Grass revetment reinforcements

A study into the effectiveness of measures applied during critical conditions

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Delft University of Technology

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LIJN IN WATER

Photo front page: by G.P. van Rinsum, 16 September 2017. Training Drents Overijsselse Delta water board and NATRES (Military: National Reserve).

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by

G.P. van Rinsum

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Preface

This report is the final version of my master thesis on the effectiveness of grass revetment reinforcement measures applied during critical conditions. This report is written as final product for completion of my Master of Science in Hydraulic Engineering at Delft University of Technology. The research has been carried out in collaboration with HKV Lijn in water and the Wiki-Noodmaatregelen group. The request for the research subject came from the Wiki-Noodmaatregelen group. A work group, funded by STOWA, working on combining and extending the knowledge of water boards on reinforcement measures applied during critical conditions.

I had close contact with the members of this group during the research by sharing the progress of my research, carrying out a workshop, interviews and observations of exercises. I thank the members of this work group for their feedback and input for my research. I want to thank two persons in particular. Eric Huijskes, the chairman of the group, for his support and feedback, using his network in organizing the workshop and nice conversations we had during the meetings and high water exercise. Secondly, I want to thank Wijnand Evers of the *Drents Overijsselse Delta* water board for his help, feedback and opportunities to observe the crisis response during high water exercises and even when the high water was reality in January 2018. It was important for this research to go out in the field and see how the crisis organization works to be able to implement this into the theoretical models. Wijnand Evers is always interested in improving the quality of the crisis organization and not afraid to share potential shortcomings of the water board as long as it leads to a better practise in the future.

I want to thank my colleagues for the great time I had at HKV. It felt as a privilege to work at HKV during this period, both in Delft and Lelystad. The nice working environment and colleagues helped me to keep going and enjoy the research. At HKV work a lot of experts in specific fields of the hydraulic engineering world, who are more than willing to share their expertise. This was both inspiring and helpful for improving the quality of my thesis.

Special thanks goes to my graduation committee: Bas Jonkman, Bas Kolen, Fred Havinga, Kasper Lendering and Mark Voorendt. The committee was well balanced in terms of expertise. I really appreciated the very constructive meetings where knowledge and feedback was shared. Every meeting gave me a new positive impulse in the right direction to improve my research. Individual meetings, for more specific discussion points, were also very helpful in steering in the right direction. Each committee member was more than willing to share their expertise in different phases of the research, despite the full agendas.

Guido van Rinsum
Delft, April 2018

Summary

The Netherlands is prone to flooding both from the rivers and the sea. A large part of the country depends on the flood protection system. The permanent defences, like the river dikes, are the most important part of the Dutch flood protection strategy. Water boards maintain these flood defences regularly to prevent flooding. Water boards also install (temporary) reinforcement measures during extreme events at weak spots in the flood defence. Measures like the containment of sand boils, installation of supporting berms and reinforcement measures for the grass revetment. The effect of these measures is often not quantified in terms of risk or failure probability reduction.

The objective of this research is to determine to what extent grass revetment reinforcement structures (Dutch: bekrammingen) contribute to the safety against flooding. Those reinforcement measures can be applied both at the inner and outer slope of the dike. This research focusses on measures applied at the outer slope to prevent erosion of the revetment during extreme conditions.

There are two options: the reinforcement measure fails or is successful. Failure of the measure can be caused by: failure of detection of the weak spot, failure of placement of the measure or technical failure of the measure itself. The flood defence does have its initial strength when the measure fails, nothing has changed. The failure probability of the flood defence changes with a successful applied reinforcement measure, this failure probability is not equal to zero.

The description above is implemented in the model:

- The failure probability of detection and placement is analysed by an event tree of these phases. The failure probabilities of the respective sub steps are quantified with the *OPSCHEP* model. This is a model to quantify the probability of failure caused by humans. This model is modified to apply it to the field of temporary reinforcement measures. The technical reliability is assessed by means of an analysis of the strength of, and load on the reinforcement structure. The detection, placement and technical reliability result in the failure probability of the measure. The second uncertainty parameter is the time required for installation, consisting of the detection and placement duration.
- The reliability of the flood defence without reinforcement measure is quantified with the WBI-2017 erosion formulas for the grass revetment under wave impact. The models are modified to account for initial damage. Initial damage can be present at the grass revetment for various reasons, such as driving tracks and damage by animals.
- The effect of a successful installed reinforcement measure is implemented in the model by means of an erosion modification factor. This factor reduces the erosion speed of the grass revetment due to the presence of the reinforcement measure.

The components above are integrated into a crude Monte Carlo simulation. For each simulation step are the hydraulic conditions discretized per hour. The cumulative erosion is calculated per time step. The erosion speed is modified when the the measure is installed successful. This reduction in erosion speed is implemented in the model after the time required for installation. The calculation method results in the failure probability of the flood defence, taking into account the reinforcement measure with a certain reliability.

The grass revetment reinforcement measures can be applied at known and unknown weak spots. These two options are assessed in two separate case studies. Case A, known weak spot, analyses a measure with a total length of 500 meter. Case B, unknown weak spot, examines a measure of 200 meter. Within these cases are four scenarios assessed: a pessimistic and optimistic scenario and the current practice at the *Rivierenland* and *Drents Overijsselse Delta* water board. The input parameters of the cases are based on observations during high water exercises, the high water of 2018, a workshop and interviews at water boards.

The failure probability of the reinforcement measure p_m is the most important parameter in the reliability assessment of the flood defence with reinforcement measures. This value is larger for unknown weak spots

compared to known weak spots due to the detection part. In the case studies are the values for p_m found according to Table 1.

Table 1: Failure probabilities of reinforcement measure p_m of the case studies

	Known weak spot	Unknown weak spot
Optimistic	0.01	0.04
Rivierenland	0.02	0.14
Drents Overijsselse Delta	0.11	0.38
Pessimistic	0.16	0.65

Grass revetment reinforcement measures for known weak spots are only potentially effective if the material, personnel and equipment are prepared and the construction rate is such that the measure can be installed in approximately 10 hours. The reliability is dominated by the placement failure probability and the effectiveness is bound by the placement capacity. The resulting effectiveness is dependent on the level of preparedness, exercises, material availability and time constraints. In the case study are average reduction values for the conditional failure probability of the flood defence found of 32 for an optimistic and 4 for a pessimistic scenario. Be aware that the pessimistic scenario still assumes a certain amount of preparation. Hence, the factor 4 in failure probability reduction is not reached without preparation.

The effectiveness for grass revetment reinforcement measures applied for unknown weak spots is less effective due to a larger value for the failure probability of the reinforcement measure and time required for installation. The resulting effectiveness is dependent on, amongst others, the detection phase, prioritization, knowledge level and training. In the case study are average reduction values for the conditional failure probability of the flood defence found of 14 for an optimistic and 1.0 (no reduction) for a pessimistic scenario. However, these values for the effectiveness rapidly decrease if the number of weak spots increase. For example the factor 14 drops to 3.3, when assuming independence, if there are 10 weak spots (with the same total length of 200 meter).

The effectiveness can firstly be increased by decreasing the failure probability of the measure. Factors influencing this failure probability are amongst others: knowledge level of inspectors, standardized procedures, logistic preparation and training of the placement of the measures.

The second parameter influencing the effectiveness is the time required for installation. This time is important since erosion of the outer slope is a time dependent failure mechanism. Measures are potentially successful when installed before the cumulative erosion exceeds the critical erosion depth. Up to a certain value of the required time does this duration not influence the effectiveness. This value is case specific, depending on the hydraulic conditions and the strength of the revetment. Decreasing the time required does therefore not for each case contribute to a more effective measure. If the length of the measure to be installed is high, or the current construction rate is low does decreasing the time required contribute to an increase in effectiveness. In the case studies is found that decreasing the time results in an increased effectiveness for:

- the known weak spot (500 meter) for a pessimistic scenario;
- the unknown weak spot (200 meter) for the *Drents Overijsselse Delta* and pessimistic scenario.

Samenvatting

Nederland is kwetsbaar voor overstromingen vanuit de rivieren en de zee. Een groot gedeelte van het land is afhankelijk van de waterkeringen die het land beschermen. Het belangrijkste onderdeel in deze strategie zijn de permanente waterkeringen, zoals rivierdijken. Waterschappen voeren regulier beheer en onderhoud uit om overstromingen te voorkomen. Ook plaatsen zij (tijdelijke) versterkingsmaatregelen gedurende hoogwaterdreigingen op zwakke plekken in de waterkeringen, zoals opkisten van zandvoerende wellen, plaatsen van steunbermen en het versterken van de grasbekleding. Het effect van de maatregelen is vaak niet gekwantificeerd in termen van risico- of faalkansreductie.

Het doel van dit onderzoek is om te bepalen in welke mate versterkingsmaatregelen voor de grasbekleding (bekrammingen) bijdragen aan het reduceren van het overstromingsrisico. Dit type versterkingsmaatregelen kan toegepast worden op zowel het binnen- als buitentalud. Dit onderzoek focust op maatregelen toegepast op het buitentalud om erosie van de bekleding tegen te gaan gedurende extreme condities.

Er zijn twee opties: de versterkingsmaatregel faalt of is succesvol. Falen van de maatregel kan worden veroorzaakt door falen van: de detectie van de zwakke plek, plaatsing van de maatregel of technisch falen van de maatregel zelf. De waterkering heeft zijn initiële sterkte wanneer de maatregel faalt, niks is gewijzigd. De faalkans van de waterkering wijzigt wanneer de maatregel succesvol wordt toegepast. Deze faalkans is niet gelijk aan nul.

De bovenstaande beschrijving is geïmplementeerd in het onderzoek:

- De faalkans van de detectie- en plaatsingsfase is geanalyseerd aan de hand van een gebeurtenissenboom. De individuele faalkansen zijn bepaald aan de hand van het *OPSCHEP* model. Dit is een model om de faalkans ten gevolge van menselijk handelen te bepalen. Dit model is aangepast om het te kunnen gebruiken in de analyse van tijdelijke versterkingsmaatregelen. De technische betrouwbaarheid is geanalyseerd met behulp van een analyse van de sterkte van, en de belasting op de versterkingsmaatregel. De betrouwbaarheid van detectie en plaatsing en de technische betrouwbaarheid resulteren in de totale faalkans van de maatregel. De tweede onzekerheidsparameter is de benodigde tijd voor het aanbrengen van de maatregel, bepaald door detectie en plaatsing.
- De initiële betrouwbaarheid, de betrouwbaarheid van de waterkering zonder versterkingsmaatregel is gekwantificeerd aan de hand van de WBI-2017 erosieformules voor de grasbekleding onder golfaanval. Deze modellen zijn aangepast om initiële schade in rekening te brengen. Deze schade kan aanwezig zijn door tal van redenen, zoals rijsporen en schade door dieren.
- Het effect van een succesvol geplaatste maatregel is geïmplementeerd met een erosiemodificatiefactor. Deze factor reduceert de erosiesnelheid van de grasbekleding door de aanwezigheid van de maatregel.

De bovenstaande componenten zijn geïntegreerd in een ruwe Monte Carlo simulatie. Voor elke stap van deze simulatie worden de hydraulische condities gediscretiseerd per uur. De cumulatieve erosie is berekend per tijdstap. De erosiesnelheid reduceert wanneer de maatregel succesvol is geplaatst, maar pas na de tijdstap die nodig is om de maatregel te plaatsen. Deze berekeningsmethode resulteert in een faalkans van de waterkering, rekening houdend met de versterkingsmaatregelen met een bepaalde onzekerheid.

De versterkingsmaatregelen voor de grasbekleding kunnen worden toegepast bij bekende en onbekende zwakke plekken. Deze twee opties zijn geanalyseerd in twee verschillende case studies. Voor case A, bekende zwakke plek, is een versterkingsmaatregel van 500 meter geanalyseerd. In case B, onbekende zwakke plek, is 200 meter genomen als uitgangspunt. Binnen deze cases zijn vier scenario's bekeken: een optimistisch en pessimistisch scenario en de huidige praktijk bij de *Rivierenland* en *Drents Overijsselse Delta* waterschappen. De invoer parameters van de cases zijn gebaseerd op observaties gedurende hoogwateroefeningen, het hoge water van 2018, een workshop en interviews bij waterschappen.

De faalkans van de versterkingsmaatregel is de belangrijkste parameter voor de betrouwbaarheid van de waterkering. Deze waarde is groter voor onbekende zwakke plekken in vergelijking tot bekende zwakke plekken, door het aandeel van detectie. In de case studies zijn de waardes volgens Table 2 gevonden.

Table 2: Faalkansen van de versterkingsmaatregel (p_m) uit de case studies.

	Bekende zwakke plek	Onbekende zwakke plek
Optimistisch	0.01	0.04
Rivierenland	0.02	0.14
Drents Overijsselse Delta	0.11	0.38
Pessimistisch	0.16	0.65

Grasbekleding versterkingsmaatregelen voor bekende zwakke plekken zijn alleen potentieel succesvol wanneer het materiaal, materieel en personeel voorbereid zijn en wanneer de aanlegsnelheid zodanig is dat de maatregel in ongeveer 10 uur aangebracht kan worden. De betrouwbaarheid wordt gedomineerd door de plaatsingsfaalkans en de effectiviteit is begrensd door de plaatsingscapaciteit. De resulterende effectiviteit is afhankelijk van de mate van voorbereiding, training, aanwezigheid van materiaal en tijdslimitaties. In de case studies zijn gemiddelde reductiewaarden voor de conditionele faalkans van de waterkering gevonden van 32 voor een optimistisch scenario en 4 voor een pessimistisch scenario. Het pessimistische scenario gaat uit van een zekere mate van voorbereiding. Dus, de reductiefactor van 4 wordt niet behaald zonder voorbereiding.

De effectiviteit van versterkingsmaatregelen voor onbekende zwakke plekken is minder effectief door de grotere faalkans van de maatregel en de benodigde tijd voor het aanbrengen van de maatregel. De resulterende effectiviteit is afhankelijk van, onder andere, de detectie fase, prioritisering, kennisniveau en training. In de case studies zijn gemiddelde reductiewaarden voor de conditionele faalkans van de waterkering gevonden van 14 voor een optimitisch scenario en 1 (geen reductie) voor een pessimistisch scenario. Echter, deze waarden voor de effectiviteit nemen snel af wanneer het aantal zwakke plekken toeneemt. Bijvoorbeeld, de factor 14 in reductie neemt af tot 3.3, uitgaande van statistische onafhankelijkheid, wanneer er 10 zwakke plekken zijn (met dezelfde totale lengte van 200 meter).

De effectiviteit kan in de eerste plaats worden verbeterd door de faalkans van de maatregel te reduceren. Factoren die beïnvloed kunnen worden zijn onder andere: het kennisniveau van de dijkinspecteurs, gestandaardiseerde procedures, logistieke voorbereiding en training van het plaatsen van de maatregelen.

De tweede parameter die de effectiviteit beïnvloedt is de benodigde tijd voor het plaatsen van de maatregel. Deze tijd is belangrijk omdat het erosiemechanisme ook een tijdsafhankelijk mechanisme is. Maatregelen kunnen succesvol zijn wanneer ze geplaatst worden voordat de cumulatieve erosie groter is dan de kritieke erosiediepte. Deze tijd is afhankelijk van de hydraulische condities en de sterkte van de bekleding. Het verminderen van deze benodigde tijd is daarom niet voor elk geval een manier om de effectiviteit te verhogen. Wanneer de lengte van de maatregel groot is of de huidige aanlegsnelheid laag, heeft verminderen van deze tijd effect op het vergroten van de effectiviteit. In de case studies is gevonden dat het verminderen van de aanlegtijd effect heeft voor:

- bekende zwakke plekken (500 meter), alleen in het pessimistische scenario;
- de onbekende zwakke plekken (200 meter), voor het pessimistische scenario en het *Drentgs Overijsselse Delta* waterschap.

Contents

Terminology

Definitions

English	Dutch	Definition
Construction capacity	Plaatsingscapaciteit	Length of reinforcement measure that can be installed in time during critical conditions as function of the potential capacity and material availability.
Control measure	Beheersmaatregel	Temporary reinforcement measure aimed at reaching a certain reliability of the flood protection system.
Cut-off	Coupure	Gap in flood defence that need to be closed in the case of high water.
Detection phase	Detectiefase	The chain of actions starting at reaching the threshold in hydraulic conditions at which inspection should start, until the placement decision.
Dike inspection	Dijkinspectie	Inspection of the flood defences, on a regular basis or during critical conditions.
Dike supervisor	Keringbeheerder	Water board employee responsible for maintenance and monitoring of the flood defences in his area of responsibility.
Dike watch	Dijkwacht	Dike inspectors (volunteers) who are deployed in the case of high water event.
Emergency measure	Noodmaatregel	Temporary reinforcement measure to increase the safety of the flood protection system, however the effect is uncertain.
Failure mechanism	Faalmechanisme	Sequence of events that leads to failure of a dike section.
Fragility curve	Kwetsbaarheidscurve	Curves describing the conditional failure probability of the flood defence given a certain hydraulic condition.
Genie	Genie	Part of the army charged with civil engineering and hydraulic engineering related tasks.
Grass revetment reinforcement	Bekramming	Geotextile, fixated to the dike body by sand bags and nails.
Geotextile	Geotextiel	Permeable or impermeable soil tight textile, usually woven.
Human error	Menselijk falen	*Not performing or incorrect performance of tasks, provided there are proper circumstances to perform the task correctly* (Heslinga, 2013).
Illustration point	Illustratiepunt	*Most probable combination of stochastic realisations that can lead to failure of the flood defence* (Diermanse, 2016).
Initial damage	Initiële schade	The absence of a part of the grass revetment and/or clay sub layer.

Inner slope	Binnentalud	Land side slope of a dike.
Ledger	Legger	*Legal document used by the Dutch Water Boards for official registration of the flood defences as regards their location, shape, dimensions and structural composition. Ledger zones indicate the area where structural modifications are restricted.* (Voorendt, 2017).
Lower river area	Benedenrivierengebied	Part of the Dutch river system influenced by both the river discharge from upstream and the water level fluctuations (storm surge and tide) from the sea.
Outer slope	Buitentalud	Water side slope of a dike.
Permanent defence	Permanente waterkering	Flood defence, permanently in place to retain water.
Placement phase	Plaatsingsfase	The chain of actions starting from the placement decision (end of detection phase) till the installation of the reinforcement measure.
Potential capacity	Potentiële capaciteit	Length of reinforcement measure that can be installed in time during critical conditions without taking material constraints into account.
Reinforcement measure	Versterkingsmaatregel	Strengthening of the flood defence, in the context of this thesis on a temporary basis to reach the required safety level.
Temporary defence	Tijdelijke waterkering	Flood defences that need to be installed if the hydraulic load exceed a predetermined level. These defences are part of the safety assessment.
Upper river area	Bovenrivierengebied	Part of the Dutch river system only influenced by the discharge and not by storm surge or astronomical tide.
Water board	Waterschap	Dutch government agency, on regional level, responsible for qualitative and quantitative water management in their domain. There are 22 water boards in the Netherlands.
Waterway dike	Schaardijk	Dike, directly next to the summer bed of the river, without flood planes.
Weak spot	Zwakke plek	Damage in the flood defence

Abbreviations

Abbreviation	**Full name**
ACW	Actie Centrum Water
DOD	Drents Overijsselse Delta
WAT	Waterschap Actie Team
HEART	Human Error Assessment and Reduction Technique
HRA	Human Reliability Analysis
NATRES	Nationale Reserve (Military)
NWO	Niet Waterkerend Object
PSF	Performance Shaping Factor
THERP	Technique for Human Error Rate Prediction
WBT	Waterschap Beleidsteam
WOT	Waterschap Operationeel Team

Roman symbols

Symbol	Unit	Description
a	m	Constant in relation wave height and strength duration for wave impact
b	hour^{-1}	Constant in relation wave height and strength duration for wave impact
c	m	Constant in relation wave height and strength duration for wave impact
c_c	-	Quality parameter clay layer (WBI-2017)
c_g	ms	Quality parameter grass revetment (PC-ring)
c_{rk}	ms	Quality parameter clay layer (PC-ring)
C	m	Construction capacity reinforcement measure construction
C_p	m	Potential construction capacity reinforcement measure
d_{core}	m	Thickness core
d_e	m	Erosion depth
d_F	m	Thickness filter layer
d_i	m	Initial damage
d_c	m	Thickness clay layer
d_T	m	Thickness top layer
d_w	m	Grass revetment thickness
E_g	m/s	Erosion speed
E_{geo}	m/s	Erosion speed reinforced grass revetment
f	-	Friction factor
f_{nwo}	-	Strength reduction factor NWO
F_{rw}	kN	Run-down force
F_{sand}	-	Sand content
F_v	N	Sum vertical forces
g	m/s^2	Gravitational acceleration
h	m	Water level
H_{m0}	m	Spectral significant wave height
H_s	m	Significant wave height
k	-	Number of inspection rounds
k_F	-	Permeability filter layer
k_T	-	Permeability top layer
L_k	m	Horizontal thickness clay layer
l_m	m	Reinforcement measure material available during high water
L_0	m	Deep water wave length
n_f	-	Number of fails
n_r	-	Number of runs
n_{teams}	-	Number of teams
p_d	-	Failure probability detection phase
p_{d1}	-	Failure probability start inspection
p_{d2}	-	Weak spot found yes/no
p_{d3}	-	Detection failure probability per detection round
p_{d4}	-	Failure probability reporting
p_{d5}	-	Probability of incorrect decision given correct reporting
p_{d6}	-	Probability of incorrect decision given incorrect reporting
p_f	-	Failure probability flood defence
$p_{f\|H}$	=	Failure probability of flood defence given a certain value for the wave height
$p_{f\|measure}$	-	Failure probability flood defence with reinforcement measure
$p_{f\|no-measure}$	-	Failure probability flood defence without reinforcement measure
p_m	-	Failure probability reinforcement measure
p_{max}	N/m^2	Maximum wave pressure
p_p	-	Failure probability placement phase

p_{p1}	-	Failure probability placement command
p_{p2}	-	Loading failure probability
p_{p3}	-	Construction failure probability
p_t	-	Technical failure probability
r	-	Reduction factor wave angle
R	m/h	Construction rate
R_d	m	Wave run-down
R_e	m/hour	Erosion speed
R_h	N	Resistance against horizontal sliding
r_h	-	Reduction factor water level
R_t	m/hour	Construction rate per team
s	m	Pressure length
T	hour	Time
T_a	hour	Available time for construction reinforcement measure
$t_{command}$	hour	Time needed for placement command
t_{dec}	hour	Decision time
t_{detec}	hour	Detection time
t_{fail}	hour	Time until failure grass revetment WBI-2017
t_{hydr}	s	Duration hydraulic conditions
t_i	s	Time shift initial damage
$t_{loading}$	hour	Loading time
$t_{placement}$	hour	Placement time
t_{mob}	hour	Mobilisation time
t_{RB}	s	Erosion time dike body
t_{report}	hour	Reporting time
T_{req}	hour	Required time for detection and placement measure
t_{RK}	s	Erosion time clay cover
t_{RT}	s	Erosion time grass revetment
$t_{transport}$	hour	Transport time
T_w	s	Wave period
x	m	x-coordinate slope
Z	-	General limit state function

Greek symbols

Symbol	Unit	Description
α_{dike}	-	Dike slope
α_{geo}	-	Modification factor erosion speed
$\alpha_{leakage}$	-	Reduction factor due to leakage
Λ	m	Leakage length
ξ	-	Iribarren number
ρ_w	kg/m^3	Water density

1

Introduction

1.1. General introduction

The protection of low-lying areas against flooding has always been a global issue. However, nowadays the importance of flood protection is especially great, because of changing hydraulic boundary conditions, due to climate change, soil subsidence and changing river discharges (ENW, 2017). Furthermore, the consequences of flooding are becoming more severe. Low lying areas are densely populated and the economic value of these areas is often very high. This is especially true of the Netherlands, where 55% of the country is at risk of flooding (IPCC, 2007). The sea contributes for 26% and the rivers for 29% to the total risk of flooding (IPCC, 2007). The actual threat of river floods in the Netherlands became even more clear after the critical high river discharges seen in 1993 and 1995. This flood threat resulted in the evacuation of 250,000 inhabitants in flood prone areas (ENW, 2017) and the application of many reinforcement measures, in a successful attempt to prevent dike breaches. What would have happened without these measures is obviously unknown. The river discharge at Lobith during that evacuation, 12,060 m^3/s (TAW, 1995) was less than during the last big river flood of 1926, which was the result of the largest ever measured river discharge at Lobith: 12,850 m^3/s (ENW, 2017). Preparation for flood threats is thus a necessity, as the 'President's Water Commission' expressed:

"However big floods get, there will always be a bigger one coming; so says one theory of extremes, and experience suggests it is true." (United States Water Recources Policy Commission, 1950)

The allowed flooding probability per area is embedded in the Dutch water law. Three types of measures are implemented to achieve the water safety goals: preventive measures, spatial adaptation and crisis response (Deltacommissaris, 2014). The first layer of this multi-layer safety approach is the most important part of the Dutch flood prevention strategy (ENW, 2017), spatial adaptation and crisis response are therefore complementary. Evacuation and reinforcement measures applied during critical conditions are part of the third layer of the multi-layer safety approach. Recent high water conditions in the Netherlands have shown that water boards apply measures to strengthen their flood defences in these events.

- During the flood threat of 1995 the *Stichtse Rijnlanden* water board used a geotextile reinforcement to repair damage on the outer slope of the dike close to the railway bridge in Culemborg (TAW, 1995), see Figure 1.1a. This was not the only geotextile reinforcement installed during the high water periods of 1993 and 1995, grass revetment reinforcements were placed on multiple occasions, (TAW, 1995).
- In January 2018, the *Drents Overijsselse Delta* water board applied approximately eight grass revetment reinforcement measures at the river *Vecht* near Zwolle.

There is limited insight into the actual contribution of the reinforcement measures to the probability against flooding, despite the fact that reinforcement measures are often applied, see for example Lendering et al. (2015) and Kolen et al. (2011). The goal of this thesis is to determine the effectiveness of one specific type of reinforcement measure: grass revetment reinforcements to increase the erosion resistance of a grass revetment. The focus will be on outer slope grass revetment reinforcement measures, an example of such a reinforcing measure is given in Figure 1.1b. The use of slope reinforcements d measures for flood protection is not restricted to the Dutch situation. Therefore are the concepts and results of this report applicable to other countries, however the focus will be on the Dutch river system.

(a) Reinforcement Culemborg 1995 (Lokhorst, 1995). (b) Exercise Drents Overijsselse Delta (16-09-2017).

Figure 1.1: Examples grass revetment reinforcements.

1.2. Flood protection in the Netherlands

The Netherlands is prone to floods both from rivers and the sea. Flooding from the sea is caused by the astronomical tide, which is predictable, and meteorological factors. The meteorological components are less predictable. High river discharges are the result of precipitation in for example the Rhine catchment area. The expected water level in the Rhine river can be foreseen with considerable accuracy three days ahead (Frieser, 2004). The probability of governing waves and discharge at the same moment in time is low (Rijkswaterstaat, 2012). However, moderate high water in combination with strong wind is probably governing for wave impact.

1.2.1. Failure mechanisms

Typical river dikes consist of a sand core with clay sub layer and grass revetment. The relevant failure mechanisms for river dikes can be seen in Figure 1.2. The inner slope is attacked by overflow and wave overtopping, failure mechanism A and B. The outer slope is subject to erosion due to wave impact.

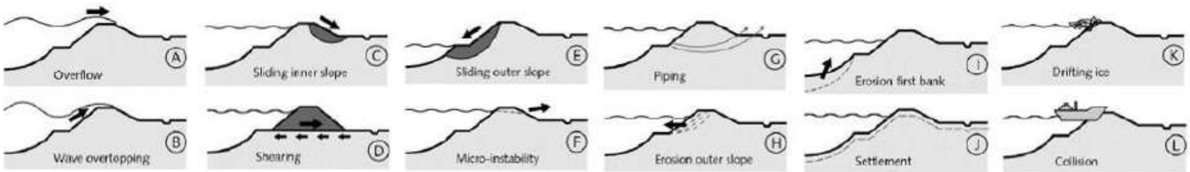


Figure 1.2: Categorization failure mechanisms (Jonkman et al., 2017)

1.2.2. Categorization flood defences

Two categories of flood defences can be distinguished in the Dutch flood defence system: primary and regional (or secondary) flood defences. The primary flood defence system protects the land against flooding from the main external waters (e.g. seas and rivers) (Jonkman et al., 2017). Regional flood defences defend land from flooding caused by other sources than the main external water sources, like canals. Water boards are responsible for the regional and most of the primary flood defences (ENW, 2017). The flood defence system can be further characterized, see Table 1.1.

Table 1.1: Categorisation flood defences (Lendering et al., 2014)

Type	Prepared	Failure by	Assessment
1a. Permanent defence	Yes	Technical failure	Yes
1b. Temporary/moveable defence	Yes	Human and technical failure	Yes
2a. Control measure	Yes	Human and technical failure	No
2b. Emergency measure	No	Human and technical failure	No

A permanent defence is a structure that is permanently in place to retain water. These structures are part of the safety assessment. Because no additional measures need to be taken in the case of high water, only technical failure contributes to the failure probability. Examples of permanent defences are dikes and dunes. **Temporary defences** are defences that need to be installed or closed when the hydraulic conditions exceed a predetermined level. These defences form part of the safety assessment. The total failure probability is determined by human and technical failure, since human action is needed to close the system in the case of critical conditions. Examples of these structures are sluices, cut-offs (Dutch: coupures), like the temporary flood defence in Kampen (Figure 1.3a) and moveable barriers, such as the Maeslantkering.

Control measures are taken when the safety shortage, the appearance of a weak spot in a flood defence, is known after inspection or assessment. These measures are *part of the flood protection system, and are aimed at achieving the required flooding probability* (ENW, 2017). A risk analysis has to be made, for which *alerts, mobilisation and implementation are particularly important* (ENW, 2017).

Emergency measures are reinforcement measures taken during critical conditions, the effect of the measures is not proved beforehand. Emergency measures are often taken under time pressure and not prepared for the site-specific conditions. Emergency measures are not part of the safety assessment (Helpdesk Water, 2017).

(a) Temporary flood defence Kampen (Drents Overijsselse Delta, 2017c).

(b) Control measure Delftweg, Delft for macro stability problem (photo November 1, 2017)

Figure 1.3: Example temporary defence and control measure.

Control versus emergency measures

The differentiation between emergency and control measures has been subject to much debate and is currently not set. Stepping into this semantic discussion is distracting from the more important issues in this thesis. From now on the term *(temporary) reinforcement measures* is therefore used in this research. The terms, control and emergency measures are discussed above because the reader should be aware of the differences. However, the reader should keep in mind that not everyone agrees to the distinction.

The type of measure can be the same for the temporary defences, control and emergency measures, but the reliability of the measures is different. The reinforcement measures can be applied in three ways:

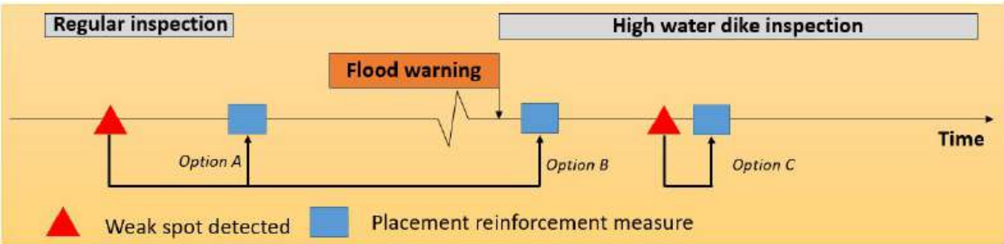


Figure 1.4: Categorization temporary reinforcement measures.

A. Based on known weak spot: a weak spot in the flood defence is known after regular inspection or assessment. Water boards can decide to apply a reinforcement measure directly without an imminent flood threat (option A, Figure 1.4). This can be done because the safety shortage is considerable or the available time to place the measures based on the predicted hydraulic conditions is small. The failure probability is determined by the technical reliability of the reinforcement measure.

B. Based on known weak spot: the same safety shortage as in option (1) but the measure is placed when needed (option B), based on the hydraulic conditions. Measures are prepared and a threshold (e.g. in the water level) is determined at which the construction should be started. Water boards have good reasons to opt for option B. In the case of grass revetment reinforcements, option A means that the geotextile is on the grass revetment for a longer period of time, this will make the revetment deteriorate even further. The failure probability is determined by: start placement after reaching threshold, placement reliability and the technical reliability.

C. Reports high water dike inspection: water authorities inspect their dikes during severe hydraulic conditions, a reinforcement measure is applied when a weak spot appears in this inspection (option C, Figure 1.4). The failure probability is determined by: the detection, placement and technical reliability.

1.3. Reinforcement measures

1.3.1. Reinforcement measures in the flood protection context

A certain flood probability is accepted per area in the Dutch flood protection philosophy. The permanent and temporary defences, without additional measures, should be enough to reach this standard. Water boards apply measures during extreme events to:

- prevent flooding, or to delay flooding to provide long enough time for evacuations (Ciria, 2013);
- reinforce unforeseen weak spots in the flood defences;
- increase the safety of the flood defences given the predicted hydraulic conditions.

These measures are additional to the regular reinforcements. The context of the reinforcement measures is illustrated in Figure 1.5. Three levels of detail are distinguished, the macro, meso and micro scale.

