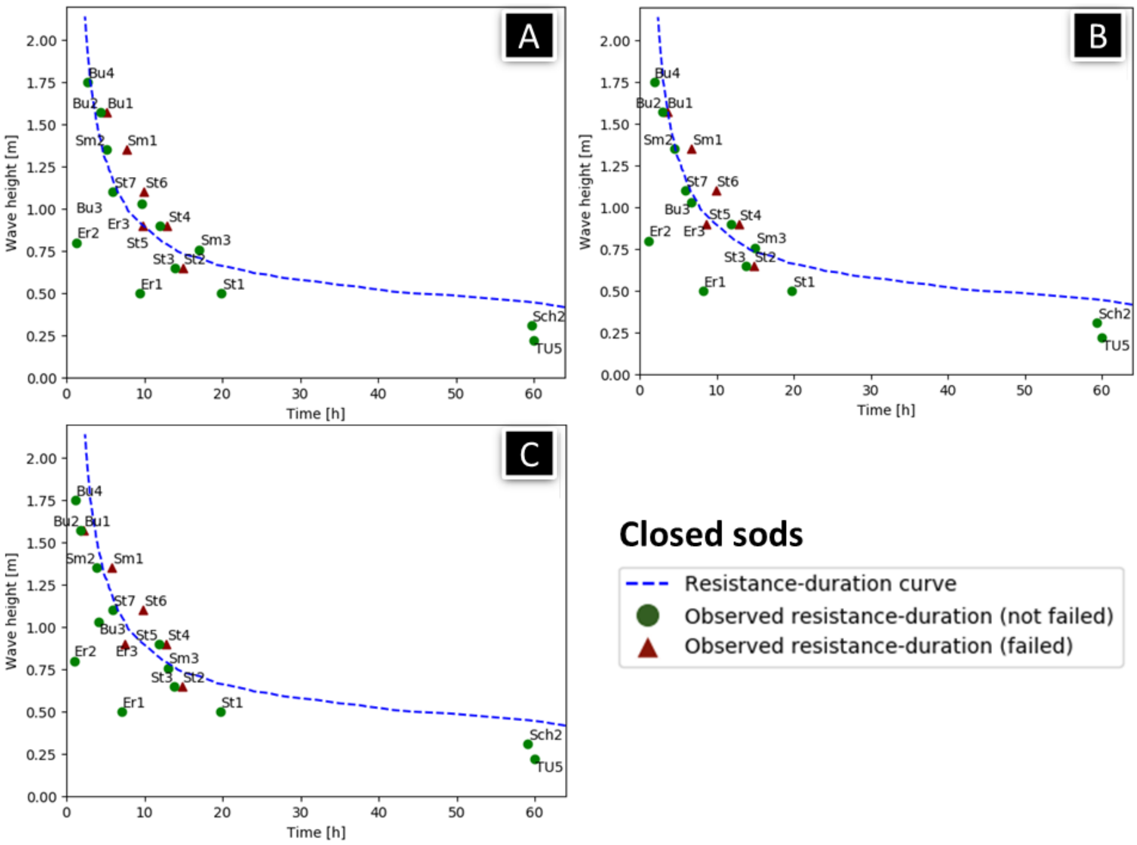

Figure 4.6: Fitted curve of the WIPE model for closed sods. A: Relation f_α (eq. 3.1.2), B: Relation n (eq. 3.1.3), C: Relation R_e (eq. 3.1.6).

Table 4.5: MAE of WIPE model after calibration with the Mean Absolute Error (MAE) and the number of points (of the total data points) that contributed to the error.

	Closed sods		Open sods	
	MAE [m]	No. of points	MAE [m]	No. of points
f_α	0.029	6/19	0.033	5/13
n	0.016	5/19	0.033	4/13
R_e	0.046	4/19	0.032	5/13

The curve of Figure 4.6B fits the best since the parameters were fitted for the relation n. In all figures, the curve is situated as expected according to the majority of the observed data points. Which means that most of the observed points of failure is located above the simulated curve and the majority of the observed points of no failure is located below the curve. Figure 4.7 shows a less expected curve. The curves in the figure are mostly below the observed data points of failure and no failure. It shows a conservative resistance-duration curve. The cause might be that the calibration was done over the error in wave height. Due to the steepness of the curve at a low resistance-duration, the error due to the data points in this region increased more when the curve

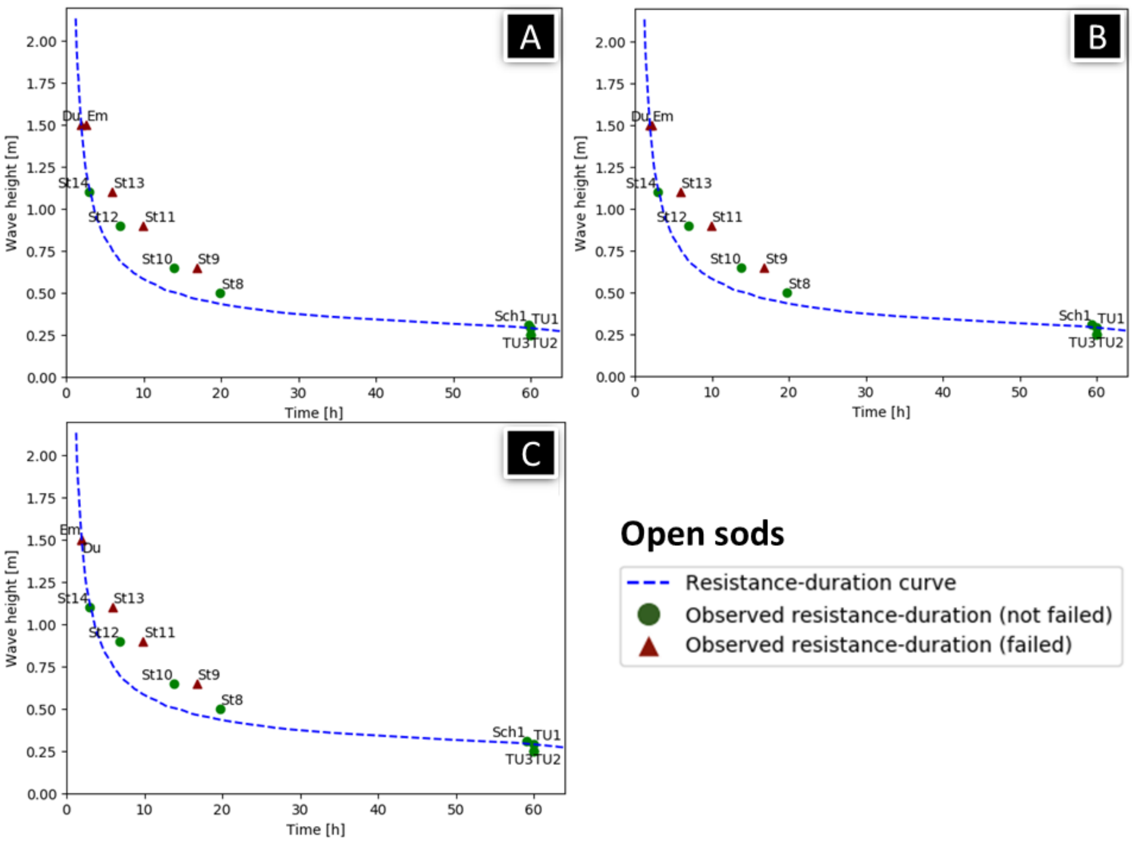

Figure 4.7: Fitted curve of the WIPE model for open sods. A: Relation f_α (eq. 3.1.2), B: Relation n (eq. 3.1.3), C: Relation R_e (eq. 3.1.6).

shifts than when the curve would be less steep. Thus, the data points 'Du' and 'Em' have a substantial impact on the calibration of the resistance-duration curve for the open sods (Figure 4.7). Another remark is that both curves show a threshold value of the duration until failure. Thus, even with high waves (around 2 meter), the resistance-duration of the grass revetment is around 2 hours. This is the time that is needed, according to the WIPE model, for the crack to grow before block erosion occurs.

4.2.3 Comparison between WBI and WIPE

To make a final conclusion on the most accurate relation between slope angle and resistance-duration, the found errors were compared. Thereafter, the error between the simulated curve and data from experiments, with a slope that was not equal to 1:3, were calculated.

From the results of the open sods, a relation could not be concluded since all observed data points were from experiments with a steep slope between 1:1.5 and 1:4. Therefore, the focus was on the results of the closed sods (Figure 4.3 and 4.6). The calibrated curve for the closed sods of the WBI model and the WIPE model both resulted in the smallest error in case of relation n.

To exclude the risk that experiments with a slope of 1:3 do have a meaningful influence on the

Table 4.6: Mean Absolute Error (MAE) of experiments with a slope that was not equal to 1:3 and the number of points (of the total data points) that contributed to the error. Only experiments with closed sods are included.

	WBI model		WIPE model	
	MAE [m]	No. of points	MAE [m]	No. of points
f_α	0.023	4/11	0.035	4/11
n	0.019	2/11	0.012	3/11
R_e	0.021	4/11	0.064	2/11

error, the simulated resistance-duration curves were also compared to the experiments with a slope different than 1:3. Table 4.6 shows the errors between the simulated resistance-duration curves and the experiments with a slope that was not equal to 1:3. These results support the conclusion that relation n describes the experiments most accurately.

To calculate the resistance-duration curves for different slope angles, the relation had to be implemented for both models. Parameter b of the WBI model describes the steepness of the resistance-duration curve, which can be changed to achieve the effect of the slope angle. Including relation n in equation 2.2.2 gives equation 4.2.1 which includes the effect of the slope angle. The effect of the slope angle in the WIPE model can be achieved by simply change the calculated resistance-duration according to the relation n.

$$t_{s,top} = \frac{1}{b * 3 * \tan \alpha} \ln(\frac{H_s - c}{a}) \tag{4.2.1}$$

4.3 Durability of grass revetment

In this section, the results from the durability of the grass revetment on slopes with different angles are discussed. The process of simulating the series of wave heights was described in the methodology. This chapter shows the effect of the relation between the slope angle and the resistance-duration on the return period of the storm when the revetment fails. The case of the wide green dike at the Dollard is used, since the location is of importance for the storm characteristics and therefore the durability of the grass revetment for various storms. Appendix E shows the exact location of the case and the input values of Hydra-NL.

4.3.1 Storm surge

Figure 3.9 shows the three different steps that were executed for the different storm scenarios. These calculations were done for the slope angles between 1:3 and 1:8 and for the scenarios with and without sea level rise.

Storms were simulated for multiple return periods to find the shortest return period when the revetment fails. The top of the total water level is always located around 28 hours for the eastern part of the Wadden Sea [Klein Breteler et al., 2017]. This is also visible in Figure 3.8 and Figure 3.9. As can be seen in the figure, the wave height was zero when the total water level was lower than the foreland. This means that there were no waves at the toe of the dike thus no wave attacked on the slope of the dike, because there was no water on the foreland.

4.3.2 Return period

The failure fractions were calculated for every 0.1 hour and summed. This was done for multiple return periods with step size of 10 years. An example is the bottom figure in Figure 3.9. When the total failure fraction exceeds the failure criteria of 1, it means that the revetment fails. Thus, in the case of a storm with a return period of 100 years, the revetment on a slope of 1:6 failed around 27.5 hours (after 15 hours of wave impact on the slope). Table 4.7 shows the return period of the storm when the grass revetment failed for the different scenarios and models. When the effect of the slope angle is not included in the calculations, the return period is equal to a slope of 1:3. Thus, for the scenario of 2023 with a slope of 1:8, the revetment will fail during a storm with a return period of 140 years instead of 10. In all cases, the revetment failed (during the storm that is shown in Table 4.7) around 29 hours which is almost at the end of the storm. This means that only for a short time, the clay layer has to withstand the incoming waves to prevent total failure of the dike.

There are a few remarks on the results. The earliest year that could be selected in Hydra-NL is 2023 with the climate scenario G, thus this was used as the scenario without climate change. There might be a small difference with the actual situation, but these differences are small and are neglected. The other scenario is 2073 with the climate scenario of W+.

The other remark is that since a return period of 10 years is the minimum according to the software, this was used as the minimum return period in Table 4.7. In the actual situation, the grass revetment might fail due to a storm with a shorter return period than 10 years.

Table 4.7: Return period (in years) of the storm when the grass revetment fails for different slope angles and models.

		1:3	1:4	1:5	1:6	1:7	1:8
2023	**WBI**	10	20	30	60	90	140
	WIPE	10	10	20	30	40	50
2073	**WBI**	10	10	20	20	40	50
	WIPE	10	10	10	10	20	20

Table 4.7 shows that the slope angle has a substantial effect on the return period of the storm when the grass revetment fails. However, the duration until failure did not substantial differ for all slope angles for the design return period of 200,000 years. According to the WBI model, the revetment failed when the waves reached a height of around 2 meter, which was at 13.6 hours for a slope of 1:3 and 13.8 hours for a slope of 1:8. According to the WIPE model, the revetment failed respectively at 14.8 and 15.3 hours during a storm with a return period of 200,000 years. Figure 4.8 shows that these times of failure were around the moment that the waves reached almost 2 meter. This makes sense since the resistance-duration curves approach a resistance-duration of 0 hours around a wave height of 2 meter.

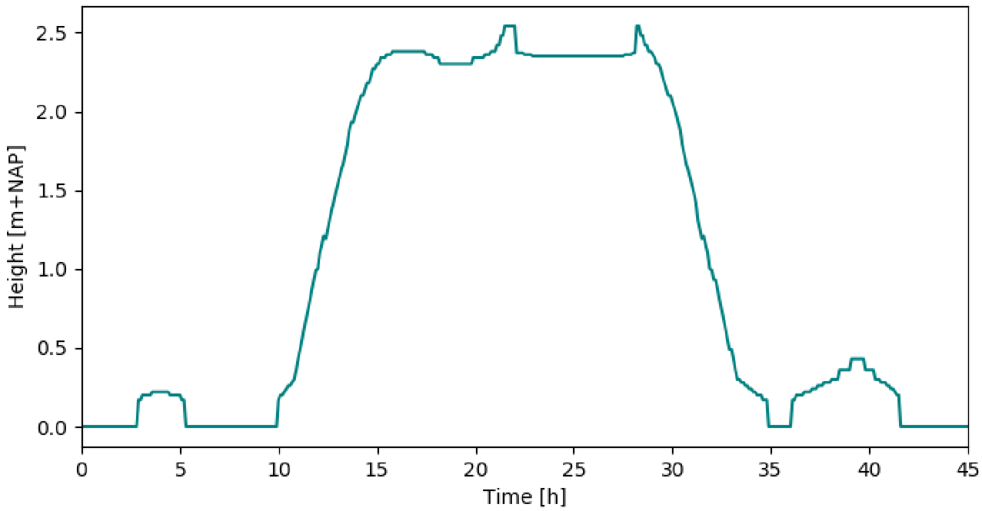

Figure 4.8: Wave height during a storm with climate change for 2073 with a return period of 200,000 years.

Thus, the slope angle does not have a large impact on the time of failure when waves reach a height of 2 meter during the storm. However, the slope angle does have a clear impact on the return period of the moment that the grass revetment fails as can be seen in Table 4.7. The return periods were also calculated for the moment that the grass revetment is damaged. The result was that in all situations the grass was damaged in less than 10 years regardless of the slope angle. Therefore, no conclusion on the effect of the slope angle on the return period for damage can be drawn.

4.4 Sensitivity of grass parameters

The sensitivity of different parameters of the models that describe the quality of the grass revetment was measured in two ways; difference in resistance-duration curve and the difference in the return period of failure of the revetment. The combinations that were used for the determination of the sensitivity are presented in Table 3.5.

4.4.1 Sensitivity on resistance-duration

For the different combinations of values of the parameters, resistance-duration curves were generated and presented for the WBI model in Figure 4.9 for a slope of 1:3 and 1:8. The difference between the generated curves and the resistance-duration curve calibrated in Chapter 4.2 is additionally shown in the figures. The calibrated resistance-duration curve generated with the WBI model (with $a = 1.77$ m and $b = -0.009$ h^{-1}) and the WIPE model (with $tr = 20 * 10^6$ N/m^2 and $RAR = 3 * 10^{-4}$) are from this point referred to as initial curves.

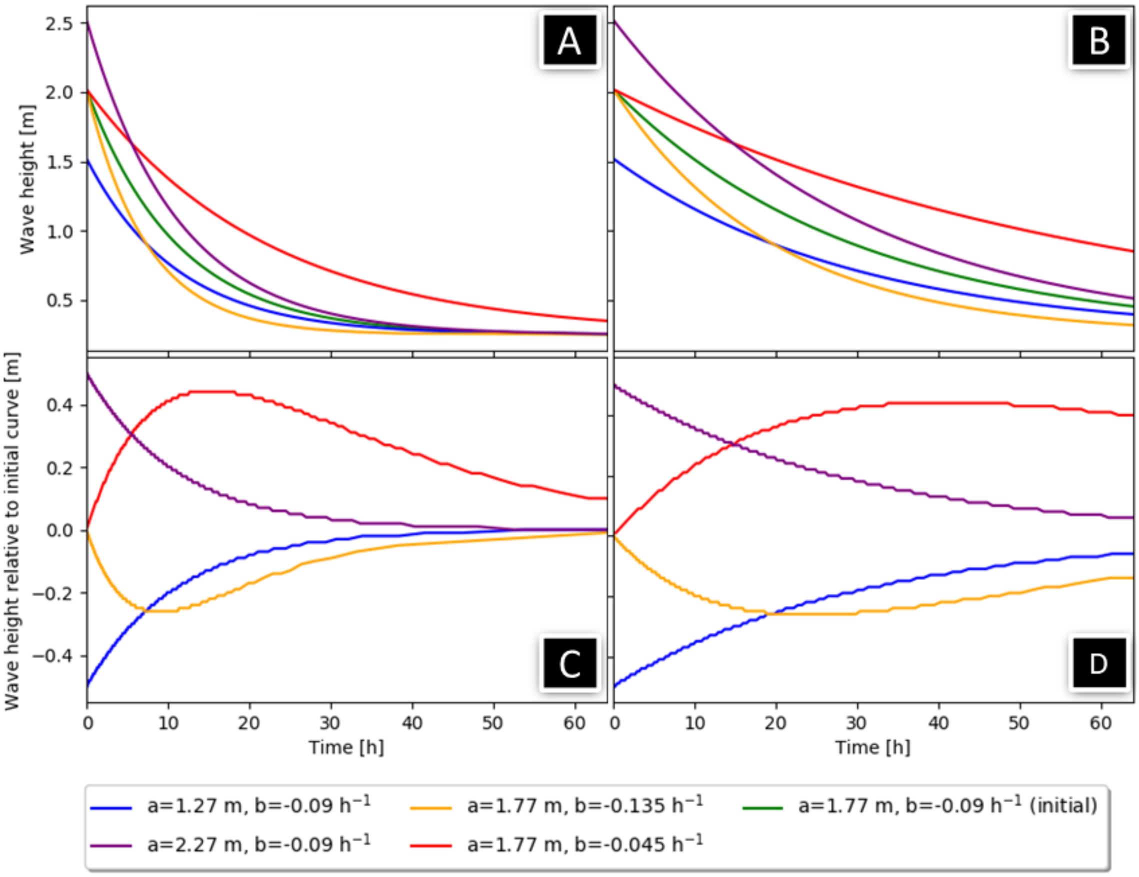

Figure 4.9: Resistance-duration curves generated with the WBI model with different values for grass quality parameters for a slope of 1:3 (Figure A) and a slope of 1:8 (Figure B). The difference between the curves and the initial resistance-duration curve for a slope of 1:3 (Figure C) and a slope of 1:8 (Figure D).

As can be seen in Figure 4.9, the sensitivity of the parameters varies along the curve. When parameter a was changed (indicated with the blue and purple line), the difference with the initial curve is the largest at 0 hours and the difference decreased when the duration increased. When parameter b was changed (indicated with the yellow and red line), the largest difference is between 5 and 20 hours for a slope of 1:3 (Figure 4.9C). Both parameters were changed 50% and have a maximum difference of around 0.4 meter. Figure 4.9D shows the sensitivity of the parameters in a case of a dike with a gentle slope of 1:8. It shows similarities as Figure 4.9C, but the moment of maximum difference with the initial curve was shifted to between 20 and 45 hours. Next to the fact that the moment of maximum difference was shifted, the difference with the initial curve was more substantial for a longer time than it is the case of a steep slope. A more gentle slope results in a larger difference over a longer time, but not in a higher difference than in the case of a steep slope.

In the case at the Dollard, the peak of the storm lasts 15 hours as can be seen in Figure 3.9. Figure 4.9 shows that the change of parameter b has a larger effect on the resistance-duration curve than the change of parameter a for a slope of 1:3 around the duration of 15 hours. Parameter a was more sensitive for waves that can be resisted for only a few hours. For a gentle slope, both parameters influenced the result in the same amount around a storm duration of 15 hours as is shown in Figure 4.9D. Thus, the sensitivity of the parameters of the WBI model depends on both the wave height and the slope angle.

Figure 4.10 shows the sensitivity of the tensile strength (tr) and root area ratio (RAR) on the resistance-duration for a slope of 1:3 (Sub-figures A and C) and a slope of 1:8 (Sub-figures B and

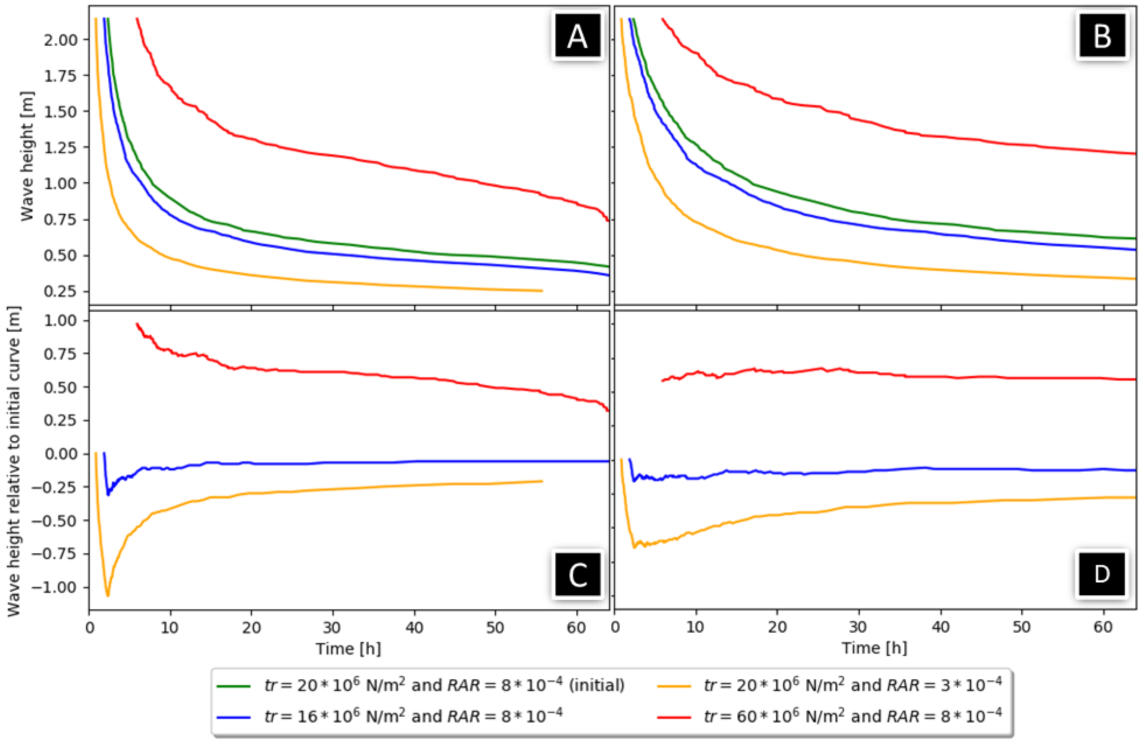

Figure 4.10: Resistance-duration curves generated with the WIPE model with different values for grass quality parameters for a slope of 1:3 (Figure A) and a slope of 1:8 (Figure B). The difference between the curves and the initial resistance-duration curve for a slope of 1:3 (Figure C) and a slope of 1:8 (Figure D).

D). A decrease of the root area ratio resulted in a large difference between 0 and 10 hours with the initial resistance-duration curve generated with the WIPE model for a steep slope. A slope of 1:8 reduced the maximum difference, but for a longer time the difference in wave height was larger than in the steep slope case. A change of the tensile strength to $16*10^6$ N/m^2 resulted in a small difference with the initial curve. The change of the tensile strength to $60*10^6$ N/m^2 gave a steady difference overall. Especially in the case of a gentle slope the difference remains constant over the time (Figure 4.10D).

The sensitivity of the parameters of the WIPE model did not depend on the slope angle to the same extend has the parameters of the WBI model. The effect of the changed parameters did not differ much between a slope of 1:3 and 1:8. Only between 0 and 10 hours, there was a noticeable difference. This was caused by the steep curve at that time interval.

4.4.2 Sensitivity on return period

The sensitivity of the grass quality parameters was also measured on the return period of failure. In Table 4.8, the return period for the different combinations of parameters are presented.

Combination 2 of the WBI model (-50% of value of parameter b) shows the largest difference in return period for the WBI model, thus parameter b is more sensitive than parameter a. In contrast to the WBI model, the parameters of the WIPE model were varied within the mentioned interval presented in Table 3.4. The results of the sensitivity analysis shows a bandwidth of the resistance-duration. Although, it is questionable if it is realistic that all roots on a slope have a similar strength of $60*10^2$ N/m^2, the effect of a high root strength is substantial. For a slope of 1:8, the storm when the revetment fails has a return period of 200,000 years for a tensile strength of $60*10^6$ N/m^2 instead of 50 years for a tensile strength of $20*10^6$ N/m^2. Thus, it is important to obtain knowledge on the tensile strength of the grass revetment to achieve reliable results.

Figure 4.11 shows the change of the return period relative to the change of the parameters for both models in one figure. When the values of the parameters becomes smaller (larger for parameter b), generally the curve becomes less steep. There are two explanations for this. As is mentioned above, the minimum return period is 10 years, thus the return period cannot be shorter.

Table 4.8: Return period (in years) of the storm when the grass revetment fails for different combinations of the parameters of different models.