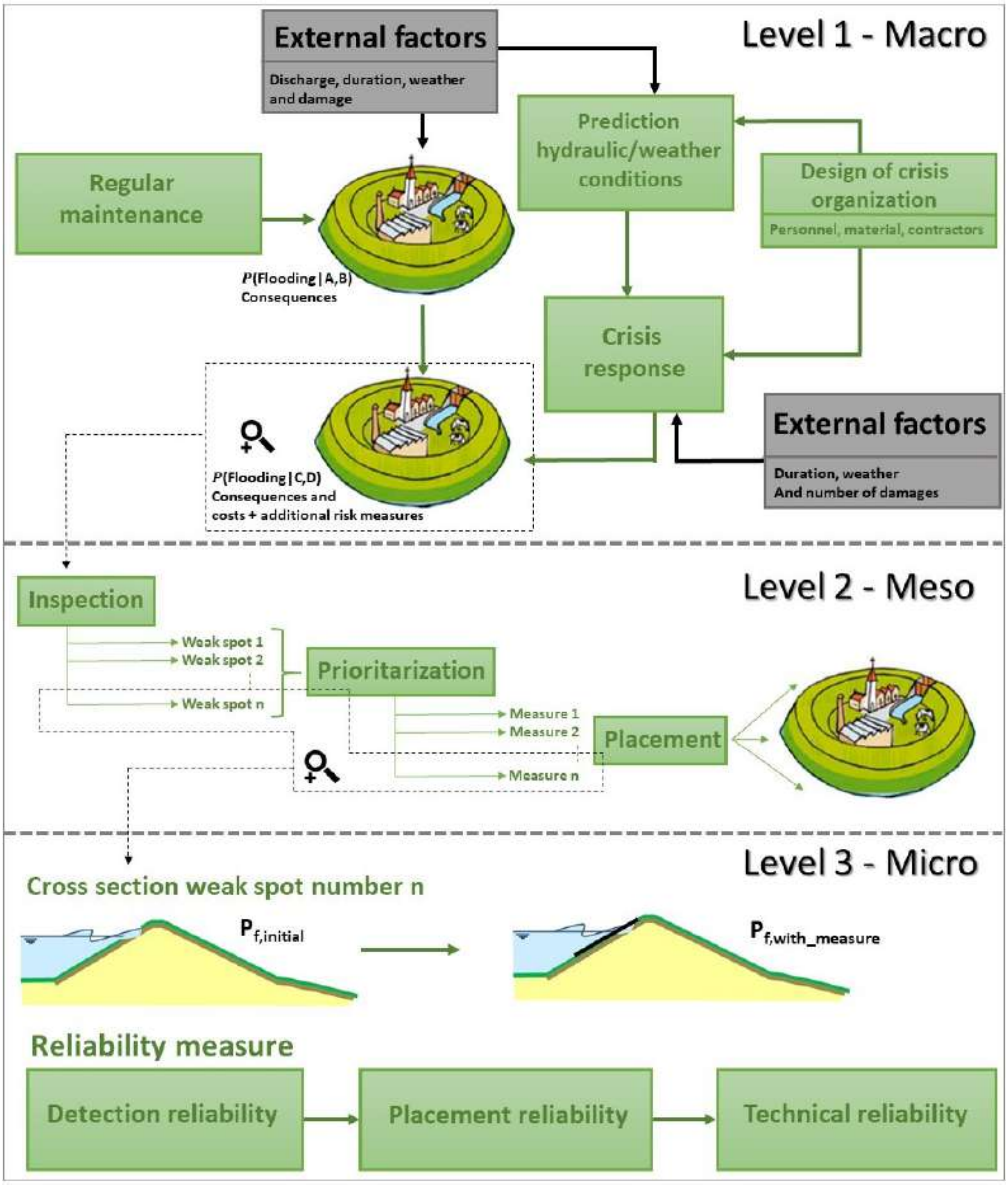


Figure 1.5: Reinforcement measures in the flood protection context.

Macro level

The probability of flooding of a dike ring, is a function of two parameters: the strength and the hydraulic load. The actual strength of the flood defence is governed by regular maintenance, the higher the intensity of the inspection and maintenance during normal conditions, the lower the probability of having a weak spot during extreme events. This flooding probability does not include the actions that water boards take during high water threats. Water boards take action to decrease the probability of flooding or try to reduce the consequences based on the predicted hydraulic and meteorological conditions. Both how accurate the predictions are and how prepared the crisis organization is during high water events is a design subject. External factors, like the weather conditions, also influence the effectiveness of the crisis response. The updated probability of flooding is a function of the initial safety and the effect of the crisis response.

Meso level
The meso level zooms in to the response during extreme events. The design of the crisis organization and the regular maintenance is taken as boundary condition. Inspection of the flood defence takes place, this results in a certain number of reports. Different measures are taken after prioritization of the weak spots, for example measures to stop piping and measures to increase the retaining height of the flood defence.

Micro level
On the micro level scale we zoom in to one reinforcement measure. A weak spot is present at one single dike segment. The failure probability of this segment is higher due to the the weak spot. The effect of the reinforcement on the failure probability is studied at this level. The reinforcement measure reliability is also part of the micro level. The reinforcement measure reliability is determined by the detection, placement reliability and structural failure. Structural failure is failure of the measure itself, after successful instalment.

1.3.2. Wiki-Noodmaatregelen

Reinforcement measures are applied in the case of extreme hydraulic conditions. Water boards have experience in the application of different methods during high water conditions and exercises. But, there is no standard or protocol. There is limited insight into the reliability and effectiveness of the measures they apply (Lendering et al., 2014). Insight into the effectiveness is desired because it can be used to optimize the crisis response. The *Wiki-Noodmaatregelen* work group is established in 2012 by STOWA[1] to combine and extend the knowledge about the measures and professionalize the day to day practice. This work group, with members from water boards, Rijkswaterstaat and Deltares, asked for studies into two specific fields of temporary reinforcement measures: piping measures and grass revetment reinforcement measures. These two fields are considered, by the work group members, to be the two most important study fields in the flood fighting strategy. The piping measures research is conducted by Mark Castelijns (University of Twente) in the same period as this research. This study is executed in cooperation with the work group, led by Eric Huijskes and Ulrich Föster.

1.3.3. Failure probability reinforcement measure

The event tree for successful implementation of the reinforcement measure during high water conditions can be seen in Figure 1.6. The reinforcement measure failure probability, assuming independence between the individual failure probabilities, is given in Equation 1.1 (Lendering et al., 2015).

$$p_m = 1 - (1 - p_d) \cdot (1 - p_p) \cdot (1 - p_t) \tag{1.1}$$

Where:				
	p_m	=	Failure probability reinforcement measure	[-]
	p_d	=	Failure probability detection	[-]
	p_p	=	Failure probability placement	[-]
	p_t	=	Technical failure probability	[-]

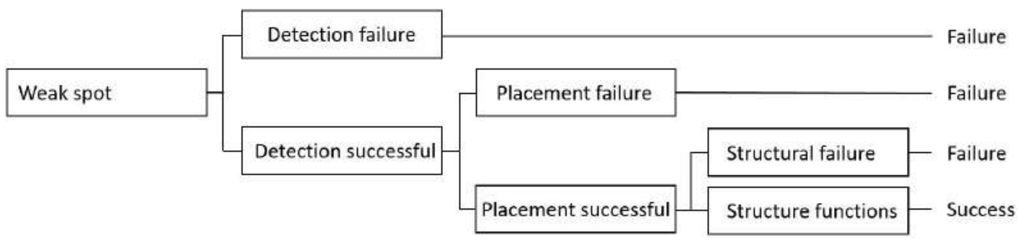


Figure 1.6: Event tree reinforcement measures, after Lendering et al. (2014)

[1] A Dutch authority for hydraulic engineering related studies, funded by water boards

Detection failure probability (p_d)

The probability of detection failure of a weak spot in a flood defence is determined by human performance and time constraints. Detection is influenced by visibility (e.g. time of day) and the knowledge level of the inspector (Lendering et al., 2014). The detection phase consists of a chain of actions, all the steps involved do have a certain error rate. Water boards rely on external parties (Rijkswaterstaat) for the water level predictions. The forecasting of water levels is known as demand management (De Leeuw et al., 2012), this phase is crucial in the high water response. Water boards decide whether or not and how often to inspect their dikes, based on water level predictions. The failure probability of the detection phase is investigated by Lendering et al. (2014) and Dupuits (2011). Dupuits constructed an event tree of all the steps and assigned failure probabilities to the distinct events. Lendering et al. (2014) determined the reliability of the detection phase based on the knowledge level of the inspector and included the time needed for inspection in the calculation.

Placement failure probability (p_p)

The placement phase starts after a weak spot is confirmed. Personnel and material are transported to the specific site after which construction starts. Time constraints, logistics and human errors contribute to the placement failure probability. Logistics are important, since dikes might not be easily accessible during high water threats. Logistics involve the preparation of materials in stock which is named inventory management (De Leeuw et al., 2012). Lendering et al. (2014) determined the failure probability of this phase for piping and overtopping measures. An analysis of the placement failure probability of grass revetment reinforcement measures is currently not available. Both the time needed to place the geotextile and the probability of human errors cannot be compared directly to the cases of the study by Lendering et al. (2014) and Dupuits (2011). The complexity of the placement of a slope reinforcement measure is higher than for overtopping measures. It is also questionable which hydraulic and meteorological conditions are suitable to apply geotextile measures.

Technical failure probability (p_t)

Technical failure of the measures is defined as failure of correctly installed structure. Failure due to errors in the construction are covered by the placement failure domain. No quantitative research is currently available on the failure probability of geotextile reinforced grass revetments. Slope reinforcements are site specific, the size and specific placement location depends on the location and size of the damaged revetment. Failure can happen due to various reasons: washing away of the sand bags or pulling out of the steel nails.

1.3.4. Failure probability flood defence with reinforcement measure

The failure probability of a flood defence with reinforcement measure can be seen in Equation 1.2 and the event tree in Figure 1.7 (Lendering et al., 2015).

$$p_f = p_m \cdot p_{f|no-measure} + (1 - p_m) \cdot p_{f|measure} \tag{1.2}$$

Where:	p_f	=	Failure probability flood defence	[-]
	p_m	=	Failure probability reinforcement measure	[-]
	$p_{f|no-measure}$	=	Failure probability flood defence without measure	[-]
	$p_{f|measure}$	=	Failure probability flood defence with measure	[-]

Failure of the reinforcement measure means that the flood defence does have its initial reliability. The flood defence does not have a failure probability of zero when the reinforcement measure is applied successfully. A flood defence can still fail when the measure is applied, however the failure probability will be lower.

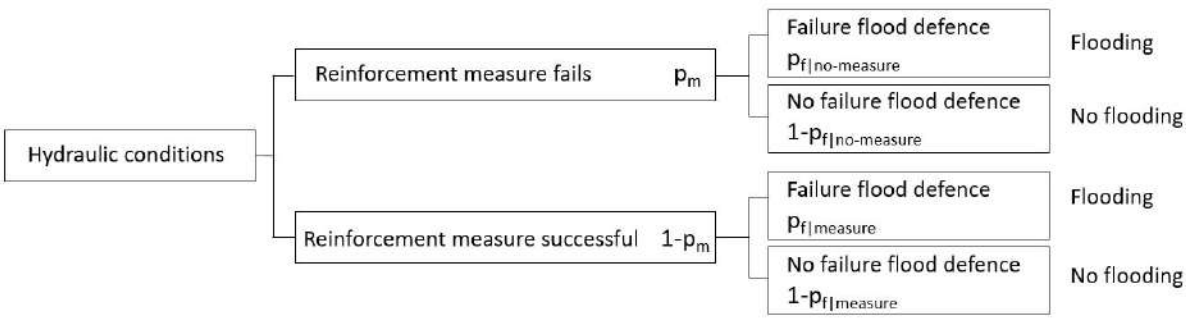


Figure 1.7: Event tree flood defence with reinforcement measure, after Lendering et al. (2015)

2

Research framework

The research framework is discussed in this chapter. The first section presents the problem formulation: the problem definition, objective, scope and research questions. The second section gives the structure of this report. The chapter ends in section three with the research method.

2.1. Problem formulation

2.1.1. Problem definition

The main problem is that the contribution of grass revetment reinforcement measures to the safety against flooding is unknown. This is undesirable since the effect of and how to improve the current practice is unknown. Two examples are given to illustrate this problem:

- Figure 2.1a shows a training of the *Rivierenland* water board. This specific dike consisted of a newly constructed grass revetment. The water board decided that the grass revetment had to be reinforced in the case of extreme conditions during the winter period. However, the criteria whether or not to install the measure were not clearly defined. The decision not to install the measure was made in the January of 2018 based on expert judgement (see Chapter 5.2.4)
- Figure 2.1b shows a grass revetment reinforcement measure at the *Vecht* dike. This reinforcement measures was installed because the grass revetment of this dike was damaged and the dike core consists of sand. The decision to install the reinforcement measure was made based on expert judgement, without a reliability assessment (see Chapter 5.2.2).

(a) Training *Rivierenland* water board. (b) Grass revetment reinforcement *Vecht* river (*Overijssel*).

Figure 2.1: Examples problem formulation.

The following knowledge gaps are distinguished in relation to the main problem:

1. Damage grass revetment
   Grass revetment reinforcement measures are applied when the grass revetment is damaged or weak. The influence of initial damage of the grass revetment on the reliability of a dike is not well described.

Moreover, the likelihood of damage to grass revetments, during high water events, is unknown (damage by for example driftwood). The likelihood of damage to a grass revetment and the effect on the reliability of a dike is relevant, because is determines the need for reinforcements.

2. Grass revetment reinforcement types
Water boards often apply geotextiles as control measure to reinforce grass revetments. Reports of the 1993 and 1995 near flooding events in the Netherlands show that geotextiles were also applied during critical conditions to prevent flooding. However, there are many differences in equipment for placement, placement teams and material used for the measures between the water boards. The differences are important for the failure probability (placement or technical) of the measures.
3. Detection phase
Lendering et al. (2014) developed a framework to assess the probability of failure of detection based on the detection phase as one task, with the probability of failure according to the knowledge level of the inspector. More research is needed to determine the probability of failure of the detection phase more accurately, taking into account the specific tasks and conditions.
4. Placement phase
No studies are available on the failure probability of the placement phase of the grass revetment reinforcement measures. The placement reliability of this measure is unknown.
5. Technical failure
No studies are done on the technical failure probability of the geotextile reinforcement measure. In other words, what is the failure probability of the grass revetment reinforcement structure, given correct placement.

2.1.2. Objective

The objective of this research is to determine to what extent grass revetment reinforcement structures contribute to the safety against flooding.

2.1.3. Boundaries and scope

The research boundaries and scope are:

- **River, grass dikes**
The focus in this thesis is on the application of reinforcement measures of river dikes. Geotextiles are used to reinforce grass revetments. Grass revetments are not present in the wave impact zone on the outer slopes of the Dutch sea defence because grass is to a very limited extent able to withstand waves.
- **Infiltration prevention**
Impermeable geotextiles can be used in an attempt to prevent seepage of water into the dike body at the outer slope of the dike to lower the phreatic level in the dike (Jonkman et al., 2017). This domain of usage is not studied in this research because experience shows that this is not an effective measure (Wiki Noodmaatregelen, 2017a).
- **Reinforcement measures during critical conditions.**
The differences between three types of measures are described in Section 1.2.2. The focus in this thesis is on the reinforcement measure type applied during high water. Option B and C of Figure 1.4.
- **Focus on wave impact outer slope**
This research focusses on erosion prevention of the outer slope. A flood defence can fail due to several different failure mechanisms, as explained in Chapter 1. The failure probability and reduction of the failure probability of one dike section as the result of erosion is investigated, see Figure 2.2.

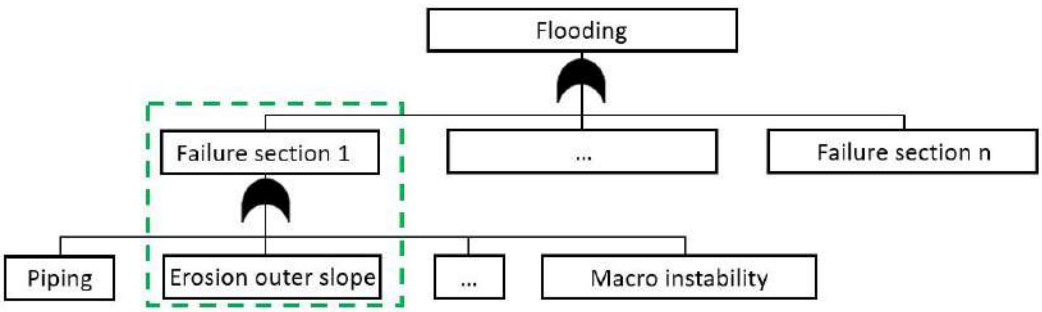


Figure 2.2: Scope research

2.1.4. Research questions

The research questions to reach the objective are given below.

Main research question
What is the effectiveness and reliability of grass revetment reinforcement measures for river dikes?

The following sub questions are used to answer the main question:

- Question 1: what is the reliability of a grass revetment taking into account initial damage?
- Question 2: what is the effect of reinforcement measures on the reliability of the grass revetment?
- Question 3: what is the reliability of the detection of a weak spot?
- Question 4: what is the placement reliability of grass revetment reinforcement measures?
- Question 5: what is the technical reliability of grass revetment reinforcement measures?

The research questions all answer one part of the event three shown in Figure 1.7.

2.2. Document structure

The topic of this thesis is introduced in the first chapter and it provides the reader with the necessary background information on subject. This chapter describes the research framework, with amongst others: the research objective, research questions and method.

The report structure follows approximately the event tree as illustrated in Figure 1.7, this event tree is shown below in Figure 2.3, with the document structure included. This figure will be given at the start of the corresponding chapters as guidance through the report. The failure probability of flood defence without reinforcement measure ($p_{f|no-measure}$) is investigated in research question one and can be found in Chapter 3. The reliability of the flood defence with successful applied reinforcement measure ($p_{f|measure}$) is studied in research question two, Chapter 4. The reliability of the reinforcement measure itself is determined by the detection (p_d), placement (p_p) and technical (p_t) failure probability. These three parts are studied in research questions three, four five and can be found in Chapter 7, 8 and 9.

The input for the latter three chapters are the field observations (*Deining en Doorbraak*, high water 2018 and the workshop) and Human Reliability Models. These two topics are discussed in Chapter 5 and 6.

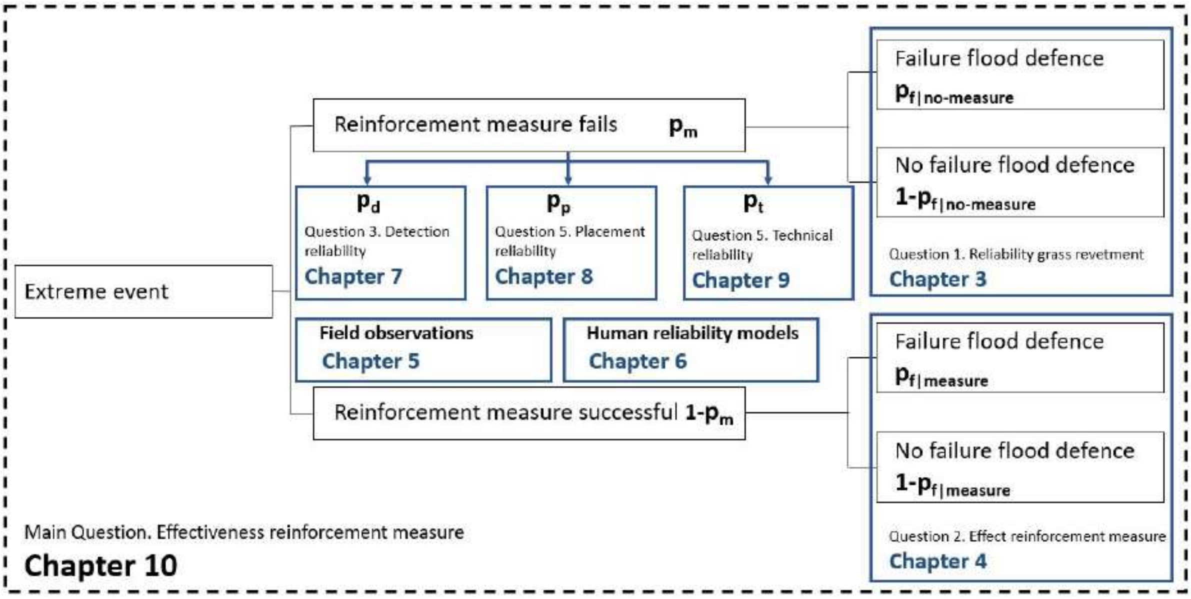


Figure 2.3: Document structure

The reliability framework (see Figure 2.3) is implemented into two different cases in Chapter 10. These cases result in the answer to the main research question. Chapter 11 contains the discussion on the validity of the results and the circumstances when they are valid. Conclusions and recommendations are the final result of this thesis and can be found in Chapter 12.

2.3. Research method

2.3.1. General method

The theoretical background of this research is based on:

- the reliability framework for reinforcement measures, see Figure 1.6 and Equation 1.1.
- the event tree for the flood defence with reinforcement measure, see Figure 1.7 and Equation 1.2.

These two equations are also shown in Figure 2.4. The sub questions and main research question are also shown in the figure. These questions all answer one part of the reliability framework.

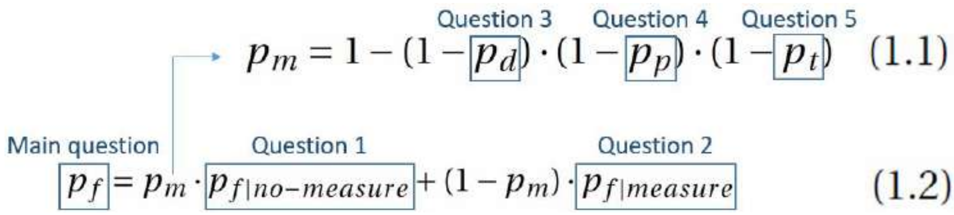


Figure 2.4: Research method

Figure 2.3 on the previous page gives the document structure and shows the same relation between the reliability framework and the sub question.

Time dependency

One important component is not included in the reliability assessment of Figure 2.4: the time needed to install the measure. An important premise in this thesis is that the uncertainty of the application of the reinforcement measure is caused by:

- the **failure probability** of the measure p_m (detection, placement or technical failure);
- the **time required** to install the reinforcement measure (T_{req}). The erosion failure mechanism is a time dependent mechanism. The measure is potentially successful when it is installed before the cumulative erosion exceeds the thickness of the grass revetment and clay sub layer.

Lendering et al. (2014) implemented this by a separate limit state function of the available time minus the required time. This results in an additional failure probability. However, this procedure is not possible for this time dependent erosion failure mechanism. There is no strict limit in available time. This is illustrated by 2.5. The figure shows a graph of the erosion depth versus the time. The solid black line represents an unreinforced revetment. The slope of the line is the erosion speed. The cumulative erosion exceeds the failure definition, the revetment fails. A reinforcement measure is applied. The effect of the reinforcement measure is an erosion reduction, this can be seen in the change of the slope (dashed lines). The shorter the time required (T_{req}) to install the measure the higher the likelihood that the erosion depth does not exceed the failure definition. Calculating the available time for this simplified example would probably be possible. However taking a stochastic erosion reduction and storm shape into account makes $p_{f|measure}$ dependent on the required time for installation.

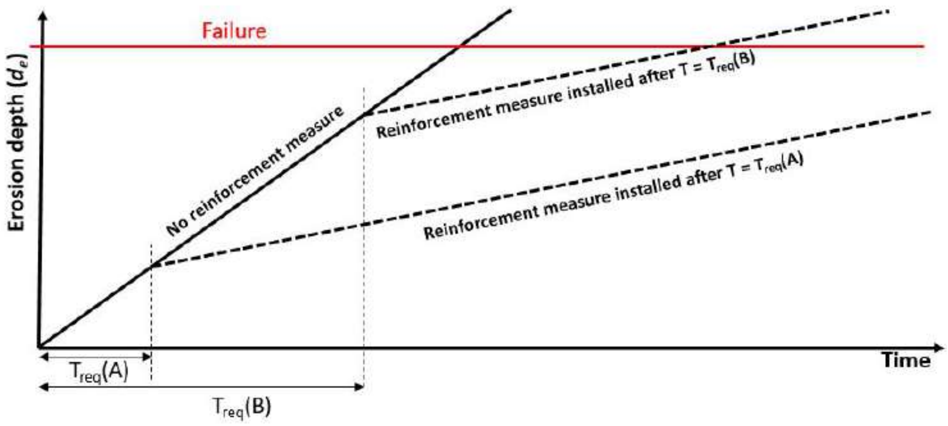


Figure 2.5: Erosion reduction due to successful applied reinforcement measure after $T = T_{req}$.

The longer the time required for installation, the further to the right in Figure 2.5, hence the higher the failure probability of the flood defence given a successful measure $p_{f|measure}$. A Monte Carlo simulation is therefore used in this thesis to calculate the failure probability of the flood defence with and without (uncertain) measure, this is explained in the next sub section.

2.3.2. Method per question

The five components of the reliability framework of Figure 2.4 are assessed separately in the five research questions. Those five components are the input parameters for the main research question.

Method sub questions

1. What is the reliability of a grass revetment taking into account initial damage?
   - A method is developed to calculate the failure probability of the flood defence without measure $p_{f|no-measure}$. Erosion models (WBI-2017) are used as basis. These models are modified to account for initial damage. A Monte Carlo analysis is used to determine the failure probability of the flood defence conditional on the wave height.
2. What is the effect of reinforcement measures on the reliability of the grass revetment?
   - A model is developed to account for the increase in erosion resistance due to the installation of the reinforcement measure. This model is used to calculate the reliability of the flood defence with reinforcement measure $p_{f|measure}$.
   - The erosion reduction is schematized by an erosion modification factor that reduces the erosion speed. This effect is implemented into the fragility curves.
3. What is the reliability of the detection of a weak spot?
   - This research question answers one of the three components (p_d) of the failure probability of the reinforcement measure (p_m). The detection phase does also contribute to the total required time (T_{req}).
   - An event tree of the detection phase is constructed and the reliability and required time are quantified. The failure probabilities are calculated based on a modified version of the *OPSCHEP* model.
   - The fact that some mistakes result in delay rather than a contribution to the total failure probability is taken into account.
   - Field observations are used in the analysis and quantification of the detection phase.
4. What is the placement reliability of grass revetment reinforcement measures?
   - This fourth research question answers one of the three components (p_p) of the failure probability of the reinforcement measure (p_m). The placement phase does also contribute to the total required time (T_{req}).
   - An event tree of the detection phase is constructed and the reliability and required time is quantified. The failure probabilities are calculated based on a modified version of the *OPSCHEP* model.
   - It is accounted for that some mistakes result in delay rather than a contribution to the total failure probability.
   - Field observations are used in the analysis and quantification of the placement phase.
5. What is the technical reliability of grass revetment reinforcements?
   - This research question answers one of the three components (p_t) of the failure probability of the reinforcement measure (p_m).
   - The load and resistance of the grass revetment reinforcement measure are quantitatively and qualitatively assessed and the technical failure probability is approximated.

Method main research question

The main research question is answered based on the five building stones developed in the sub questions. The main question is: *what is the effectiveness and reliability of grass revetment reinforcement measures for river dikes?*

The main research question integrates the five parts, this is explained based on Figure 2.6. The numbers in the figure represent:

1. Erosions of the grass cover starts at $T = 0$, the erosion speed is determined by the strength of the grass revetment and the hydraulic conditions. Erosion models are used in to describe the erosion speed, based on research question 1.
2. No changes in the erosion speed occur; when the reinforcement measure fails the line continues with the same slope. The failure probability of the flood defence is then equal to the failure probability without reinforcement measure ($p_{f|no-measure}$). Whether or not the reinforcement measure fails is determined by p_m, based on research question 3, 4 and 5.
3. When the measure is installed successfully $(1 - p_m)$ the second uncertainty parameter comes into play: the time needed to install the measure (T_{req}). Although installed correctly, the more time needed to install the measure the higher the failure probability of the flood defence ($p_{f|measure}$). The time required is determined by the detection and placement phase, based on research question 3 and 4.
4. The reduced erosion speed is implemented when the measure is installed $(1 - p_m)$ before failure of the revetment ($T_{req} < t_{failure}$). Number four represents the effect of the measure on the erosion speed of the grass revetment. The erosion speed is not necessarily zero when the geotextile is installed. This part of the graph leads to the failure probability given a correctly placed measure $p_{f|measure}$. This updated erosion speed due to the presence of the measure is based on research question 2.
5. Failure is defined when the erosion depth exceeds a certain level. The limit state function will therefore be defined in terms of erosion depth. This failure definition is based on research question 1.

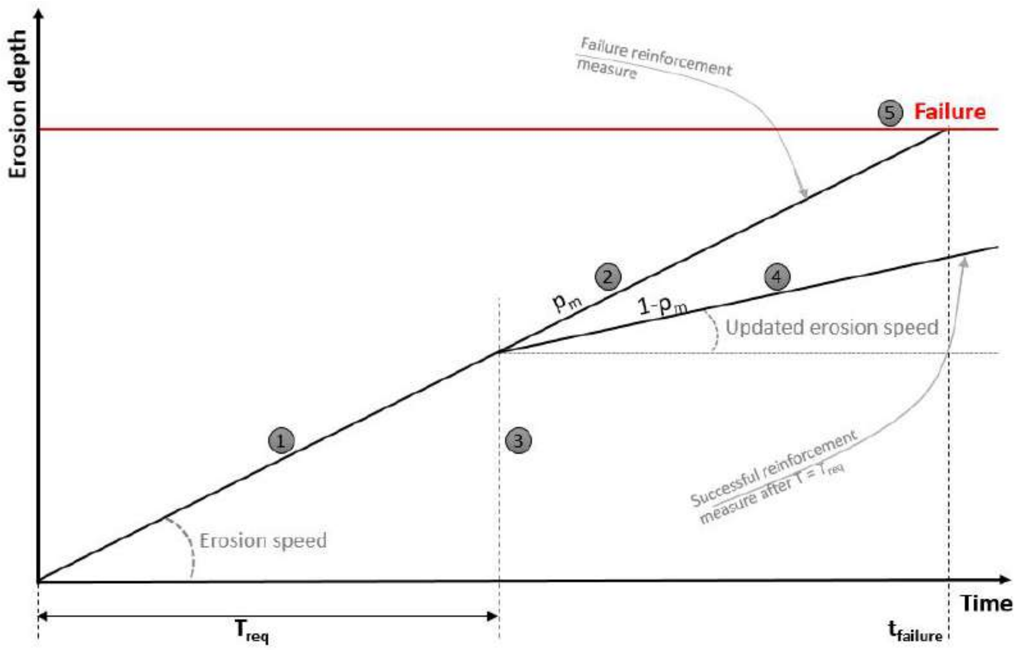


Figure 2.6: General calculation method.

The explanation above is a simplified example. The following parts are included in the calculation method:

- Grass revetment reinforcement measures are installed at damaged locations in the revetment. Initial damage is included in the reliability assessment by taking into account an initial erosion depth.
- Different erosion models are used for the grass revetment and clay sub layer. This results in different erosion speeds per layer.
- Inhomogeneous hydraulic conditions are implemented in the model by means of a schematized wave distribution over time. The wave height is discretized per hour and the cumulative erosion is calculated.
- Most parameters are implemented in the model stochastically, such as the erosion modification factor given correct placement.
- The failure probabilities are calculated with a crude Monte Carlo simulation with fragility curves as result. This will be further explained in the next section.

The following stochastic variables are implemented into the crude Monte Carlo simulatin:

- **Hydraulic parameters**

  - Wave height
  - Storm shape and duration
- **Strength parameters**
  - Thickness grass revetment
  - Erosion resistance grass revetment
  - Thickness clay sub layer
  - Erosion resistance clay layer
- **Uncertainty reinforcement measure**
  - Failure probability measure (p_m)
  - Time required for installation (T_{req})
  - Erosion modification factor for a correctly installed (α_{geo}) reinforcement measure.

For each run are the hydraulic conditions determined. Based on these condition is the erosion speed per time step calculated. This erosion speed is modified by the effect of the measure when the reinforcement measure is successful and after the time required to install the measure. This calculation procedure does lead to the failure probability of the flood defence.

The Monte Carlo simulation is more extensively discussed in:

- Chapter 3, Figure 3.3 for the grass revetment without measure.
- Chapter 10, Figure 10.2 for the grass revetment with (uncertain) measure.

Two case studies are used to calculate the effectiveness of the reinforcement measures, based on the above described calculation method.

Field observations

The field observations are used in the analysis of the detection and placement phase and the technical reliability. An overview of all the observations can be found in a *List of observations and interviews* at page 117.

- ***Deining en Doorbraak* exercise**
  Five water boards, with the large rivers in their management domain, have held a high water exercise during the last week of September. Data was gathered during this exercise and information about the detection and placement phase and methods was obtained. More placement and detection (exercises) are observed for this research, besides the *Deining en Doorbraak* exercise.
- **Workshop**
  A workshop has been organized where the participants had to tackle a fictitious case, the crisis response, assumptions and considerations of the participants[2] resulted in data and understanding of the system.
- **Interviews and meetings**
  Interviews with experts at several water boards and the Wiki-Noodmaatregelen meetings provided input for this research.
- **High water 2018**
  The Dutch river system experience two relatively mild high water conditions during the period of this research. Multiple reinforcement measures were installed and the dike inspection was intensified. Observations during this high water are part of this thesis.

[2]The following water boards participated in the workshop: *Aa & Maas*, *Drents Overijsselse Delta*, *Rijnland*, *Rivierenland*, *Hoogheemraadschap De Stichtse Rijnlanden* and *Vallei & Veluwe* and *Calamiteiten Team Waterkeringen* (Rijkswaterstaat and Deltares.

3

Reliability grass revetment

This chapter answers research question one: *what is the reliability of a grass revetment taking into account initial damage?* This research question leads to the failure probability of the flood defence without measure $p_{f|no-measure}$. The blue part of the reliability framework is analysed, see Figure 3.1.

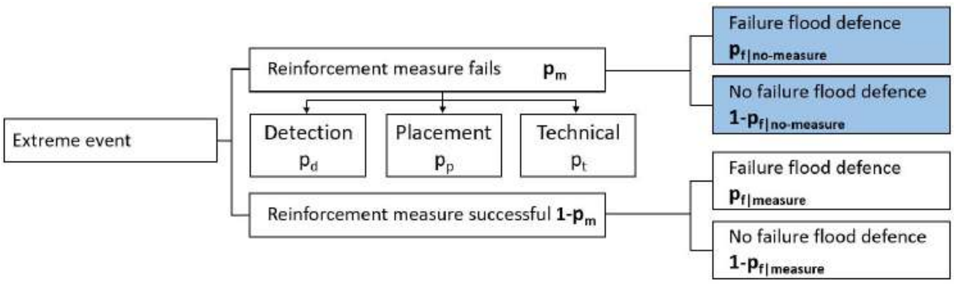


Figure 3.1: Place in reliability framework reinforcement measures.

Section one concentrates on failure of the outer slope grass revetment due to erosion. The second section extends the erosion models by taking into account initial damage. The erosion models, with initial damage, are implemented into fragility curves to determine the failure probability of the flood defence without reinforcement measure $p_{f|no-measure}$. The fourth section presents the results. The chapter ends with conclusions, the answer to research question one.

3.1. Failure grass revetment

3.1.1. Definition grass revetment

Many of the Dutch river dikes are covered with grass, the erosion resistance is determined by the grass revetment and sub layers. The grass revetment definition according to the TAW (1998) is shown in Figure 3.2.

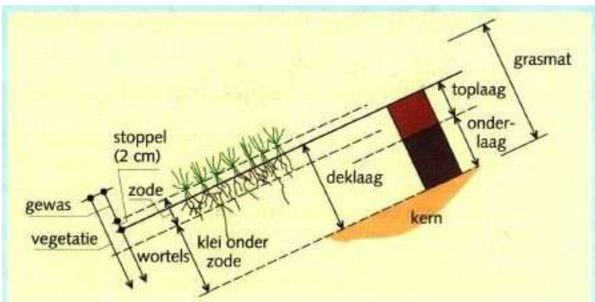


Figure 3.2: Definition grass revetment (TAW, 1998).