			2023		2073	
			1:3	**1:8**	**1:3**	**1:8**
WBI	1	-50% of a	10	30	10	20
	2	-50% of b	60	1000	20	1000
	3	+50% of b	10	40	10	20
	4	+50% of a	10	1000	10	230
		Initial	10	140	10	50
WIPE	1	-20% of tr	10	40	10	20
	2	-62.5% of RAR	10	10	10	10
	3	+200% of tr	1000	200,000	120	1000
		Initial	10	50	10	20

The other explanation is for the WIPE model. Without grass, the top revetment has still some resistance due to cohesion and the weight of the soil which is included in the WIPE model (Figure 2.1. This also resulted in a minimum return period. The figure shows that the tensile strength has a steeper slope when the value increases than the other parameters. This is in line with the earlier observation that the tensile strength is the most sensitive parameter for the return period.

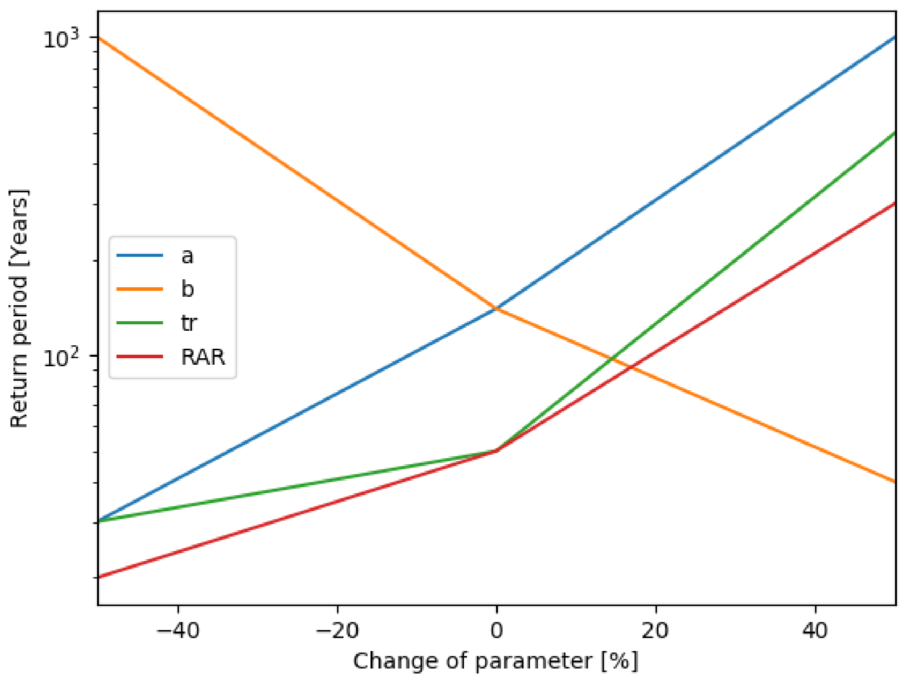

Figure 4.11: The return period (for a slope of 1:8 and scenario of 2023) relative to the change of the grass quality parameters. Two empirical parameters of the WBI (a and b) and for the WIPE model the tensile strength (tr) and the Root Area Ratio (RAR).

Chapter 5

Discussion

The purpose of this study was to obtain knowledge on the effect of the slope angle of a green dike on the durability of the grass revetment in the wave impact zone. The findings suggest that the slope angle affects the resistance-duration according to relation n. The results also show that the slope angle hardly influences the duration until failure during an extreme storm, but that it does have an impact on the return period of failure.

In this chapter, the results of this study are discussed in more detail. Firstly, the resistance-duration curves of the WBI and WIPE model are discussed, followed by a comparison of the two models. Secondly, a discussion on the return period is presented. The general remarks on the reliability of the results and the limitations are discussed in the end.

5.1 Resistance-duration curve

The resistance-duration curves of the WBI and WIPE model were calibrated on the experiments by changing the calibration parameters of the two model. Next to adapting the calibration parameters, assumptions on values of parameters were made. First the WBI calibration is discussed followed by the WIPE model. In the end, the method of the calibration is discussed.

5.1.1 WBI model

The WBI model contains only four parameters, namely the wave height as input, two empirical parameters (parameters a and b) and the threshold of the wave height (parameter c). The calibration of the WBI model was done by changing the empirical parameters, while the threshold parameter was set on 0.25 meter for both open and closed sods. This means that waves lower than 0.25 meter will not damage the revetment. However, this study indicates that waves lower than 0.5 meter did not damage the grass revetment either. This is supported by multiple studies and no experiments with failure due to waves lower than 0.5 meter were found [Verheij and Kruse, 1998, Piontkowitz and Christensen, 2012]. Experiments with waves equal or lower than 0.5 meter were executed with open and closed sods and no erosion was observed [Wolffenbuttel, 1989, Kruse, 2010, Van Steeg, 2014]. When the threshold value of the WBI is set on 0.5 meter instead of 0.25 meter, the calibration parameters have to be adjusted to represent the results of the experiments. The calibration of the WBI model was repeated with the threshold value set on 0.5 meter. The results are shown in Figure 5.1 and Table 5.1.

Table 5.1: Results calibration of the WBI model with threshold value (c) of 0.5 meter.

	a [m]	b [h^-1]	MAE [m]
f_α	2.05	-0.14	0.0158
n	1.56	-0.12	0.0147
R_e	1.46	-0.14	0.0158

The results show that the relation n results in the smallest error and therefore describes the experiments the most accurately. A comparison with the results of the calibration with a threshold value of 0.25 meter, shows that the threshold of 0.5 meter results in a lower error for all different relations. The WIPE model does not contain a clear threshold value for the wave height, but the resistance-duration curve for the closed sods remains above a wave height of 0.5 meter, as is shown in Figure 4.6. Taking these arguments into account, it is likely that the threshold value of the

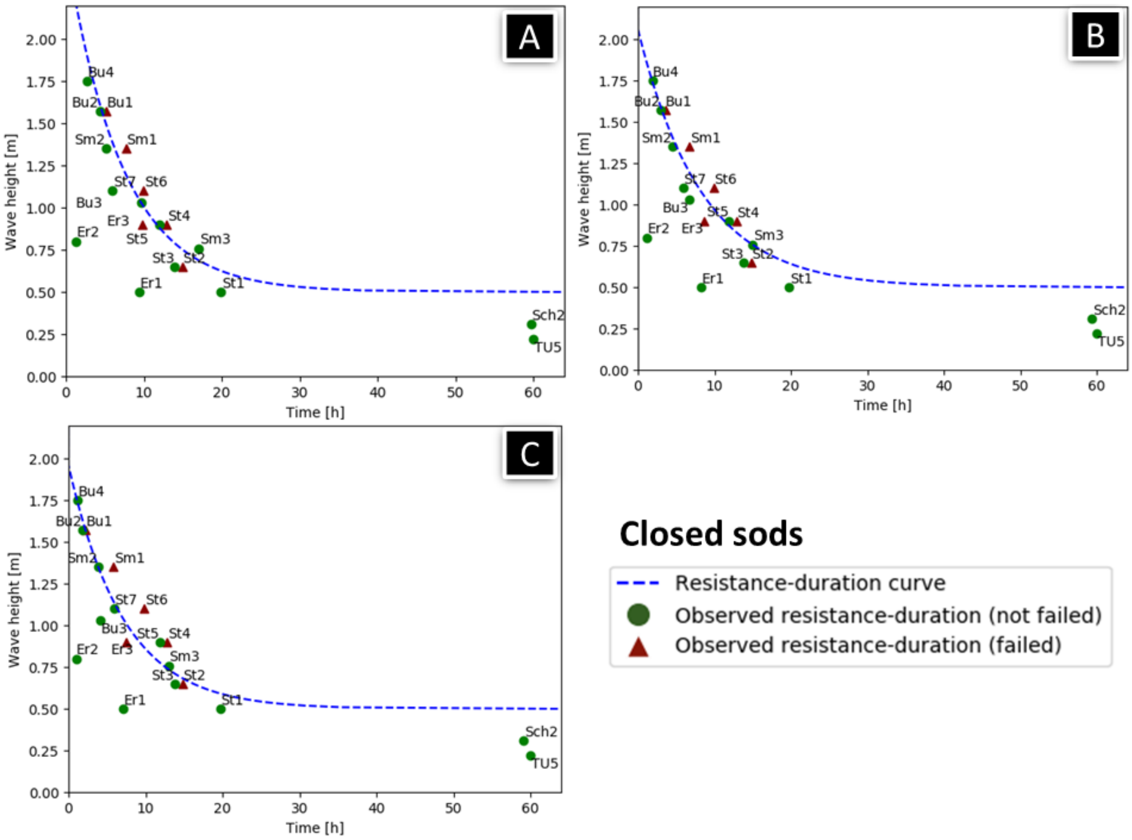

Figure 5.1: Transposed data (equals to a slope of 1:3) for closed sods with plotted resistance-duration curves with a wave height threshold of 0.5 meter. A: Relation f_{α} (eq. 3.1.2), B: Relation n (eq. 3.1.3), C: Relation R_e (eq. 3.1.6).

wave height of 0.25 is too conservative and a wave height of 0.5 meter is more in line with the experiments.

5.1.2 WIPE model

The WIPE model contains more parameters than the WBI model. The influence of the wave impact and the strength of the grass are discussed below.

The Rayleigh distribution was proposed to calculate the maximum pressure for every incoming wave [Müller et al., 2003]. However, the measured wave impact of the EroGRASS experiment was not distributed in the same way [Mous, 2010]. Figure 4.5 shows that the Gamma distribution resulted in similar values as the measured wave impact of the EroGRASS experiment, thus the Gamma distribution was used in this study. The simulated series of waves of this study contain circa 33% more waves with a wave impact between 10 and 15 kPa than the measured waves by EroGRASS, resulting in a higher load. A higher load results in a shorter resistance-duration. Thus, the computed resistance-duration of the WIPE model was possibly too conservative due to some waves with a high wave impact pressure.

The load was compared to the strength of the grass revetment which is a combination of multiple forces. In the WIPE model it is assumed that the roots are uniform along the slope and that all properties of the grass and soil are constant. This is mostly not true in practise, where some spots will be weaker and erode more easily. Whether the effect of this variation results in a shorter resistance-duration than was calculated, is not included in this study.

5.1.3 Calculating the error

The calibration of the resistance-duration curves of the models was done by calculating the minimum Mean Absolute Error (MAE). On the other hand, the Root Mean Square Error (RMSE) is also a commonly used error. The RMSE gives more weight to outliers, while the MAE focuses on the total error with equal weights [Chai and Draxler, 2014]. The RMSE was also calculated for the calibrated results for the closed sods, to make sure the chosen relation was not only based on the decision to calculate the MAE. The results (with the results of the MAE) are shown in Table 5.2.

$$RMSE = \sqrt{\frac{1}{n_v}\sum_{1}^{n_v}((Y_t - F_t)^2)} \tag{5.1.1}$$

Table 5.2: RMSE and MAE of the calibrated resistance-duration curves for closed sods.

	WBI model			**WIPE model**		
	f_α	n	R_e	f_α	n	R_e
RMSE [m]	0.046	0.044	0.048	0.051	0.031	0.136
MAE [m]	0.022	0.020	0.021	0.029	0.016	0.046

The RMSE results show a similar pattern as the MAE results. The RMSE between the resistance-duration curve and the transposed experiments was also the lowest in both models for the relation n. The outcome shows that the results of this study did not depend on the used error. Additionally, it supports the conclusion that relation n describes the experiments the most accurately.

The error was only calculated for a slope of 1:3, since this is the slope angle that is represented by the WBI model. The WBI model was also fitted on the experiments transposed to a slope of 1:6 and 1:8. The results are shown in Table 5.3. Again, the relation R_e results in the highest error. However, for a slope of 1:8 the relation f_α results in a smaller error than the relation n (0.0179 m versus 0.0184 m). This is a contradiction with the conclusion after the fitting of the experiments on a slope of 1:3.

In contrast to the calibration on a slope of 1:3, it is not possible to conclude which values of a and b are more realistic, since the values according to the WBI should be different due to the slope angle. The values of the parameter show that parameter b decreases when the slope angle decreases. This is expected to be, because the resistance-duration curve is less steep when the slope is less steep. This is also visible in the equation in which the relation is included (equation 4.2.1). There is no clear increase or decrease visible of the value of parameter a. This was also expected, because the wave height that corresponds to a resistance-duration of 0 hours remains constant when the slope angle changes. Thus, this study does not show that the standard parameter values a and b have to change.

Table 5.3: Results calibration of the WBI model with experiments transposed to a slope of 1:6 and 1:8.

	1:6			**1:8**		
	a [m]	b [h^{-1}]	MAE [m]	a [m]	b [h^{-1}]	MAE [m]
f_α	1.91	-0.06	0.0189	1.97	-0.05	0.0179
n	1.83	-0.05	0.0168	1.68	-0.03	0.0184
R_e	1.59	-0.03	0.0195	1.60	-0.02	0.0205

5.2 Comparison WBI and WIPE model

With the chosen relation n, the resistance-duration curves for slope angles in the range of 1:3 to 1:8 were generated, as can be seen in Figure 5.2. In both sub-figures, the resistance-duration curves for the different slope angles meet around a wave height of 2 meter. Führboter and Sparboom [1988] claim that the wave impact decreases when the slope becomes smaller. It is thus more likely that the more gentle slopes will have a higher value of the wave height for a resistance-duration of 0 hours. Unfortunately, this statement can not be validated, because no experiments with waves higher than 2 meter were executed.

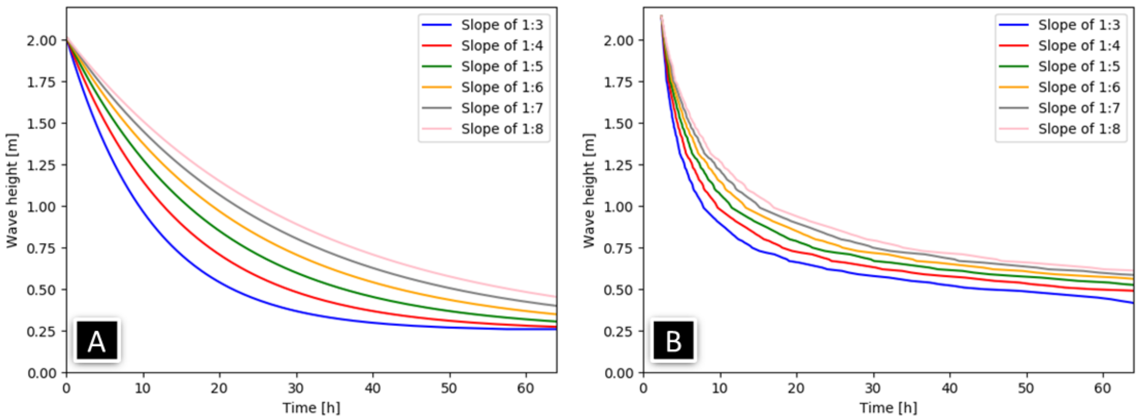

Figure 5.2: Resistance-duration curves for different slope angles according to relation n generated with the WBI model (Figure A) and WIPE model (Figure B).

Although both models were calibrated on the same experiments, the WBI curve is less steep compared to the WIPE model. The other difference between the two models is that the minimum wave height differs; 0.25 m for WBI and around 0.5 m for WIPE. When the threshold value at the WBI model was raised to 0.5 m, the curve became steeper (as is shown in Figure 5.1) and is visually more similar to the WIPE model. The error of the resistance-duration curve of the WIPE model with relation n was 0.012 m while the error of the curve of the WBI model with relation n was 0.019 m (threshold of 0.25 m) and 0.015 m (threshold of 0.5 m). This means that the resistance-duration curve of the WIPE model represents the experiments more accurately than the WBI model, but the difference is small.

The disadvantage of the WIPE model is the long time to run the model. It must also be mentioned that not many experiments were executed, thus the models were calibrated and the error was calculated on only a few data points. The WIPE model does not have an advantage over the WBI model for assessing the revetment. To conclude, the WIPE model has added value for research though, because it describes the process of wave impact and the effect of different parameters on the strength of the revetment.

5.3 Return period

The return period for the failure of the grass revetment was calculated using the resistance-duration curves and the wave heights during the storm. The wave height was derived from the water level which is a combination of the storm surge and the astronomical tide. The astronomical tide was based on data of the past years from Rijkswaterstaat. The chosen tidal period was 12.5 hours and the amplitude was 1.35 meter. To study the effect of a different astronomical tide, the wave height for a storm with a tidal period of 12 hours and 1.5 meter was calculated and an example is presented in Figure 5.3.

Changing the parameters had only a small effect on the wave height during the storm. This is caused by the fact that the maximum water level is adjusted to match the return period. The maximum water level does not change due to changes of the tide or storm surge. However, the tide does affect the shape of the water level during the storm; a shorter tidal period resulted in a shorter period of the extreme high waves. The increased amplitude specifically had an effect for a storm with a relative short return period, thus for a storm of once in 100 years as is shown in Figure 5.3. Around 20 hours, the wave height was lower when the tide had an larger amplitude than was used in this study. This was caused by the tide that reached its minimum around 20 hours, as can be seen in Figure 3.9. In all wave height series of Figure 5.3, the wave height is relatively constant during the peak of the storm (between 15 and 30 hours). At a storm with a longer return period, the wave height during the peak was even more constant than at a storm with short return period, since the tide had relatively less effect on the final wave height. To conclude, a change of the amplitude or period of the tides have a small effect on the wave height series during the storm.

It is suggested in this study to do a quick assessment without calculating the failure fractions

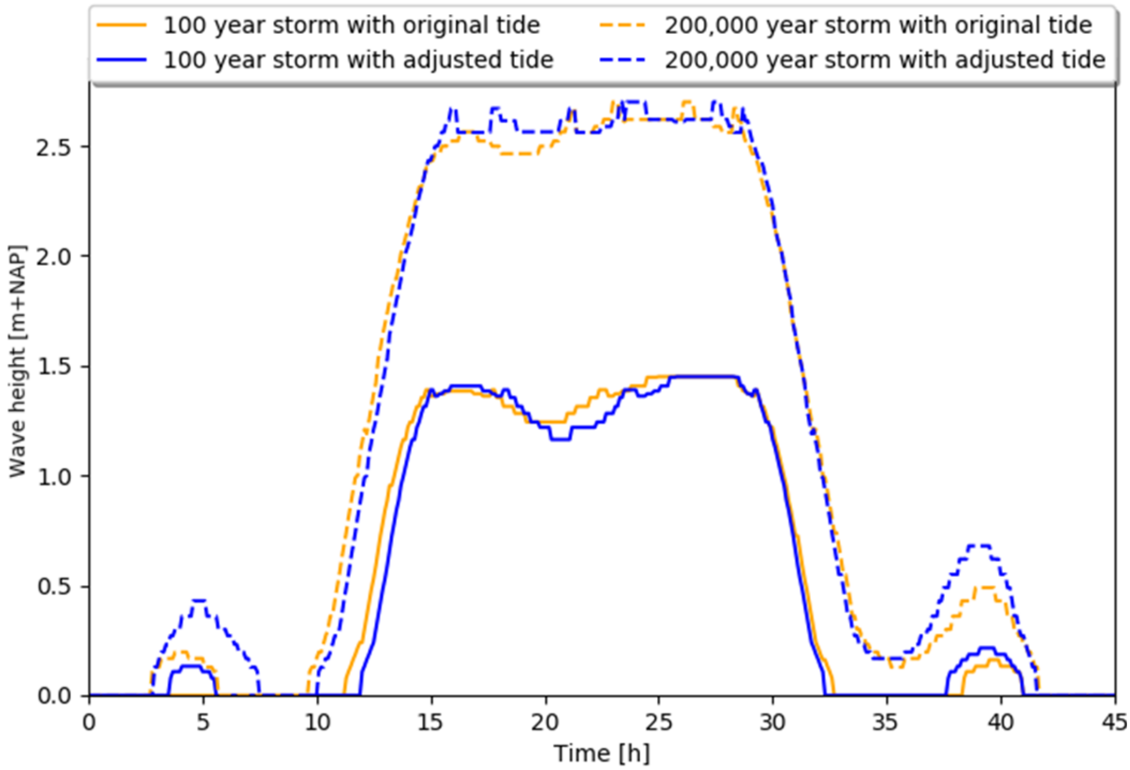

Figure 5.3: The effect of different tide parameters on the wave height for 2073 scenario. Original has an amplitude of 1.35 m and a period of 12.5 h and adjusted has an amplitude of 1.50 m and a period of 12 h.

when the wave height remains constant during the peak of a storm. The quick assessment consists of a comparison of the wave height of a simulated storm with the resistance-duration curves. The first step is to generate the wave height series of the storm and to determine the peak duration. The second step is to find the wave height of the resistance-duration curve that corresponds to the peak duration. The third step is to compare the wave height of the storm with the maximum wave height from the resistance-duration curve. When the waves of the storm are higher than those of the resistance-duration curve, the revetment fails. With this quick assessment some calculation time can be saved and an estimation of which storm will lead to failure can easily be made.

As an example of this quick assessment, a dike with a slope of 1:6 is assessed for a storm with a return period of 100 years at the Dollard. Figure 3.9 shows the wave height series and the peak duration of this storm is 15 hours with a wave height of around 1.4 m. The maximum wave height the revetment can withstand for 15 hours on a slope of 1:6 is around 1.2 m (Figure 5.2). The waves are larger during the storm, thus the revetment will probably fail. This conclusion is supported by the calculation of the failure fraction as is shown in the bottom figure of 3.9.

The results of effect of the slope angle on the return period (Table 4.7) also showed that there is a large difference between the return periods for the 2023 and the 2073 scenario. Climate change clearly affects the durability of the revetment. For example, the return period of failure for a slope of 1:8 was 140 years without climate change and 50 years with climate change. For the 2073 scenario, the most extreme climate scenario was used. These results show the importance of climate change for future design decisions of a dike. Climate change has to be considered for the application of green dikes at the coast, because when the sea level continuous to rise, the revetment fails more often. It is then questionable if the construction of a grass revetment is a sustainable process due to frequent replacement.

Next to the effect of climate change, the effect of the different relations on the resistance-duration was also considered. The effect of the different relations on the resistance-duration curve seems to be small. However, the sensitivity analysis already showed that small differences in the resistance-duration curve might lead to a substantial different return period. To look into the effect of the three different relations on the return period, the calculation of the storm leading to failure of the revetment was repeated with the other two relations. The results are presented in

Table 5.4: The effect of the different relations on the return period (in years) of the storm when the grass revetment fails. Calculations are based on the WBI model.

	Relation f_α		**Relation n**		**Relation R_e**	
	2023	2073	2023	2073	2023	2073
1:3	10	10	10	10	10	10
1:4	10	10	20	10	30	10
1:5	20	10	30	20	70	30
1:6	30	10	60	30	160	60
1:7	30	20	90	40	400*	120
1:8	40	20	140	50	800*	220

*the return period is estimated

Table 5.4. The results show that the different relations have a substantial effect on the calculation of the return period of the storm when the grass revetment fails. This observation emphasizes the importance of this study and follow-up studies to this effect. This study already showed that relation n resulted in an accurate representation of the experiments due to the low error. However, the relation is not optimised and can probably be improved.

5.4 Limitations and assumptions

During the study, multiple assumptions were made. To analyse to what extend these assumptions influenced the final result, a few changes in the assumptions and calculations are discussed below.

First, this study focused on the moment of failure of the grass revetment, but the definition of failure of the different experiments might differ. In this study, failure was defined as the moment the top 20 cm of the revetment with grass is eroded. However, roots are mostly present until a depth of around 50 centimeter [Sprangers, 1989]. A side note is that the density of roots rapidly decreases over depth. Some additional strength due to the roots of the grass might contribute to the strength below the top revetment of 20 cm, but this was estimated to be small and was thus not included in this research.

Additionally, the documentation of a few experiments did not describe the failure definition and therefore it is not clear whether the same moment of failure was used as in this study. Some documentation did describe the erosion rate. From this information, the moment of failure of the revetment was established with the assumption that the erosion was linear. It is possible that the erosion rate of the top few centimeters is lower than below, since the density of the roots decrease over depth. Thus, the establishment of the moment of failure from erosion rates contains some uncertainty.

Second, in reality, the water level and wave height varies during a storm as is shown in Figure 3.9. The experiments, with an exception for the experiment by Burger, used a constant water level and wave height. When the water level and wave height varies, the location on the slope of the wave impact differs. When the wave attacks at different heights, the duration until failure will probably be higher than when a wave attacks repeatedly at the same location. This effect was not included in this study.

Next to that, potential wave run-up was also not included in this study. When the water level increases, it is possible that the grass is damaged due to wave run-up before the waves directly attack that location on the dike. However, this effect will probably not lead to different results since wave impact is dominant over wave run-up [Van Hoven, 2015a]. Moreover the failure fractions are summed regardless the exact location of impact.

Third, the number of experiments is limited. At the start of this research, a experiments with closed and open sods were separated. Due to the limited number of experiments on open sods, it will not be reliable to draw conclusions on the resistance-duration curves of open sods. Besides, the variation in slope angles between the experiments with open sods was limited, thus it was not reliable to deduct a relation between the slope angle and the resistance-duration. However, it is expected that the relation (relation n) that is concluded based on experiments with closed sods gives a good indication for cases with open sods. On the other hand, when the grass density on the slope decreases, the velocity of the water that runs down on the slope after a wave attack increases. This results in a less effective damping effect. The extend of the decrease of the damping effect is probably small in comparison to the effect of the slope angle on the damping effect. Relation n will therefore be a good indication for open sods cases.

Fourth, the relation is only reliable for slope angles between 1:1.5 and 1:8 since this was the range of the slopes used in the experiments. For open sods, the reliable interval is only 1:1.5 to 1:4. Next to this, the maximum wave height of the experiments was around 1.8 meter. Thus, for storms with waves higher than 1.8 meter, the resistance-duration curves are not reliable. When it is desirable to use the found relation to estimate the resistance-duration curve for gentle slopes, it is important to keep in mind that the relation is based on a limited amount of experiments with different grass qualities.

Next to the assumptions and limitations of this study, the results of this research can be applied to other cases. This study was focused on a sea dike, but the effect of the slope angle is also applicable on green dikes around a lake. Additionally, the effect is probably applicable on green dikes next to rivers. However, the continuous flow of water in rivers can already affect the strength of the revetment. Additional research has to be executed to include this effect. The return periods were calculated for the case at the Dollard, but the calculations of the return period of the storm when the grass revetment fails can be applied to other cases with wave impact on grass revetment. When the designed storm contains waves smaller than 2 meter, the results of this study can have a large impact on the safety assessment of the flood defence structure. When the relation between slope angle and resistance-duration is applied and the slope is gentle, this study can show that the structure is safe and will not fail. Additionally, when the design storm has a wave height that exceeds 2 meter, this study can still contribute to the safety assessment and the strategy of maintenance of the revetment.

Chapter 6

Conclusion and recommendations

In this chapter the conclusions are presented for every research question. Thereafter, some recommendations for further research and for executing the safety assessment are given.