Vegetation is present above ground level, this is not necessarily only grass, also herbs can be found. The first soil layer is the top layer of the grass revetment. The root system results in a strong first layer of the dike. The network of small and larger roots makes the grass revetment strong and flexible (TAW, 1998). The density of the root system is the most important parameter for the erosion resistance of the grass revetment (TAW, 1998). No high quality erosion resistant clay is needed. Sandy-clay (maximum of 50% sand) is suitable for the top layer to get an erosion resistant grass revetment, provided that the root system is well developed (TAW, 1998). The second layer is named the sub layer, this sub layer has hardly any roots. The erosion resistance of this soil layer is thus determined by the erosion resistance of the soil itself. The sub layer thickness is not clearly defined when the dike core consists of clay as well. The erosion resistance of grass revetments on dikes was assumed small in the past, a very limited amount of overtopping discharge was allowed on grass revetments. Recent large scale simulations have proven that the erosion resistance of a good quality grass revetment is significant, see for example Steendam et al. (2010). This study also shows that *damage to the grass sod (ripping of) does not directly mean that the top layer of the grass cover (roughly 20 cm thick) in total will fail* (Steendam et al., 2010). Vulnerable spots in the grass revetment are at the transition between toe and slope, the transition between different materials, around objects and at bare spots (Le Trung et al., 2014).

3.1.2. Failure mechanisms grass revetment

Failure of the inner or outer slope grass revetment of dikes can be caused by two main failure modes: erosion or sliding of the grass revetment. The sliding mechanism is sliding of the grass revetment and clay sub layer. This mechanism is the result of water infiltration through the inner slope, which causes an increase in pore water pressure and thereby a decrease in shear strength (Van Hoven et al., 2010). A decrease in water pressure due to wave run-down is the initiating factor for sliding of the outer slope. The failure tree for grass revetment failure is shown in Figure 3.3. Erosion and sliding of the inner and outer slope of the dike are caused by different hydraulic conditions. The hydraulic conditions on the outer slope are governed by wave impact, wave run-up and water flow, the inner slope is subjected to overtopping and overflow.

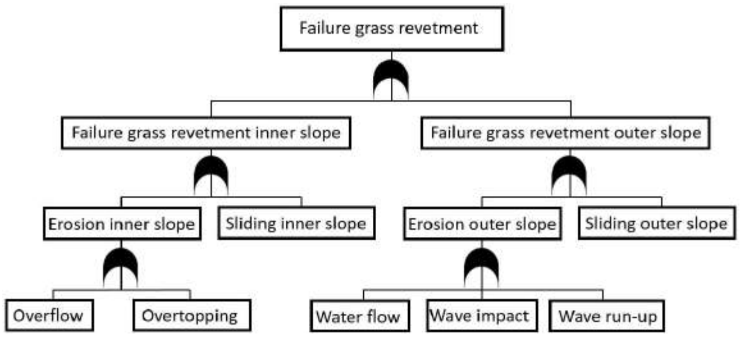


Figure 3.3: Failure tree grass revetment.

The focus in this thesis is on the outer slope erosion mechanism (see Chapter 2). Outer slope erosion can be caused by three different hydraulic loads, a summary is given in Table 3.1.

- **Water flow.** The influence of water flow is in general of minor importance, there are cases in which water flow might cause non-negligible hydraulic loading to the revetment. Waterway dikes (Dutch: schaardijk) are an example where water flow might be the governing hydraulic load. The hydraulic load caused by water flow is lower than waves with a wave height of several decimetres (TAW, 1998). In the Dutch assessment method no water flow alongside the river dike is taken into account in the erosion calculation (Rijkswaterstaat, 2016). Water flow is therefore neglected as erosion mechanism.
- **Wave impact.** Wave impact is the largest load on the outer slope of a dike. Impacting waves exert a local high pressure, in a short time period (Rijkswaterstaat, 2016). The location of wave impact on the outer slope is between the still water line and half of the wave height below this level ('t Hart et al., 2016).
- **Wave run-up.** A grass revetment will fail in the wave impact zone when the grass revetment is homogeneous. Wave impact is a more severe loading compared to wave run-up ('t Hart et al., 2016). A dike can however fail in the wave run-up zone when the wave impact zone is reinforced (e.g. stone revetment). Only homogeneous grass revetments are dealt with in this thesis, therefore is wave run-up neglected.

Table 3.1: Hydraulic loads and their relevance in erosion and sliding modelling of the outer slope grass revetment.

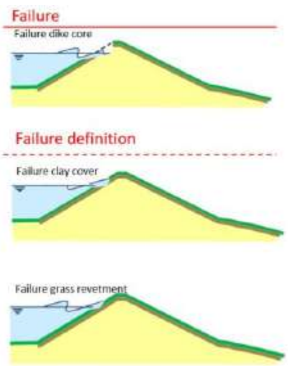
	Wave impact	**Wave run-up**	**Water flow**
Effect on	Erosion and sliding	Erosion	Erosion
Severity	High	Small	Small
Included in analysis	Yes	No	No

3.1.3. Failure definition erosion mechanism

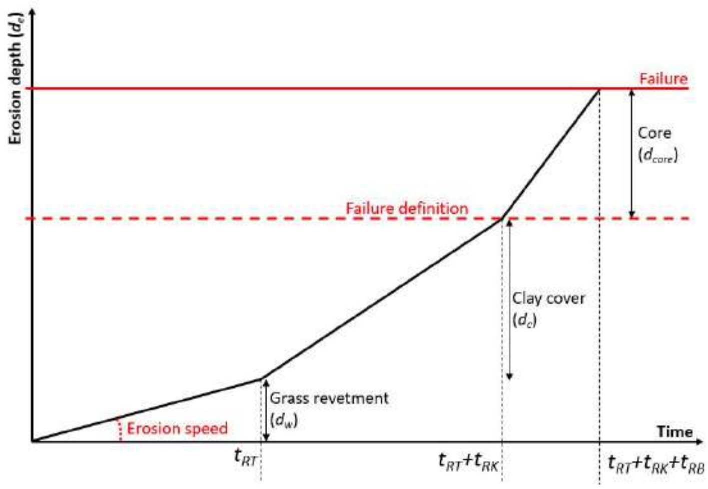
The limit state function for failure of the grass revetment due to erosion, as a function of time and with constant hydraulic conditions, is expressed in Equation 3.1. In general: failure of the grass revetment (erosion depth d_w after time t_{RT}), clay sub layer (erosion depth d_c after time t_{RK}) and dike core (erosion depth d_{core} after time t_{RB}) will lead to failure of the flood defence. The erosion failure phenomenon is visualized in Figure 3.4. The slope of the solid line in the graph is the erosion speed, which varies per layer. The slopes of the lines in the graph are an indication, the *core* line will be steeper when the core consists of sand. The erosion depth is a function of the hydraulic conditions and duration. The time dependency is important because in further assessment of the applicability of reinforcement measures can the time until failure be compared with the time needed to apply reinforcement measures.

$$Z = d_w + d_c + d_{core} - d_e \tag{3.1}$$

Where:	d_w	=	Thickness grass revetment	[m]
	d_c	=	Thickness clay layer	[m]
	d_{core}	=	Thickness core	[m]
	d_e	=	Erosion depth	[m]
	t_{RT}	=	Time needed to damage grass revetment	[s]
	t_{RK}	=	Time needed to damage clay cover	[s]
	t_{RB}	=	Time needed to damage dike body	[s]



(a) Failure due to wave impact, after Rijkswaterstaat (2016)



(b) Time until failure of the grass revetment, clay cover and core of dike.

Figure 3.4: Time until failure and failure definition (uniform hydraulic conditions).

The strength parameters of Equation 3.1 are d_w, d_c and d_{core}. Erosion models are available for all these three components, with wave impact as hydraulic load. For other mechanisms, for example wave run-up, is the residual strength of the dike core not taken into account (Rijkswaterstaat, 2016). A dike core consisting of sandy material has very limited erosion resistance, often modelled as zero residual strength (Steenbergen et al., 2007), this is in contrast to clay which has considerable erosion resistance. Failure due to erosion is in this thesis defined as failure of the grass revetment and clay sub layer (see Figure 3.4), because:

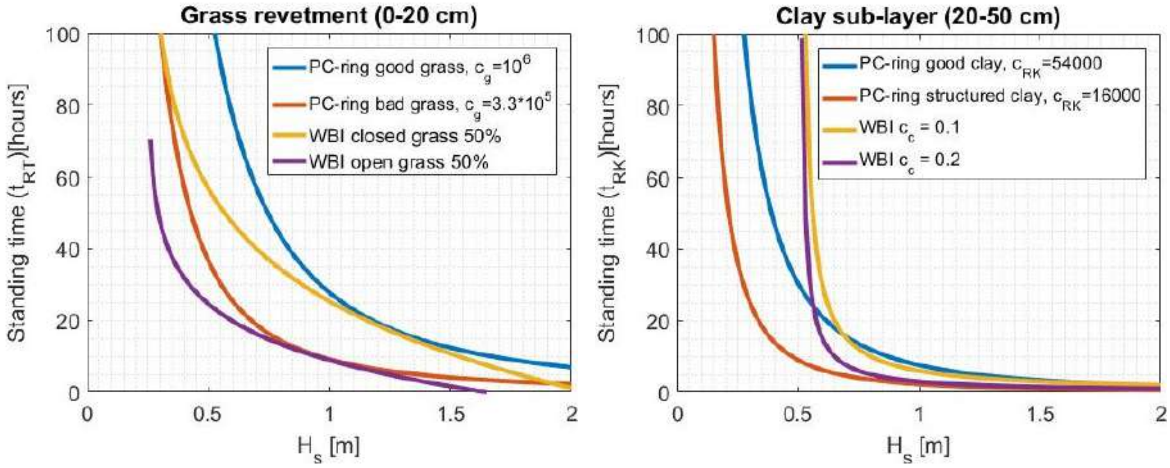
- Placement of the reinforcement measure will become more difficult when the grass revetment and clay sub layers have eroded. It is assumed that the reinforcement measures can be placed as long as there is a (part of the) clay cover present.
- Residual strength of the dike core material cannot be taken into account for each hydraulic loading condition. It can be taken into account for wave impact, but not for run-up. The residual strength of the dike core is not taken into account in order to apply the same procedure to each mechanism.

The limit state function according to Equation 3.2 will be used, the d_{core} component is neglected.

$$Z = d_w + d_c - d_e \tag{3.2}$$

3.1.4. Model choice erosion mechanism

An overview of the erosion models used in PC-ring (model used in VNK2[3]) and WBI-2017 (new Dutch safety assessment) can be found in Appendix A. Both models describe the standing time of the grass revetment and clay sub layer as function of the wave height. The two models are compared for wave impact, see Figures 3.5a and 3.5b. Direct comparison is impossible because of the differences in definition for grass and clay quality and the definition of revetment thickness. The erosion of the grass layer (20 cm) and clay sub layer (20 - 50 cm) is calculated for the WBI-2017 erosion formulas. In the PC-ring method is failure of the grass revetment defined as erosion of the first 10 cm (VNK, 2013). The clay layer thickness for the PC-ring calculation is chosen as 40 centimetre, because then the same erosion depths are compared in the analysis .The PC-ring method (good quality grass and clay and bad quality grass and structured clay) is compared with the WBI-2017 method (closed grass 50% and open grass 50%), see Figures 3.5a and 3.5b.



(a) Standing time grass revetment. (b) Standing time clay layer.

Figure 3.5: Comparison WBI-2017 and PC-ring erosion models.

From the figures above (Figure 3.5a and 3.5b) is concluded that:

- The standing time is consistent for both models in the high wave height range above H_s of 1 meter.
- The WBI-2017 methods do give less conservative standing times for the grass revetment for waves smaller than 1 meter.
- The WBI-2017 method has a start-erosion-threshold (H_s = 0.5), whereas the PC-ring models still gives erosion for these wave heights.

The WBI-2017 method will be used in this thesis because:

- The grass revetment qualities of the PC-ring method are poorly defined. *Very good, good, structured* are possible choices to model the erosion resistance. However, it is not clear what defines these values. The WBI-2017 method gives (photo) examples of the grass revetment qualities, which makes this model more verifiable, see Appendix A.
- The PC-ring method does give considerable erosion rates for waves with a significant wave height lower than 0.5 meter, in comparison to the WBI-2017 method, see Figure 3.5b. The WBI-2017 threshold of erosion is based on multiple tests that were carried out to simulate storm conditions (duration 20 hour), no erosion was observed at all (Klein Breteler, 2015).
- Multiple studies show that Non Water Retaining Objects (NWO) are critical for the resistance of grass revetments and clay layers. These NWO's can be implemented in the erosion model for the clay layer.
- The WBI-2017 method is the current practice as used in the Netherlands. The findings of this research can be more easily implemented in flood protection strategy by using these models.
- The sensitivity of the PC-ring formula to its parameters seems to be higher than the WBI-method (see Appendix A.4 and A.5). This cannot be used as evidence to decide which of the two methods is better, because information about the inhomogeneity might be lost in the WBI method. However the effect of the reinforcement measures is better expressed by the WBI-2017 method as the parameters itself do produce less scatter.

[3]Veiligheid Nederland in Kaart, a project that ended in 2014 where the flood risk in the Netherlands was analysed.

3.1.5. Erosion models

Erosion grass revetment

The formula for the grass revetment failure can be seen in Equation 3.3. This model describes the failure of the first 20 centimetre of the revetment (Rijkswaterstaat, 2016).

$$H_{m0} = a \cdot e^{b \cdot t_{RT}} + c \tag{3.3}$$

The model gives the standing time given constant wave height. However, the wave height will not be constant and the cumulative erosion has to be calculated. It is assumed that the fraction of the time at that certain wave height is also equal to the fraction of the erosion. For example: when a certain wave height and model parameters result in a standing time of 10 hours, but the actual duration of that wave height is 5 hours: then the erosion depth is also 50%. See also Equation 3.4.

$$d_e = \frac{\Delta T}{t_{fail}} \cdot d_w \tag{3.4}$$

Erosion clay layer

The strength of the top 50 centimetre of the clay layer is studied by Klein Breteler (2015). An analytical formula is derived to assess the erosion rate after damage of the top layer (20 centimetre). See Equation 3.5 and 3.6.

$$R_e = c_c \cdot \frac{(H_s - 0.5)}{f_{NWO}} \tag{3.5}$$

$$d_e = R_e \cdot \Delta T \tag{3.6}$$

Where:				
	R_e	=	Erosion rate (increase of erosion depth per hour)	[m/h]
	H_{m0}	=	Spectral significant wave height	[m]
	d_e	=	Erosion depth	[m]
	f_{NWO}	=	Influence of transition structures and NWO's	[-]
	ΔT	=	Time step	[hours]
	d_w	=	Thickness grass revetment	[m]
	a, b, c	=	Model parameter	[m; hour^{-1}; m]
	c_c	=	Constant dependent on the sand content	[hour^{-1}]
	d_c	=	Clay thickness	[m]

The models and model parameters are described in detail in Appendix A.

3.1.6. Load parameter

Storm peak and duration

The load is determined by the duration of the hydraulic conditions that are assessed. It is not necessarily equal to the duration of the high water, erosion is for example dominated by wave impact (see Table 3.1). The governing wave impact situation is for example likely due to a combination of high water and storm conditions, which will be limited in duration, whereas overflow can occur over a much longer period of time.

The storm duration and shape of the storm is an important parameter in the erosion mechanism calculation however these parameters are uncertain. Geerse (2006) did a statistical analysis of the historic storms in the Netherlands and came up with the discrete probability distribution according to Table 3.2.

Table 3.2: Storm distribution according to Geerse (2006). The original base duration of the wide storm was proposed to be 76, this is modified in 77 because that will result in an even number for the flanks of the storm.

Storm	**Probability [-]**	**Base duration [hour]**	**Peak duration [hour]**
Narrow	0.3	21	1
Middle	0.5	48	2
Wide	0.2	77	3

All the storms in the Netherlands (1971-2018) with an hour averaged wind velocity larger than 20 m/s in the same graph as the *middle* storm schematization can be seen in Appendix A.1.2 to show the quality of the schematization.

Wave height

The wind velocity should be translated to a wave height. Taking into account (1) that the wave height and wind velocity are approximately linearly related when the water depth and fetch are constant, according to the Bretschneider calculations and (2) considering that the river water depth does not chance significantly on the time scale of the storm is assumed that the same (wind velocity) storm schematization, as described in Section 3.1.6, is applicable to the wave height. Waves do not appear instantaneously at the start of the storm, a certain time period is needed for waves to develop. For certain realistic parameters (fetch, water depth, wind velocity) is checked according to a formula from the Rock Manual (Rock manual, 2007). This resulting develop time is in the order of 30 minutes. The duration of the storm is much longer, therefore is no development time is taken into account. The wave height distribution is discretized to be able to calculate the cumulative erosion. The wave height is taken constant per hour and the resulting erosion is therefore also calculated per hour. The wave height distribution for a storm with a peak significant wave height of 1.0 meter, a peak duration of 2 hour and a duration of 48 hour can be seen in Figure 3.6.

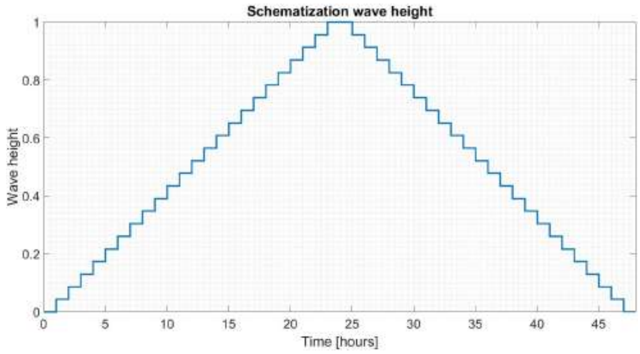


Figure 3.6: Schematization wave height during storm.

Cumulative erosion

The hydraulic conditions are not constant, the erosion speed due to wave impact can for example be written as a function of the significant wave height. However, the significant wave height will not be constant for a long period of time. The method to account for inhomogeneities in the hydraulic conditions is explained based on an example, see Figure 3.7. The hydraulic conditions are discretized into two different significant wave heights over time. Failure would have happened after time t_{RT1} when the wave height was constantly equal to H_{s1}. However, the wave height increases after time t_1, the erosion speed increases. This procedure is applied to a more discretized wave height distribution.

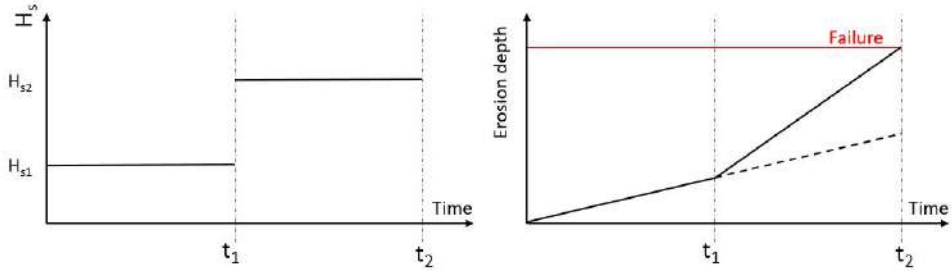


Figure 3.7: Erosion and changing hydraulic conditions.

In the erosion calculation is the erosion depth per hour calculated because the wave height distribution is also discretized per hour. The cumulative erosion is the sum of the individual erosion depths. The erosion formula for the grass revetment is used as long as the cumulative erosion is smaller than the thickness of the grass revetment. The clay layer erosion formula is used when the cumulative erosion exceeds the thickness of the grass revetment.

3.2. Initial damage grass revetment

So far no initial damage is taken into account, however initial damage can be present on slope of a dike due to various reasons. The damage has two effects on the reliability of the dike. First, the erosion resistance of a dike is decreased due to initial damage, because of a decrease in thickness of the protecting layer. The second effect is enhanced water seepage into the dike body. This can increase the level of the phreatic line in the dike body and thereby decrease the safety against macro and micro instability.

3.2.1. Initial damage

Damage to a grass revetment can have various causes. The origin and likelihood of the damage does matter in the reinforcement measures assessment. The following initial damage causes are distinguished:

- **Driftwood and floating debris**
  Trees, wood and debris is picked up from the flood planes during high water events. These objects floating in the water enhance the load on the dike revetments. See also Appendix A.3.
- **Driving tracks**
  Vehicles driving on the revetment can damage the grass. During high water conditions is the likelihood of occurrence higher because the revetment is probably saturated with water, this makes the grass revetment weak.
- **Ship collision**
  Ships can hit the flood defences during high water conditions. This can in most cases only happen during these extreme conditions, because then the flood planes are covered with water. The likelihood of occurrence of this type of damage is low, however the damage can be severe. An example of such event can be seen in Figure 3.8, a ship damaged the river dike during the high water event in 2012.

Figure 3.8: Ship collision on river dike during high water event (De Stentor, 2012).

- **Excavations by animals**
  Excavations by animals are a threat to the river dikes, however not specifically related to high water conditions. Moreover, the damage is difficult to observe as the outer slope of the river dike is covered with water and rats start their excavation normally below the water line (DHV Groep, 2006).
- **Ice**
  Drifting ice can form ice dams in the river and thereby blocking the river. Ice can also damage the grass revetment. This has not been a problem during the last century for the Dutch river dikes, however the problem might come back due to for example climate change and less warming of the river water by cooling water of plants (Jonkman et al., 2017).
- **Local instability.**
  Instability of the grass revetment or macro instability might result in an exposed residual profile of the dike body. This dike body can be protected by a geotextile to increase the erosion resistance.
- **Hydraulic factors**
  The term hydraulic factors in the initial damage domain might be misleading. In fact, hydraulic conditions are not the initial damage factors, but the main erosion initiating loads. However, dike watches can observe damage due to for example waves during their inspection. The damage as present at the inspection is then marked as initial damage. A part of the available time till failure due to erosion is already gone as will be explained in Section 3.2.2.

3.2.2. Initial damage modelling

The limit state function from Equation 3.1 is modified to integrate initial damage in the reliability assessment. The procedure is visualized in Figure 3.9, initial damage results in a different starting point on the erosion graph. Initial damage is modelled as a time and erosion depth shift in the original erosion graph (Figure 3.4b). The resulting limit state function can be seen in Equation 3.7. The initial damage depth is subtracted from the available revetment thickness.

$$Z = d_w + d_c - d_e - d_i \tag{3.7}$$

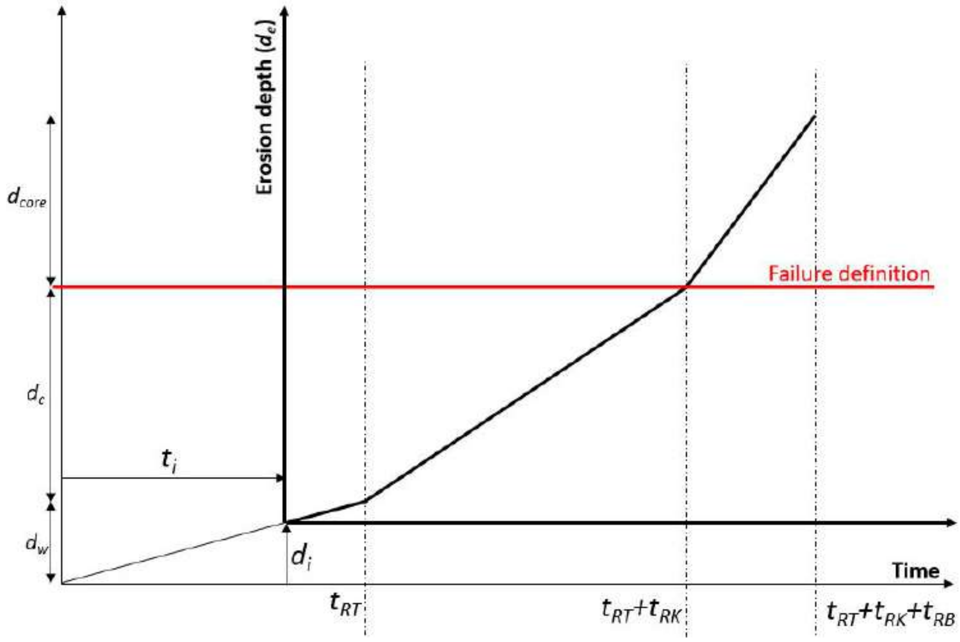
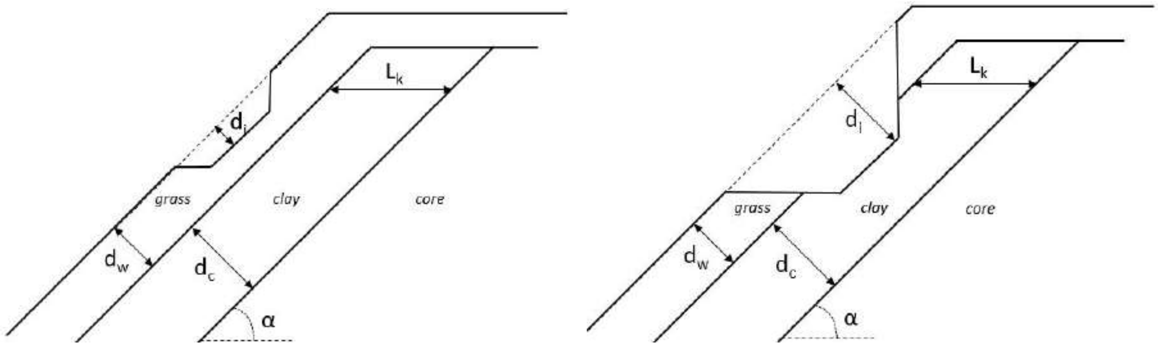


Figure 3.9: Modification erosion model initial damage.

Initial damage is defined perpendicular to the revetment and can either be smaller or larger than the thickness of the grass revetment, see Figure 3.10.



(a) Initial damage grass revetment. (b) Initial damage clay layer.

Figure 3.10: Initial damage determination resistance time.

Example 3.1 Deterministic erosion calculation

This example box presents a deterministic erosion calculation for non constant hydraulic conditions. A grass revetment with a clay sub layer is considered, with the following characteristics:

- closed sod grass revetment: model parameters $a = 1.82$, $b = -0.035$ and $c = 0.25$
- initial damage (d_i): 0 cm
- peak significant wave height (H_s) 1.4 meter, storm duration 48 hours
- thickness grass revetment (d_w): 20 cm
- thickness clay sub layer (d_c): 30 cm
- clay quality parameter (c_c) = 0.1

The storm schematization can be seen in Figure 3.11 by the orange dots. The peak of the storm corresponds to a wave height of 1.4 meter, with 2 hours at maximum wave height. The rest of the wave heights are discretized per hour from zero to the peak and vice versa. The erosion per hour is calculated with the corresponding wave height and revetment quality parameters. The blue line in the figure represents the cumulative erosion. The grass revetment (20 cm) fails after crossing the yellow line, the clay sub layer (20-50 cm) fails after crossing the red line. The grass revetment fails for this specific deterministic calculation because the cumulative erosion exceeds 0.5 meter.

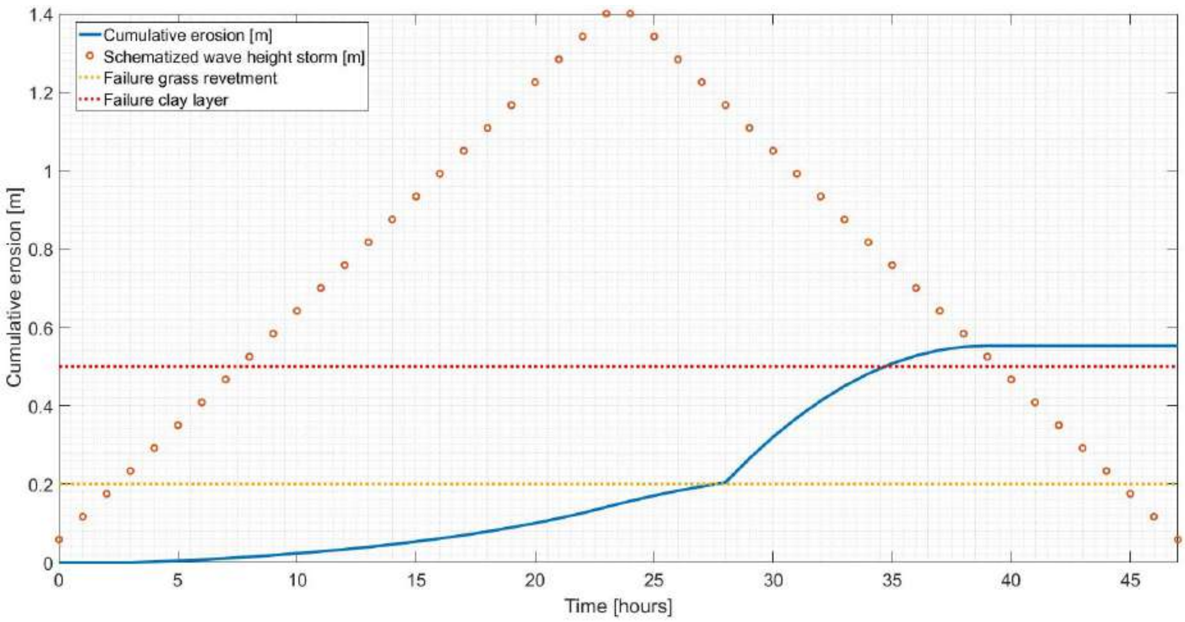


Figure 3.11: Cumulative erosion revetment.

From te example can be deduced that the erosion resistance of clay is much lower than for the grass revetment. This phenomenon is the cause for the kink in the cumulative erosion line at $T \approx 28$ hours. The residual strength of the clay layer is therefore limited. A sandy sub layer would result in a vertical continuing line at a cumulative erosion depth of 0.2 meter, because the residual strength of sand is zero, according to the erosion models.

3.3. Fragility curves

Fragility curves will be used to illustrate the reliability of a dike segment, because it provides quick and extensive insight into the dikes reliability (Wojciechowska et al., 2015). Lendering et al. (2014) used fragility curves to visualize the contribution of reinforcement measures on the failure probability for water level driven failure mechanism.

The difficulty with the use of fragility curves for wave height driven failure mechanism is that it is not only a function of the wave height but also of the duration. Furthermore the wave height is also not constant. This problem is tackled by treating the storm stochastically. The storm distribution according to Geerse (2006) is implemented in the model (see Section 3.1.6. This distribution describes a duration of the peak wave height and the duration of the front and back flank of the storm.

> The fragility curve is conditional on the wave height. This wave height is the peak significant wave height of the storm. This peak has a duration of one, two or three hours. The wave height increases linearly from zero to the peak over the duration of the front flank.

A crude Monte Carlo Analysis, a level III reliability method[4] (Jonkman et al., 2015), is used to calculate the fragility curves, because the method is accurate (VNK, 2013). A disadvantage of the Monte Carlo Analysis is that it can become time consuming.

The crude Monte Carlo procedure is visualized on the next page, see Figure 3.12. In principle, the deterministic calculation of the previous page is executed n times (order 100,000). Every calculation step values out of the marginal statistical distributions are drawn randomly. After this erosion calculation is checked whether or not the erosion depth is larger than the thickness of the grass revetment and clay sub layer. This limit state function can be seen in Equation 3.8, with failure when Z is smaller than zero.

$$Z = d_w + d_c - d_i - d_e \tag{3.8}$$

Where:				
	d_w	=	Thickness grass revetment	[m]
	d_c	=	Thickness clay layer	[m]
	d_i	=	Initial damage depth	[m]
	d_e	=	Erosion depth	[-]

This calculation is repeated n times for each mth wave height (m=50), the failure probability (conditional on this wave height) is equal to the total number of fails divided by the number of runs (n), see Equation 3.9.

$$p(f|H_s) = \frac{n_f}{n_r} \tag{3.9}$$

Where:				
	$p(f\|H_s)$	=	Conditional failure probability	[-]
	n_f	=	Number of fails	[-]
	n_r	=	Number of runs	[-]

Fragility curves will prove to be a convenient tool to visualize the implementation of reinforcement measures. The erosion reduction (due to the grass revetment reinforcement measure), after a certain time with a certain failure probability can be implemented in the model (stochastically).

[4] Uncertain parameters are modelled by their own joint statistical distribution functions.

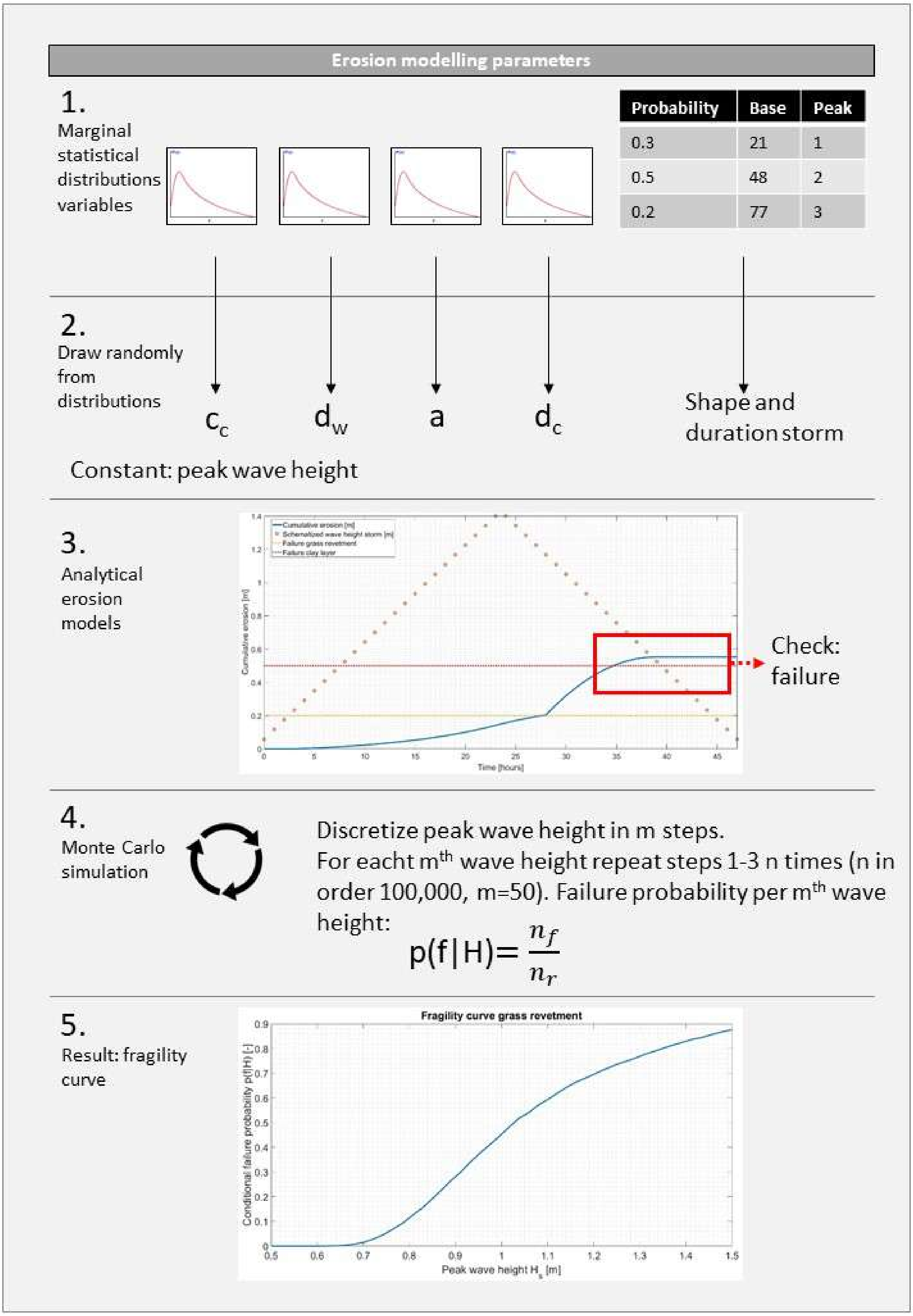


Figure 3.12: Calculation procedure fragility curve

3.3.1. Marginal distributions

The marginal distributions as used in the Monte Carlo Analysis are described in this section. Please notice: no statistical distribution for the wave height is needed, because the fragility curves are determined conditional on this wave height.

Storm duration

The storm peak duration and base duration according to Section 3.1.6 will be used. The statistical (discrete) distribution can be found in Table 3.2.

Grass revetment quality

The grass revetment quality is expressed in three different model parameters (a, b and c). The distribution of the model parameters can be seen in Table 3.3 (Klerk and Jongejan, 2016).

Table 3.3: Model parameters grass revetment quality.

Closed	Distribution	Mean	Standard deviation	Open	Distribution	Mean	Standard deviation
a	Lognormal	1.82	0.62	a	Lognormal	1.4	0.5
b	Constant	-0.035	0	b	Constant	-0.07	0
c	Constant	0.25	0	c	Constant	0.25	0

Thickness grass revetment and clay layer

The formula for the determination of the standing time of the grass revetment is based on a grass revetment thickness of 20 centimetre. This thickness can be less than expected, no statistical distribution is given in the WBI-2017. Therefore, the distribution for the grass revetment thickness of the PC-ring calculation method is used. The statistical distribution, according to Steenbergen et al. (2007), is used in the analysis and can be seen in Table 3.4. The same distribution is used for the clay layer as can be seen in the table.

Table 3.4: Statistical distribution d_w

Parameter	Distribution	Mean	Coefficient of variation
d_w	Lognormal	20 cm	0.2
d_c	Lognormal	30 cm	0.2

Quality clay sub layer

The quality of the clay sub layer is expressed by the formula 3.10. This formula is further explained in Appendix A. No statistical distribution is given, this equation represents the mean value. For the 95% formula the value of 0.1 has to be changed in 0.2. A lognormal distribution has been determined that matches this criteria, see Table 3.5.

$$c_c = 0.1 + max(0; 1.5 \cdot (F_{sand} - 0.7)) \tag{3.10}$$

Table 3.5: Statistical distribution d_w

Parameter	Distribution	Mean	Coefficient of variation
c_c	Lognormal	0.1	0.52

3.3.2. Sensitivity parameters

In Appendix A.4 are graphs shown of the sensitivity of the six parameters. The two most important parameters are the storm peak and base duration and the wave height. The wave height is obviously important as it is the main driving force behind the erosion. The wave height is the condition in the fragility curve, so the failure probability will be determined for all values of H_s. The storm duration is also of large importance. The schematization according to Geerse (2006) has been used. This discrete statistical distribution is derived pragmatically and gives a realistic representation of the storms based on visual analysis of 20 historic storms.

The parameters for the thickness and quality of the grass and clay layer do also have a large impact on the outcome of the calculation. However, those distributions are known and thereby is the effect implemented in the model.

3.4. Results reliability grass revetment

Different grass revetment qualities WBI-2017

The fragility curve for a grass revetment without initial damage for the three distinct (WBI) grass qualities is given in Figure 3.13. The solid lines represent the open, closed and fragmented grass revetments. No strength at all is assigned to the grass revetment when it is fragmented, hence an instantiation erosion depth equal to the grass revetment thickness (20 cm) is modelled.

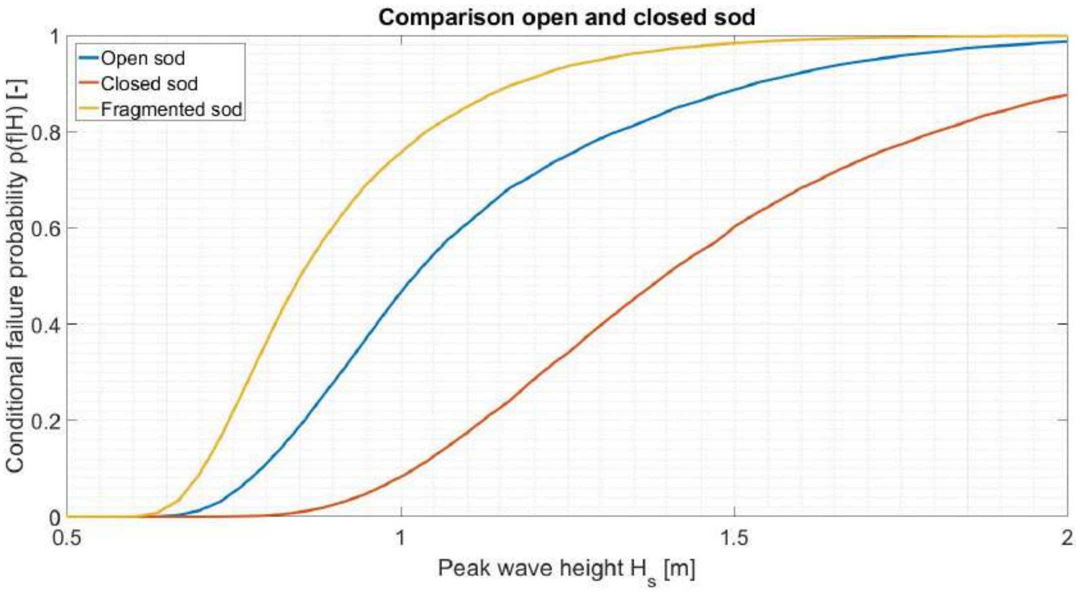


Figure 3.13: Comparison closed, open and fragmented grass revetments (n=10,000 simulations).

Influence initial damage

The influence of initial damage on the conditional failure probability can be seen in Figure 3.14. The failure probability increases rapidly in the case of initial damage.

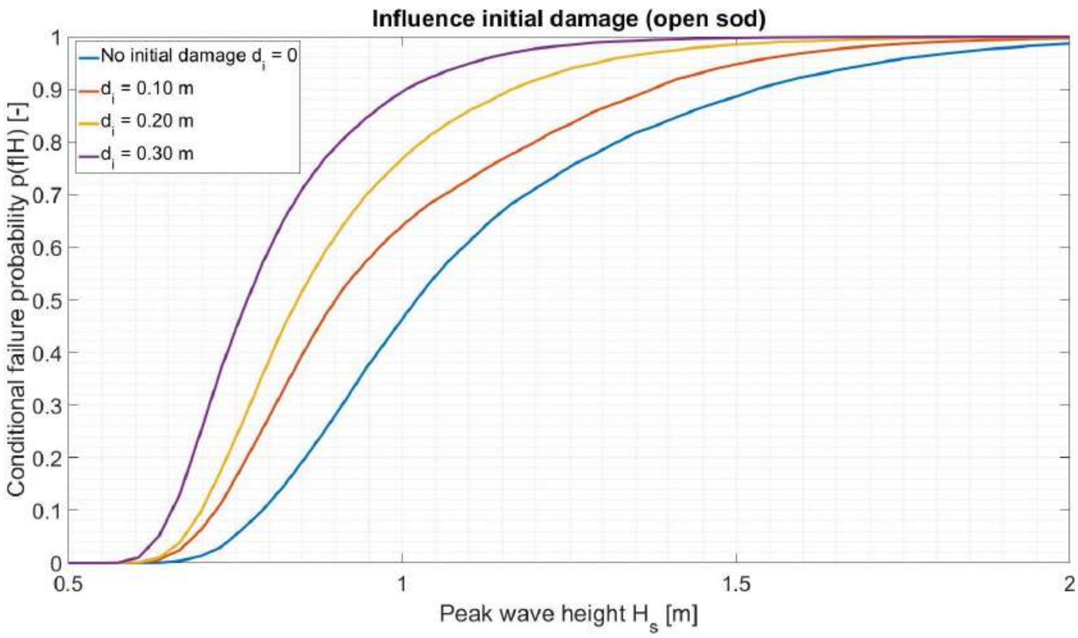


Figure 3.14: Influence initial damage on reliability dike segment (n=10,000 simulations).

3.5. Conclusion reliability grass revetment

Research question one is answered in this section: *what is the reliability of a grass revetment taking into account initial damage?*

Wave impact as governing hydraulic load

The focus in this chapter has been on the outer slope grass revetment. The outer slope is subjected to wave impact, wave run-up and water flow. The latter one is in general of minor importance and is therefore not included as load in the Dutch safety assessment for river dikes. Wave impact is dominant over wave run-up for a slope entirely covered with grass. Wave run-up is therefore only important to consider when the wave impact zone is reinforced with for example stones.

Wave impact erosion requires the wave to reach the river dike, which is at many locations in the Dutch riverine area only possible during high water. Furthermore, large waves can only develop when the fetch is long enough (more than one kilometre), which is often only the case when the flood planes are covered with water. Therefore is, at most locations in the riverine area, a (moderate) high water in combination with strong wind (storm) required for waves to develop.

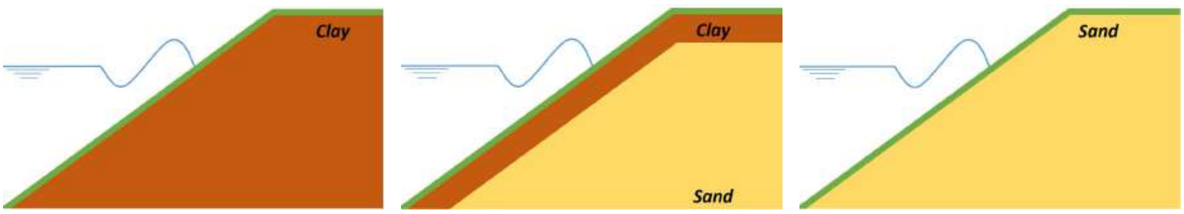
Erosion modelling and effect initial damage

Erosion due to wave impact is modelled based on WBI-2017 erosion models. Failure is defined as failure of the grass revetment (20 centimetre) and clay sub layer (20-50 centimetre). The failure probability of a closed sod grass revetment[5] is low ($p_{f|H}$ = 0-0.08) for peak significant wave heights up to 1 meter. This conditional failure probability rapidly increases with decreasing grass quality (open and fragmented sod) and increasing initial damage. Initial damage can be present due to many different causes, related to the high water or not.

Failure flood defence

Failure of the revetment should be prevented because it can lead to flooding of the hinterland. Failure is defined in this chapter as failure of the grass revetment and clay sub layer. This situation is schematically shown in Figure 3.15b, the core of the dike consists of sand with negligible erosion resistance. The dike does have considerable residual strength when the sub layer and core consists of clay, see Figure 3.15a.
On the other hand, the resistance will be much less when the dike core and grass sub layer consist of sand[6], see Figure 3.15c.

The erosion calculation and fragility curves that are deduced in this chapter are applicable to the situation of Figure 3.15b. The procedure is too conservative for the situation with a clay core with much more resistance against degradation. The conditional failure probability is certainly not applicable to the sand sub layer case. The assumption that water flow is negligible for this situation is probably not valid. The theoretical strength of this dike will reduce to zero when the quality of the grass revetment is low (see Chapter 5.2.2) or when there is initial damage.



(a) Clay sub layer and core. (b) Clay sub layer and sand core. (c) Sand sub layer and core.

Figure 3.15: Three different dike soil compositions.

[5]Highest quality of WBI-2017 classification.
[6]This is the case for the *Overijsselse Vecht* dikes in the Netherlands.

4

Grass revetment reinforcement measures

This chapter deals with the reinforcement measures that are meant to increase the erosion resistance of the grass revetment, this will be answered by research question two: *what is the effect of reinforcement measures on the reliability of the grass revetment?* This research question leads to the failure probability of the flood defence with measure $p_{f|measure}$. The blue part of the reliability framework, see Figure 4.1.

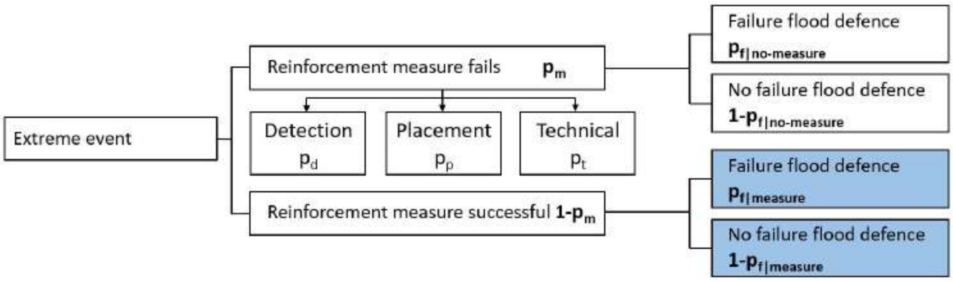


Figure 4.1: Place in reliability framework reinforcement measures.

The chapter starts in the first section with an overview of the effects that can lead to failure of the dike and that are to be reinforced. The second section describes the current practice as used by the water boards for grass revetment reinforcements of the outer slope. The third section gives an overview of the effects of the reinforcements on the dike. The chapter ends with results and conclusions.

The focus of this thesis is on the reinforcement measures for the outer slope. The same analysis as presented in this chapter for the inner slope can be found in Appendix C because it does not contribute to the main subject of this thesis.

4.1. Purpose reinforcement measure

Damage to the grass revetment can have four different effects on the dike safety. The effects are illustrated in Figure 4.2.

A. Initial damage shortens the erosion process of the outer slope of a dike. Heavy wave impact can also initiate erosion.
B. The infiltration rate through the outer slope is increased by a damaged outer slope, due to a decrease in clay layer thickness. Higher infiltration rates increase the phreatic level of the dike.
C. Overtopping and overflow can cause progressive erosion of the inner slope, initial damage shortens this process.
D. Overflow and overtopping result in infiltration of water into the dike body. This has a negative effect on the safety against sliding of the inner slope revetment.

A perfectly working reinforcement measure mitigates effects C and D for an inner slope reinforcement and effects A and B for the outer slope reinforcement. The outer slope and inner slope should be water tight, or at least as water tight as it was before damage. Mitigation of effect A (infiltration outer slope) is however difficult to achieve, this will be explained in the next section.

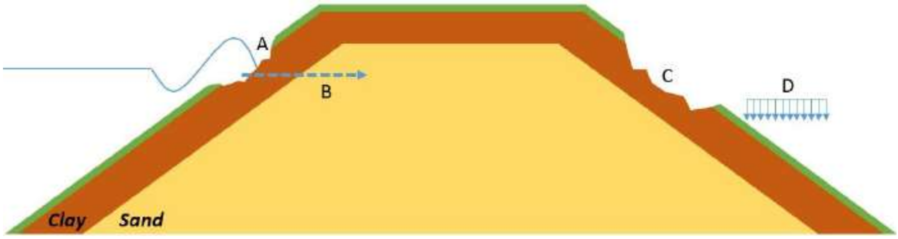


Figure 4.2: Effect damaged grass revetment on dike safety.

4.2. Current practice grass revetment reinforcement design outer slope

4.2.1. Permeable geotextile

Permeable geotextiles are applied by water boards (see Figure 4.3a) on the outer slope of the dike revetment as reinforcement measure. There are two reasons to apply a permeable geotextile instead of an impermeable one:

1. Permeable geotextiles are difficult to place during high water conditions. It is problematic to overcome the water pressures below the geotextile and immerse the geotextile. Water can flow through the pores of a permeable geotextile, which makes it easier to immerse.
2. Water flow or waves can dissipate through the pores when water flow or waves are present behind the geotextile (in between geotextile and dike body). The forces can damage the geotextile structure if water cannot escape through the pores of the geotextile.

An impermeable geotextile would be used to seal of the outer slope and prevent water from entering the dike body. However, based on expert judgement (by experts at the water boards *Rivierenland* and *Drents Overijsselse Delta*) is assumed that even an impermeable geotextile will not stop the increased seepage into the dike body (effect B, Figure 4.2). This reasoning seams justifiable because leakage will take place, even if an impermeable is used. This grass revetment reinforcement structure will be placed partly below the water line, when used as reinforcement measure during high water. Placement below the water line, during high water conditions will probably result in leakage at the borders, because it is very difficult to place a continuous line of sand bags without leakage points. The current design of the outer slope reinforcement used by water board *Rivierenland* (Rivierenland, 2011) does not even prescribe a fully covered border by sand bags. Furthermore, the width of the geotextile is limited (approximately 5 meter), so for large damages overlapping geotextiles are placed. Leakage will take place at the overlapping points. Lastly, the geotextile is damaged by the steel nails through the textile, which can also initiate leakage.

(a) Permeable geotextile.

(b) Impermeable geotextile.

Figure 4.3: Two types of geotextile used at water board Drents Overijsselse Delta (photos dated September 16, 2017).

There are numerous methods of geotextile reinforced grass revetments. The methods can be roughly divided into two types (for the outer slope). The methods are different because the first type is applied above and the second one below water level.

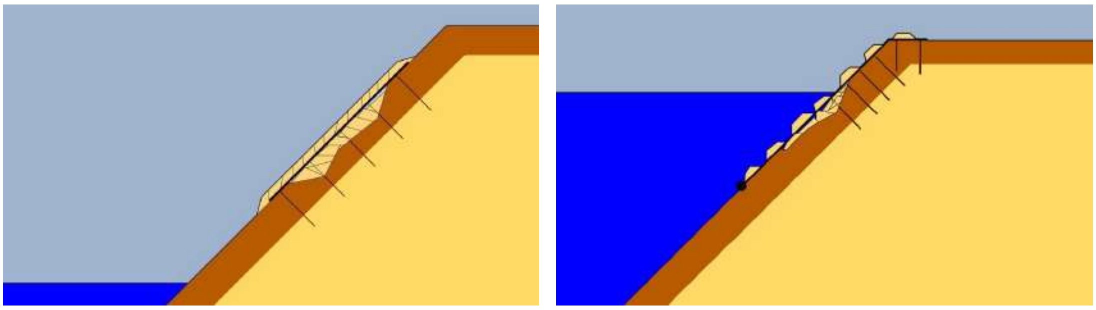
4.2.2. Type 1

A reinforcement measure according to Figure 4.4a can be applied when the water level is below the level of the damage. The gaps in the grass revetment are first filled with sand bags. Secondly, a geotextile is placed over the damaged area. This geotextile is then fixated with sand bags, steel wire and steel nails. A detailed description of this type of measure is given in Section B.1.1. The main characteristics of this type of reinforcement measure are:

- The geotextile can be placed above the water line, easy to check whether the sand bags, steel nails and steel wires are in the right place.
- It is easy to check whether the geotextile covers the damaged area completely.
- This type of measure is mostly applied as reinforcement measure before the arrival of the high water wave, because the nails and the steel wire cannot be placed below the water line.

4.2.3. Type 2

The second type of reinforcement measure used at the outer slope of a dike is illustrated in Figure 4.4b. This type of measure is applied when the geotextile has to be placed partly below the water line. This geotextile is rolled down the slope, with help of the weight at the bottom end of the geotextile. The geotextile is fixated to the dike body by nails and sand bags. A detailed description can be seen in Section B.1.2.



(a) Reinforcement measure type 1 (light brown: sand bags).

(b) Reinforcement measure type 2 (light brown: sand bags).

Figure 4.4: Example grass reinforcement measure outer slope.

4.3. Influence geotextile reinforcement on dike performance outer slope

The placement of a slope reinforcement grass protection measure influences the performance of a dike. The influence is discussed qualitatively below for an outer slope reinforcement measure. The effects are categorized as *main function* (capital letter) and *side effects* (lower case letter) in the figures. The influence of a geotextile measure on the outer slope is illustrated in Figure 4.5.

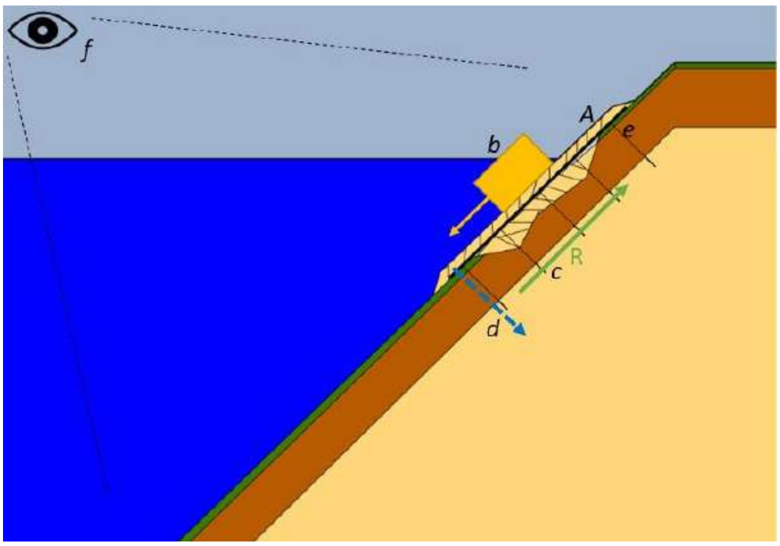


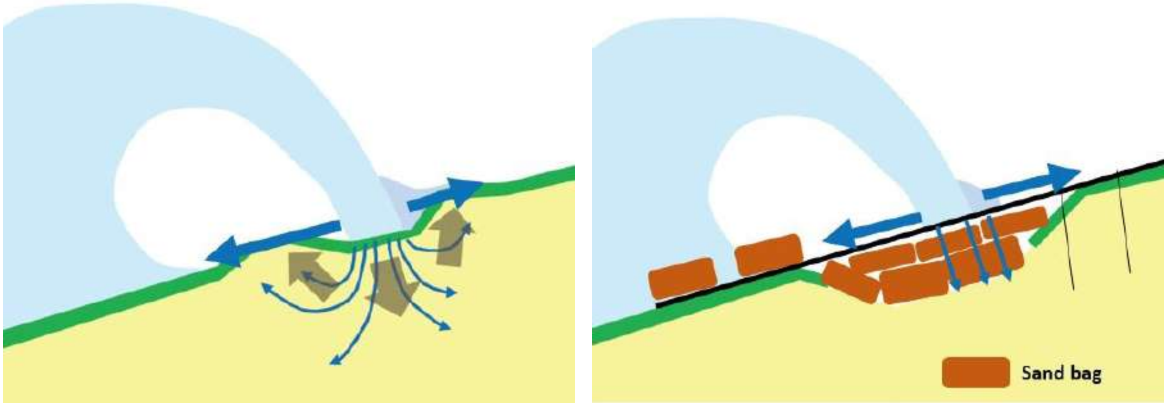
Figure 4.5: Influence reinforcement measure outer slope on dike performance (Not To Scale).

4.3.1. Main function

A. Erosion resistance [positive, main function]

Phenomenological description

A correctly placed geotextile increases the erosion resistance of a (damaged) grass revetment. The grass revetment, clay sub-layer or sand core is not directly exposed to waves or water flow due to the geotextile (assuming that the borders of the geotextile are fixed to the dike body). Wave impact on an outer slope grass revetment is visualized in Figure 4.6a. The impacting wave exerts a high pressure on the grass revetment, this can lead to damage. Small amounts of water will infiltrate into the dike body because clay has a low permeability, water will therefore flow sideways (large blue arrows, Figure 4.6a). This water flow will transport (erode) the grass revetment material (grass and soil). A reinforced outer slope is illustrated in Figure 4.6b. Sand bags will be placed in the damaged hole, the damage depth will determine the number of sand bags used, for small damage depths no sand bags will be used. The sand bags will absorb the wave pressure. Water will flow partly through the pores of the geotextile. However, the pores of the geotextile (see Figure 4.4a) are small, large amounts of water will therefore flow over the geotextile sideways.



(a) Wave impact grass revetment after 't Hart et al. (2016). (b) Wave impact geotextile reinforced grass revetment.

Figure 4.6: Wave impact phenomenological.

Modelling of effect

It is assumed, based on the phenomenological description, that a geotextile structure will reduce the erosion speed. The wave impact pressure is reduced and the water flow (transportation of soil and grass) is decreased. The reduction in erosion speed is modelled according to Equation 4.1. The initial erosion speed is scaled with a modification factor (α_{geo}). This factor is equal to zero if erosion is stopped completely. The reinforcement measure has no effect when the factor is equal to one, no change in erosion speed.

$$E_{geo} = \alpha_{geo} \cdot E_g \tag{4.1}$$

Where:	E_{geo}	=	Erosion speed geotextile reinforced revetment	[m/s]
	E_g	=	Erosion speed non-reinforced slope	[m/s]
	α_{geo}	=	Modification factor erosion speed	[-]

A visual representation of the decreased erosion rate can be seen in Figure 4.7. The erosion rate is modelled linearly and is constant until the correct placement of the reinforcement measure at $T = T_{req}$. The line continuous horizontally if the erosion is stopped completely ($\alpha_{geo} = 0$). The slope of the line does not change when there is no effect on the erosion speed ($\alpha_{geo} = 1$).

The exact value for α_{geo} is unknown as no (large) scale tests are done or tests that are comparable to this situation. It is assumed, based on engineering judgement, that most of the wave energy is absorbed by the geotextile and the underlying sand bags, because:

- a large part of the wave energy will be absorbed by the geotextile structure and underlying sand bags;
- most of the water will flow sideways over the geotextile, thereby not able to transport soil particles, see Figure 4.6b;
- the dike core will provide much more residual strength because of the presence of the measure. Residual strength of the dike core is not taken into account for unprotected revetments (see Chapter 3).

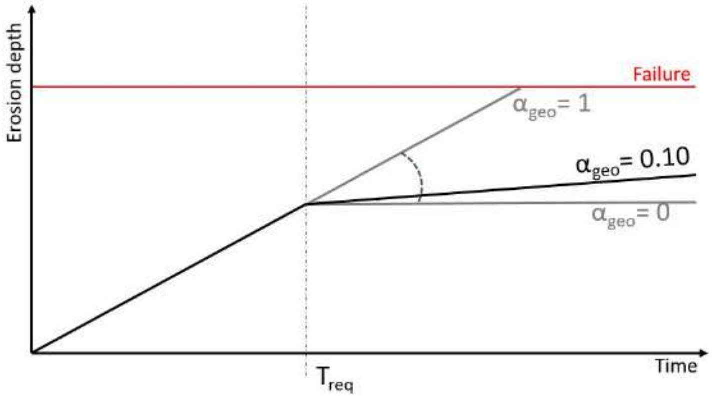


Figure 4.7: Effect geotextile on erosion resistance.

The α_{geo} factor is treated stochastically, as it is unknown. A lognormal distribution with parameters according to Table 4.1 is assumed, based on the explanation above. The mean value is also visualized in Figure 4.7.

Table 4.1: Statistical distribution α_{geo}

Parameter	Distribution	Mean	Coefficient of variation
α_{geo}	lognormal	0.1	0.05

The effect of the grass revetment reinforcement measures on the reliability of a dike is implemented in the fragility curves (Section 3.3) by multiplying the erosion rate with the α_{geo} factor. This effect is visualized for different initial damage depths, see Appendix B.2. The case of an initial damage depth of 20 cm is shown in Figure 4.8. The blue line represents the reliability of an undamaged dike, the red line the effect of initial damage and the other three lines the resulting reliability when a reinforcement is applied (for different α_{geo} factors).

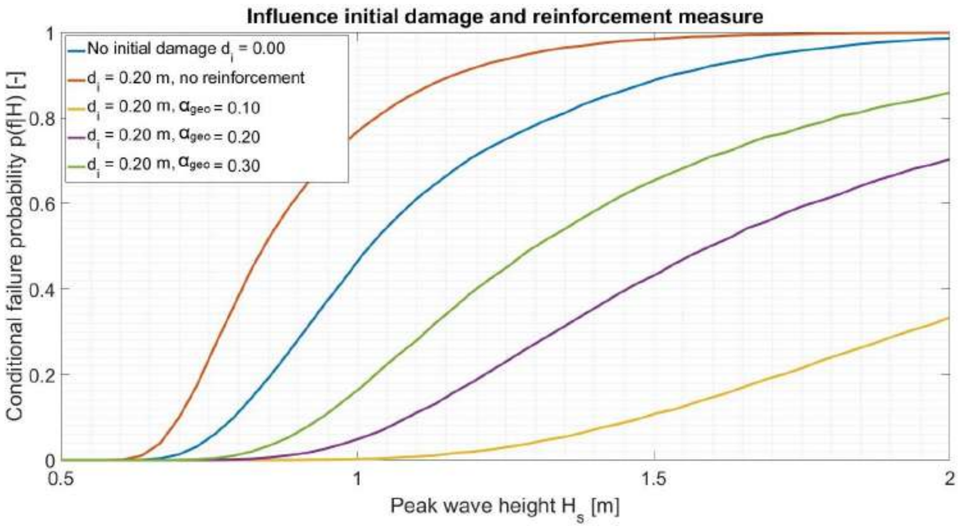


Figure 4.8: Effect grass revetment reinforcement on failure probability dike. [Disclaimer: these graphs do show the effect of reinforcement measures on the conditional failure probability without taking the reliability of the detection, placement and technical reliability into account.]

The analysis shows that for the initial damage depths of 0, 0.10, 0.20 and 0.30 m all α_{geo} factors (0.1, 0.2 and 0.3) result in a reliability that is larger than the undamaged reliability of the dike. It also shows that the effect of the factor on the reliability is high.

4.3.2. Side effects

b. Weight sand bags [negative, side effect]

Sand bags placed on the outer slope revetment increase the downward force on the grass revetment. The safety against outer slope sliding and macro stability is influenced negatively. Macro stability problems are normally only a problem, for the outer slope, when the water level decreases, due to disappearance of the hydrostatic water pressure on the outer slope and a high phreatic line in the dike body.

c. Resistance steel nails [negligible]
The steel nails hammered into the dike body can increase the resistance against grass revetment sliding. The influence is dependent on the length of the nails and the thickness of the clay layer. The resistance will be higher when the nails have a large length. The influence is assumed to be negligible because the length of the nails is approximately equal to a “normal” clay layer thickness (60 á 70 cm).

d. Infiltration [effect measure negligible]
Infiltration into the dike body can be influenced by a geotextile structure. If the outer slope of the dike is damaged, infiltration into the dike body might be large and thus a problem. The infiltration rate depends on the type of geotextile, an impermeable geotextile is most effective, however difficult to place during high water (as it floats). A permeable geotextile will have a negligible influence on the infiltration rate, as water can easily flow through the pores.

e. Deterioration grass revetment [negligible / negative]
The reinforcement structure on a dike body will cover the grass revetment. The grass revetment will deteriorate over time. For reinforcement measures during high water (short term) this is less of a problem when compared to control measures which might be on the dike revetment for a longer period of time. The deterioration of the the grass revetment is not a big problem as long as the geotextile is in place. But, the borders of the geotextile structure might become a weak spot for wave impact and water flow.

f. Effect on further visual inspection [negative]
Visual inspection of the dike during high water is negatively influenced by a grass revetment cover. The development of the weak spot and the possible cracks (due to for example macro instability problems) are difficult to observe. This problem is of limited relevance for the outer slope because inspection of the outer slope is already difficult with high water levels. Furthermore, macro stability problems are mostly not relevant for the outer slope during high water conditions.

4.3.3. General

A general influence on the performance of the dike, both for inner and outer slope is the additional load on the dike crest during construction of the reinforcement measure. Driving on the crest can even be impossible, because of stability problems or driving issues due to the soggy grass cover.

4.4. Conclusion effect reinforcement measure

The second research question, is answered based on the analysis presented in this chapter: *what is the effect of reinforcement measures on the reliability of the grass revetment?*

A correctly installed grass revetment reinforcement measure increases the erosion resistance of the grass revetment. The exact value for the erosion reduction is unknown because no tests have currently been carried out. The geotextile structure:

- reduces the wave impact load;
- most of the volume of the impacting wave will flow sideways over the geotextile and thereby not transporting soil particles.

The erosion modification factor is therefore assumed to be lognormal distributed with a mean value of 0.10. This factor means that the erosion speed is 10% of its initial value. A sensitivity analysis shows that the erosion modification parameter has a large influence on the failure probability of the flood defence. The reliability of a flood defence with initial damage up to 30 centimetre with correctly installed reinforcement measure is more reliable than an open sod[7] grass revetment without measure (for modification factors α_{geo} up to 0.30). Please notice that this statement is valid for the case that the reinforcement measure is installed correctly at the start of the wave impact, see for an example Figure 4.8.

Infiltration into the outer slope of the the dike body is impossible to prevent by applying an impermeable geotextile. Furthermore, permeable geotextiles are to be used on the outer slope to prevent erosion because impermeable geotextiles are difficult to place during high water conditions and to prevent pressure built up.

[7] Second highest category of WBI-2017 quality classification.

5

Field observations

This chapter gives an overview and evaluation of field observations that provided input for this thesis, see Figure 5.1. The first section describes the *Deining en Doorbraak* high water exercise. The second section discusses the high water in January 2018. The workshop data can be found in the third section. The fourth section gives the concluding remarks.

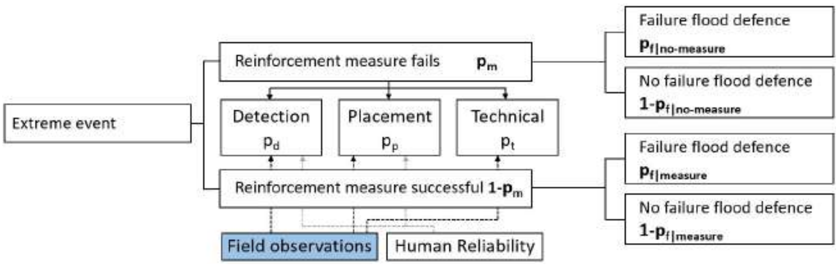


Figure 5.1: Place in reliability framework reinforcement measures.

5.1. Deining en Doorbraak at the *Drents Overijsselse Delta* water board

Five water boards in the Netherlands have practised a high water threat during the last week of September 2017. The water boards *Rivierenland, Drents Overijsselse Delta, Rijn en IJssel, Vallei en Veluwe* and *Stichtse Rijnlanden* participated in this exercise named *Deining en Doorbraak*. The total number of participants at the five water boards is estimated to be 1000 dike watches and 300 office employees (Booltink and Vonk, 2018). Different stages of crisis management were simulated during this training week. The data was mainly gathered at the *Drents Overijsselse Delta* water board. The high water exercise had a five day duration (Drents Overijsselse Delta, 2017b). The deployment of dike watches and the application of reinforcement measures was trained on the 27^{th} of September.

5.1.1. Exercise goals

The following main exercise goals were formulated by the five water boards (Derckx et al., 2017):

1. Designing of a joint water threat prediction by the five water boards.
2. Aligning of the crisis communication between the five water boards.
3. The simultaneous monitoring of the dikes along the Rhine branches.

5.1.2. Limitations exercise

The *Drents Overijsselse Delta* water board simulated the highest stage in the crisis response (dike inspection):

- Only 13 of the 31 dike posts were mobilized during the exercise. This means that the total information and work load will be significantly higher during a real high water threat.
- All four dike supervisors were involved in the exercise, either as participant or in the exercise leadership.