6.1 Conclusions

The goal of the study was to obtain knowledge on the effect of the slope angle of a green dike on the durability of the grass revetment. To achieve this, four different research questions were set up and these are answered below.

How can experiments on grass erosion due to wave impact with different slope angles be compared?

Experiments were performed using different slope angles, grass qualities and wave heights which made them hard to compare. The WBI suggests three different grass qualities: closed, open and fragmented sods. All the experiments had closed or open sods and were categorised accordingly. To compare the experiments with different slope angles, three possible relations between slope angle and resistance-duration were found in literature. The effect of the slope angle on the resistance-duration of clay (relation f_α), on the maximum wave impact (relation n) and on the erosion rate (relation R_e). All the experiments were transposed to a slope of 1:3 according to this relations. In this way, resistance-duration curves could be generated for the different grass qualities and according to the different relations to compare the variety of experiments.

Which relation between slope angle and resistance-duration describes the empirical data the most accurately?

With both the WBI and WIPE model, resistance-duration curves were generated for the closed and open sods and per relation. The errors between the resistance-duration curves and the experiments were calculated and the relation between the slope angle and the wave impact (relation n) resulted in the smallest error. Relation n is a linear negative correlation between the slope angle and resistance-duration. This means that a grass revetment on a slope of 1:6 has twice the resistance-duration compared to a revetment on a slope of 1:3 with similar wave conditions. The conclusion is mainly based on the experiments with closed sods, since the few experiments with open sods lacked variety in slope angle. However, relation n gives a good indication for the effect of the slope angle in open sods cases, because the slope angle affects the impact of waves to a greater extend than the density of the roots do.

What is the effect of the slope angle on the failure probability?

For the wide green dike at the Dollard, the resistance-duration was calculated for the different slope angles. From these calculations, two major conclusions can be drawn. During a storm with large waves, the slope hardly influences the moment that the revetment fails. This is caused by the fact that the difference in resistance-duration between the slope angles is small when the wave heights are large. The other conclusion is that the slope angle has a large effect on the return period of failure. For the scenario of 2023, the return period for a slope of 1:3 is 10 years, and for a slope of 1:8 is 140 years according to the WBI model. Without the relation included in the calculation of the return period, a dike with a slope of 1:8 will be assessed similar as a dike with a slope of 1:3. The WIPE model also showed differences between the slope angles, but less extreme. The calculations with the WIPE model resulted in the same scenario in a return period of 50 years for a slope of 1:8.

How is the resistance-duration affected by grass quality parameters?

Variation in the grass quality affects the resistance-duration different for the WBI and WIPE model. Variation in the steepness of the resistance-duration curve of the WBI model (parameter b) affects the return period more than variation in the maximum wave heights for a few hours (parameter a of the WBI model). The change of the parameters of the WIPE model did not lead to a variation in the steepness of the resistance-duration curve. The tensile strength is an uncertain parameter which also affects the resistance-duration more than the root area ratio.

6.2 Recommendations

The recommendation are classified as recommendations for further research to increase the knowledge and recommendations for the safety assessment nowadays.

6.2.1 Further research

Due to a small amount of experiments on wave impact, the uncertainty of the resistance-duration is high and the knowledge on the effect of different conditions on the resistance-duration is limited. Extra full-scale wave impact on grass revetment experiments can contribute to a decrease in the uncertainty. It is recommended to execute the experiments on a gentle slope, because most experiments were executed on a steep slope of around 1:3 or 1:4. It is also recommended to focus on the wave height between 0.5 m and 1.5 m. It is likely that a wave height in this interval has a resistance-duration that is close to the peak of the maximum storm the revetment can withstand, which is a duration of around 20 hours. Experiments with both closed and open sods will contribute to the understanding of the effect of the slope angle on the resistance-duration. As was mentioned before, it is expected that the effect of the slope angle on resistance-duration will be similar in both cases.

As was shown in the results of the sensitivity analysis, the tensile strength is sensitive and has a substantial impact on the resistance-duration. The values of the tensile strength are diverse according to a variety of studies [Trükmann et al., 2009,Valk, 2009,Hoffmans et al., 2010]. To achieve reliable results, it is of great importance that the tensile strength can be accurately estimated or measured. Additionally, it is valuable to gain insight in the variation of the tensile strength of the grass. For examples when the grass is young, the roots will probably not be developed to its fullest and the grass will be weaker. Also, due to natural variation, the tensile strength can vary along grasses with the same species. If there is a spot on the slope where the tensile strength is lower, the revetment will probably fail at that specific location. This affects the safety of the dike. In the WBI, there is no distinction between grass species with a different tensile strength while it has a large impact on the resistance-duration curve. There was already research executed on the tensile strength of different species. It is highly recommended to include this parameter in the WBI safety assessment to achieve reliable results.

Various experiments were executed to measure the maximum wave impact on a hard revetment instead of grass. There are two additional studies needed to improve our understanding of the load on the revetment due to wave impact. The force that damages the grass revetment is the uplifting force that is a result of the wave impact pressure. The uplift force is less than the wave impact force and extra studies could aid in understanding the translation of the wave impact to the uplift force. The other recommendation is to execute experiments in which waves attack the slope on different locations due to variations in water level. In this way, a more realistic storm can be simulated and eventually the resistance-duration can be estimated more accurately for the sea dikes. The effect of a changing water level will probably increase the resistance-duration of the revetment since different parts of the grass revetment are loaded.

Next to the suggested experiments, the demonstration project “Wide Green Dike” at the Dollard can be used for further research. Primary, it is advised to monitor the grass revetment and to measure the wave heights at the toe of the dike during a storm. With these measurements, relation n can be validated for a slope of 1:7. Since the project is a demonstration project, it might be possible to vary the root density or the type of the grass along the coastline. When the root density is varied, research can be executed to find the relation between open and closed sods. When the type of grass is varied along the slope, measurements can contribute to research the effect of the tensile strength on the resistance-duration. Additionally, it can result in the implementation of the tensile strength parameter in the safety assessment.

6.2.2 Safety assessment

The main finding of this study is the relation of the slope angle with the resistance-duration. Therefore, it is advised to use the found relation (relation n) to estimate the resistance-duration for a case with gentle slope. It is recommended to use this relation in the customised assessment of the WBI. More research, as is mentioned above, has to be executed to increase the reliability of the effect. The effect of the slope angle was found to be large, thus it should be implemented in the detailed assessment as soon as possible as well.

Next to the found relation of the slope angle on the resistance-duration, this study showed that the threshold value on the WBI model can be increased. Both literature and the WIPE model do not show failure of the revetment due to waves lower than 0.5 m. Therefore, it is recommended to increase the threshold in the WBI model from 0.25 to 0.5 m in the detailed assessment. Parameter a of the WBI model has to be adjusted to compensate for the increase of the threshold. This means that the value of parameter a decreases with 0.25 m when the threshold value increases with 0.25 m. Additionally, the fitting of this study showed small differences with the suggested values of the WBI: higher waves at resistance-duration of 0 hours (increase of parameter a) and a steeper curve (decrease of parameter b) for a slope of 1:3. Since, the differences are small, it is advised to use the suggested values of the WBI for parameter a and b.

This study showed that the effect of the grass revetment is neglectable when waves exceed 2 meter. However, no experiments with waves higher than 2 meter were used in this study. Thus, more research has to be executed on the resistance-duration of the grass revetment on a gentle slope against waves higher than 2 meter.

When a safety assessment has to be executed and the maximum wave height is between 0.5 m and 2 m, it is recommended to do a quick assessment as is described in the discussion. The quick assessment checks if the resistance-duration, that corresponds to the maximum wave height, is longer than the peak of the storm. In the case of the Dollard with a foreland, this peak is around 15 hours. When the resistance-duration that corresponds to the maximum wave height is shorter than the storm, it can be assumed that the revetment will fail. When no clear conclusion can be drawn from the quick calculation, it is recommended to execute the safety assessment and calculate the failure fractions.

Next to the importance of the resistance-duration of the grass revetment for the design of a dike, the resistance-duration is indirectly valuable for the maintenance of the revetment. It is recommended to compute the return period of the storm that leads to failure of the revetment as was done in this research. An estimation of the costs and the maintenance strategy can then be made.

As was mentioned before, a change of the tensile strength has a large impact on the resistance-duration. Thus, a good prediction of the tensile strength is of great importance to calculate resistance-duration with the WIPE model. Next to the tensile strength, there is a variety of soil parameters and coefficients in the WIPE model. To determine the values of these parameters, much research on the site has to be executed. Another disadvantage of the WIPE model is that it takes a long time to run the model and there are no indications in this study that the WIPE model performs better than the WBI model. It is thus recommended to continue using the WBI model for the safety assessment as long as the values of the parameters remain uncertain.

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Appendices

Appendix A

List of parameters

A	Surface area	[m^2]
A_{block}	Surface area of the block	[m^2]
A_r	Root area	[m^2]
a	Empirical parameter	[m]
b	Empirical parameter	[h^{-1}]
c	Threshold wave height	[m]
c_{clay}	Cohesion of clay	[N/m^2]
$c_{clay,c}$	Critical clay cohesion	[N/m^2]
c_{grass}	Artificial grass cohesion	[N/m^2]
$c_{grass,c}$	Critical grass cohesion	[N/m^2]
c_{soil}	Cohesion	[N/m^2]
d_a	Aggregate diameter at the surface	[m]
d_c	Distance in crack	[m]
d_e	Maximum erosion depth	[m^3/m]
d_r	Root diameter	[m]
f_α	Linear slope angle correction factor	[-]
F_c	Cohesion force	[N]
F_{frac}	Failure fraction	[-]
F_g	Grass reinforcement	[N]
F_p	Uplift force	[N]
F_s	Shear force	[N]
F_t	Predicted value	[-]
F_w	Force due to own weight	[N]
g	Gravitational acceleration	[m/s^2]
H_s	Significant wave height	[m]
MAE	Mean absolute error	[-]
n	Porosity	[-]
n_v	Number of values	[-]
$p(q)$	Chance of occurrence of impact factor	[-]
p_c	Critical uplift pressure	[N/m^2]
p_{max}	Maximum wave impact	[N/m^2]
p_{up}	Uplift pressure	[N/m^2]
p_w	Pore water pressure	[N/m^2]
q	Impact factor	[-]
q_{avg}	Average impact factor	[-]
r_a	Factor slope angle effect	[-]
RAR_0	Root area ratio at the surface	[-]
R_e	Erosion rate	[m/h]
$RMSE$	Root Mean Square Error	[-]
t	Time	[h]
T	Return period	[year]
t_{imp}	Characteristic impact time	[s]
t_r	Root tensile strength	[N/m^2]
$t_{s,top}$	Time to failure of grass revetment	[h]
$t_{s,top,max}$	Maximum value for the strength duration of the top layer	[h]

$t_{s,top,min}$	Minimum value for the strength duration of the top layer	[h]
V_e	Erosion velocity	[m^3/m]
Y_t	Predicted value	[-]
z_{min}	Depth of minimum fracture strength	[m]
α	Dike slope angle	[°]
α_{crack}	Crack calibration parameter	[-]
α_{soil}	Soil calibration parameter	[-]
β	Root decay parameter	[-]
Δt	Time step	[h]
θ	Root angle of rotation	[°]
μ	Pressure reduction coefficient	[m^{-1}]
ρ_s	Density of soil	[kg/m^3]
ρ_w	Density of water	[kg/m^3]
σ	Normal stress	[N/m^2]
σ'	Effective normal stress	[N/m^2]
σ_f	Fracture resistance	[N/m^2]
σ_{grass}	Normal grass strength	[N/m^2]
$\sigma_{grass,c}$	Critical normal grass strength	[N/m^2]
σ_q	Parameter probability density function	[-]
σ_{std}	Standard deviation	[-]
τ	Soil shear stress	[N/m^2]
ϕ'	Effective angle of internal friction	[°]

Appendix B

WIPE model

Basic equation

$$\gamma_m = \sum_{1}^{N_{imp}} \frac{(p_{up}(z) - p_c(z)) * t_{imp}}{E_p(z)}$$

Where:

γ_m : Erosion depth [m]

z : Depth [m]

N_{imp} : Number of waves causing an impact [-]

p_{up} : Uplift pressure underneath an aggregate after wave impact [N/m^2]

p_c : Critical uplift pressure [N/m^2]

t_{imp} : Characteristic impact time [s]

E_p : Erosion parameter [kg/m^{2}s]

Load terms

$$N_{imp} = \alpha_w N_w$$

$$N_w = \frac{T_{storm}}{T_m}$$

$$p_{up}(z) = \frac{p_{max,i}}{1 + \mu d_c}$$

Where:

α_w : Wave impact coefficient between 0.0-1.0 [-]

N_w : Number of waves in a storm [-]

T_{storm} : Storm duration [s]

T_m : Average wave period [s]

$p_{max,i}$: Maximum impact pressure exceeded by i% of the waves [N/m^2]

μ : Pressure reduction coefficient [m^{-1}]

d_c : Distance in crack [m]

Grass strength and Characteristic aggregate parameter

$$\sigma_{grass,c}(z) = t_{r,c} * RAR_0 * e^{-\beta z}$$
$$c_{grass,c}(z) = 1.2 * t_{r,c} * RAR_0 * e^{-\beta z}$$
$$d_a = \sqrt{\frac{A}{n_r}} + 0.08 * z$$

Where:

$\sigma_{grass,c}$: Critical grass normal strength [N/m^2]
$t_{r,c}$: Critical grass tensile strength [N/m^2]
RAR_0 : Root Area Ratio at the surface [-]
β : Coefficient of root decrease over depth [m^{-1}]
$c_{grass,c}$: Critical root cohesion [N/m^2]
d_a : Aggregate diameter [m]
A : Surface area of the soil [m^2]
n_r : Number of roots [-]

Block erosion

$$p_c = (1-n)(\rho_s - \rho_w)gz_{min} + \frac{0.5 n_s f(\rho_s - \rho_w) g z_{min}^2}{d_a} + \frac{n_s(\int_0^{z_{min}} c_{grass,c}(z) + c_{clay,c} z_{min})}{d_a} + \sigma_{grass,c} z_{min}$$
$$E_p(d_a)) = \alpha_{soil} * \frac{\rho_s}{\rho_w} * \frac{p_c(d_a)}{\sqrt{g d_a}}$$
$$\sigma_f = (1-n)(\rho_s - \rho_w)gz + \frac{0.5 n_s f(\rho_s - \rho_w) g z^2}{d_a} + \sigma_{grass,c}(z)$$
$$\Delta A_{block} = \frac{(p_{up}(d_a) - \sigma_{f,min}(d_a))A_{block}}{\alpha_{crack}(\sigma_{f,min}(d_a) + c_{clay,c})}$$

Where:

A_{block} : Surface area of the block [m^2]
n : Porosity [-]
ρ_s : Density of the soil [kg/m^3]
ρ_w : Density of water [kg/m^3]
n_s : Side wall coefficient [-]
f : Friction factor $tan(\phi)$ [-]
z_{min} : Depth of minimum fracture strength [m]
a_{block} : Block area [m^2]
$\sigma_{f,min}$: Minimum fracture strength [N/m^2]
α_{soil} : Calibration coefficient [m]
α_{crack} : Crack extension coefficient [-]

Appendix C

Python code

C.1 Reference

Different packages are used additionally to Python 3.7 to reach the objective of this study. The used packages are shown below.