- The crisis organization is gradually intensified during real high water threats. The highest state of dike inspection and crisis response was instantaneously started at 00:01 hour (Wednesday 27th September 2017). This is probably more hectic and confusing than during actual high water events.
- High water events are normally long in duration (order of weeks). This long duration causes fatigue in the whole crisis organization. This element is not included in the *Deining en Doorbraak* exercise.
- The weather was good for inspection and placement of reinforcement measures (rain: 0.0 mm, average temperature: 13.6 degree Celsius, sun hours: 6.3 hour and average wind speed: 2.3 m/s[8]).
- There were no accessibility issues due to traffic jams, bad weather etcetera.

5.1.3. Detection phase

The *Drents Overijsselse Delta* water board inspected their dikes during the exercise with help of volunteers every four hours, in total six inspection rounds per dike post. The procedure is:

- Two volunteers walk the inspection segment (approximately 5 km) back and forth, see Figure 5.2a.
- They report their findings to the dike post commander (also volunteer) by radio.
- The dike post commander report the inspection details to the Head Central Dike Post (volunteer at the Action Centre Water) by an computer application, see Figure 5.2b.
- The prioritization can be set to: no priority, low, middle, high or to be determined. This prioritization is being made based on the qualitative judgement by the dike post commander. Preferably based on a risk consideration, however seemingly based on deviations from the *normal* situation.
  - The Head Central Dike Post and technical specialist can discuss the situation with other specialists in complicated cases. The exercise evaluation states that there is a need for consistent prioritization by an expert and that several reports were not even prioritized (Drents Overijsselse Delta, 2017a).
- The Head Central Dike Post (HCD), a volunteer, decides together with a technical specialist at the Action Centre Water what reinforcements have to be installed, see Figure 5.2c.
  - The HCD and the technical specialist can ask for additional information when the situation is unclear. They can send it to the dike post commander (this means that the next inspection shift will provide this information) or send one of the dike supervisors (Dutch: keringbeheerder) to the location. The latter one means that the information is provided quicker and that the knowledge level of the inspector is higher. However, the exercise revealed that the capacity of the supervisors was insufficient (Drents Overijsselse Delta, 2017a) even during the exercise situation[9].
  - The exercise evaluation reveals that there was no good overview of the water threats or the actions that were going on at several layers in the organization (Drents Overijsselse Delta, 2017a). Dike post commanders were not well informed about the status of the measures installed in their area (Drents Overijsselse Delta, 2017a). The commander cannot take action if no (correct) action was taken for the specific threat without knowing the status. There is also need for a better overview of the reports and reinforcement measures at the Action Centre Water (Drents Overijsselse Delta, 2017a).

(a) Dike watch during dike inspection at the *Vecht* river.

(b) Dike post commander at dike post.

(c) Head Central Dike post and technical specialist at ACW.

Figure 5.2: Communication chain dike inspection.

The dike supervisors are the water boards employees with extensive knowledge of the flood defences. These people were not able to inspect the dikes during the exercise because of obligations at the Action Centre Water

[8] Averages from measure station De Bilt (KNMI, 2018)

[9] See Section 5.1 for the reasons why a real critical situation is probably even worse than the exercise situation.

(Drents Overijsselse Delta, 2017a). The dike supervisors were therefore not able to to inspect the installed reinforcement measures. The water board distinguishes this bottleneck in capacity during real high water threats: *it is likely that a crisis situation in a larger part of the water board area, compared to the exercise, results in insufficient capacity of experienced and educated employees* (Drents Overijsselse Delta, 2017a).

Data detection phase

A placement plan for the fictitious weak spots and log of reports is available of the detection phase at the *Drents Overijsselse Delta* water board. The problem with this data is that the reliability is questionable, see the text box *data reliability* on page 38. Analysis of the data shows that 26 out of 52 weak spots were not found. This data can only be used to show an order of magnitude of the detection reliability. The detection probability of not finding a weak spot is estimated to be in the order of 10^{-1}, based on the data and discussions with the supervisors of the *Drents Overijsselse Delta* water board. This data is supported by the internal evaluation of the water board, which states that multiple damages were missed due to lacking knowledge and experience of the dike watches (Drents Overijsselse Delta, 2017a).

A second important observation is that the number of reports far exceed the number of weak spots that were placed. There were 166 reports logged, more than three times as many as the placed weak spots. This does however not imply that all the additional reports were useless, because weak spots can be present in the dike system for real and found during the exercise. However it shows that the information load will be severe during dike inspection.

In total 166 reports of weak spots were logged, most of these reports where describing distinct locations. In 15 (≈ 10%) of these reports the HCD asked for additional information to make a prioritization. Questions like:

- Where on the dike body is the weak spot located? Inner slope, outer slope?
- What are the dimensions of the damage and is water exiting the weak spot?

These questions are in line with a qualitative observation[10] during the dike inspection. In one particular case, the dike watches described the damage to a very limited extent, only the dimensions of the damage were mentioned. The damage itself was misinterpreted: a crack in the dike body was reported, but the actual damage was a gap in the revetment. It seemed not possible to make a good prioritization and assessment of the damage based on the information reported by the dike watches. These observations are supported by the internal evaluation of the water board where it is stated that the reports of the dike watches were of very different qualities. (Drents Overijsselse Delta, 2017a). The location and dimensions (meter or centimetre) of the weak spot were sometimes unclear.

What the exercise also shows is that there is a substantial difference in prioritization between the dike watch and supervisors based on the same information. The priority of the damage is estimated by the dike watch, based on the same information a second estimation of the priority is given by the supervisor. The results of this prioritization can be seen in Table 5.1.

Table 5.1: Prioritization by dike watch and supervisor for the same incident, based on the same information. Disclaimer: do not draw conclusions based on this table without reading the text box *data reliability* on page 38.

Priority	**Dike watch**	**Supervisor**
Low	73	104
Middle	23	13
High	25	23
No priority	27	14
To be determined	18	12

[10] Camping Haven-Severingen, September 27, 2017 01:40 A.M. by G.P. van Rinsum

Data reliability
Weak spots are obviously not made in the dike for real, as it weakens the actual flood defence. The weak spots are imitated. The following observations are made at the *Deining and Doorbraak* exercise:

- Damage to the grass revetment is sometimes rebuilt realistically with a large photo on the grass revetment in the same matte colours as the actual revetment. On other locations the damage is indicated with a photo on a pole (see Figure 5.3), which is far more easy to observe than real damages. Debris and driftwood is placed on the slopes, which is a realistic representation. Several sand boils were built with sand, which is a good representation of reality, other sand boils are imitated with photos, this is less realistic.

Figure 5.3: Unrealistic imitation damage grass revetment.

- The land behind the flood defences is probably soggy during high water conditions, which makes for example piping difficult to observe. This was not the case during the high water exercise.
- There was not a real sense of urgency during the exercise, which will be there during high water threats.

The inspection data needed for the determination of the detection phase reliability would preferably consist of:

- Percentages of weak spots found.
- Data on how many inspection shifts missed the weak spot before actual detection.
- The time until a decision by the water board to place an reinforcement measure or not.

The data available is:

- A log of reports by dike watches.
- An overview of weak spots to be placed by the water boards.

These data are combined to determine the time until the weak spot is found. However this data can be flawed due to the fact that:

- It is not completely certain whether all weak spots are placed correctly according to the placement plan.
- The locations in the log of reports are sometimes (slightly) different from the location in the placement plan. It is not certain whether the report by the dike watch is correct for those cases;
- The time of detection is sometimes before the planned time of placement of the fictitious weak spot. The placement time is modified in these cases.

Conclusion
Based on the above reasoning is suggested to use the data carefully as indication of the order of magnitude of the failure probability and not as the solid foundation for a reliability assessment. The amount of data is also limited, so it cannot be used as statistical proof even if the data were completely reliable and a good representation of reality.

Interpretation data and observations

Based on the data and observations during the exercise can be concluded that:

- The detection failure probability (not finding a weak spot) has an order of magnitude of 10^{-1}. This finding is supported by Lendering et al. (2013), who observed a failure of detection rate of 0.09 (4 out 46 weak spots not found) for the *Conecto* (2013) high water exercise.
- The dike watch and dike post commander do not provide sufficient information in their reports. because in 15 (approximately 10%) of these reports the Head Dike Post asked for additional information to make a prioritization.
- The number of reports way exceeds the number of actual weak spots. For the *Deining en Doorbraak* exercise this was a factor of 3.2. For the *Conecto* exercise a factor 4 was found (Lendering et al., 2013).
- There is a difference in prioritization between the dike watch and dike post commander and the Head

Central Dike post in combination with the technical specialist. It seems that the dike watch overestimates the priority, based on Table 5.1.

- The 12 reports that are to be prioritized by the supervisor at the end of the exercise raises the question whether the work load during the exercise was already too high or that it is caused by a lack of knowledge. It is impossible to draw a hard conclusion, however it does show the uncertainty involved in this part of the action chain.
- The communication chain: dike watch > dike post commander > Head Central Dike Post & Technical specialist > Placement decision > Placement team, is a serial system and therefore prone to errors. This conclusion was substantiated by one observation during the high water exercise. The dike watches reported a damaged grass revetment of 100 by 40 centimetre. The 100 centimetre was also correctly entered in the application. The placement team prepared a reinforcement measure for 100 meter. It is not clear where in the system this error was made, however it does show the weakness of a serial system, apparently without sufficient repair mechanisms.
  A possible repair system would be when the dike post commander can view the status of the action. However, the evaluation shows that there is no overview for the dike post commander of the status of the actions taken in his management area (Derckx et al., 2017).

5.1.4. Placement phase

Multiple types of reinforcement measure were placed during the *Deining en Doorbraak* exercise, a complete overview of the specific circumstances per installation can be found in Appendix F. The following conclusions are drawn based based on the observations:

- The exercises at the *Drents Overijsselse Delta* water board are done by the water board personnel. However this work is delegated to the contractors when multiple reinforcements have to be placed at the same time. The skill level of these contractors might be much less because they do not participate in the exercises.
- The *Drents Overijsselse Delta* water board personnel (who are doing the regular maintenance as their daily job to the culverts grass revetment etcetera) are responsible for the supervision during placement of reinforcement measures when the NATRES or contractors are deployed. However, these people are not used to monitor the work of others. This was also observed by one of the placements, they were doing the work themselves without properly supervising. A (small) mistake was made in the placement of the geotextile, however this was only observed afterwards by the supervisor.
- It is normal practice to drive with heavy equipment on the dike crest, even when it is not necessary, see Figure 5.4. When asked several persons respond by saying that this is only the case in exercise situations. However, no one can guarantee that this will not be the case during high water threats when the time pressure is high and peoples are fatigued.

(a) Situation 1. (b) Situation 2. (c) Situation 3.

Figure 5.4: Heavy equipment on dike crest.

- The water board personnel is familiar with the installation of grass revetment reinforcement measures, they do not need work instructions. However, contractors or other personnel might need those instructions. However they are not available (Drents Overijsselse Delta, 2017a).
- Reinforcement measures that can only be installed without water at the outer slope were placed during the exercise. The placement method of grass revetment reinforcement measures installed below and above the water line are fundamentally different, see Chapter 4. Furthermore, the road at the outer side of the dike was used for the transport of material and equipment, this road is fictitiously covered with water according to the exercise scenario. No exercise leaders or observers were present at those locations to look after the realism of the exercise.
- Damaged sand bags are still placed even when sand is flowing out during installation. The percentage

of damaged sand bags is estimated to be between 5% and 10% based on observations during *Deining and Doorbraak*, see Figure 5.5. Furthermore, the dike supervisors were not satisfied in the way the sand bags were installed during the exercise. They were not installed according to the placement protocol.

Figure 5.5: Damaged sand bags.

5.2. High water 2018

The Dutch river system experienced elevated water levels during the first weeks of January 2018. The water levels are characterised as high water, but not extreme. Four events in the context of this high water are discussed in this section:

1. The deployment of the KEI-brigade[11] to place sand bags near Kampen.
2. The placement of grass revetment reinforcements in the wake of the high water on the *Vecht* river.
3. The dike inspection by volunteers at the *Drents Overijsselse Delta* water board.
4. The decision not to reinforce the dikes at the *Rivierenland* and *Stichtse Rijnlanden* water board.

5.2.1. Deployment KEI-brigade

A part of the dikes near Kampen (Kampereiland) do not comply to the current safety standards. The safety shortage is known, however the dikes are still not reinforced. The KEI-brigade (Kampereiland brigade) is established to heighten the dike with sand bags during high water conditions. The water levels were expected to rise. This plan was put into action on January the 3th. The water board relies on the availability of volunteers of the KEI-brigade and from the Dutch Ready2Help network[12]. The following observations are made:

- 10.000 sand bags were placed during that day.
- The KEI-brigade consists of 140 volunteers, 60 showed up.
- 100 Ready2Help peoples helped, those people were however not as good prepared as the KEI-brigade volunteers, in terms of clothing.
- The weather conditions were bad, heavy rain and wind.

5.2.2. Placement grass revetment reinforcement measures

The grass revetment of the *Vecht* dikes were damaged due to: driving tracks (one spot) and insects (Engerlingen) that have damaged the grass revetment at multiple locations, see Figure 5.6a.

(a) Damaged grass revetment by *Engerlingen*, hardly any roots present.

(b) Grass revetment reinforcement at the *Vecht* river dike near Zwolle.

Figure 5.6: Damage and reinforcement.

These weak spots were known at the *Drents Overijsselse Delta* water board. Grass revetment reinforcements were placed in the wake of the storm and the high water. A special type of geotextile was used, see Figure 5.6b, this geotextile is strengthened by a plastic grid. This geotextile type was chosen because it can be installed

[11] Kampereiland

[12] A network of people in the Netherlands that can be called when help is needed for several types of calamities such as: threatening high water conditions, refugees and heat waves.

very quickly. No sand bags or steel wire was used, only nails. All the grass revetment reinforcements could be placed in one day.

5.2.3. Dike inspection *Drents Overijsselse Delta*

The *Drents Overijsselse Delta* water board started daily dike inspection by volunteers for the *Vecht* river dikes for 4, 5, 6 and 7 January. Ten dike segments of approximately 5 kilometre were inspected by volunteers. The intensified dike inspection was installed for two reasons:

- The dike supervisors (4 for the *Drents Overijsselse Delta* water board) were busy with work for the high water levels on the *IJssel* river, these high water levels were expected later.
- Dike inspection during real high water is also a good practice for the dike watches and a way to keep their enthusiasm for the job.

5.2.4. Decision: no placement reinforcement measure

I. Grass revetment reinforcement hoogheemraadschap *De Stichtse Rijnlanden*

The *Stichtse Rijnlanden* water board had a dike (1200 meter) in its management area with the revetment in bad condition. In the summer of 2017 the water board had reconstructed the top (clay) layer. The clay was of bad quality due unfavourable weather conditions during storage and placement of the material. Furthermore, had there been a sliding over 50 meter of the slope. There was no grass on the revetment during the high water wave in January 2018.

The initial decision of the water board was to install a reinforcement measure on top of the revetment, preparatory measures were started based on a predicted water level of NAP+15.50 meter. It soon became clear that the available time was limited and that the extent of the construction would be large. Based on the size of the operation and the downgraded predictions in water level was the need for the reinforcement measure reviewed. Based on the fact that a bare slope would provide sufficient resistance for one year according to the TAW was decided not to reinforce the slope. The only reason why reinforcing the slope would have become necessary was in the case of wave impact conditions. However, the dike is oriented South and the fact that the wind was predicted in opposite direction resulted in the decision not to reinforce the dike. No damage has occurred to the revetment during the high water wave (Weijs, 2018).

II. Grass revetment reinforcement *Rivierenland* water board

In October 2017 the *Rivierenland* water board trained the installation of a grass revetment reinforcement measure for a specific dike segment, which was newly constructed and therefore not in optimal condition, see also Chapter 2.1.1. In January 2018 the decision was made not to reinforce the grass revetment based on expert judgement and the predictions of the wind conditions.

Interpretation

The decision not to install the reinforcement measure was made at the two water boards. A qualitative risk consideration was made for these two cases: based on the predicted load and the known weakness of the revetment was decided not to reinforce the flood defence.

The case at the *Stichtse Rijnlanden* shows that the measure was not prepared or trained and that the reliability of the reinforcement measure was not taken into consideration at the water board before the winter season.

5.3. Workshop January 2018

A workshop has been organized to provide input for this research on the effectiveness of grass revetment reinforcements and measures to prevent piping. The participants worked on a fictitious case and were asked to come up with strategies, solutions and experts opinions.

5.3.1. Goal workshop

A workshop has been carried out to provide input for this thesis. The response of the water boards on a fictitious high water threat has been examined. The goal of this workshop was to substantiate the assumptions of this thesis, to provide a better quantification of the failure probabilities and to better understand the system.

5.3.2. Participants workshop

The workshop has been held twice with the following participants:

- Waterschap Vallei & Veluwe (2 persons)
- Waterschap *Drents Overijsselse Delta* (1 person)
- Hoogheemraadschap *De Stichtse Rijnlanden* (5 persons)
- Waterschap *Rijnland* (2 persons)
- Calamiteiten Team Waterkeringen (Deltares and Rijkswaterstaat) (5 persons)
- Waterschap *Rivierenland* (3 persons)
- Waterschap *Aa en Maas* (3 persons)

Regarding the participants:

- The 21 participants were divided into 9 groups.
- Most of the participants are dike supervisors or have another role in the crisis organization.
- The participants had experience for 2 till 32 years, on average 17.4 year.
- All the data that the groups provided is given in Appendix I.

5.3.3. Results workshop

The workshop provided a vast amount of data, which will not be all discussed in the main report. All the data gathered during the workshop can be found in Appendix I. The main findings, that are also implemented into the next two chapters are discussed in this section.

Availability dike inspectors

The participants were asked to come up with causes for the unavailability of their dike inspectors and to assign probabilities of occurrence given high water. The percentages are not usable, because the participants have probably misinterpreted these percentages as the cumulative percentage is very high and sometimes even above 100%. The results does show that the unavailability of dike inspectors is not unlikely given high water. Causes as: evacuation, no motivation, protecting own property or relatives, traffic jam, epidemic and holidays are mentioned as possible causes.

Quality dike inspection

The quality of the dike inspection is influenced by a certain number of factors. Five factors were already mentioned in the case and the participants could also come up with own suggestions. They had to score the factors (1=not important, 10=extremely important). Only the pre-given factors are shown as they did not came up with many the same suggestions. The result can be seen in Table 5.2. The average value and standard deviation is given, the latter one is a measure for the level of agreement between the workshop participants.

Table 5.2: Results quality dike inspection

Aspect	**Importance**	**Standard deviation**
Weather	6.6	2.1
Time of the day	8.4	1.5
Communication	7.3	2.2
Damage registration forms	6.3	2.3
Knowledge level / experience	7.9	0.8

The factors influencing whether a weak spot is found at all is given by the participants according to Table 5.3

Table 5.3: Results finding weak spot at all

Aspect	Importance	Standard deviation
Knowledge level / experience	8.6	1.0
Type of weak spot	7.7	0.90
Work conditions	7.4	1.9

The factors according to Table 5.4 are important for successful communication after finding the weak spot.

Table 5.4: Factors influencing successful communication

Aspect	Importance	Standard deviation
Knowledge level / experience	7.9	0.8
Damage registration forms	6.2	2.3
Time pressure	6.3	0.8

If we then zoom in to the different types of weak spots, the difference in level of difficulty to find is according to Table 5.5. The participants had to distribute 100 points, the more points the more difficult to find.

Table 5.5: Differences per weak spot

Aspect	Importance	Standard deviation
Damage revetment inner slope	10	6.1
Damage revetment outer slope	18.9	9.6
Piping	27.2	12.5
Macro instability	26.7	12.5
Micro instability	17.2	8.7

Transport

The exercise was designed such that there were roughly two transport options: (1) Over the dike crest, they had to drive 500 meter over the dike crest, (2) over the grassland. One group took the transport route through the grassland, two other groups would gather more information on whether the dike was still accessible and five groups would use the road on the dike crest.

Loading, transport and placement

Eight out of the nine groups explained that they would use contractors for the placement of the reinforcement measure. However, own personnel is mostly the supervisor. The estimated durations for the loading, transport and placement phase can be found in Table 5.6.

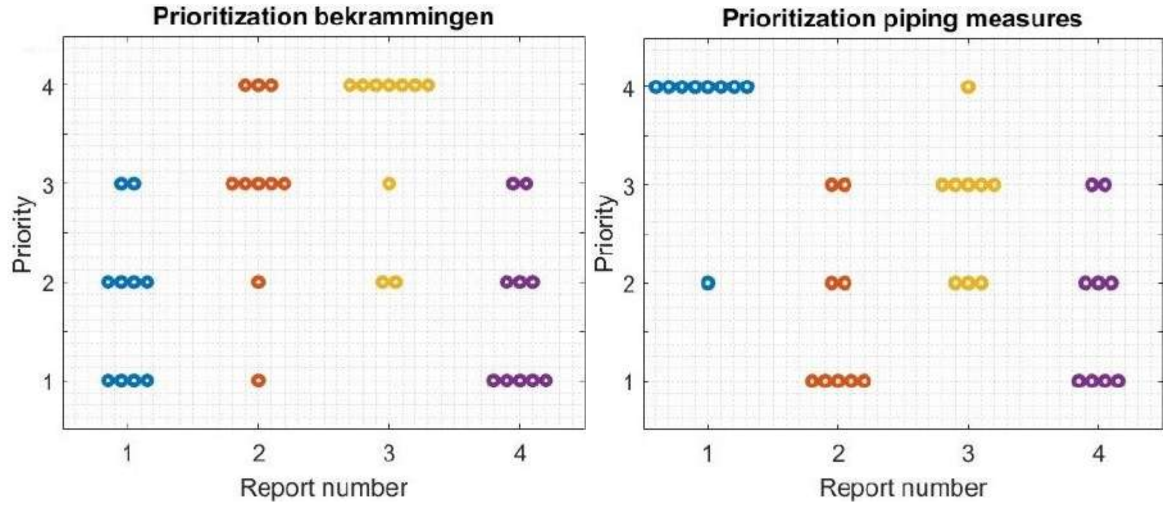
Table 5.6: Duration loading transport and placement

	A01	A02	A03	A04	A05	A06	A07	B01	B02
Loading	3-4 days	0.5 hour	2 days	2 days	0.5 hour	1 hour	0.5 day	1 hour	3 hour
Transport	30 min	1.5 hour	4 hour	2-4 hour	1 hour	1 hour	1 hour	45 ,om	1 hour
Placement	1 day	6 hour	1-2 days	1 day	4-5 hour	1.5-2 hour	1.5 day	4 hour	3-24 hour

Prioritization

The participants were asked to prioritize four distinct weak spots based on the same information. For the characteristics of the case, see Appendix I. The results of the question can be seen in Figure 5.7a, with on the horizontal axis is the number of the report of a weak spot, and on the vertical axis the priority that the participants gave to the reports. The graph shows that the participants were not in agreement on the priority. Furthermore, not the the same failure mechanism was deduced by all the members. Damage on the outer slope was marked as a possible piping problem, macro stability problem and revetment failure. A similar prioritization question is given to the participants in the piping workshop. This resulting prioritization can be seen in Figure 5.7b.

Many of the groups seemed to prioritize the weak spots mainly based on the damage (strength) or *deviation from normal* and not in combination with the load. In more than 50% of the answers was damage at the outer slope at a location with probably very limited wave action was prioritized higher than overtopping and an outer slope grass revetment damage with probably high waves. The load and strength are the determining factors in the reliability of the flood defence. A risk based prioritization would require to consider both the failure probability of the flood defence and the expected consequences.



(a) Prioritization grass revetment damages 10 respondents (1 more than workshop groups, additional respondent for this specific question).

(b) Differentiation in prioritization for piping reports between 9 respondents, figure based on data by Castelijns and Huijskes (2018).

Figure 5.7: Prioritization. On vertical axis: 1=highest priority; 4=lowest priority..

The prioritization questions are answered without much time pressure and the number of reports is limited (only 4). The total information load and fatigue will come into play during high water events. On the other hand, the dike supervisors had no knowledge of the fictitious flood defence in contrast to dikes in their own area. However, they do not have experience with extreme events more severe than in the past.

Designing reinforcement measure

The workshop members were asked to design a reinforcement measure for report number 1. Waves were damaging the grass revetment over a length of 100 meter. The following solutions were proposed:

- Filling of the gaps with sand bags and applying a geotextile vertically. Fixation of the geotextile with nails, sand bags and beams.
- Installation of a geotextile from a floating pontoon.
- A combination of a supporting berm and installation of geotextile at outer slope.
- Dumping of stones to stop erosion.

The level of detail in the solutions varied significantly between the groups. Furthermore, it stands out that the number of different solutions was large.

5.4. Conclusions field observations

Specific conclusions and interpretations on the three events (*Deining en Doorbraak*, high water and the workshop) can be found in the respective sections. Some general conclusions are:

- Prioritization of the weak spots is a critical part of the action chain and is prone to errors, based on the *Deining en Doorbraak* exercise and the workshop.
- The decision whether or not to install a reinforcement measure is not based on a quantified risk or reliability assessment. This is based on the placement decisions made at three water boards during the high water wave in January 2018, see Section 5.2.
- The goals of the crisis organizations are not formulated in terms of risk reduction or aim in terms of number of reinforcement measures in a certain amount of time.
- Human performance has a large influence on the reliability of the crisis organization.
- The availability of volunteers is not guaranteed. The deployment of volunteers during the high water in 2018 and the results of the workshop shows that the probability of unavailability is not negligible.
- The current capacity of water boards is limited. The internal evaluation of the *Deining en Doorbraak* exercise at the *Drents Overijsselse Delta* water board acknowledges that the capacity is probably insufficient during more severe conditions (Drents Overijsselse Delta, 2017a). 55% of the workshop participants answered positively on the question whether the capacity of the dike supervisors should be increased to be able to manage the work during an extreme event.

6

Human Reliability Analysis

The application of reinforcement measures during critical conditions influenced by the performance level of humans. The circumstances at which this work has to be carried out is probably governed by conditions never experienced before. These conditions are hard to mimic during exercises, the sense of urgency, work load, duration and time pressure are less critical during the training sessions. The Human Performance, the failure probability of a certain action, can therefore not be based on data gathered during exercises solely, even if there was plenty *reliable* data available. The above described problem does not only appear in the flood protection context. Human Reliability Models are developed to approximate the performance of human actions, given the specific conditions.

This chapter describes several models that are available to determine the failure probability of human failure. This chapter is the background of the models that will be used in the reliability analysis of the *detection phase* (Chapter 7) and *placement phase* (Chapter 8), see also Figure 6.1.

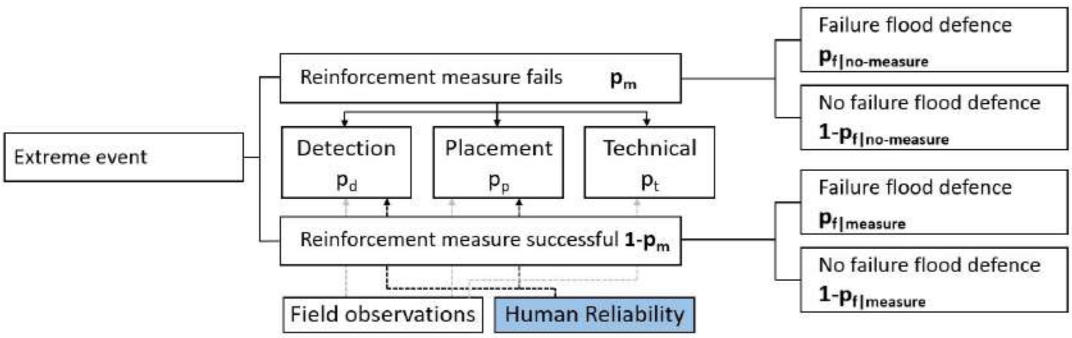


Figure 6.1: Place in reliability framework reinforcement measures.

6.1. Modelling Human Reliability

Human and organizational factors are a large (80%) contributor to failure of engineered systems (De Corn and Inkabi, 2013). Lendering et al. (2014) found, specifically for reinforcement measures in flood defence systems, that the reliability of these measures is largely determined by human performance in the detection and placement phase. Therefore, it is important to assess the reliability of human performance. Human errors are defined as not performing or incorrect performance of tasks, provided there are proper circumstances to perform the task correctly (Heslinga, 2013).

6.1.1. Methods

Methods to determine the reliability of human actions (HRA) are developed in the nuclear industry. These HRA-methods and failure probabilities determined in the nuclear sector are applied in other industries as well, see for example Heslinga (2013).

THERP* and *HEART

Two main categories of Human Reliability Assessment (HRA) can be distinguished: based on a database or on expert judgement (Kirwan, 1996). Generic failure probabilities (based on real industrial data) are used in the method using a database, see for example Figure 6.2. This generic failure probabilities are then modified using Performance Shaping factors (PSF) (Kirwan, 1996). These PSF take into account the specific conditions, different from the base failure probabilities. Examples of this method are the Human Error Assessment and Reduction Technique (HEART) and the Technique for Human Error Rate Prediction (THERP). The THERP technique decomposes the task into different actions, whereas the HEART technique considers the task as a whole (Kirwan, 1996). Performance shaping Factors change the base failure probability according to the specific conditions. The error producing conditions have a prescribed maximum contribution factor to the base error rate in the HEART method. This maximum factor has to be scaled to the assessed proportion of effect, ranging from 0 to 1 (Williams, 1988). The resulting error probability is the failure probability of the specific task. In the THERP method is the task decomposed into different elements. A nominal failure probability is assigned to each element. This nominal failure probability is multiplied with a Performance Shaping Factor (PSF). The effect of each PSF is quantified for each element. Dependence between different tasks is calculated, after which the failure probability is quantified, based on an event tree.

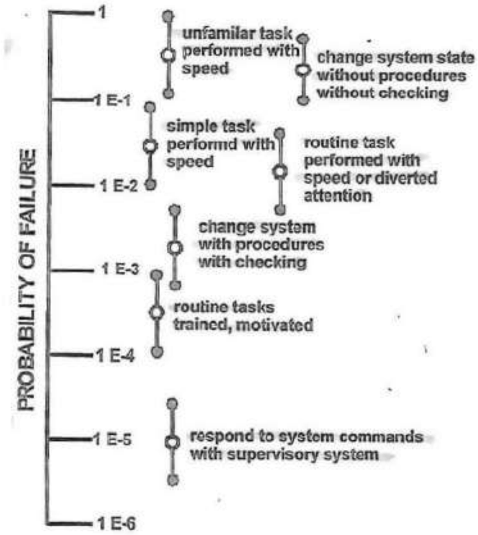


Figure 6.2: Generic human task failure (Williams, 1988).

Performance Shaping Factors

The Performance Shaping Factors make the model flexible, the failure probability can be modified based on the specific conditions. A disadvantage of the PSF is that they have a certain degree of subjectivity. A choice is made which factors to include and to exclude in the analysis. In the Dutch guideline to assess human errors for temporary flood defences, is advised to use a maximum of three factors. If more factors are used, the failure probability can become extremely low or high (Heslinga, 2013). Dupuits (2011) used nominal failure probabilities for the different tasks (placement and detection) in the research on piping measures. The nominal failure probability is determined based on an analysis of the tasks. The total failure probability for the different phases (detection and placement) is calculated based on the different tasks in the event tree. Lendering et al. (2014) used the skill level of the humans involved to determine the failure probability per task. The performance levels are divided into skill based, rule based and knowledge based (ascending order of failure probability). De Corn and Inkabi (2013), divided the human interaction with the reinforcement measures into several tasks. The nominal failure probabilities, were multiplied by a performance shaping factor, taking into account the specific conditions, both positive and negative influence.

6.2. OPSCHEP model

The assessment of human errors in the Dutch flood defence system is currently modelled based on a model named *OPSCHEP* model (Oke Project Software for the Calculation of Human Error Probabilities) (Heslinga, 2013). The total task is decomposed into different sub tasks and base error rates are assigned based on the Technique for Human Error Rate Prediction (THERP). The base error rate can be increased or decreased based on the specific circumstances by Performance Shaping Factors (e.g. stress, availability work plan and knowledge level). Performance Shaping Factors give insight into the contribution of the influencing factors (like time pressure and bad visibility). A disadvantage of the use of Performance Shaping Factors is that they have a certain degree of subjectivity.

6.2.1. Calculation individual failure probabilities

Six types of errors are distinguished (Heslinga, 2013):

- Type 1: no detection of the need for action or incorrect diagnosis in a dynamical situation.
- Type 2: omission error, no correct action taken in time.
- Type 3: execution error.
- Type 4: no correct response to correct undesired situation.
- Type 5: no correct execution of repair action, due to for example stress.
- Type 6: no correction of latent errors.

Type 1 error

The procedure of determining the failure probability consists of two steps:

1. Determine the number of factors influencing the failure probability;
2. Look up the failure probability in Table 6.1, based on the number of influencing factors.

Table 6.1: Failure probability based on number of influencing factors (Heslinga, 2013).

Number of influencing factors	0	1	2	3	4	5	6
Failure probability (p)	1.0E-5	1.0E-4	1.0E-3	1.0E-2	0.05	0.5	1.0

Heslinga (2013) recommends not to use more than four influencing factors

Type 2 error

The type 2 error is calculated based on a general base error rate of $p = 0.003$. This base error rate is generic and should be modified based on the specific circumstances. The failure probability can increase or decrease based on positive or negative effects. For example:

- No time pressure: x1 ($p = 0.003$).
- Little time pressure x2 ($p = 0.006$).
- Much time pressure x5 ($p = 0.015$).

Type 3 - 6 error

The type 3, 5 and 6 error is also determined by a base error rate, influenced by performance shaping factors. The type 4 error is calculated based in another way, however this failure probability is not used in this thesis and will therefore not be discussed here, see Heslinga (2013).

6.3. Conclusion

The *OPSCHEP* model will be used in the determination of the failure probability of human actions for the detection and placement phase, because:

- It is relatively easy in use and gives quick insight into the relevant factors.
- The model is used as guideline in the assessment of the Dutch flood defences, this makes the reinforcement measures comparable with these types of defences.
- The observations, as described in Chapter 5, will be used to determine:
  - Which factors are of importance in the determination of the failure probability.
    Based on observations during the high water exercise and high water and based on expert judgement of the dike supervisors (workshop).
  - To validate and calibrate the failure probabilities.
    An order of magnitude can be deduced from the observed data.

The model will be modified because there are relevant differences between temporary defences and reinforcement measures which makes other factors more important, for example the fact that volunteers play a role in the chain of actions.

7

Reliability detection phase

Research question three is discussed in this chapter: *what is the reliability of the detection of a weak spot?* The detection (p_d) part of the reinforcement measures reliability framework is analysed, see Figure 7.1.

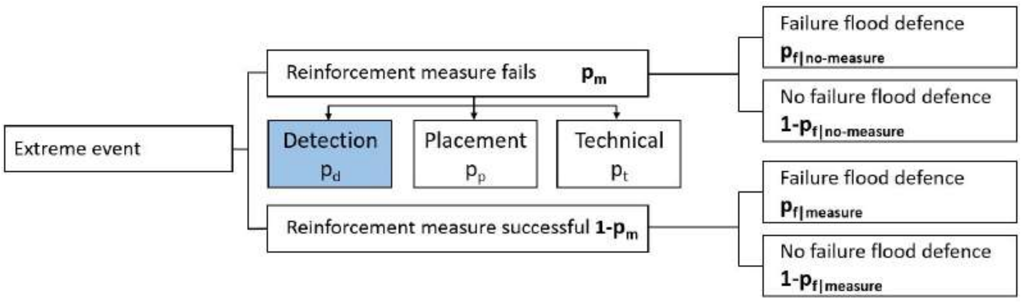


Figure 7.1: Place in reliability framework reinforcement measures.