Package	Version
AdjustText	0.7.3
Matplotlib	3.1.1
Numpy	1.16.4
Pandas	0.24.2

C.2 Code

The Python scripts are shown in the appendix. Since many codes that are almost similar are written, some codes are excluded to remain the overview. The data is transposed according to three different relations, but only one of the three is shown since it is clear in the code what and where to change for the different relations.

C.2.1 Transposing the data

```
import math
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from adjustText import adjust_text
from matplotlib.lines import Line2D

grassquality = 'Closed'  # Fill in the option (Open OR Closed)

#                                                                            INPUT
# ---------------------------------------------------------------------------------

# Input parameters from experiments via excel
df = pd.read_excel(r'C:\Users\NLMPET\Documents\Python\V2\Input.xlsx',
                   sheet_name=grassquality)
Hout = df.loc[0]  # Wave height values [m]
alpha = df.loc[1]  # Slope [-]
output = df.loc[2]  # Output tstop according tot the experiments [h]
fail = df.loc[3]  # Failed at t (1 = yes, 0 = no)
title = df.loc[4]  # Titles of experiment

Hout = np.delete(np.array(Hout), [0])
alpha = np.delete(np.array(alpha), [0])
output = np.delete(np.array(output), [0])
```

```
fail = np.delete(np.array(fail), [0])
expcode = np.delete(np.array(df.columns), [0])

prob = [50, 95, 99]
if grassquality == 'Open':
    a = [1.4, 0.8, 0.4]  # Empirical parameter [m]
    b = -0.07  # Empirical parameter [h-1]
elif grassquality == 'Closed':
    a = [1.81, 1, 0.5]  # Empirical parameter [m]
    b = -0.035  # Empirical parameter [h-1]

c = 0.25  # Empirical parameter [m]

# Other input parameters
tstopmax = 65  # Maximum resistance-duration [h]

#                                                                   STANDARDISING
# -------------------------------------------------------------------------------
ra = 1.51  # Slope angle effect factor [-]
fa = ((ra - 1) / 3) / alpha + 2 - ra  # Slope correlation factor [-]
tstopexp = output / fa  # Standardised resistance-duration of experiments [h]
tstopexp = np.where(tstopexp < tstopmax - 5, tstopexp, 60)

#                                                         GENERATE INITIAL CURVES
# -------------------------------------------------------------------------------
Hsstored = []
tstopprob = []
for p in range(0, len(prob)):
    Hmin = c  # Minimum value of wave height that can be calculated [m]
    Hmax = a[p] + c  # Maximum value of wave height that can be calculated [m]
    Hs = np.around(np.arange(Hmin, Hmax, 0.01), decimals=2)# Boundary of Hs
                                                          # for curve
    tstopstoredinitial = []
    for x in range(0, len(Hs)):
        if Hs[x] >= a[p] + c or a[p] == 0:
            tstopgen = 0  # Generated resistance-duration [h]
        elif Hs[x] <= c:
            tstopgen = tstopmax
        else:
            tstopgen = 1 / b * math.log((Hs[x] - c) / a[p])
        if tstopgen > tstopmax:
            tstopfinal = tstopmax
        else:
            tstopfinal = tstopgen
        tstopstoredinitial.append(tstopfinal)
    tstopprob.append(tstopstoredinitial)
    Hsstored.append(Hs)
Hsstored = pd.DataFrame(Hsstored)
tstopprob = pd.DataFrame(tstopprob)
Hs50 = Hsstored.loc[0]
Hs90 = Hsstored.loc[1]
Hs99 = Hsstored.loc[2]
tstop50 = tstopprob.loc[0]
tstop90 = tstopprob.loc[1]
tstop99 = tstopprob.loc[2]

# Plot resistance-duration curve (initial) against observed values
f, ax = plt.subplots()
```

```
ax.plot(tstop50, Hs50, color='blue', linestyle='dashed',
        label='Resistance-duration curve (prob = 50%)')
ax.plot(tstop90, Hs90, color='black', linestyle='dashed',
        label='Resistance-duration curve (prob = 90%)')
ax.plot(tstop99, Hs99, color='grey', linestyle='dashed',
        label='Resistance-duration curve (prob = 99%)')
plt.scatter(tstopexp, Hout, alpha=1, c=fail, cmap='RdYlGn_r', s=40,
            label='Observed resistance-duration')   # Red = failed,
                                                     # Green = not failed
texts = [plt.text(tstopexp[i], Hout[i], expcode[i]) for i in
         range(len(output))]
adjust_text(texts)

legend_elements =  [Line2D(tstop50, Hs50, color='blue', linestyle='dashed',
        label='Resistance-duration curve (prob = 50%)'),
                   Line2D(tstop90, Hs90, color='black', linestyle='dashed',
        label='Resistance-duration curve (prob = 90%)'),
                   Line2D(tstop99, Hs99, color='grey', linestyle='dashed',
        label='Resistance-duration curve (prob = 99%)'),
                   Line2D([0], [0], marker='o', color='w',
                          label='Observed resistance-duration (not failed)',
                          markerfacecolor='#335e22', markersize=12),
                   Line2D([0], [0], marker='o', color='w',
                          label='Observed resistance-duration (failed)',
                          markerfacecolor='#891508', markersize=12),
                   ]

plt.xlim(0, tstopmax-1)
plt.ylim(0, 2.2)
plt.xlabel('Time [h]')
plt.ylabel('Wave height [m]')
plt.title(grassquality, fontsize=15)
ax.legend(handles = legend_elements)
plt.show()
```

C.2.2 Fitting WBI model

```
import math
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from adjustText import adjust_text
from matplotlib.lines import Line2D

grassquality = 'Closed'  # Fill in the option (Open OR Closed)
calibrate = 'ab'  # Fill in to calibrate on a or b

#                                                               DEFINE FUNCTIONS
# ------------------------------------------------------------------------------

def find_nearest(array, value):
    array = np.asarray(array)
    idx = (np.abs(array - value)).argmin()
    return array[idx]

#                                                                          INPUT
# ------------------------------------------------------------------------------
```

```
# Input parameters from experiments via excel
df = pd.read_excel(r'C:\Users\NLMPET\Documents\Python\V2\Input.xlsx',
                   sheet_name=grassquality)
Hout = df.loc[0]  # Wave height values [m]
alpha = df.loc[1]  # Slope [-]
output = df.loc[2]  # Output tstop according tot the experiments [h]
fail = df.loc[3]  # Failed at t (1 = yes, 0 = no)
title = df.loc[4]  # Titles of experiment

Hout = np.delete(np.array(Hout), [0])
alpha = np.delete(np.array(alpha), [0])
output = np.delete(np.array(output), [0])
fail = np.delete(np.array(fail), [0])
expcode = np.delete(np.array(df.columns), [0])


if grassquality == 'Open':
    a = 1.4  # Empirical parameter [m]
    b = -0.07  # Empirical parameter [h-1]
elif grassquality == 'Closed':
    a = 1.81  # Empirical parameter [m]
    b = -0.035  # Empirical parameter [h-1]

c = 0.25  # Empirical parameter [m]

# Other input parameters
tstopmax = 65  # Maximum resistance-duration [h]

#                                                               STANDARDISING
# ---------------------------------------------------------------------------
ra = 1.51  # Slope angle effect factor [-]
fa = ((ra - 1) / 3) / alpha + 2 - ra  # Slope correlation factor [-]
tstopexp = output / fa  # Standardised resistance-duration of experiments [h]
tstopexp = np.where(tstopexp < tstopmax - 5, tstopexp, 60)

#                                                     GENERATE INITIAL CURVES
# ---------------------------------------------------------------------------
Hmin = c  # Minimum value of wave height that can be calculated [m]
Hmax = a + c  # Maximum value of wave height that can be calculated [m]
Hs = np.around(np.arange(Hmin, Hmax, 0.01), decimals=2)# Boundary of Hs
                                                         # for curve


#                                                      CALCULATE LOWEST ERROR
# ---------------------------------------------------------------------------
aserie = np.around(np.arange(0, a + 1, 0.01), decimals=2)
bserie = np.around(np.arange(-0.1, -0.01, 0.01), decimals=2)
totalMAEstored = []
MAEmin = 100

if calibrate == 'a':
    print('calibration on a')
    for ax in range(0, len(aserie)):
        a = aserie[ax]
        tstopstored = []
        diffstored = []
        totalMAEstored = []
        for x in range(0, len(Hs)):
```

```
            if Hs[x] >= a + c or a == 0:
                tstop = 0  # Resistance-duration [h]
            elif Hs[x] <= c:
                tstop = tstopmax
            else:
                tstop = 1 / b * math.log((Hs[x] - c) / a)
            if tstop > tstopmax:
                tstopfinal = tstopmax
            else:
                tstopfinal = tstop
            tstopstored.append(tstopfinal)

        count = 0
        for y in range(0, len(tstopexp)):
            tstopfound = find_nearest(tstopstored,
                                      tstopexp[y])  # Search for closest
            # resistance-duration value to the value of the experiment
            tindex = np.where(tstopstored == tstopfound)  # Search for index
            HWBI = Hs[int(tindex[0][0])]  # Search for corresponding wave height

            if fail[y] == 0 and Hout[y] > HWBI:
                diff = abs(Hout[y] - HWBI)
            elif fail[y] == 1 and Hout[y] < HWBI:
                diff = abs(Hout[y] - HWBI)
            else:
                diff = 0
            count = count + 1
            diffstored.append(diff)

        MAE = 1 / count * np.sum(diffstored)
        totalMAEstored.append(MAE)
        if MAE < MAEmin:
            MAEmin = MAE
            axmin = ax
    a = aserie[axmin]

elif calibrate == 'b':
    print('calibration on b')
    for bx in range(0, len(bserie)):
        b = bserie[bx]
        tstopstored = []
        diffstored = []

        for x in range(0, len(Hs)):
            if Hs[x] >= a + c or a == 0:
                tstop = 0  # Resistance-duration [h]
            elif Hs[x] <= c:
                tstop = tstopmax
            else:
                tstop = 1 / b * math.log((Hs[x] - c) / a)
            if tstop > tstopmax:
                tstopfinal = tstopmax
            else:
                tstopfinal = tstop
            tstopstored.append(tstopfinal)

        count = 0
        for y in range(0, len(tstopexp)):
```

```
            tstopfound = find_nearest(tstopstored,
                                      tstopexp[y])  # Search for closest
            # resistance-duration value to the value of the experiment
            tindex = np.where(tstopstored == tstopfound)  # Search for index
            HWBI = Hs[int(tindex[0][0])]  # Search for corresponding wave height

            if fail[y] == 0 and Hout[y] > HWBI:
                diff = abs(Hout[y] - HWBI)
            elif fail[y] == 1 and Hout[y] < HWBI:
                diff = abs(Hout[y] - HWBI)
            else:
                diff = 0
            count = count + 1
            diffstored.append(diff)

        MAE = 1 / count * np.sum(diffstored)
        totalMAEstored.append(MAE)
        if MAE < MAEmin:
            MAEmin = MAE
            bxmin = bx
    b = bserie[bxmin]

elif calibrate == 'ab':
    print('calibration on both a and b')
    for bx in range(0, len(bserie)):
        b = bserie[bx]
        totalMAEstored = []

        for ax in range(0, len(aserie)):
            a = aserie[ax]
            tstopstored = []
            diffstored = []

            for x in range(0, len(Hs)):
                if Hs[x] >= a + c or a == 0:
                    tstop = 0  # Resistance-duration [h]
                elif Hs[x] <= c:
                    tstop = tstopmax
                else:
                    tstop = 1 / b * math.log((Hs[x] - c) / a)
                if tstop > tstopmax:
                    tstopfinal = tstopmax
                else:
                    tstopfinal = tstop
                tstopstored.append(tstopfinal)

            count = 0
            for y in range(0, len(tstopexp)):
                tstopfound = find_nearest(tstopstored,
                                          tstopexp[y])  # Search for closest
                # resistance-duration value to the value of the experiment
                tindex = np.where(tstopstored == tstopfound)  # Search for index
                HWBI = Hs[
                    int(tindex[0][0])]  # Search for corresponding wave height

                if fail[y] == 0 and Hout[y] > HWBI:
                    diff = abs(Hout[y] - HWBI)
                elif fail[y] == 1 and Hout[y] < HWBI:
```

```
                diff = abs(Hout[y] - HWBI)
            else:
                diff = 0
            count = count + 1
            diffstored.append(diff)

        MAE = 1 / count * np.sum(diffstored)
        totalMAEstored.append(MAE)
        if MAE < MAEmin:
            MAEmin = MAE
            axmin = ax
            bxmin = bx
    a = aserie[axmin]
    b = bserie[bxmin]
else:
    print('no calibration done')

print(a, b)
print(MAEmin)

#                                                         CALCULATE FINAL CURVE
# -----------------------------------------------------------------------------

tstopinitial = []
for x in range(0, len(Hs)):
    if Hs[x] >= a + c or a == 0:
        tstopgen = 0   # Generated resistance-duration [h]
    elif Hs[x] <= c:
        tstopgen = tstopmax
    else:
        tstopgen = 1 / b * math.log((Hs[x] - c) / a)
    if tstopgen > tstopmax:
        tstopfinal = tstopmax
    else:
        tstopfinal = tstopgen
    tstopinitial.append(tstopfinal)

#                                                                          PLOT
# -----------------------------------------------------------------------------
# Plot resistance-duration curve (initial) against observed values
f, ax = plt.subplots()
ax.plot(tstopinitial, Hs, color='blue', linestyle='dashed',
        label='Resistance-duration curve')
plt.scatter(tstopexp, Hout, alpha=1, c=fail, cmap='RdYlGn_r', s=40,
            label='Observed resistance-duration')   # Red = failed,
                                                    # Green = not failed
texts = [plt.text(tstopexp[i], Hout[i], expcode[i]) for i in
         range(len(tstopexp))]
adjust_text(texts)

legend_elements =  [Line2D(tstopinitial, Hs, color='blue', linestyle='dashed',
        label='Resistance-duration curve'),
                   Line2D([0], [0], marker='o', color='w',
                          label='Observed resistance-duration (not failed)',
                          markerfacecolor='#335e22', markersize=12),
                   Line2D([0], [0], marker='o', color='w',
                          label='Observed resistance-duration (failed)',
                          markerfacecolor='#891508', markersize=12),
```

```
                   ]

plt.xlim(0, tstopmax-1)
plt.ylim(0, 2.2)
plt.xlabel('Time [h]')
plt.ylabel('Wave height [m]')
plt.title(grassquality, fontsize=15)
ax.legend(handles = legend_elements)
plt.show()
```

C.2.3 Fitting WIPE model

```
import math
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from adjustText import adjust_text
from matplotlib.lines import Line2D

def find_nearest(array, value):
    array = np.asarray(array)
    idx = (np.abs(array - value)).argmin()
    return array[idx]

grassquality = 'Closed'  # Fill in the option (Open OR Closed)
it = 150

#                                                                    CALCULATE PMAX
# --------------------------------------------------------------------------------

q_dist = pd.read_excel(r'C:\Users\NLMPET\Documents\Python\Prob_function_V2.xlsx',
                       sheet_name='gamma', header=None)
q = np.array(q_dist.loc[0])
prob = np.array(q_dist.loc[3])
Hmin = 0.25
Hmax = 2.15
Hs = np.around(np.arange(Hmin, Hmax, 0.01), decimals=2)
alpha = 1 / 3

#                                                                        LOAD DATA
# --------------------------------------------------------------------------------

# Input parameters from experiments via excel
df = pd.read_excel(r'C:\Users\NLMPET\Documents\Python\V2\Input.xlsx',
                   sheet_name=grassquality)
Hout = df.loc[0]  # Wave height values [m]
alphaexp = df.loc[1]  # Slope [-]
output = df.loc[2]  # Output tstop according tot the experiments [h]
fail = df.loc[3]  # Failed at t (1 = yes, 0 = no)
title = df.loc[4]  # Titles of experiment

Hout = np.delete(np.array(Hout), [0])
alphaexp = np.delete(np.array(alphaexp), [0])
output = np.delete(np.array(output), [0])
fail = np.delete(np.array(fail), [0])
expcode = np.delete(np.array(df.columns), [0])

#                                                                  STANDARDISING
```

```
# ------------------------------------------------------------------------------
tstopmax = 65  # Maximum resistance-duration [h]
ra = 1.51  # Slope angle effect factor [-]
fa = ((ra - 1) / 3) / alpha + 2 - ra  # Slope correlation factor [-]
tstopexp = output / fa  # Standardised resistance-duration of experiments [h]
tstopexp = np.where(tstopexp < tstopmax - 5, tstopexp, 60)
#                                                                     PROPERTIES
# ------------------------------------------------------------------------------

# Material properties
rhow = 1000  # Density of water [kg/m3]
rhos = 2000  # Density of the soil [kg/m3]
n = 0.4  # Porosity [-]
phi = 35  # Natural angle of response [-]
f = math.tan(phi)  # Friction factor sides of cube [-]
cclay = 30000  # Clay cohesion [N/m2]
cclayc = cclay / 80  # Critical clay cohesion [N/m2]
g = 9.81  # Acceleration of gravity [m/s2]

# Grass properties
dr = 0.13 * 10 ** - 3  # Root diameter [m]
tr = 20e6  # Root tensile strength [N/m2]
B = 22.32  # Beta root decay coefficient [m-1]
ns = 2  # Number of sides of the cube providing strength [-]

if grassquality == 'Closed':
    RAR0 = 0.0008  # Root Area Ratio [-]
else:
    RAR0 = 0.0004  # Root Area Ratio [-]

# Detectability parameter
alphasoil = [0.5, 1.5, 2.5, 3.5, 4.5]  # Calibration parameter [-]
alphacrack = 430  # Calibration parameter cracks [-]

# Load properties
mur = 5  # Pressure reduction coefficient in cracks [m-1]
timpact = 0.350  # Averaged impact duration [s]
Tstorm = 234000  # Storm duration [s] (equals to 65 hours)
T = 5  # Averaged wave period [s]
alphaw = 0.1  # Wave impact coefficient between 0.0-1.0 [-]
Nimp = alphaw * Tstorm / T  # Amount of wave impacts [-]

#                                                             START CALCULATIONS
# ------------------------------------------------------------------------------
tstopmeantotal = []
for cal in range(0, len(alphasoil)):
    tstoptable = []
    print(cal)
    for i in range(0, it):
        # Input
        random = np.random.rand(int(Nimp) + 1)  # Random generator
        print('i =', i)

        # Store values
        Pmaxmatrix = []

        for Ny in range(0, int(Nimp) + 1):
            totalPmax = []
```

```
    indexq = list(prob).index(find_nearest(prob, random[Ny]))
    for Nx in range(0, len(Hs)):
        NPmax = q[indexq] * rhow * g * Hs[
            Nx] * alpha / 0.25  # Impact pressure
        # [N/m2]
        totalPmax.append(NPmax)
    Pmaxmatrix.append(totalPmax)

Pmaxall = pd.DataFrame(Pmaxmatrix)
Pmaxall.columns = [Hs]

#                                                           STORE VALUES
# ----------------------------------------------------------------------
sigmafstored = []
RARzstored = []
sigmagrasscstored = []
cgrasscstored = []
sigmasblockstored = []
Epstored = []
Ablockstored = []
dblockstored = []
RMSEstored = []
diffstored = []
tstopstored = []

Pmaxmatrix = []
Pupmatrix = []
Ecmatrix = []
sigmafblockmatrix = []
totalerosion = 0
z = np.linspace(0, 0.2, 201)  # Depth [m]

#                                                          GENERATE CURVE
# ----------------------------------------------------------------------
for c in range(0, len(Pmaxall.iloc[0])):
    # Store values per wave height
    Pmaxstored = []
    Pupstored = []
    Ecstored = []
    sigmafblockstored = []

    for x in range(0, len(z)):
        # Initial values
        dblock = 0.004 + 0.08 * z[x]  # Aggregate diameter [m]
        RARz = RAR0 * math.exp(-B * z[x])  # Vertical RAR profile [-]
        sigmagrassc = 1.0 * RARz * tr  # Grass normal strength at depth z
        cgrassc = 1.2 * tr * RARz  # Critical grass cohesion
        sigmaf = ((1 - n) * (rhos - rhow) * g * z[x] + sigmagrassc + (
                0.5 * ns * f * (rhos - rhow) * g * z[x] ** 2) / dblock)
        # Fracture strength [N/m2]

        # Store values over z
        dblockstored.append(dblock)
        RARzstored.append(RARz)
        sigmagrasscstored.append(sigmagrassc)
        cgrasscstored.append(cgrassc)
        sigmafstored.append(sigmaf)
```

```
sigmafmin = sigmafstored.index(
    min(sigmafstored))  # Index of z of lowest
# value of sigmas [N/m2]
zmin = 0.001 * (
            sigmafmin - 1)  # Depth of minimum fracture strength [m]
RARzmin = RAR0 * math.exp(-B * zmin)  # Root area ration at zmin [-]
sigmagrasscmin = 1.0 * RARzmin * tr  # Grass normal critical strength at
# zmin [N/m2]
cgrasscint = (- 1 / B * 1.2 * RAR0 * tr * math.exp(- B * zmin)) - (
        - 1 / B * 1.2 * RAR0 * tr * math.exp(
    - B * 0))  # Integral of root cohesion
# over depth [N/km3]
dblock = dblockstored[
    sigmafmin - 1]  # Determine the aggregate diameter on
# the depth of minimum fracture
# strength [m]

for y in range(0, int(Nimp) + 1):
    # Large cracks/block erosion
    sigmafblock = (1 - n) * (
            rhos - rhow) * g * zmin + sigmagrasscmin + (
                          0.5 * ns * f * (
                          rhos - rhow) * g * zmin ** 2) / dblock
    # Fracture resistance block [N/m2]
    sigmasblock = (1 - n) * (
            rhos - rhow) * g * zmin + sigmagrasscmin + (
                          0.5 * ns * f * (
                          rhos - rhow) * g * zmin ** 2) / dblock + ns * (
                          cgrasscint + (cclayc * zmin)) / dblock
    # Critical uplift pressure block
    # Load
    Pmax = int(Pmaxall.iloc[y][Hs[c]])  # Impact pressure [N/m2]
    Pup = Pmax / (1 + mur * (
            zmin + 0.5 * dblock))  # Uplift pressure [N/m2]

    Ep = alphasoil[cal] * (rhos / rhow) * sigmasblock / math.sqrt(
        g * dblock)
    # Detachability parameter impact erosion [kg/m2 s]

    # Crack growth
    if Pup > sigmafblock:
        deltaAblock = ((Pup - sigmafblock) * dblock ** 2) / (
                alphacrack * (cclayc + sigmafblock))
    else:
        deltaAblock = 0

    dblock = dblock + math.sqrt(deltaAblock)
    Ablock = dblock ** 2

    # Block erosion
    Ec = ((Pup - sigmasblock) * timpact) / Ep

    # Store values over Nimp
    sigmafblockstored.append(sigmafblock)
    sigmasblockstored.append(sigmasblock)
    Pmaxstored.append(Pmax)
    Pupstored.append(Pup)
    Epstored.append(Ep)
```

```
                Ablockstored.append(Ablock)
                Ecstored.append(Ec)

                if Ec > zmin:  # Erosion criterion
                    break

            tstopfinal = y * T / alphaw / 3600
            Pmaxmatrix.append(Pmaxstored)
            Pupmatrix.append(Pupstored)
            Ecmatrix.append(Ecstored)
            sigmafblockmatrix.append(sigmafblockstored)
            tstopstored.append(tstopfinal)
        tstoptable.append(tstopstored)
    tstoptable = pd.DataFrame(tstoptable)
    tstoptable.columns = [Hs]
    tstopmean = tstoptable.mean(axis=0)
    tstopmeantotal.append(tstopmean)

tstopmeantotal = pd.DataFrame(tstopmeantotal)
print(tstopmeantotal)
tstopmeantotal.to_excel\
    (r'C:\Users\NLMPET\Documents\Python\tstopmeantotalcalnewopen.xlsx')

#                                                                   PLOT CURVE
# ----------------------------------------------------------------------------
f, ax = plt.subplots()
ax.plot(tstopmeantotal.iloc[0,:], Hs, color='blue', linestyle='dashed',
        label='Resistance-duration curve (alphasoil = 0.5')
ax.plot(tstopmeantotal.iloc[1,:], Hs, color='red', linestyle='dashed',
        label='Resistance-duration curve (alphasoil = 1.5')
ax.plot(tstopmeantotal.iloc[2,:], Hs, color='yellow', linestyle='dashed',
        label='Resistance-duration curve (alphasoil = 2.5')
ax.plot(tstopmeantotal.iloc[3,:], Hs, color='green', linestyle='dashed',
        label='Resistance-duration curve (alphasoil = 3.5')
ax.plot(tstopmeantotal.iloc[4,:], Hs, color='gray', linestyle='dashed',
        label='Resistance-duration curve (alphasoil = 4.5')
plt.scatter(tstopexp, Hout, alpha=1, c=fail, cmap='RdYlGn_r', s=40,
            label='Observed resistance-duration')   # Red = failed,
                                                    # Green = not failed
texts = [plt.text(tstopexp[i], Hout[i], expcode[i]) for i in
         range(len(tstopexp))]
adjust_text(texts)

legend_elements =  [Line2D(tstopmeantotal.iloc[0,:], Hs, color='blue',
                           linestyle='dashed',
        label='Resistance-duration curve (alphasoil = 1.5'),
                   Line2D(tstopmeantotal.iloc[1,:], Hs, color='red',
                          linestyle='dashed',
        label='Resistance-duration curve (alphasoil = 1.5'),
                   Line2D(tstopmeantotal.iloc[2,:], Hs, color='yellow',
                          linestyle='dashed',
        label='Resistance-duration curve (alphasoil = 2.5'),
                   Line2D(tstopmeantotal.iloc[3,:], Hs, color='green',
                          linestyle='dashed',
        label='Resistance-duration curve (alphasoil = 3.5'),
                   Line2D(tstopmeantotal.iloc[4,:], Hs, color='gray',
                          linestyle='dashed',
        label='Resistance-duration curve (alphasoil = 4.5'),
```

```
                   Line2D([0], [0], marker='o', color='w',
                          label='Observed resistance-duration (not failed)',
                          markerfacecolor='#335e22', markersize=12),
                   Line2D([0], [0], marker='o', color='w',
                          label='Observed resistance-duration (failed)',
                          markerfacecolor='#891508', markersize=12),
                   ]

plt.xlim(0, tstopmax-1)
plt.ylim(0, 2.2)
plt.xlabel('Time [h]')
plt.ylabel('Wave height [m]')
plt.title(grassquality, fontsize=15)
ax.legend(handles = legend_elements)
plt.show()
```