The detection phase is discussed in the first section. The detection reliability model developed in this thesis is discussed in section two. The model parameters are determined in the third section. Results and examples follow in section four. This chapter ends with a conclusion in the last section.

7.1. Detection phase

7.1.1. Definition detection phase

The detection phase is defined as: the chain of actions starting at reaching the threshold in hydraulic conditions at which inspection should start, until the placement decision.

The detection phase definition is illustrated in Figure 7.2. The chain of actions consists of:

- **inspection:** procedures to inspect the dikes (e.g. mobilising personnel) start after reaching the *start-inspection-threshold* in the hydraulic conditions.
- **detection:** the inspection personnel (e.g. dike watch) detects a weak spot in the flood defence. Inspection of the flood defences takes place continuously, a weak spot can be missed the first time but found the second or third inspection round. The factor time until detection is therefore important. However, as evidence from high water exercises shows: several weak spots are not found at all.
- **reporting:** the inspection personnel reports the weak spot based on the procedures of the water board organization.
- **placement decision:** the supervisors decide whether or not to install the reinforcement measure based on information provided by the inspection personnel.

Figure 7.2: Chain of action after reaching certain threshold water level.

7.1.2. Detection phase in the crisis organization context

Water boards try to prevent flooding or to limit the consequences of flooding during high water events. Placement of control measures, intensified inspection of the flood defences and placement of reinforcement measures are part of this crisis response. All these actions are taken after a certain threshold in hydraulic conditions (water level or wave height) has been reached (Figure 7.3), the exact level of the thresholds is different per water board. There are various intensities of dike inspection, commonly first by dike supervisors (high knowledge level, low capacity) and during more severe conditions by dike watches (low knowledge, high capacity).

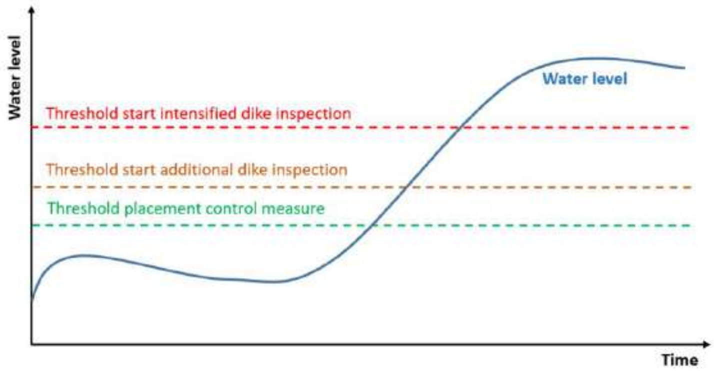


Figure 7.3: Actions based on threshold in water level.

This thesis focusses on the situation where the water boards are in the most intensified stage of dike inspection. The threat to the river dikes is highest in this phase and thereby the possible need for reinforcement measures.

The design of the crisis organization is the boundary condition for the crisis response during flood threats. The water authorities have designed their crisis organization differently. There is not one right way of organizing the crisis organization because the hydraulic system that they manage is distinct (river or sea) and also the total length of flood defences differs per water board. For example, the *Vallei en Veluwe* water board inspect their dikes during flood threats by water board employees, whereas the *Rivierenland* water board uses volunteers, with a less high knowledge level. There are also knowledge level differences within the water boards. Not all volunteers have the same performance level and not all inspectors at the *Vallei en Veluwe* water board are experts. There are also historic reasons for the differences in crisis organization, water boards are independent governmental organizations that evolved over time. The crisis organization of two water boards (*Rivierenland* and *Drents Overijsselse Delta*) is discussed in more detail in Appendix D.

7.1.3. Performance detection phase

The detection phase performance is based on two parameters:

- the **failure probability** of detection (p_d);
  Failure of the detection phase is defined as: *no command to place a reinforcement measure is given while a weak spots exists in the flood defence.*
- and when the detection phase is successful: the **time until detection**.

It is important not only to express the performance level in terms of failure probabilities. The factor time is crucial, especially for the time dependent erosion mechanisms. A water board can have highly skilled dike inspectors, the probability of detection will then be high. However, the time until detection will also be high when their capacity is low.

Influencing factors

A perfect performing detection phase means that:

- inspection is started directly after reaching the threshold in water level;
- all weak spots are found;
- all weak spots are reported correctly;
- all weak spots are interpreted perfectly, and the placement decision is given after flawless prioritization.

The detection phase performance level is influenced by numerous factors, a list of influencing elements per stage of the detection phase is given in Table 7.1. Several factors can be influenced by the design of the crisis organization (e.g. number of volunteers and level of training) others are external factors and cannot be influenced (e.g. the weather). The list of influencing factors is based on Chapter 5 (the workshop results and observations).

Table 7.1: Factors of importance in the four phases of the detection phase

Start inspection	Detection	Reporting	Placement decision
1. Predetermined hydraulic conditions start inspection 2. Quality water level prediction models 3. Training and experience decision makers 4. Availability or motivation inspectors 5. Quality and reliability communication mobilisation inspectors 6. ICT failure 7. Weather conditions too extreme	1. Knowledge level and experience inspectors 2. Weather conditions 3. Type of weak spot 4. Accessibility dike 5 .Time pressure 6. Time of the day 7. Physical condition (tired or hungry) 8. Knowledge of area 9. Communication 10. Water level river	1. Damage forms used 2. Knowledge level and experience inspector 3. Number of links in reporting chain 5. Reliability and communication 6. Uniformity 7. Feedback 8. Uncomplicated terminology 9. Tools (light etc.)	1. Workload (number of reports) 2. Knowledge level and experience supervisor 3. Physical condition (tired or hungry) 4. Quality reports 5. Knowledge flood defence 7. Erosion speed

7.2. Modelling reliability detection phase

7.2.1. Model choice

Two options are considered for modelling of the uncertainty in the detection phase:

- **event tree / fault tree modelling;**
  Event tree, or fault tree modelling, is a possibility to model the uncertainty. Fault trees and event trees are two different ways of representing the same model. A fault tree is: *a graphical model of the various parallel and sequential combinations of faults that will result in the occurrence of the predefined undesired event* (Veserly et al., 1981). The fault tree approach is restricting in incorporating influencing factors in the model. The individual failure probabilities of the event tree can be calculated based on:
  - data;
  - (structured) expert judgement;
  - Human Reliability Models (this will be explained in Section 6.1).
- **Bayesian Network modelling.**
  Bayesian Network modelling would be a good option to model the uncertainty, because influencing factors (like the ones from Table 7.1) can be included in this graphical model. However, problems arise in the quantification of the Bayesian Network. The nodes (variables) and arcs (influences) of the Bayesian network can be determined based on:
  - data;
  - expert judgement.

The lack of reliable data is problematic both for the event tree modelling and Bayesian Network modelling. Structured expert judgement faces also the problem of lack of reliable calibration data. The event tree modelling is chosen to model the detection phase performance, because:

- The Human Reliability Modelling of the individual failure probabilities is preferred over the expert judgement in the Bayesian Network modelling, as a lot of distributions and influences have to be approximated in the latter one. The Human Reliability approach implicitly incorporates expert judgement as well, for example the choice which factors to take into account in the model. However, quantification of the factors is based on Human Reliability models rather than just expert judgement.
- The event tree modelling can be used to determine the time needed for detection. An iterative procedure is implemented to determine after how many inspection rounds the weak spot is found.

The model is represented by an event tree, because it gives the information in a more condensed way compared to the fault tree, it is thereby clearer. The influencing factors (like knowledge level and weather conditions) are included in the model by Performance Shaping Factors of the Human Reliability Analysis (see Chapter 6).

7.2.2. Model detection phase

The event tree to model the failure probability of the detection phase (p_d) and the time until successful detection can be seen in Figure 7.4. The resulting failure probability is the failure probability of detection of one particular weak spot at one specific location.

The steps of the event tree are in accordance with the definition of the detection phase. The four steps from Figure 7.2): inspection, detection, reporting and placement decision can also be found in the event tree. These four steps are indicated with a coloured boarder in the figure, this colour can also be found in the event tree to indicate which part of the detection phase corresponds to the parts of the event tree.

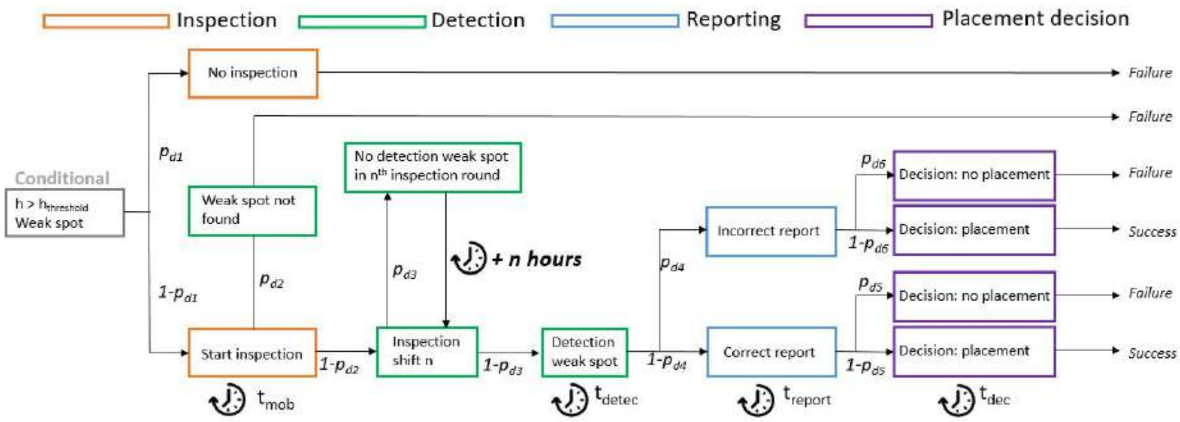


Figure 7.4: Probabilistic framework reliability detection phase.

The steps in the event tree are listed below, an overview and description of the parameters per stage is given in Table 7.2:

- **Conditional / starting point:** the starting point is that the threshold in hydraulic conditions at which inspection should start is reached and that a weak spot exists in the flood defence. The detection phase cannot fail if the threshold is not reached, because dike inspection is not an issue. Detection is also irrelevant when no weak spot in the flood defence exists as nothing can be detected.
- **Inspection:** whether inspection starts given the above described conditions is analysed in this first part of the event tree. This stage contributes both to the total failure probability as to the time of detection.
- **Detection:** in this stage it is analysed whether the weak spot in the flood defence is actually detected during repeated inspection and how much time is needed for this inspection. An important characteristic of the dike inspection is that it takes place repeatability, a weak spot can be missed in the first inspection round, but detected in the second or third shift. The following procedure is incorporated in the model to mimic reality:
  - first the failure probability of not finding a weak spot at all is incorporated in the model, the *weak spot not found* branch in the model;
  - in the *inspection shift n* and *no detection weak...round* branch of the event tree it is analysed after how many inspection rounds the weak spot is detected. Every new inspection round that is needed for detection costs time. Please notice, the failure probability p_{d3} does therefore **not contribute to the failure probability** of detection, but it determines the number of detection rounds and thereby the time needed for detection.

  The cyclic character of the inspection would be omitted when only the failure probability p_{d2} was used in the model. On the contrary, a weak spot would always be found if only p_{d3} was used in the model.
- **Reporting:** whether dike watches report correctly or not is determined in this stage. Incorrect reporting does not immediately lead to a negative placement decision but it influences the failure probability of this next stage, as it is more difficult to make a correct decision based on flawed information.

- **Placement decision:** supervisors decide in this stage whether or not to install the reinforcement measure. This decision has to be made based on a correct or incorrect report by the dike inspectors.

Table 7.2: Overview parameters detection phase

Phase	Parameter	Dimension	Description
Inspection	p_{d1}	-	Failure probability start inspection
	t_{mob}	hour	Mobilisation time inspectors
Placement	p_{d2}	-	Weak spot found yes/no
	p_{d3}	-	Failure probability per detection round
	t_{det}	hour	Time needed for detection
	+ n hours	hour	Increase in detection time per extra inspection round
Reporting	p_{d4}	-	Incorrect or correct reporting
	t_{report}	hour	Time needed for reporting weak spot
Placement decision	p_{d5}	-	Probability of incorrect decision given correct report
	p_{d6}	-	Probability of incorrect decision given incorrect report
	t_{dec}	hour	Time needed for placement decision

The failure probability, assuming independence, can be seen in Equation 7.1.

$$p_d = p_{d1} + (1 - p_{d1}) \cdot p_{d2} + (1 - p_{d1}) \cdot (1 - p_{d2}) \cdot (p_{d4} \cdot p_{d6} + (1 - p_{d4}) \cdot p_{d5}) \tag{7.1}$$

The probabilistic framework, see Figure 7.4, is also modelled based on Monte Carlo analysis, in order to determine the distribution of the time needed for detection. The Matlab code for analysis, based on fictitious values, can be seen in Appendix E.

7.2.3. Model limitations

The probabilistic model of the detection phase gives a relatively detailed representation of the procedures followed during high water situations. However, it is a model and thus a simplified representation of reality:

- Incorrect reporting and no placement decision do not necessarily mean failure, when the damage evolves and becomes more severe dike watches can again report that there is a problem, this is not incorporated in the model.
- Vulnerable locations are inspected more extensively by the dike supervisors, this results in a higher chance of detection. On the other hand, experienced dike supervisors have also no knowledge of the behaviour of the dikes for water levels above the previously observed high water events.
- The fraction of weak spots not found at all is implemented in the model by the failure probability p_{d2}. How many inspection rounds are needed until successful detection is still a question. This number is determined based p_{d3}, this is the failure probability of detection per inspection round. It might be confusing that the weak spot is found anyway after this step in the event tree. The reasoning is that the three main components that determine whether a weak spot is found are: the knowledge level of the inspector and the type and dimensions of the weak spot. The time until successful detection is dependent on these same parameters and additionally the conditions during inspection.

The first two discussion points increase the chance of the right command to place a reinforcement measure. These factors are omitted to develop a not too complicated (black-box) model and because the likelihood of the above described actions is highly uncertain.

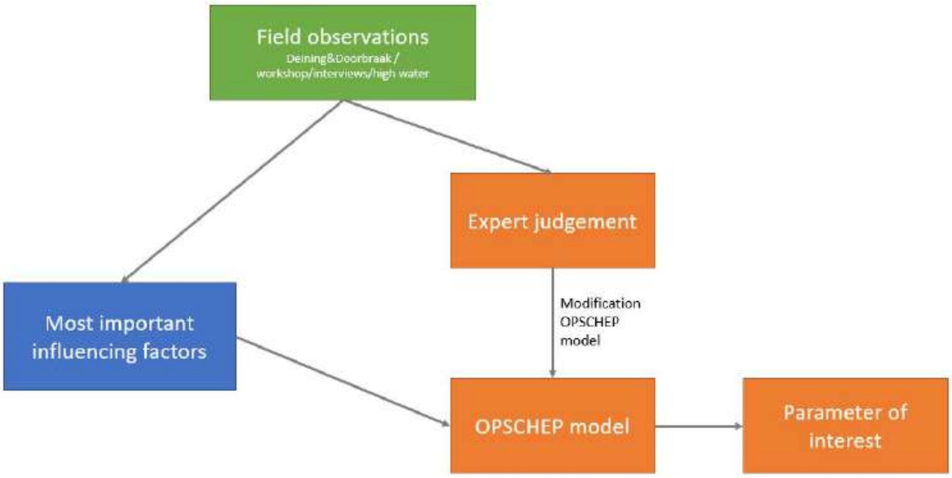
7.3. Quantification parameters event tree detection phase

The model parameters (individual failure probabilities and distribution for the durations) are being quantified in this section. The quantification will be done based on field observations, expert judgement and the *OPSCHEP* model. The *OPSCHEP* model is used for the quantification of human action in the reliability analysis. The background, limitations and advantages of the model can be read in Chapter 6.

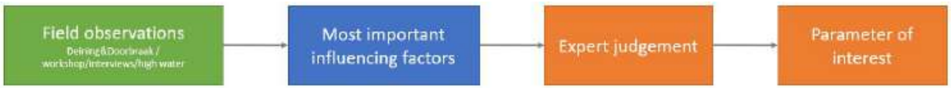
The quantification is roughly carried out in two ways:

- According to Figure 7.5a: the most important factors that influence the failure probability are determined based on field observations. These factors are implemented in the *OPSCHEP* model, this leads to the quantification of the parameter (failure probability) of interest. However, the *OPSCHEP* model is not tailor made for the application in the reinforcement measure domain, the model is sometimes modified based on expert judgement and the field observations.

- According to Figure 7.5b: the *OPSCHEP* model is not used for all parameters, for example the time distributions. Expert judgement is used to estimate the parameter of interest in these cases. The field observations are the input for the expert judgement analysis.



(a) Method 1: (modified) *OPSCHEP* model.



(b) Method 2: expert judgement method.

Figure 7.5: Two methods that are being used in the quantification of the model parameters.

The model parameters (individual failure probabilities) are discussed separately in the following sections. A summary of the method of calculation and the factors that are taken into account in the failure probability calculation is presented in Table 7.3.

Table 7.3: Calculation method and factors that are taken into account.

Parameter	**Influenced by**	**Calculation method**
p_{d1}	Availability dike inspectors Communication Failure decision start inspection	*OPSCHEP* model and expert judgement
p_{d2}	Knowledge level / experience Type of weak spot Dimensions weak spot	*OPSCHEP* model, modified
p_{d3}	p_{d2} and additional PSF working conditions	*OPSCHEP* model, modified
p_{d4}	Knowledge level Damage registration forms Time pressure	*OPSCHEP* model, modified
p_{d5}	Knowledge level Standardized procedures Time pressure	*OPSCHEP* model, modified
p_{d6}	p_{d5} Difficulty decision on flawed information	Expert judgement

7.3.1. Inspection (p_{d1})

The inspection task from Figure 7.4 (orange) covers whether or not intensified inspection starts. Water boards rely for the (predicted) hydraulic conditions on information provided by *Rijkswaterstaat* (Drents Overijsselse

Delta, 2016). The premise in the crisis organization for the river dike inspection in the case of extreme river discharges is that the dike watches are available. However, dike watches are rarely deployed in this structured manner. In an analysis of the 1995 high river discharges it is stated that several contractors, water board employees and dike watches were not available due to evacuation obligations (TAW, 1995). Furthermore, dike watches may want to save their own property instead of showing up as volunteer. During the high river discharge in January 2018 in the Netherlands the *Drents Overijsselse Delta* water board mobilised their *KEI-brigade*, a group volunteers for laying sand bags at a too low dike (see Chapter 5): 60 of the 140 volunteers showed up.
The workshop members, see Chapter 5, were also asked to think of possible causes for the unavailability of dike watches during high water and to assign probability of occurrences to the causes. They came up with a lot of possible causes (illness till traffic jams etc, see Appendix I) and assigned rather high probability of occurrences to them[13]. This does show that the unavailability of dike watches is a non-negligible failure cause.

Three possible failure causes are deduced from the reasoning above, see also Figure 7.6:

- No inspectors available.
  Given the large number of possible causes[14] that the workshop participants came up with and the large failure probabilities that they assigned to the causes is assumed that the unavailability of the inspectors is a non-negligible effect. This failure probability is estimated based on expert judgement
- Failure of mobilisation communication.
  Failure of communication is mentioned by the workshop members as a possible cause for failure of inspection. This failure probability is estimated based on expert judgement.
- No decision to start inspection.
  This failure probability is estimated based the type 1 error of the *OPSCHEP* model, see Chapter 6.

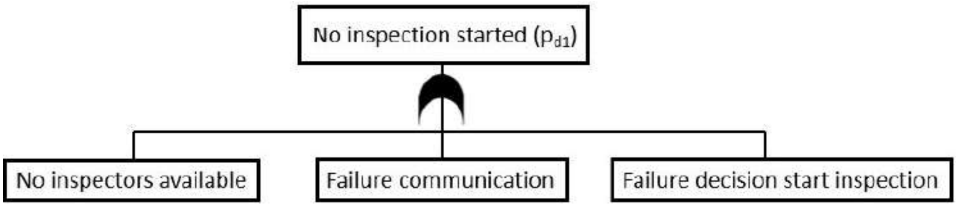


Figure 7.6: Failure tree start inspection.

Calculation method failure probability p_{d1}

1. No inspectors available [expert judgement]
The probability of failure is estimated to be 0.05 for volunteers and 0.01 for water board personnel.

2. Failure communication [expert judgement]
The probability of failure is estimated to be 0.01.

3. No decision to start inspection [Type 1 error *OPSCHEP* model, no modification model]
The failure probability of this stage is classified as a type one error of the *OPSCHEP* model. The threshold in the water level at which inspection should take place is comparable with a threshold in water level for closure of temporary flood defences, the original version of the *OPSCHEP* model will therefore be used.

The type 1 error of the *OPSCHEP* model is quantified based on two steps (see Chapter 6):

1. Determine the number of factors influencing the failure probability;
2. Look up the failure probability in Table 6.1, based on the number of influencing factors.

[13] The percentages are not usable because the members seem to have misinterpreted the question, as the summation of the probabilities was extremely high and often even above 100%.
[14] Evacuation water board area, no motivation, protection own property or relatives, vacation, other work (related to high water), epidemic, deployment at other water boards, and traffic.

Resulting failure probability p_{d1} (example)

The resulting failure probability p_{d1} is dependent on the situation. Volunteers are used as dike inspectors in most cases, the first two contributions to the failure probability calculation are therefore 0.05 and 0.01. An example for the conditions for the *decision start inspection part* is given in Table 7.4. One of the criteria is regarded as relevant to the case of the start of inspection, the failure probability is therefore 1.0E-3.

Table 7.4: Determination failure probability based on type 1 error OPSCHEP model.

OPSCHEP model influencing factor	Relevant	Explanation
Indications for action are weak or bad instructions	No	The indications are very clear. The high water warning by *Rijkswaterstaat* will in practice not be a completely unexpected warning. The primary task of dike supervisors is to maintain their dikes and make sure that the flood defences are in good condition. It will have the water boards full attention in the wake of high river discharges.
Competition with other actions	Yes	There is competition with other actions, as water board personnel will be busy in the wake of high river discharges.
No training	No	The personnel that decides whether or not to inspect is trained.
Relatively limited time available for recovering of actions.	Yes	There is limited time to make the decision, due to waves as governing hydraulic load.
Counter intuitive action	No	It is not counter intuitive, as inspection is a logical reaction on river high river discharges.
Bad physical conditions	No	Bad physical conditions is probably not applicable to this case because the *start inspection call* has to be made at the start of the extreme river discharge so the busiest time has still to come.

The failure probability is equal to the product of one minus the individual failure probabilities, assuming independence. For the example above is the final failure probability $p_{d1} = 0.06$.

7.3.2. Detection weak spot (p_{d2})

Water boards inspect their dikes intensively in this stage. Several water authorities use volunteers (the *Rivierenland* and *Drents Overijsselse Delta* water board) others put in own personnel, who are more skilled.
Several weak spots are not found at all (incorporated in the model by the failure probability p_{d2}), despite the efforts of the dike inspectors, as evidence from high water exercises shows. Based on the data from the Conecto high water exercise Lendering et al. (2013), the field observations and the study of Lendering et al. (2014), is concluded that the fraction of weak spots not found at all is in the order of 10^{-1}.
It is also likely that there are differences between types of weak spots, in failure rate. Piping is for example difficult to observe because the hinterland is often soggy (Knotter, 2017), see for example Figure 7.7, and piping can occur over a large spatial area.

Figure 7.7: Soggy hinterland *Waal* river (27 January 2018).

The type 2 error (base error rate of 0.003) from the *OPSCHEP* model will be used, one can argue that type 3 (base error rate 0.0003) would also be a possibility, based on the error definition (see Chapter 6). However,

evidence from the exercises shows that the failure probability is in the order of 10^{-1}, which will also be the result when using the type 2 error in combination with the Performance Shaping Factors.
The fraction of weak spots not found at all is assumed to be dependent on three factors[15]: the knowledge level of the inspector (based on expert judgement and the study by Lendering et al. (2014)), the type of weak spot and the dimensions of the weak spot.

Calculation method failure probability p_{d2}

The failure probability p_{d2} is calculated with the type 2 error from the *OPSCHEP* model, with a base error rate of 0.003. This base error rate is modified with Performance Shaping Factors. These factors are presented in Table 7.5. The background can be found below the text box.

Table 7.5: Performance Shaping Factors for modification failure probability p_{d2}

Knowledge level	PSF	Type of weak spot	PSF	Dimensions weak spot	PSF
Supervisor	x1	Damage grass inner slope	x1	Small	x5
District	x3	Damage grass outer slope	x2	Large	x1
Dike watch	x5	Piping	x3		
		Macro instability	x3		

Performance Shaping Factor: knowledge level
The Performance Shaping Factor for the knowledge level is taken equal to the ones used in the *OPSCHEP* model. However, the knowledge levels *sufficient knowledge*, *some knowledge* and *little knowledge* are assigned to the three knowledge levels for dike inspectors: supervisor, district and dike watch, according to Lendering et al. (2014)

Performance Shaping Factor: type of weak spot
The Performance Shaping Factors for the type of weak spot are determined based on expert judgement of the nine groups that participated in the workshop, see Chapter 5. The average values of difficulty are normalized and rounded, this resulted in the PSF, see Table 7.6

Table 7.6: Differences per weak spot. Importance-column based on outcome workshop.

Aspect	Importance	Normalized	Rounded = PSF
Damage revetment inner slope	10	1	1
Damage revetment outer slope	18.9	1.9	2
Piping	27.2	2.7	3
Macro instability	26.7	2.7	3

Performance Shaping Factor: dimensions weak spot
The Performance Shaping Factors for the type of weak spot are determined based on expert judgement. Taking into consideration that:

- damage over a large area is much more easy to detect compared to a relatively small damage;
- multiple sand boils over a certain area are harder to miss than one distinct sand boil.

A small damage is for example one distinct piping well or a small (1 meter) damage by animals. Large damage is the occurrence of multiple piping wells at the same location or damage of the grass revetment over more than five meters. The Performance Shaping Factors for large damages is taken equal to one (base case) and it is assumed that small damages are five times less likely to be observed during inspection.

- large dimensions or large number of weak spots: PSF x1;
- small dimensions or small number of weak spots: PSF x5.

Resulting failure probability p_{d2}

The resulting failure probabilities for p_{d2} can be seen in Table 7.7. The Performance Shaping Factors for knowledge level, type of weak spot and dimensions of the damage are also shown in the table.

[15] Based on the field observations and the study of Lendering et al. (2014)

Table 7.7: Fraction of weak spots not found at all. Base error rate of 0.003 modified based on the two Performance Shaping Factors (PSF).

			Dike watch	**District**	**Supervisor**
		PSF	*5*	*3*	*1*
Piping	**Small**	*15*	0.225	0.135	0.045
	Large	*3*	0.045	0.027	0.009
Macro instability	**Small**	*15*	0.225	0.135	0.045
	Large	*3*	0.045	0.027	0.009
Damage outer slope	**Small**	*10*	0.15	0.09	0.03
	Large	*2*	0.03	0.018	0.006
Damage inner slope	**Small**	*5*	0.075	0.045	0.015
	Large	*1*	0.015	0.009	0.003

7.3.3. Detection weak spot (p_{d3})

This failure probability is the probability of detection failure per detection round. It is assumed that the same Performance Shaping Factors apply as for the calculation of failure probability p_{d2}. As these failure probabilities already determine the level of difficulty to find the weak spot. However, the (weather) conditions during inspection do also influence the number of inspection rounds. Observations during the *Deining en Doorbraak* high water exercise showed that inspection during the night have a much lower success rate. The *Rivierenland* water board does not even look for piping wells during the night, because the success rate is negligible (Knotter, 2017).

Based on the above described reasoning is the following procedure followed to determine p_{d3}:

- the failure probabilities p_{d2} is taken as starting point;
- the working conditions are implemented in the model by multiplying the failure probabilities by an additional Performance Shaping Factor, see Table 7.8;
  The values of these Performance Shaping Factors are determined based on expert judgement. The value of detection of piping of one distinct piping well approximates 1, which is in line with the reasoning of the *Rivierenland* water board (Knotter, 2017).

Calculation method failure probability p_{d3}

The failure probability p_{d3} is calculated with failure probability p_{d2} as base error rate. One additional Performance Shaping Factor is taken into account, see Table 7.8.

Table 7.8: Performance Shaping Factor factor working conditions

Condition	**Performance shaping factor**
Night	4
Day light, bad conditions	2
Good conditions	1

7.3.4. Reporting weak spot (p_{d4})

The current procedure used by water board *Drents Overijsselse Delta* for reporting of a weak spot is as follows:

- the dike watch reports its findings to a the dike post commander (also a volunteer) by radio;
- the dike post commander reports the weak spot in an application on a computer;
- the Head Central Dike post (volunteer) together with a technical specialist at the Action Centre Water judges the reports.

The information in the reports to the dike post commander by the dike watch was minimal during the exercise, based on observations during the actual inspections and based on the logs of al the reports by the dike watches. In nearly 10% of the cases the Head Central Dike post asked for additional information before making a judgement, see Chapter 5. This will result in a delayed detection because the dike watches are long passed the weak spot when the question is asked.

Validated procedures exist to standardize the reports. The *Rivierenland* water board uses a form (Rivierenland, 2012) which the dike watches have to fill in. It is unlikely that dike watches miss certain relevant aspects because it will result in incomplete forms. As an illustrative example, during the *Deining en Doorbraak* exercise dike watches reported a crack (which was not even a crack but rather a gap). The only information given was the length and width, that it was located on the outer slope and the location on the dike segment. If the *Rivierenland* form was filled in correctly information like the depth of the damage, the distance from the water line, type of revetment and whether soil is washing away was more likely to be provided.

For the determination of the failure probability p_{d4} the type two failure probability from the *OPSCHEP* model is used. Three Performance Shaping Factors are used to modify the base error rate of 0.003. These three PSF's are directly retrieved from the *OPSCHEP* model[16].

Calculation method failure probability p_{d4}

The failure probability p_{d4} is calculated with 0.003 as base error rate. The Performance Shaping Factors that are taken into account, can be seen in Table 7.9.

Table 7.9: Performance Shaping Factors for modification failure probability p_{d4}

Knowledge level	PSF	Usage damage registration forms	PSF	Time pressure	PSF
Supervisor	x1	Yes	/3	No	x1
District	x3	Yes, but not correctly	x1	Limited	x2
Dike watch	x5	No	x3	Much	x5

The failure probability is 0.225 when dike watches report the damages under time pressure, without damage registration forms, this failure probability drops to 0.025 when damage registration forms are used correctly.

7.3.5. Placement decision (p_{d5})

Supervisors (e.g. at the Action Centre Water) decides whether or not to place a reinforcement measure based on the report of the weak spot. The reports entering the system are correct or flawed, as modelled in the probabilistic model. The conditions at which the supervisors have to decide whether or not to place a measure is likely to be under time pressure because the total load of reports far exceeds the actual number of weak spots, see Chapter 5. At the *Deining en Doorbraak* exercise three times as many weak spots were reported, than actually present at the dikes. During *Conecto* this was even a factor four. The factors that are assumed to influence the performance of the *placement decision* are: the knowledge level of the decision maker, time pressure and whether standardized procedures are used. The same assessment procedure as used for the failure probability of reporting (failure probability p_{d4}) is used, see Section 7.3.4.

Calculation method failure probability p_{d5}

The failure probability p_{d5} is calculated with 0.003 as base error rate. The Performance Shaping Factors that are taken into account, can be seen in Table 7.10.

Table 7.10: Performance Shaping Factors for modification failure probability p_{d4}

Knowledge level	PSF	Standardized procedures	PSF	Time pressure	PSF
Supervisor	x1	Yes	/3	No	x1
District	x3	Yes, but not correctly	x1	Limited	x2
Dike watch	x5	No	x3	Much	x5

The failure probability is equal to 0.045 if no general procedures are used and the work is carried out under time pressure.

7.3.6. Placement decision (p_{d6})

Dike watches can report incorrectly in several ways. Dike watches can underestimate, overestimate or even not report the weak spots. The supervisors have to make a decision based on the incorrect report. In practice the supervisors will sometimes ask for additional information or send specialists to the location. This stage is simplified in *decision: no placement decision* and *decision: placement* . The failure probability of this branch is not covered very well in the determination of the *omission error* (*OPSCHEP* model). However, for

[16] The *OPSCHEP* model Performance Shaping Factor: there is rule-based behaviour is interpreted in this context as the usage of damage registration forms.

the type one error a difference with a factor of 10 is found when the indications for action are weak of bad instructions are given (Heslinga, 2013). This same factor is used for the failure probability p_{d6}, see Equation 7.2.

Calculation method failure probability p_{d6}

The failure probability p_{d6} is calculated based on expert judgement and can be seen in Equation 7.2.

$$p_{d6} = 10 \cdot p_{d5} \tag{7.2}$$

7.3.7. Duration detection phase

In the event tree (see Figure 7.4) can be seen that the total time needed until successful detection is a function of five contributions:

1. Mobilisation time: t_{mob}
2. Detection time: t_{detec}
3. Reporting time: t_{report}
4. Decision time: t_{dec}

The quantification of these parameters should be done for each specific case. The mobilisation time is for example not relevant for damages that emerge when the intensified dike inspection has already started. Furthermore, the mobilisation time, inspection interval etcetera are different per water board. The five contributions are discussed in the sections below.

Mobilisation time t_{mob}

The mobilisation time is the time needed to mobilize the inspection apparatus. A Gaussian distribution for the mobilisation time is assumed, with a mean value and standard deviation different per water board.

The workshop members have estimated the mobilisation time, this can be see in Appendix I. The modus, most given answer, is equal to four hours.

Detection time t_{detec}

The time needed to detect the weak spot is dependent on the inspection interval used by the water boards and the number of inspections needed to find the weak spot.

The time until detection is described by the discrete geometrical distribution, which expresses the number of events until success (Dekking et al., 2005). The probability density function is given in Equation 7.3. Please notice that this distribution assumes a constant failure probability per detection round, however in the model a different value for this failure probability is used during daylight and during the night. This can be incorporated in the failure probability calculation easily. Calculating the probability of success during inspection round k means multiplying $k-1$ times the probability of failure $(1-p)$ and one times the probability of success (p). The failure probability p can be changed per detection round.

$$p_x(k) = P(x = k) = (1 - p)^{k-1} \cdot p \tag{7.3}$$

Where:	p_x	=	Probability of successful detection in inspection round k	[-]
	p	=	Probability of detection per inspection round	[-]
	k	=	Number of inspection round	[-]

In the detection reliability model a probability of failure is defined, though the geometrical distribution has the success probability as input parameter. The probability in the model is therefore according to Equation 7.4.

$$p = 1 - p_{d3} \tag{7.4}$$

The mean value of the number of inspection rounds until successful detection is shown in Equation 7.5 (Dekking et al., 2005).

$$E(X) = \frac{1}{p} \tag{7.5}$$

Reporting time t_{report}
The time needed for reporting is limited and omitted in the analysis. The time needed for filling in a form is negligible compared to for example the inspection interval.

Decision time t_{dec}
The time needed to make a decision whether or not to apply a reinforcement measure was small during the exercise *Deining en Doorbraak*. In most cases only a maximum of half an hour was needed. Only a part of the dike posts were in use during the *Deining en Doorbraak* exercise. In practice, during extreme river discharges, probably all dike posts are in play. This leads to an increased work load and probably a longer duration for the placement decision. Therefore is a normal distributed duration with a mean of one hour and a standard deviation of 20% will be used in the analysis.

7.4. Results and examples

7.4.1. Failure of detection

Failure of detection is the failure probability for one distinct weak spot. An overview of the range of failure probabilities can be seen in Table 7.11. The following variables are varied:

- damage type and dimension;
- knowledge level of inspector and whether damage registration forms are used;
- whether standardized procedures are used at the Action Centre Water (ACW). The place where the decision to place a reinforcement measure is made.

The following Performance Shaping Factors are kept constant in the failure probability calculation:

- Time pressure in the *placement decision* phase. It is unlikely that this phase will be without time pressure during real high water threats.
- The failure probability of *start inspection* is constant (0.06 for volunteers and 0.02 for water board personnel).
- The knowledge level of the person(s) that decide whether or not to place the reinforcement measure is assumed to be high (supervisor level).

Table 7.11: Failure probability per weak spot of the detection phase for characteristic conditions.

Dike inspector		Dike watch			District			Supervisor		
Damage registration forms used		no	yes	yes	no	yes	yes	no	yes	yes
Standardized procedures at ACW		no	no	yes	no	no	yes	no	no	yes
piping	small	0.37	0.31	0.28	0.18	0.15	0.11	0.12	0.11	0.07
	large	0.22	0.15	0.11	0.12	0.08	0.04	0.09	0.07	0.03
macro	small	0.37	0.31	0.28	0.18	0.15	0.11	0.12	0.11	0.07
	large	0.22	0.15	0.11	0.12	0.08	0.04	0.09	0.07	0.03
outer	small	0.31	0.25	0.21	0.15	0.12	0.08	0.11	0.09	0.05
	large	0.21	0.14	0.09	0.11	0.08	0.04	0.09	0.07	0.03
inner	small	0.25	0.18	0.14	0.13	0.10	0.05	0.10	0.08	0.04
	large	0.20	0.13	0.08	0.11	0.07	0.03	0.08	0.07	0.03

The following can be concluded based on Table 7.11:

- The failure probability is highly sensitive to the value of p_{d2}. The failure probability converges to the value of p_{d2} when the *reporting* and *placement decision* phase is well organized. This is makes sense physically, because everything can be standardized apart from the actual detection.
- The use of damage registration forms is an important factor in the reliability of detection phase, especially for the low skilled inspectors (dike watches). The use of damage registration forms reduces the failure probability, based on this model, by 7% on average for the dike watches. The reduction is lower for the supervisors because the Performance Shaping Factor for knowledge level is also lower.

7.4.2. Time until detection

The detection time is modelled based on a Monte Carlo analysis of the probabilistic framework of Figure 7.4. The Monte Carlo analysis is carried out in Matlab (for the script see Appendix E) with 100000 simulations.

Whether the failure probability has converged can be checked because the failure probability can be calculated analytically, the Monte Carlo analysis is only needed for the distribution of the detection time.

The following primary observations are made:

- The detection time is case specific, as for example the mobilisation time is largely dependent on the procedures used by the different water boards.
- The detection time is influenced by the p_{d3} failure probability. This failure probability does not contribute to the *detection failure probability*, because failure probability p_{d3} means that the specific inspection round does not result in detection, however one of the following inspection rounds will result in detection of the weak spot at the cost of time.
- Failure probability p_{d3} is taken different for night and day conditions. Detection during night hours is far more difficult as visibility is a limiting factor. The daylight hours are dependent on the time of the year. River floods are most likely to occur during winter conditions in the Netherlands, so as a first approximation 08:00 - 17:00 will suffice.
- Starting during night hours will lead to a larger detection time compared to starting in the morning during the light hours. The failure probability at night is higher compared to inspection during daylight. The time until start of detection (no nigh inspection) should then be added to the total detection time.
- The time until detection assumes that the weak spot was present in the dike from the start of detection. A weak spot can also emerge during high water. The calculation should then be modified as for example the mobilisation time for the inspection apparatus is not applicable, this should then be omitted.

7.4.3. Number of inspection rounds

Failure probability p_{d3} determines the number of detection rounds until successful detection. The statistical distribution is described by the geometric distribution, as described in Section 7.3.7. The expected value of the number of inspection rounds until successful detection is plotted versus the probability of successful detection per detection round, see Figure 7.8 . Please notice that p_{d3} is defined as the probability of failure, so $p_{success} = 1 - p_{d3}$.

What can be observed from the Figure 7.8 is that:

- The difference in required inspection rounds changes relatively quickly for the small success probabilities and relatively slow for the large success probabilities.
  - for $p = 0.1$, $E(X) = 10$ and $p = 0.2$, $E(X) = 5$
  - for $p = 0.8$, $E(X) = 1.25$ and $p = 0.9$, $E(X) = 1.11$

This phenomenon is due to the asymptotic character, $p \to 0$, $n \to \inf$. The implication is that the total detection time is not highly sensitive to the required number of inspection rounds for the failure probabilities as used in this model.

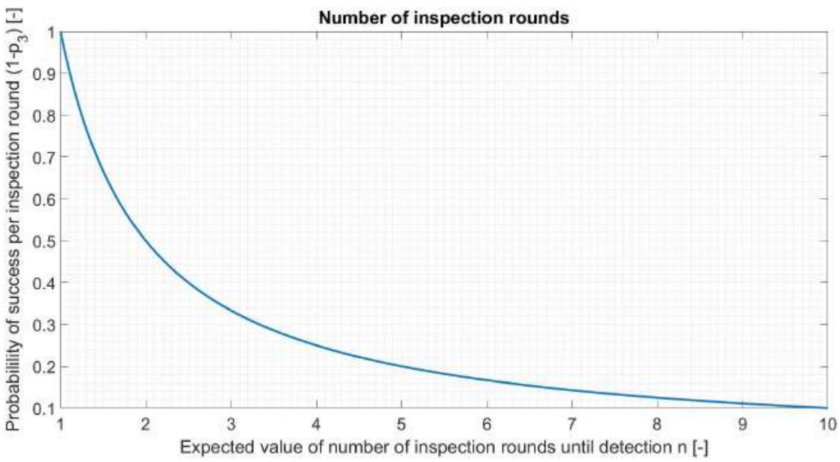


Figure 7.8: Expected value of number of inspection rounds until successful detection.

Example 7.1 Detection time

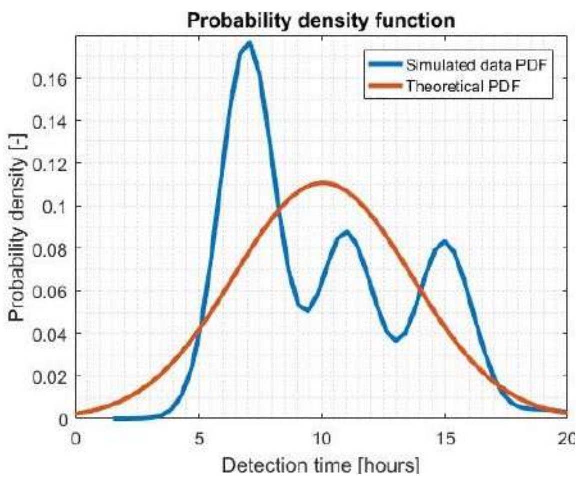
An illustrative example is worked out for the *Drents Overijsselse Delta* water board. The following time distributions are assumed based on observations during the high water exercise, interviews and expert judgement.

- Mobilisation time (t_{mob}): the mobilisation time is approximated by a normal distribution with a mean value of four hours with a standard deviation of one hour.
- Detection time: (t_{detec}): the inspection interval is four hours at this water board. The dike watches walk a dike trajectory back and forth. So, a normal distribution of the detection time is assumed with a mean value of two hours and a standard deviation of 0.25 hour, 15 minutes.
- Delay time (+ n hours): the additional time after a failed inspection round is four hours.
- Reporting time (t_{report}): the reporting time is neglected, because filling in a form will take negligible time compared to the other phases.
- Decision time (t_{dec}): The time needed to make a decision whether or not to apply a reinforcement measure is estimated to be one hour with a standard deviation of 20%.

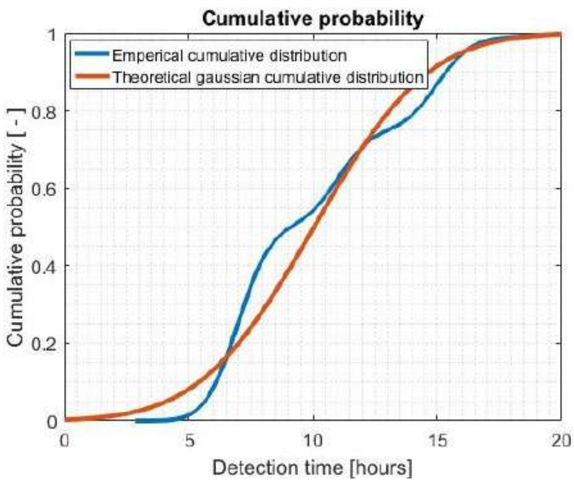
The simulated data (Monte Carlo) is visualized using an empirical cumulative distribution using the inbuilt Matlab function. This empirical distribution is approximated using the Method of Moments to estimate the parameters (mean value and standard deviation) of the Gaussian distribution. The parameters are:

- mean value: 10.5 hours;
- standard deviation: 4.1 hour.

The probability density function can be seen in Figure 7.9a and the cumulative probability is visualized in Figure 7.9b. The multiple peeks in the probability density function and the slope changes in the cumulative probability function are caused by the cyclic character of the inspection. If the weak spot is not found in the first inspection round, does it automatically result in an increase in detection time of at least the inspection interval (in this case four hours). The peaks are so pronounced because the high initial failure probability due to the start of inspection at night. The failure probability of the first two inspection intervals (night at 00:00 and 04:00) are 0.50, whereas the failure probability at 08:00 is equal to 0.05. If the inspection interval is started at 08:00 the peaks are much less pronounced, this example is given in Appendix E.3.



(a) Probability density function, multiple peaks due to cyclic character detection interval, see explanation above.



(b) Cumulative probability function of detection duration.

Figure 7.9: Empirical cumulative probability function and Gaussian approximation (p_{d1} = 0.06; p_{d2} = 0.05; $p_{d3,day}$ = 0.05; $p_{d3,night}$ = 0.5; p_{d4} = 0.225; p_{d5} = 0.45; p_6 = 0.045; start at 00:00).

The theoretical distribution does not describe the empirical fit accurately. The detection time is overestimated as long as the orange line is right of the blue line in cumulative fit. This is the case around the mean, the approximation underestimates the detection time in the tails. This is a first approximation, a more accurate approximation would be preferred. The fit is much better when the inspection interval is started during day hours, see for this example Appendix E.3.

A pragmatic solution is to add a value to the mean (horizontal shift), such that the orange line is right of the blue line over the whole range, this is advised as first approximation when the result is highly time sensitive.

7.5. Conclusion reliability detection phase

Sub question three is answered in this chapter: *what is the reliability of detection of a weak spot?*

The detection phase is defined as: the chain of actions starting at reaching the threshold in hydraulic conditions at which inspection should start, until the placement decision.

The reliability (or uncertainty) of the detection phase consists of two different parameters:

- the failure probability of detection;
- the time until successful detection.

The probability of failure of the detection phase (p_d) is dependent on numerous factors, such as: the knowledge level of the inspector, the type of weak spot and the dimensions of the weak spot. The failure probability is defined as the probability of not finding one particular weak spot. This value ranges from 0.03 to 0.37 depending on the specific circumstances, for instance whether damage registration forms are used, the type of weak spot and the knowledge level of the inspector.

The failure probability is determined by factors that can be influenced and external factors. The knowledge level of the inspector and whether standardized damage registration forms are used is a matter of design choice, whereas the weather and the type of weak spot cannot be influenced.

The time until successful detection is determined by, amongst others, the failure probability of detection per detection round. A weak spot can be missed the first shift, but detected the second or third detection round. Dike shifts are carried out with a certain time interval, the longer this interval the longer the inspection time after missing the weak spot the first inspection round.

The time needed for the detection phase is part of the total time needed for the installation of the reinforcement measure. How much time is available is also a function of the type of failure mechanism, see for example Barendregt and Van Noortwijk (2004).

8

Reliability of placement phase

Research question four is discussed in this chapter: *what is the placement reliability of grass revetment reinforcement measures?* The placement part (p_p) of the reinforcement measures reliability framework is analysed, see Figure 8.1.

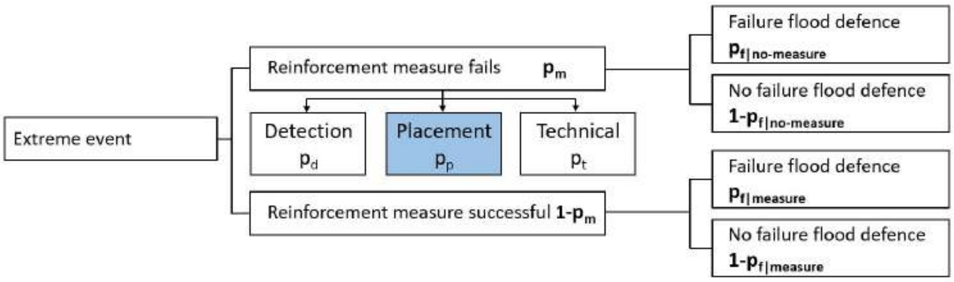


Figure 8.1: Place in reliability framework reinforcement measures.

The placement phase is discussed in the first section. The second section describes the model of the placement phase. The model Quantification can be found in the third section of this chapter. Section four discusses the placement capacity. Results are given in section five. The conclusion of the placement phase reliability can be found in the final section.

8.1. Placement phase

8.1.1. Definition placement phase

The placement decision marks the end of the detection phase. Who the command gives to execute the reinforcements differs per water board. Equipment, material and personnel is transported to the site and after that the reinforcement measure is installed. The placement phase is defined as: the chain of actions starting at the placement decision (end of detection phase) till the installation of the reinforcement measure. The definition is visualised in Figure 8.2.

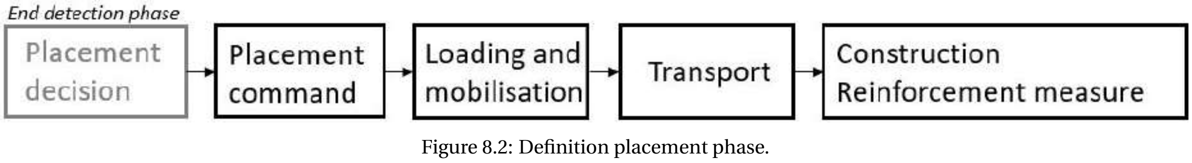


Figure 8.2: Definition placement phase.

8.1.2. Placement phase in the crisis organization context

The placement phase in the context of the crisis organization is described in the introduction of this thesis (Chapter 1), Section 1.3.1. Water boards are probably going to reinforce their dikes at numerous locations to prevent failure of the dike by different failure mechanisms. The most critical spots should be reinforced at first, this is not necessarily the grass revetment. Whether water boards can reinforce all weak spots during high water is also a function of material availability. The dikes cannot be reinforced effectively if less material is available than needed to strengthen all the weak spots. The focus in this chapter is on the placement reliability of one distinct grass revetment reinforcement measure.

Logistics

Logistics during a high water event includes the transportation of equipment, personnel and materials to the site where the reinforcement measure has to be placed. Logistics also involve the preparation of materials available in stock, named inventory management (De Leeuw et al., 2012) and where to distribute these materials over the water board area, the later one determines the transportation reliability and duration. Water boards do have a certain amount of material in stock, however they also assume that the contractors have a certain amount of material at their disposal (geotextile, sand bags etcetera). Inventory management is most often based on experience and "having sufficient material in stock" rather than cost-benefit analysis or a reliability study. This behaviour is in line with the findings of Jongejan et al. (2010). This article explains that cost benefit analysis is rarely used in disaster preparation and that *governments seek to refuge in symbolic preparation* (Jongejan et al., 2010).
Water level measurements or predictions are a trigger for starting to install temporary flood defences and reinforcement measures. Logistics is accounted for in the reliability assessment of these types of reinforcements, for example the time needed to place the measure, the amount of material in stock and the number of people needed to place the defences).
Damages that are detected during critical conditions cannot be prepared completely, the locations, number of weak spots and specific conditions are not known beforehand. It is difficult to predict the location and characteristics of the weak spots in advance, especially for water levels higher than the extreme events in the past. Water boards do not prepare the route to the locations of potential weak spots on the flood defences for the case of high water. Locations vulnerable for overtopping or wave impact could for example be determined beforehand. The *Rivierenland* water board assumes that the dikes are still accessible with a small vehicle during high water events (Knotter, 2017). The route to the placement location of the reinforcement measure was not prepared for the placement team during the *Deining en Doorbraak* high water exercise. The transporting personnel decided for themselves how to take the route to the placement location. A certain position for installing of a geotextile reinforcement was difficult accessible, however the placement team took the road at the water side of the dike, which is covered with water during real high water events. Furthermore, vehicles (heavy tractors) were driving on top of the grass revetment on multiple occasions (damage can occur on the soggy grass revetment). In summary: water boards do not prepare the route to possible locations of weak spots on the dikes and do not train this stage of the reinforcement measure placement operation realistically.

Figure 8.3: Transport and unloading at placement location during exercise at the *Drents Overijsselse Delta* water board (16 September 2017).

The transportation stage is crucial, even if the road on top of the dike is accessible and can be used. There is often only space for one vehicle next to each other, which means that trucks cannot overtake. Loading of the trucks is in these cases also important because forklift trucks can then only unload the vehicle from the back. Unloading is then a problem when the truck is loaded at the depot from the side. Figure 8.3 shows an example of transportation of material to the placement location. An observation during this exercises is that the water board personnel know the local situation by heart and think of such practical issues beforehand. The placement of reinforcement measures can however been outsourced to for example contractors during actual extreme high water events, when the placement of measures is intensified. These people might be less familiar with the local situation.

Installing reinforcement measure

The personnel that actually installs the reinforcement measures depends on the situation and on the water board crisis organization. In general there are four categories of placement teams: water board personnel, the military, contractors and volunteers. The advantages and disadvantages of the different placement teams are discussed in Appendix D.4 a summary can be found in Table 8.1.

Table 8.1: Advantages and disadvantages different placement personnel.

	Water board personnel	Military		Contractors	Volunteers
		NATRES	Genie		
Certainty of availability	High	Middle	Middle	High	Low
Number of available man	Low	Middle	Middle	High	High
Specific knowledge reinforcement measures	High	Low	Low	Middle	Low
Site specific knowledge	High	Low	Low	Middle	Middle
Hydraulic engineering knowledge	High	Low	Middle	High	Low

8.1.3. Performance placement phase

The placement phase quality is based on three parameters:

- the **failure probability** of placement;
  Failure of the placement is defined as: *the reinforcement measure is not installed or not installed correctly.*
- the **time until successful placement**;
- the **capacity** of the placement team.

Influencing factors

A perfect performing placement phase means that:

- all reinforcement measures are installed correctly;
- all reinforcement measures are placed as quickly as possible.

The placement phase performance is influenced by numerous factors. Four parts are distinguished in the placement phase. First the *boundary conditions*, for example the availability of material. Secondly the *placement command* that is given after successful detection, *loading and transport* and lastly the actual *placement*. The factors that influence the performance are summarized in Table 8.2.

Table 8.2: Influencing factors placement phase

Boundary conditions	Placement command	Loading and transport	Placement
1. Availability equipment personnel and material 2. Number of weak spots 3. Knowledge and training personnel	1. Reliability communication 2. Number of weak spots at the same time 3. Confirmation of receiving command 4. Number of people responsible for same task	1. Materials described that should be loaded 2. Experience, knowledge and training personnel 3. Time pressure 4. Accessibility dike 5. Weather conditions 6. Time of the day	1. Knowledge, training and experience 2. Work instructions available 3. Time pressure 4. Supervisor available at site 5. Weather

8.2. Modelling reliability placement phase

8.2.1. Model choice

The placement phase reliability is modelled with an event tree, based on the same reasoning as described for the detection phase, see Section 7.2.1.

8.2.2. Model placement phase

The event tree to model the placement failure probability and the time until successful placement can be seen in Figure 8.4. The resulting failure probability is the failure probability of the placement of one particular reinforcement measure. The steps of the event tree are in accordance with the definition of the placement phase. The four steps from Figure 8.1: placement command, loading, transport and installation can also be found in the event tree. These four steps are indicated with a coloured boarder in the figure, this colour can also be found in the event tree to indicate which part of the detection phase corresponds to the parts of the event tree.

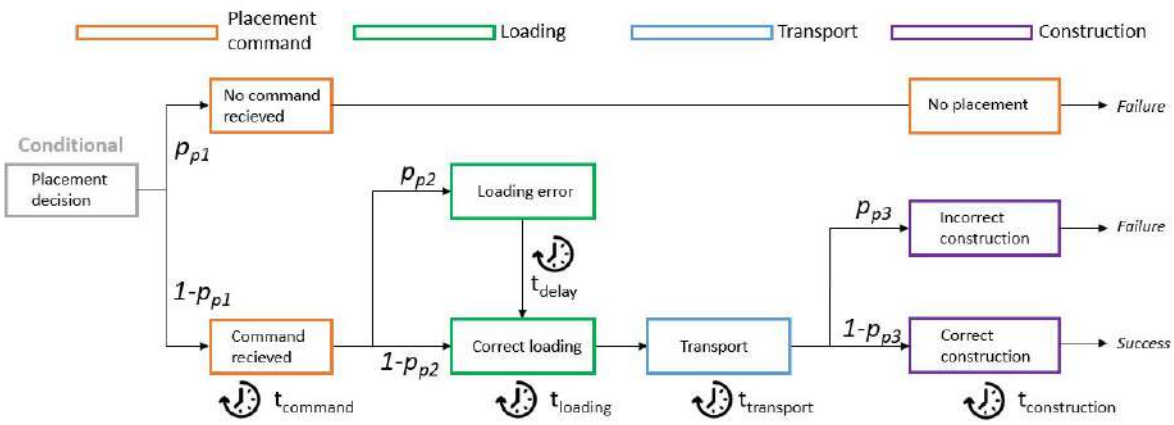


Figure 8.4: Event tree placement phase.

An overview of the model parameters is given in Table 8.3, the steps in the event tree are discussed below:

- **Conditional / starting point:** the placement phase is the next step after the detection phase. The starting point of the placement phase is that a decision is made to reinforce a (weak) spot in the flood defence after successful detection.
- **Placement command:** a command to place the reinforcement measure is given after the placement decision has been made. This command is given to a contractor, the military or own employees, depending on the situation. Mistakes can be made, especially when the work is carried out under time pressure or bad physical conditions (e.g. shortage of sleep).
- **Loading:** the materials needed to reinforce the grass revetment are loaded at the depot when the placement command is given. Mistakes can be made in this stage, these errors can be recovered at the cost of time. It is very unlikely that a placement team will fail to install the reinforcement measure due to loading errors. This is implemented in the event tree by the loop *loading error*. Failure probability p_{p2} determines the probability of errors in the loading phase, incorrect loading will result in delay (t_{delay}). So, the *loading* phase does in the end not contribute to the placement phase failure probability.
- **Transport:** the personnel, equipment and materials are transported to the weak spot. The uncertainty of this stage is modelled based on the time needed for transport. No failure probability is assigned to this stage, it is assumed that the flood defences can be reached at all times, however it can cost more time when the dikes are not easily accessible.
- **Construction:** the reinforcement measure is installed by the placement team. This stage contributes to both sources of uncertainty (failure probability and duration).

Table 8.3: Overview parameters placement phase

Phase	Parameter	Dimension	Description
Placement command	p_{p1}	-	Failure probability placement command
	$t_{command}$	hour	Time needed for placement command
Loading	p_{p2}	-	Failure probability loading
	$t_{loading}$	hour	Loading time
	t_{delay}	hour	Delay time loading
Transport	$t_{transport}$	hour	Transportation time
Construction	p_{p3}	-	Failure probability construction
	$t_{construction}$	hour	Construction time

The failure probability of the placement phase can be seen in Equation 8.1. Independence between the failure probabilities is assumed.

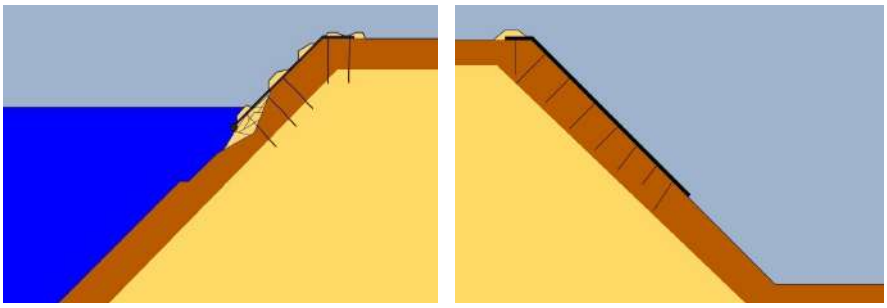
$$p_p = p_{p1} + (1 - p_{p1}) \cdot p_{p3} \tag{8.1}$$

The second source of uncertainty, the distribution of the time needed until successful placement, is modelled based on a Monte Carlo simulation. The Matlab script can be seen in Appendix E.

8.2.3. Model limitations

The probabilistic model used in the analysis of the detection phase covers the most important parts of the procedures followed by the water boards in the placement phase. However, the model is still a simplification of reality because:

- **Discrete modelling**
  The actual placement (installation phase Figure 8.4) of the measure is modelled in a discrete way. Numerous errors can be made in placement that influences the strength, and thereby reduces the technical reliability, of the reinforcement measure. For example the technical reliability of the reinforcement measures is less if too little nails are placed, however it will not immediately lead to failure of the reinforcement measure. This is a simplification because mistakes made in the placement of the measure do not necessary result in failure of the structure. Errors can also result in an increased structural failure probability, but no instant failure. For example, a fraction of the sand bags placed during the *Deining en Doorbraak* exercise at the *Drents Overijsselse Delta* water board were damaged. Sand from the sand bags can be washed away more easily, however the strength of the reinforcement measure will not be equal to zero. The errors made in the correct versus incorrect placement stage are assumed to result in failure of the measure. Examples of these kind of mistakes are given in Figure 8.5. In Figure 8.5a is an example of a reinforcement measure not covering the damaged area completely. The reinforcement measure for the inner slope (see Figure 8.5b) is not placed correctly because the most vulnerable location (transition slope and toe) is not covered.



(a) Example placement error outer slope: damaged area not completely covered by the reinforcement measure.

(b) Example placement error inner slope: vulnerable spot (transition slope) not covered by the reinforcement measure.

Figure 8.5: Placement errors grass revetment reinforcement measures that are assumed to result in failure.

- **Length effect**
  The length effect is not included in the model: the longer the reinforcement measure the higher the placement failure probability. This effect is neglected for the grass revetment reinforcement measures because the weak spots are often limited in length (driving tracks, damage by animals etcetera) and fundamental placement mistakes are probably the result of lacking knowledge, this does not increase with increasing length of the reinforcement measure. **Be aware that this effect might be non-negligible for other reinforcement measure types**.
- **Loading error**
  A loading error can be mitigated by sending for example one person back to the depot, which will cost less time and will not result in much delay.
- **Placement command**
  Failure of the first stage of the event tree (no placement command received) can be recovered by sending a second placement request after it becomes clear that the placement phase has not started. This recovery mechanism is conservatively omitted in the model.

8.3. Quantification event tree

The individual failure probabilities and time distributions are quantified in this section. The quantification is based on the *OPSCHEP* model, the same as for the detection phase see Chapter 7.3. The background of this model and why this model is used can be found in Section 6.1. Which factors to include in the model is based on expert judgement, interviews and observations during exercises, see also Table 8.4.

Table 8.4: Calculation method and factors that are taken into account.

Parameter	Influenced by	Calculation method
p_{p1}	Formal procedures or work instructions Complexity task Time pressure	*OPSCHEP* model
p_{p2}	Specification materials Experience and skill level Time pressure	*OPSCHEP* model
p_{p3}	Knowledge level Work instructions Time pressure	*OPSCHEP* model

8.3.1. Placement command (p_{p1})

This stage does have as starting point that a correct placement decision is made. Different methods of communication for the placement command were used at the *Drents Overijsselse Delta* water board during the *Deining and Doorbraak* exercise. E-mail, telephone and even hard copy placement requests were used. Elements influencing the failure probability p_{p1} are amongst others whether:

- it is clear who sends the actual placement request;
- multiple reinforcement measures are to be placed at the same time, time pressure can lead to mistakes, damaged areas can be mixed up; especially when weak spots are close to each other and comparable in characteristics;
- it is procedure to send a formal confirmation of receiving the command.

The failure probability is calculated based on type two human errors from the *OPSCHEP* model. The three factors that are assumed to influence the failure probability are: whether formal procedures are used, the complexity of the task and time pressure. Decisions made by the Action Centre Water are logged and marked as *completed* or *not completed*. Data from the high water exercises shows that the supervisors will take action (ask for a new status report or more information) if the status of certain incidents remains *not completed*. This shows that there is in practice a recovery mechanism that will increase the chance that a request to place the reinforcement is received correctly.

Calculation method failure probability p_{p1}

The failure probability p_{p1} is calculated based on the type two error from the *OPSCHEP* model, with a base error rate of 0.003. The Performance Shaping Factors that influence the base error rate are given in Table 8.5.

Table 8.5: Performance Shaping Factors placement phase p_{p1}

Formal procedures or work instructions used	PSF	Complexity of the task	PSF	Time pressure	PSF
Yes	/3	Not complex	x1	No	x1
Yes, but not correctly	x1	Multiple systems at the same time	x2	Limited	x2
No	x3	Multiple persons work on the same system	x5	Much	x5

The failure probability of this stage is 0.075 when formal procedures are used, the work is carried out under time pressure and multiple persons work on the same system. These conditions are assigned to the current practice at the *Drents Overijsselse Delta* water board.

8.3.2. Loading p_{p2}

Loading of the right type and quantity of material is assumed to be determined by three factors:

- to what extent the material to be transported is specified, three levels are distinguished (all three levels observed during the *Deining en Doorbraak* high water exercise);
  - Type and quantity of the materials specified.
    Example: grass revetment reinforcement outer slope damage 15x15m: 20x20 permeable geotextile, 60 nails, 25 sand bags.
  - Materials and dimensions of the reinforcement measure specified.
    Example: grass revetment reinforcement outer slope 15x15m: permeable geotextile, nails and sand bags.
  - Type of reinforcement measure specified.
    Example: grass revetment reinforcement outer slope 15x15m.
- how much experience the personnel have;
  Experienced personnel do have a better feeling for which materials they need to take to the placement location.
- time pressure;
  Errors are more likely to occur when the work is carried out under time pressure.

Calculation method failure probability p_{p2}

The failure probability p_{p2} is calculated based on the type two error from the *OPSCHEP* model, with a base error rate of 0.003. The Performance Shaping Factors that influence the base error rate are given in Table 8.6.

Table 8.6: Performance Shaping Factors placement phase p_{p2}

Specification of materials	PSF	Experience / skill level	PSF	Time pressure	PSF
Type and quantity specified	/3	Sufficient experience	x1	No	x1
Type of materials specified	x1	Some experience	x3	Limited	x2
Type of reinforcement measure specified	x3	No experience	x5	Much	x5

The resulting failure probabilities for p_{p2} can be found in Table 8.7.

Table 8.7: Failure probability p_{p2} as function of knowledge level and specification materials, time pressure taken constantly as PSF = 5 (much time pressure).

		Specification material		
		Material and quantity	**Material**	**Type measure**
Knowledge level	*PSF*	*0.33*	*1*	*3*
Sufficient experience	*1*	0.005	0.015	0.045
Some experience	*3*	0.015	0.045	0.135
No experience	*5*	0.025	0.075	0.225

8.3.3. Construction phase p_{p3}

Construction of the reinforcement measure can go wrong in several ways. Mistakes do not necessarily mean failure of the reinforcement measure. However, mistakes covered in this stage are assumed to result in failure, see Section 8.2.3. The failure probability is assumed to be determined by: the knowledge level of placement team, whether work instructions are used and time pressure.

Calculation method failure probability p_{p3}

The failure probability p_{p3} is calculated based on the type two error from the *OPSCHEP* model, with a base error rate of 0.003. The Performance Shaping Factors that influence the base error rate are given in Table 8.8.

Table 8.8: Performance Shaping Factors failure probability p_{p3}, base error rate 0.003.

Knowledge level placement team	PSF	Usage work instruction	PSF	Time pressure	PSF
Good	x1	Yes	/3	No	x1
Average	x2	Yes, but not correctly	x1	Limited	x2
Bad	x5	No experience	x3	Much	x5

During the *Deining en Doorbraak* exercise work instructions were available but not used, the placement team was familiar with the reinforcement measures. This results in a failure probability of 0.045. The failure probability p_{p3} for the different knowledge levels and instructions can be seen in Table 8.9, assuming that the construction work is carried out under time pressure (PSF time pressure is equal to 5).

Table 8.9: Failure probability p_{p3}, assuming work is carried out under time pressure (time pressure PSF = 5).

		Knowledge		
		Good	Average	Bad
Instructions	Used	0.005	0.015	0.025
	Not used correctly	0.015	0.045	0.075
	Not used	0.045	0.135	0.225

8.3.4. Duration placement phase

Command time $t_{command}$

The time needed to give the placement command will be determined by how many things are going for the decision makers. This stage will not take much time (order of minutes) when there are just a few reinforcements going on in the water board area.

Loading time $t_{loading}$

The loading time distribution should be determined for each specific situation as amongst others:

- the loading time depends on the number of people in the placement team and the dimensions of the weak spot;
- the loading time for the *Rivierenland* water board is limited as the materials are ready packed in containers that can be picked up.

As an illustration, for the *Drents Overijsselse Delta* water board, based on observations during the *Deining en Doorbraak* exercise, see Appendix F: the loading time is assumed to be normal distributed with a mean value of one hour and a standard deviation of 10%.

Delay time t_{delay}

Incorrect loading will result in loss of time, dependent on when the mistake is discovered. It is most likely that the loading error (not having sufficient or the right materials) is observed at the placement location. Incorrect loading will probably result in driving back to the stockroom to gather the right materials. The duration of the delay is therefore probably a factor two of the transportation time.

Duration transportation phase $t_{transport}$

A realistic value for the transportation time $t_{transport}$ has to be determined for the specific conditions.