C.2.4 Generate storm series

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt

def find_nearest(array, value):
    array = np.asarray(array)
    idx = (np.abs(array - value)).argmin()
    return array[idx]

t=np.arange(0, 45.1, 0.1)
year=2073  # Choose from 2023 OR 2073

#                                                                      LOAD EXCEL SHEETS
# ------------------------------------------------------------------------------
dfTide=pd.read_excel(
    r'C:\Users\NLMPET\Documents\Python\V2\Q3\Waterstandsverloop.xlsx',
    sheet_name="Tide")
dfTide=dfTide.iloc[:,1]  # Tide with amplitude of 1.35 and period of 12.5 hours [m]

dfStorm=pd.read_excel(
    r'C:\Users\NLMPET\Documents\Python\V2\Q3\Waterstandsverloop.xlsx',
    sheet_name="Storm_surge")
dfStorm=dfStorm.iloc[:,1]  # Normalised storm (with hmax=1) [m]

dfwaterperiod=pd.read_excel(
    r'C:\Users\NLMPET\Documents\Python\V2\Q3\V2\Waterlevel.xlsx')
dfperiod=dfwaterperiod.iloc[:, 0]  # Used return periods

if year==2023:
    dfhyear= dfwaterperiod.iloc[:, 1]  # Water level in 2023 [m]
elif year==2073:
    dfhyear = dfwaterperiod.iloc[:, 4]  # Water level in 2073 [m]

#                                                                           STORE VALUES
# ------------------------------------------------------------------------------

totaldfStorm = []
totalh0=[]
totalh0max=[]
totalerror = []
```

```
totalhstormperiod=[]
totalwatersurge=[]

#                                         CALCULATE STORM SURGE PER RETURN PERIOD
# ------------------------------------------------------------------------------

hstormmax= np.arange(5, 9.4, 0.01)
for a in range(0,len(hstormmax)):  # Generate all possible series of the water
                                    # level (tide + storm surge)
    dfStorm0=dfStorm*hstormmax[a]
    h0=dfStorm0+dfTide
    h0max=np.max(h0)
    totaldfStorm.append(dfStorm0)
    totalh0.append(h0)
    totalh0max.append(h0max)

for b in range(0,len(dfperiod)):  # Select the series of water level for each
                                    # return period
    hfound=find_nearest(totalh0max, dfhyear[b])
    error=abs(hfound - dfhyear[b])
    hindex=np.where(totalh0max==hfound)
    hstormperiod=hstormmax[hindex]
    totalerror.append(error)
    totalhstormperiod.append(hstormperiod)

print(totalerror)
print(totalhstormperiod)
#                                                     CALCULATE WATER LEVEL SURGE
# ------------------------------------------------------------------------------

for c in range(0, len(totalhstormperiod)):
    dfStorm0=dfStorm*totalhstormperiod[c]
    watersurge=dfStorm0+dfTide
    totalwatersurge.append(watersurge)

pdwatersurge=pd.DataFrame(totalwatersurge)
print(pdwatersurge)
pdwatersurge.index=dfperiod
if year==2023:
    pdwatersurge.to_excel\
        (r'C:\Users\NLMPET\Documents\Python\V2\Q3\V2\Storm2023_per_return_period.xlsx',
         header=t)
elif year==2073:
    pdwatersurge.to_excel\
        (r'C:\Users\NLMPET\Documents\Python\V2\Q3\V2\Storm2073_per_return_period.xlsx',
         header=t)
print(hfound)
```

Appendix D

Calibration WIPE model

The calibration of the WIPE model is done in three steps. The crack parameter (α_{crack}) is less sensitive than the other calibration parameter, thus the soil parameter (α_{soil}) is calibrated first. The value of the crack parameter is set in the most likely interval on 430 [Mous, 2010]. When the soil parameter was finished calibrating, the crack parameter is calibrated. The three steps are described below. For every step, the MAE for every relation and value is calculated.

1. $0.5 \leq \alpha_{soil} \leq 4.5$ with step size of 1
2. Value of parameter with smallest MAE value from step 1 ± 0.5 with step size of 0.2
3. Value of parameter with smallest MAE value from step 2 with $390 \leq \alpha_{crack} \leq 450$ with step size of 10

The results for each step are presented in a table. Table D.1 shows the results of step 1. The green MAE values are the smallest errors for every relation. It shows that the smallest error is around 0.015 m. Therefore the interval of α_{soil} for step 2 is from 1.0 to 2.0.

Table D.1: MAE of calibration WIPE step 1 with smallest error in green.

	Closed sods			Open sods		
α_{soil}	f_α	n	R_e	f_α	n	R_e
0.5	0.047	0.017	0.042	0.043	0.043	0.042
1.5	0.031	0.015	0.046	0.033	0.034	0.035
2.5	0.018	0.025	0.051	0.035	0.035	0.047
3.5	0.019	0.034	0.056	0.035	0.042	0.056
4.5	0.031	0.051	0.071	0.035	0.046	0.060

Table D.2 shows the errors of the second step of the calibration. The difference in error between the different relations for the closed sods is larger than in the case of the open sods. Most errors are small around a value of 1.4 for the soil calibration parameter. Therefore, 1.4 is chosen to be the input for the soil calibration parameter for step 3 of the calibration.

Table D.2: MAE of calibration WIPE step 2 with smallest error in green.

	Closed sods			Open sods		
α_{soil}	f_α	n	R_e	f_α	n	R_e
1.0	0.036	0.014	0.046	0.036	0.036	0.035
1.2	0.036	0.013	0.045	0.035	0.035	0.036
1.4	0.029	0.016	0.046	0.033	0.033	0.032
1.6	0.029	0.016	0.047	0.038	0.038	0.047
1.8	0.026	0.017	0.047	0.037	0.036	0.045
2.0	0.022	0.018	0.049	0.036	0.037	0.048

For the third step the crack calibration parameter is changed. The errors for the different values are presented in Table D.3. The difference between the errors due to the changing in the value of the parameter is low. The changing in the parameter does not result in smaller errors. Therefore the calibration is finished with the parameter values of 1.4 (for α_{soil}) and 430 (for α_{crack}).

Table D.3: MAE of calibration WIPE step 3 with smallest error in green.

	Closed sods			**Open sods**		
α_{crack}	f_α	n	R_e	f_α	n	R_e
390	0.036	0.014	0.046	0.036	0.035	0.036
400	0.037	0.013	0.045	0.035	0.035	0.035
410	0.034	0.012	0.046	0.036	0.037	0.041
420	0.032	0.015	0.046	0.036	0.036	0.039
430	0.029	0.016	0.046	0.033	0.033	0.032
440	0.028	0.016	0.047	0.035	0.035	0.037
450	0.027	0.015	0.047	0.036	0.035	0.042

Appendix E

Schematisation of the dike in Hydra-NL

Changes in the slope angle of the dike, does not result in large differences in water levels and wave heights. However, the foreland and berm do have a noticeable effect on the hydraulic conditions. Since the location point is located 30 meter from the dike, a foreland of 30 meter is used. Figure E.1 shows the exact location that is used for the calculations in Hydra-NL and Figure 1.6 shows the cross-section of the dike. Table E.1 shows the exact input values of the cross-section of the dike for Hydra-NL.

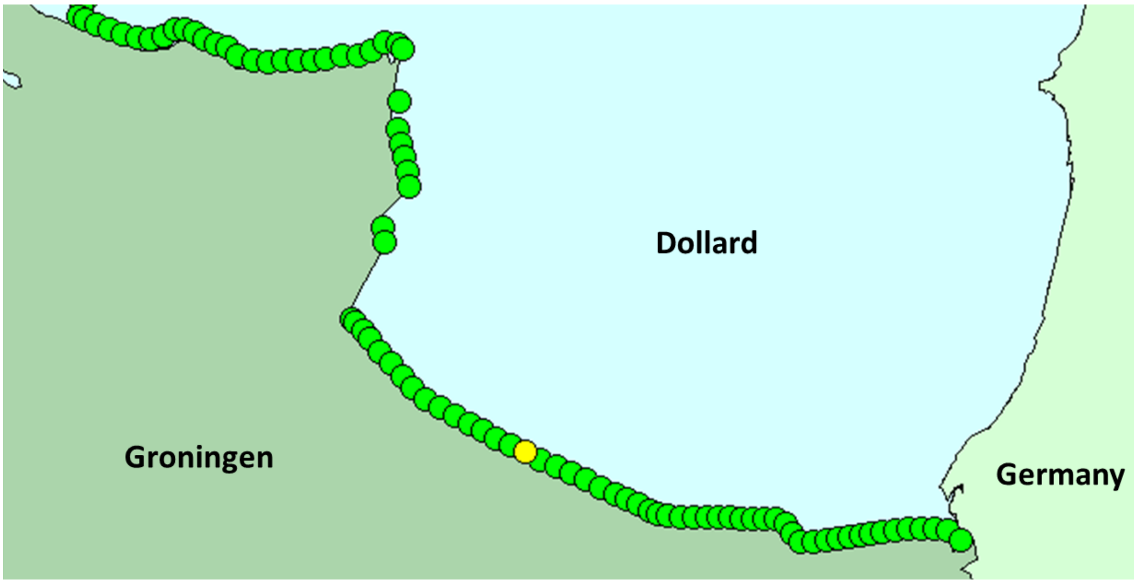

Figure E.1: Location calculation point (WZ_1_6-7_dk_00148) indicated by the yellow point in Hydra-NL

Table E.1: Cross-section of the dike as input for Hydra-NL.

From		To		
Distance [m]	Height [m + NAP]	Distance [m]	Height [m + NAP]	Slope [-]
0	2.45	30	2.45	0
30	2.45	37.7	3.55	1:7
17.7	3.55	40.7	3.7	1:20
40.7	3.7	77.1	8.9	1:7

Appendix F

Exceedance frequencies

The maximum water levels that corresponds to a return period are presented below. The earliest year that could be selected in Hydra-NL is 2023 with the climate scenario G, thus this is used as 'current' situation. Thus, there might be some small differences with the actual current situation, but these differences are small and neglectable.

Table F.1: Maximum water levels per return period for the case of the Dollard

Return period	Maximum water levels [m + NAP]			
[years]	2023	2050	2100	2073
10	4.655	4.903	5.403	5.133
20	4.948	5.196	5.696	5.426
30	5.111	5.358	5.858	5.588
40	5.223	5.470	5.970	5.70
50	5.308	5.555	6.055	5.785
60	5.376	5.623	6.123	5.853
70	5.433	5.680	6.180	5.910
80	5.482	5.729	6.229	5.959
90	5.525	5.772	6.272	6.002
100	5.563	5.810	6.310	6.040
110	5.598	5.844	6.344	6.074
120	5.629	5.876	6.376	6.106
130	5.657	5.904	6.404	6.134
140	5.684	5.931	6.431	6.161
150	5.708	5.955	6.455	6.185
160	5.731	5.978	6.478	6.208
170	5.752	5.999	6.499	6.229
180	5.772	6.019	6.519	6.249
190	5.791	6.038	6.538	6.268
200	5.809	6.055	6.555	6.285
210	5.825	6.072	6.572	6.302
220	5.841	6.088	6.588	6.318
230	5.857	6.104	6.604	6.334
240	5.871	6.118	6.618	6.348
250	5.885	6.132	6.632	6.362
300	5.947	6.193	6.693	6.423
1,000	6.339	6.585	7.085	6.815
10,000	7.044	7.290	7.790	7.520
200,000	7.889	8.135	8.635	8.365