Duration construction phase

The duration of the construction phase is determined by the amount of personnel available and the dimensions of the reinforcement measures. Indications for the time needed to place the measures are given in Appendix F. A realistic distribution of the duration should be assumed for the specific situations.

Example 8.1 Duration construction phase:
The durations are different per water board and per situation, an order of magnitude is given for the *Drents Overijsselse Delta* water board, based on observations during the *Deining en Doorbraak* exercise (see Appendix F).

Table 8.10: Estimations duration placement phase *Drents Overijsselse Delta* during *Deining en Doorbraak*.

Part	$t_{command}$	$t_{loading}$	$t_{transport}$	$t_{placement}$
Duration	0.5 hour	1 hour	0.5 hour	1-2 hour

Failure probability p_{p2} influences the duration by the loading error probability. This failure probability is estimated to be 0.015 for this specific case (Base error rate 0.003. Performance Shaping Factors: Type of material are specified x1, time pressure x5 and sufficient experience x1.). The contribution of loading error to the total duration is therefore negligible in this case.

The time until successful placement is for this specific example 3 to 4 hours.

8.4. Placement capacity

The installation of one reinforcement measure without time pressure will probably not be a difficult task. Reinforcing the grass revetment during critical conditions with time pressure will be more complicated. Time pressure, an overload of information for decision makers, incorrect prioritization and the placement of multiple reinforcement measures at the same time is accounted for in the Performance Shaping Factors.

The length of reinforcement measures that can be (potential capacity) constructed in time is dependent the available time and total construction rate, see Equation 8.2. The total construction rate is determined by the number of placement teams and the construction rate per team, see Equation 8.3. The final potential capacity can be seen in Equation 8.4.

$$C_p = R \cdot T_a \tag{8.2}$$

$$R = n_{teams} \cdot R_t \tag{8.3}$$

$$C_p = n_{teams} \cdot R_t \cdot T_a \tag{8.4}$$

The actual length of reinforcement measure that can be installed is limited by the total length of reinforcement measure material that is available in time, see Equation 8.5.

$$C = \min(l_m, C_p) \tag{8.5}$$

Where:	C	=	Capacity reinforcement measure	[m]
	C_p	=	Potential capacity reinforcement measure	[m]
	l_m	=	Reinforcement measure material available during high water	[m]
	n_{teams}	=	Number of teams	[-]
	R	=	Construction rate	[m/hour]
	R_t	=	Construction rate per team	[m/hour]
	T_a	=	Available time for construction reinforcement measures	[hour]

Number of teams and construction rate per team

The capacity of the own water board personnel is too low and contractors are willing to help during high water threats, see for example TAW (1993) and TAW (1995). Water boards often do have so called *waakvlam* contracts to guarantee the availability of the contractors during high water events.

The number of contractors in the neighbourhood will therefore probably not be the limiting factor. All the water boards that participated in the workshop rely on contractors for the installation of the reinforcement measures, however own personnel will be supervising the placement. The *Deining en Doorbraak* exercise shows that the work load is extensive during such events and the exercise was not even on full scale.

The construction rate per team is highly dependent on the level of experience, exercises and preparation. The *Rivierenland* water board have all materials for the placement in one container. The geotextile can be rolled down the slope directly, because a steel pipe is already attached at the bottom end of the geotextile. The construction rate will drop when the material that is needed for the reinforcement measures has to be gathered during high water event

Available time for construction

The time available for construction is dependent on the start time and the storm shape, see Figure 10.3.

Availability material

Water boards have certain amounts of materials in stock, however they also rely on contractors in the neighbourhood for the supply of materials, personnel and equipment. Ninety percent of the workshop participants (see Appendix I) answered positively on the statement: *a water board can rely, during extreme high water, on contractors for materials for the reinforcement measures.*
There are also differences in level of preparation between the water boards:

- The *Rivierenland* water board does have per dike post (6 in total) containers with 240 meter of geotextile, prepared to roll down the slope with a heavy pipe already fixed. The containers also contain sand bags, nails, ropes and working gear. A contractor can pick up the container and the contractor is trained in how to install this type of measure (Knotter, 2017).
- The *Drents Overijsselse Delta* water board does have geotextile, sand bags and nails in stock. However they only train and prepare the installation of the reinforcement measure type 1[17].
- The *Aa en Maas* does not have material for grass revetment reinforcement measures in stock.

The preparation of materials does have its influence on the placement reliability. The participants of the workshop were asked how much time they expected to need to get the materials. *Hoogheemraadschap De Stichtse Rijnlanden* and the *Calamiteiten Team Waterkeringen* estimated this to be more than one day, whereas the other participants expected to need much less time (order 2-3 hours).

Example 8.2 Capacity calculation
The capacity of the *Rivierenland* and *Drents Overijsselse Delta* water board is used as example. Please notice, the estimations of the numerical values are based on expert judgement.

The main difference between the two water boards is that the *Rivierenland* water board does have the materials ready in one container. The geotextile can be easily rolled down the slope, because the heavy weight is already attached at the bottom end of the textile. The *Drents Overijsselse Delta* water board does have geotextiles in stock, but not ready to roll down the slope. The difference in the capacity calculation is therefore found in the construction rate.

The total length of available reinforcement measure is 1500 meter for the *Rivierenland* water board, this value is unclear for the *Drents Overijsselse Delta* water board, for this example is a value of 500 meter is assumed.

The *Rivierenland* water board does have six dike posts, each dike post does have two containers with geotextile reinforcements. One team per dike post is assumed in the capacity calculation. All weak spots are managed at the Action Centre Water at the *Drents Overijsselse Delta* water board, it is assumed that two teams are deployed there. Other types of reinforcement measures are probably also installed, so two teams for the grass revetment reinforcement measures is assumed to be realistic.

The differences in (potential) capacity, for different values of available time, can be seen in Table 8.11. The first two capacities for the *Rivierenland* water board are limited by the availability of material.

Table 8.11: Example capacity calculation for the *Rivierenland* and *Drents Overijsselse Delta* water board.

			T_a = 12 hour		T_a = 8 hour		T_a= 4 hour	
Waterboard	Teams [-]	Rate [m/hour]	C_p [m]	**C [m]**	C_p [m]	**C [m]**	C_p [m]	**C [m]**
Rivierenland	6	50	3600	**1500**	2400	**1500**	1200	**1200**
WDOD	2	10	240	**240**	160	**160**	80	**80**

The capacity for the *Hoogheemraadschap De Stichtse Rijnlanden* is zero based on the consideration that their water board supervisors estimate the time needed for gathering the material at approximately one day.

8.5. Results placement reliability

The reliability of the placement phase consists of three different parameters:

- the failure probability of detection;
- the time until successful detection;
- the capacity of the placement teams.

These three parameters are discussed separately in this section.

8.5.1. Failure of placement

The failure probability of placement is the failure probability of one particular reinforcement measure. The failure probabilities resulting from the model, for the specific conditions can be found in Table 8.12. Time

[17] See Appendix B for the differences between type 1 and 2.

pressure is kept constant, with the Performance Shaping Factor of 5.

The following boundary conditions are varied in the table:

- Placement command phase: whether work instructions / formal procedures are used for giving the placement command, the complexity of the task for the supervisors and time pressure.
- Construction phase: knowledge level of placement team (only good and bad knowledge, no average knowledge), whether work instructions are used and time pressure.

Table 8.12: Failure probabilities placement phase given time pressure (PSF time pressure = 5)

	Placement team	**Good knowledge**			**Bad knowledge**		
Complexity	**Work instructions**	**Used**	**Not used correctly**	**Not used**	**Used**	**Not used correctly**	**Not used**
Not complex	**Used**	0.01	0.02	0.05	0.03	0.08	0.23
	Not used correctly	0.02	0.03	0.06	0.04	0.09	0.24
	Not used	0.05	0.06	0.09	0.07	0.12	0.26
Multiple systems used at the same time	**Used**	0.01	0.02	0.05	0.03	0.08	0.23
	Not used correctly	0.03	0.04	0.07	0.05	0.10	0.25
	time	0.09	0.10	0.13	0.11	0.16	0.29
Multiple persons at the same time	**Used**	0.03	0.04	0.07	0.05	0.10	0.24
	Not used correctly	0.08	0.09	0.12	0.10	0.14	0.28
	Not used	0.23	0.24	0.26	0.24	0.28	0.40

The following is concluded for the failure probability of the placement phase:

- The failure probabilities, shown in Table 8.12, are based on the assumption that the work is carried out under much time pressure. This is likely to be the case during high water threats but for reinforcements carried out in the wake of high water might this be an overestimation.
- The range of failure probabilities is large. Minimum failure probability equal to 0.01 and a maximum of 0.40.
  As an indication for the failure probabilities:
  - The *Rivierenland* water board have prepared the reinforcements, which are to be placed during high water, and this placement method is exercised. At the dike post one person manages the reinforcements, so this person has the overview, standardized procedures are used in the decision making. This brings the placement failure probability to 0.01.
  - There are also water boards with no prepared grass revetment reinforcements (which can be placed during high water) and do not have work instructions. This is classified as *bad knowledge level* and *no work instructions used.* The failure probability ranges from 0.23 to 0.40 depending how organized the crisis organization is.
- The Performance Shaping Factors on the horizontal and vertical axis are equal, that results in a symmetrical table of failure probabilities.
- The length effect[18] is not taken into account in the failure probability calculation. The length effect could influence the *construction* part of the event tree, the larger the reinforcement the larger the chance that a mistake is made. However, most of the errors will result in a reduced strength of the reinforcement measure (e.g. less nails or incorrectly placed sand bags). The errors analysed in the *construction* part of the event tree are assumed to result in a completely failing reinforcement measure, so a strength of zero (as explained in Section 8.2.3). Those types of errors are fundamental errors, as the result of lacking knowledge, no work instructions or time pressure. The failure probability does therefore not necessarily increase with increasing length of the reinforcement see for example Figure 8.5, the error of not covering the transition of the slope occurs possibly because the placement team does not know that the slope transition is the most vulnerable spot. The failure probability is therefore assumed not to be higher with increasing length of the reinforcement measure.

8.5.2. Time until placement

The time until successful placement is modelled based on a Monte Carlo analysis of the event tree. The Matlab script for the Monte Carlo analysis can be found in in Appendix E. The convergence can be checked

[18]The phenomenon that the failure probability increases with length of the reinforcement.

because the failure probability is known analytically, but not the distribution of the time needed for the placement phase.

The time until successful placement is the result of:

- The time needed to give a placement command ($t_{command}$).
  This might take some time when there are a lot of weak spots detected at the same time.
- The time needed for loading of the materials ($t_{loading}$).
  Dependent on the dimensions of the reinforcement and how prepared the water board is (e.g. sand bags already filled).
- The failure probability p_{p2} determines whether the materials are loaded correctly, the delay time (t_{delay}) has to be taken into account when this is not the case. So, the failure probability p_{p2} influences the time needed for the placement and not the failure probability of the placement phase.
  The failure probability p_{p2} is shown in Table 8.7. The failure probability ranges from approximately 0.01 to 0.23, depending on the specific circumstances. Failure leads to an increased transportation time (driving back and forth to the stock room).
- The time needed for transportation of the materials to the placement location ($t_{transport}$).
  This value is completely determined by location of the stock room and the location of the weak spot.
- The time needed for construction of the reinforcement measure ($t_{placement}$).
  Determined by the dimensions of the weak spot, experience and number of people in the placement team.

8.5.3. Placement capacity

The capacity of a water board is influenced by the number of placement teams, the placement rate per team and the available time. The upper bound is the length of reinforcement measure material that is available.

The capacity calculation is a simplification of reality, because there is a difference between large weak spots (those require a large value for R_t) and multiple small weak spots (those require a large value for n_{teams}). Large weak spots are probably more likely for known weak spots (new grass revetment, insects etcetera), whereas small damages are to be expected during high water inspection (damage by driftwood and animals).

8.6. Conclusion reliability placement phase

Sub question four is answered in this chapter: *what is the placement reliability of grass revetment reinforcement measures?*

The reliability of the placement phase is modelled based on a placement phase failure probability (p_p) and the time needed to install the reinforcement measure. The longer the placement duration is, the further the erosion might have progressed.

Placement failure probability

The lower bound of the failure probability of the placement phase p_p is equal to 0.01 when every stage is trained, prepared and work instructions are used. The upper bound of the failure probability is equal to 0.40 when the level of training is low, no work instructions are used and many reinforcement measures are installed at the same time.

Time until successful placement

The time until successful placement is dependent on specific conditions. The length of the reinforcement measure, the number of persons working on the placement etcetera. Examples of this and the effect on the reliability will be examined in the case studies of the effectiveness (see Chapter 10) because discussing the placement phase individually is less relevant as the total time and total failure probability determines the effectiveness.

Capacity

The capacity of the crisis organization is an important factor in the effectiveness of the reinforcement measures. The total length of reinforcement measures that can be installed during critical conditions is bounded by the potential capacity of the placement teams and the total length of reinforcement measures that is available in time.

9

Technical reliability

Research question five is discussed in this chapter: *what is the technical reliability of grass revetment reinforcement measures?* In other words, what is the technical failure probability (p_t) of the measure given correct placement. The technical reliability in the context of the total reliability framework is shown in Figure 9.1.

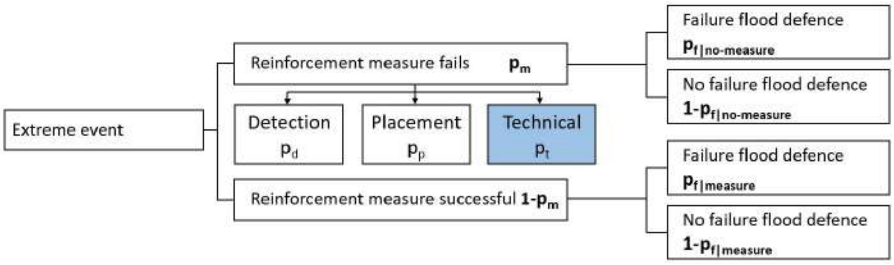


Figure 9.1: Place of research question in reliability framework reinforcement measures.

This chapter starts in the first section with the definition of the technical reliability. Failure of the structure is discussed in the second section. Section three describes the load on and the resistance of the structure. The chapter ends, in section four, with conclusions on research question five.

9.1. Definition technical reliability

The technical reliability of the reinforcement measures is determined by the strength of the measure and the load. The starting point in the determination of the likelihood of technical failure is that the reinforcement measure is placed correctly. Errors made in the placement of the measure are covered by the *placement* failure domain, thereby implicitly assuming that placement errors result in a structure with zero strength (see Chapter 8). The goal of this chapter is to make clear which failure mechanisms can cause failing of the grass revetment reinforcement measure and what their likelihood of occurrence is. The combination of the individual failure probabilities lead to the total probability of failure: the undesired top event.

Deterioration of the grass revetment reinforcement due to long term loading is not included in this study, because reinforcement measures applied during critical conditions are the scope of this analysis. Permanent reinforcements or geotextiles that are on the grass revetment for a long period of time (more than a month) are therefore not included in the analysis. An example of long term degradation of geotextiles is depreciation of the quality of the geotextile due to exposure to UV-radiation (Bhartu, 2015).

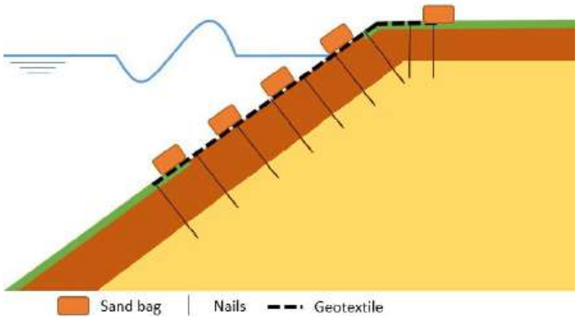
9.2. Failure grass revetment reinforcement structure

9.2.1. Grass revetment reinforcement measure

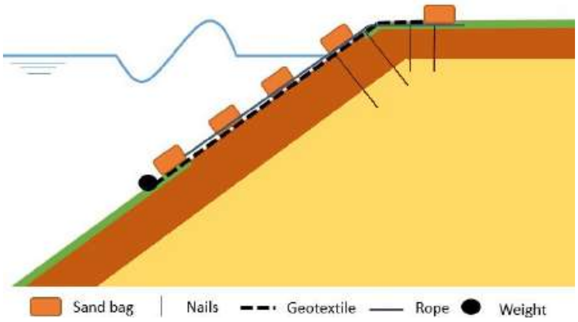
The types of grass revetment reinforcement structures as used by the water boards are described in Chapter 4 and Appendix B. Many different techniques are used at the various water boards, the differences are mainly found in how the geotextile is fixated to the dike body. Two different types of outer slope grass revetment reinforcement structures are considered in this chapter (based on Chapter 4):

1. Outer slope grass revetment reinforcement installed during low water conditions, see Figure 9.2a. The permeable geotextile is fixated to the dike body with nails and sometimes sand bags. This is the preferred fixation, as it is considered to be the strongest structure, but is only possible to construct during *low* water, because installing of the nails below the water line is impossible.
2. Outer slope grass revetment reinforcement installed during high water, see Figure 9.2b. The permeable geotextile is fixated to the dike body by nails (above water) and sand bags below water (sand bags kept in place by a rope). There is a heavy steel pipe at the bottom end of the geotextile, to be able to roll down the geotextile below the water line and to keep the geotextile in place after construction.

These two reinforcement types are considered to be representative for the current practice at different water boards. The distinction between these two types of outer slope reinforcements is made because the fixation is fundamentally different for the reinforcements placed during high and low water conditions.



(a) Reinforcement measure placed during *low* water.



(b) Reinforcement measure placed during *high* water.

Figure 9.2: Two different grass revetment reinforcement types (outer slope).

Sand bags

Several types of sand bags are used, three of them are discussed in this section, see Figure 9.3. These three types are currently in use at the *Drents Overijsselse Delta* water board. The nylon sand bag (see Figure 9.3a) is the strongest, most durable, but it is also the most expensive one. The polymer sand bag (see Figure 9.3b) is less strong and durable but has also lower costs. The last one is the plastic prefabricated “sand” bag, this is the cheapest but it is also a very weak bag and it is not possible to attach a rope to this bag.

(a) Nylon sand bag.

(b) Polymer sand bag.

(c) Plastic (cement) sand bag.

Figure 9.3: Three different sand bag types.

$$R_h = f \cdot F_v \tag{9.1}$$

Where:	R_h	=	Resistance against horizontal sliding	[N]
	F_v	=	Sum vertical forces	[N]
	f	=	Friction factor	[-]

The weight of the different sand bag types is approximately the same, however the friction factor differs. This friction factor depends on the type of sand bag and where it is placed on. A grass revetment (with a rough top layer) will provide much more resistance against sliding than sand bags placed on top of a plastic geotextile, see for example Figure 9.4. The friction factor can become very low when the cement sand bag (Figure 9.3c) is used on top of a wet geotextile. Van Dillen (2001) proposed to use a value of 0.25 as friction factor for the sand bags. This value should be reduced when the sand bags are placed on top of the geotextile as the resistance reduces.

Figure 9.4: Fixation inner slope grass revetment

Nails

The nails for fixation are most often made of (concrete) reinforcement steel. L-shaped (see Figure 9.5) and U-shaped nails are used, the nails have a varying length. The nails obtain their strength through friction between the steel and the soil.

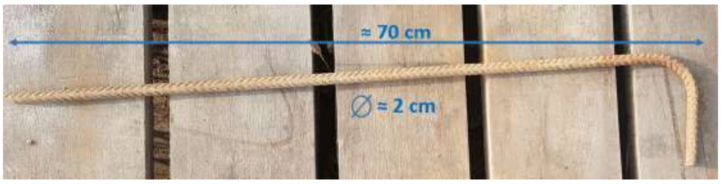


Figure 9.5: L-shaped fixation nail

9.2.2. Failure definition

The failure modes of the grass revetment reinforcement are analysed in this section. Failure of the grass revetment reinforcement can be caused by two failure modes, see Figure 9.6

1. Failure of the fixation
   The fixation (e.g. sand bags and nails) of the geotextile is different per type of reinforcement, but in general: failure of the fixation will lead to failure of the reinforcement structure.
2. Rupture of the geotextile
   Rupture of the geotextile will lead to failure of the grass revetment reinforcement, because the grass revetment is no longer protected.

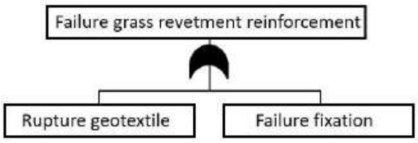


Figure 9.6: Failure tree grass revetment reinforcement measure.

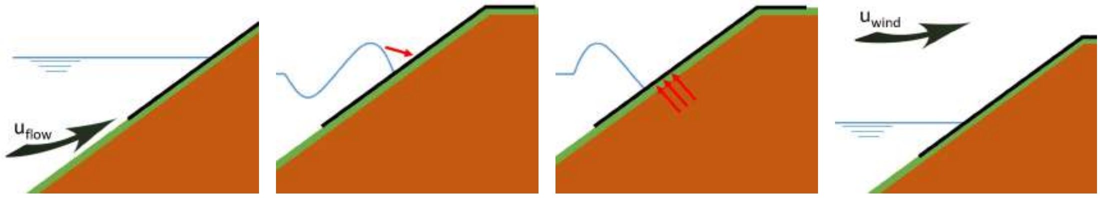
9.3. Load and resistance

9.3.1. Load

The outer slope grass revetment reinforcement is subjected to four different load types, see Figure 9.7:

1. **Water flow**
   Water flows in lateral direction with respect to the reinforcement structure and exerts a load. Water flow is neglected in the erosion calculations (see Chapter 3), because it results in a very small load. It is therefore assumed that water flow is also of minor importance for failure of the reinforcement measure.
2. **Wave impact**
   Wave impact is a severe loading, however the geotextile is pressed against the dike body by the load. This is a positive effect for the strength of the structure and therefore not considered in the calculations. Oblique wave attack could however damage the borders of the grass revetment reinforcement, when the sand bags are for example displaced by the waves. This phenomenon is neglected in the analysis.
3. **Wave run-down**
   Wave run-down is potentially important, due to the reduced water pressure on the outside and high water pressure inside the dike. The resulting outward directed force can lead to failure of the structure.

4. **Wind**
   Grass revetment reinforcements are installed to protect the grass cover against severe wave attack. Waves only occur in windy conditions. Wind also exposes the reinforcement measure.



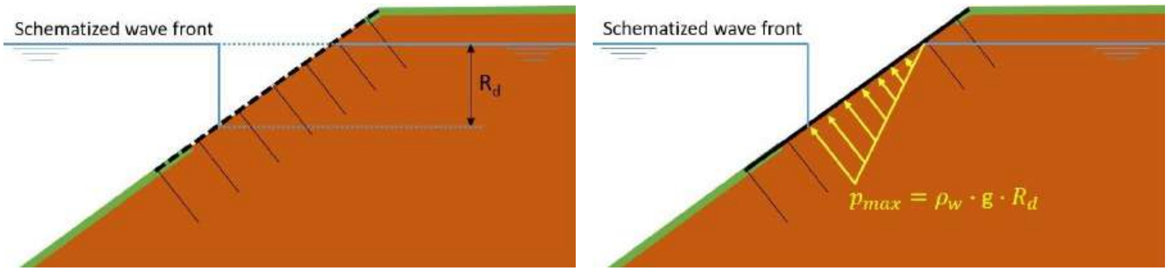
(a) Water flow. (b) Wave impact. (c) Wave run-down. (d) Wind.

Figure 9.7: Load on outer slope grass revetment reinforcement structure.

Water flow and wave impact are neglected. Wave run-down and wind are discussed in the next two sections.

9.3.2. Wave run-down

The wave run-down load is deduced in analogy to the stone pitching stability calculations, the front of the wave is schematized as a block, according to Schiereck and Verhagen (2012), see Figure 9.8a. The phreatic level in the dike does not change on the time scale of the waves, therefore is the water pressure in the dike higher than outside, this results in an outward directed water pressure. Wave run-down is a function of the wave height, slope angle and wave length (see Appendix G.1.1). What this outward directed water pressure would look like when the the outer layer were impermeable is shown in Figure 9.8b. But, the geotextile is permeable, therefore can the pressure partly escape through the pores of the geotextile. A way to express this reduction is by the leakage length, this is a measure for the response of the pressure head in the layer under the protection layer (Rock manual, 2007), the concept is explained below. The most favourable situation is an impermeable sub layer and permeable top layer. This situation occurs when the geotextile is placed on a clay layer.



(a) Schematization wave front. (b) Wave run-down pressure impermeable top layer.

Figure 9.8: Schematization hydraulic loading wave run-down.

Leakage length

The response of the water pressure in the filter layer to the pressure differences caused by wave run-down is a function of the leakage length, see Equation 9.2 (Schiereck and Verhagen, 2012).

$$\Lambda = \sqrt{\frac{k_F \cdot d_F \cdot d_T}{k_T}} \tag{9.2}$$

Where:	Λ	=	Leakage length	[m]
	k_F	=	Permeability filter layer	[-]
	k_T	=	Permeability top layer	[-]
	d_F	=	Thickness filter layer	[m]
	d_T	=	Thickness top layer	[m]

The influence of the leakage length on the pressure distribution of the filter layer is visualized in Figure 9.9. A drop in the outside water level as the result of wave run-down is partly followed by a drop of the pressure in the filter layer. The pressure in the filter layer is higher than the outside pressure over a length that is determined by the value of the leakage length.

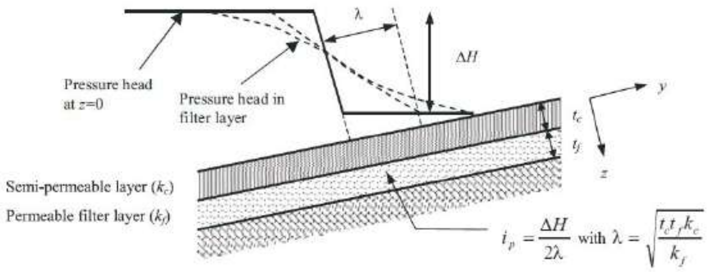


Figure 9.9: Definitions leakage length (Rock manual, 2007).

A high value for the leakage length is unfavourable for the stability of the top layer. An impermeable top layer (leakage length equal to infinity) means that the pressure in the filter layer is not influenced at all (e.g an asphalt revetment). A very low value of the leakage length, due to for example an impermeable sub layer and permeable top layer, means that the pressure in the top layer follows completely the outside wave pressure (e.g. loose stone on clay).

Reduction water pressure

The decay in hydraulic head in different soil layers under a dike, as function of the same leakage factor, is modelled as exponentially decreasing. This exponential decay is proposed by TAW (2004) and although it is not tailor made for this specific situation, it will be used. The decay observed in Figure 9.9 is therefore approximated by that same exponential decay. This method is conservative as the maximum pressure at the wave front is taken as starting point of the line (while it is much lower in Figure 9.9) and the pressure difference is zero in Figure 9.9 after a length of two times the leakage length, while the pressure is still 13% (e^{-2}) of the initial value for the exponential decay method. The reduction factor as function of the leakage length and x-coordinate can be seen in Equation 9.3 (TAW, 2004)

$$\alpha_{leakage} = exp\left(\frac{-x}{\Lambda}\right) \tag{9.3}$$

Where:	$\alpha_{leakage}$	=	Reduction factor	[-]
	x	=	x-coordinate on slope	[m]

This exponential decay is illustrated (see Figure 9.10a) for three different revetment types: rock, blocks and asphalt. The typical values for the parameters (d_T, d_F, k_T and k_F) are given in Table 9.1.

Table 9.1: Typical values leakage length parameters (Schiereck and Verhagen 2012)

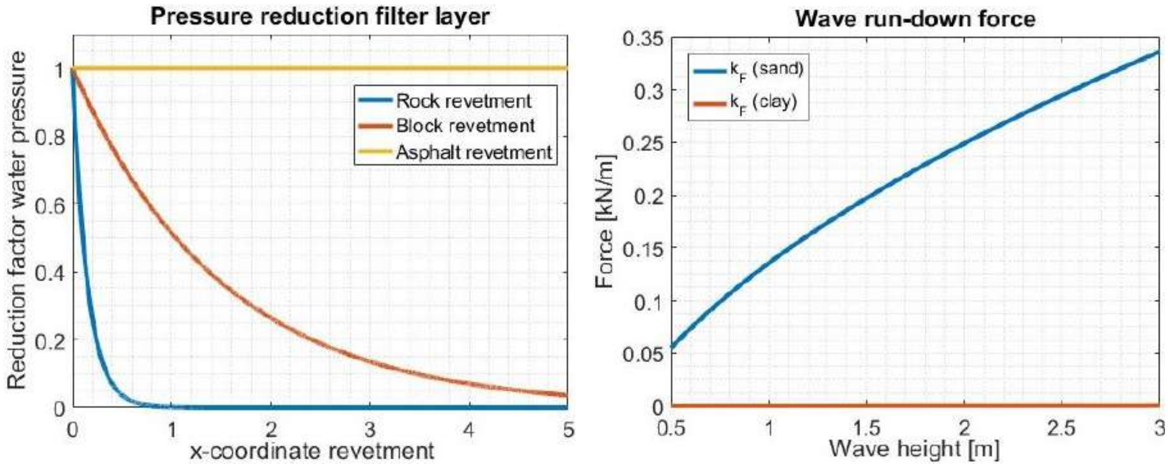
Parameter	Rock	Blocks	Asphalt
d_T (m)	0.5	0.25	0.25
d_F (m)	0.25	0.2	2
K_T (m/s)	0.5	0.001	0
K_F (m/s)	0.1	0.05	0.0001
Λ (m)	0.16	1.58	∞

The impermeable asphalt layer shows no reduction while the reduction is the largest for the rock revetment. Please notice that these lines show an order of magnitude. The reduction differs per revetment, dependent on the permeability and thickness of the layers.

The multiplication of the initial pressure and the reduction factor (Equation 9.3) gives the resulting water pressure under the geotextile. This pressure is integrated to get an expression for the force (per unit width), see Equation 9.4. The derivation and background of this formula can be found in Appendix G, Section G.2.

$$F_{rw} = \frac{\Lambda^2 \cdot p_{max}}{s} \cdot exp\left(\frac{-s}{\Lambda}\right) - \frac{\Lambda \cdot p_{max}}{s} \cdot (\Lambda - s) \tag{9.4}$$

Where:	p_{max}	=	Maximum water pressure	[kN/m^2]
	s	=	Pressure length	[m]
	F_{rw}	=	Run-down force per meter width	[kN]



(a) Spatial pressure reduction per revetment type. (b) Wave run-down pressure.

Figure 9.10: Wave run-down force.

Permeability geotextiles

Typical values for the permeability of three different soil types are shown in Table 9.2. The permeability of the geotextile as currently used at the *Drents Overijsselse Delta* and *Rivierenland* water board is assumed to be more permeable than sand, but less than gravel, based on visual observations. The permeability of the geotextiles is therefore assumed to be 10^{-3} m/s.

Table 9.2: Typical values for permeability (Fitts, 2002)

Type	Clay	Sand	Gravel
Permeability [m/s]	10^{-9}	10^{-4}	10^{-2}

Quantification wave run-down load

A calculation is done, with realistic parameters, to determine the order of magnitude of the run-down load. The parameters for the calculation are estimated and are as shown in Table 9.3.

Table 9.3: Parameters used in wave run-down calculation

Parameter	**Value**	**Dimension**
Slope	1:3	-
Wave period	3	s
k_F (sand)	10^{-4}	m/s
k_F (clay)	10^{-9}	m/s
k_T	10^{-3}	m/s
d_F (sand)	1	m
d_F (clay)	0.10	m
d_T	0.005	m

The result can be seen in Figure 9.10b. Please notice that the graph only shows an order of magnitude, the parameters used in the calculation are chosen realistically but can be different for distinct cases. The figure shows the force per unit width as function of the wave height. To get an idea, 0.20 kN is approximately the weight of one sand bag (20 kg). The calculation method is meant to analyse whether the load can be neglected in the analysis of failure of the reinforcement measure. The calculation method has the following limitations:

- The exponential decay method is not specifically applicable to this situation, however it is probably an overestimation, as discussed in this section.
- The calculation method assumes a geotextile that is present directly on top of the soil. However, in practice there is space between the soil and the geotextile, this space is firstly filled when the wave is running down, which results in a pressure reduction and therefore a structure that is more safe.

Based on the calculation is concluded that:

- The wave run-down load can be neglected when the geotextile is placed on a clay sub soil.

- The wave run-down load is not negligible when the reinforcement measure is placed on sandy soil. An accurate value for the outward directed load cannot be given on the basis of this calculation method. However, for realistic values of waves in the riverine area (H<1.5 meter) the force does not exceed 0.20 kN/m which is counteracted by one sand bag per meter length.

9.3.3. Wind

Grass revetment reinforcement measures are installed to prevent erosion by waves. High wave can only occur during windy conditions. Wind can also expose the geotextile, however only when the wind can get grip on the textile. An example is given in Figure 9.11, which shows the placement of a geotextile during windy conditions, but relatively mild (5 Bft) compared to what the wind conditions can be during storms).

Figure 9.11: Placement geotextile inner slope during exercise water board Drents Overijsselse Delta (Drents Overijsselse Delta, 2011) during relatively windy conditions 5 Bft (8 m/s) measured at De Bilt (KNMI, 2018) (7 December 2011).

Quantification load

It is difficult to quantify the load that wind exerts on the geotextile during storm conditions, because:

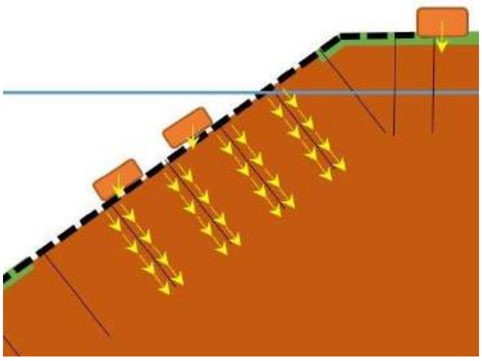
- It is difficult to quantify the area of the geotextile that is exposed to the wind.
- The wind pressure is largely dependent on the local circumstances.
- The geotextile is permeable, so the pressure can partly escape.

It is assumed, based on expert judgement, that wind can cause failure of the geotextile structure when the borders are not solidly fixed to the grass revetment. Therefore is it advised to use nails and sand bags at the borders of the geotextile to prevent exposure of the reinforcement to wind load.

9.3.4. Resistance

The resistance of the geotextile reinforcement is provided by (see also Figure 9.12a):

- The friction resistance between the soil and the steel nails (pulling out of the nails).
- The weight of the sand bags.
  Sand bags provide resistance by their own weight, sand bags are normally 0.2 kN (20 kg) in weight.
- (Tensile) strength of the geotextile.
  An example of a geotextile (used by the *Drents Overijsselse Delta* water board) is shown in Figure 9.12b.



(a) Fixation grass revetment reinforcement.

(b) Example geotextile.

Figure 9.12: Resistance reinforcement.

Proven strength

The *Drents Overijsselse Delta* water board have placed multiple (approximately 10) grass revetment reinforcements in January 2018. The Netherlands experienced storm conditions the day after the placement (3 January 2018). These storm conditions[19] have not damaged the grass revetment reinforcements, the photos (see Figure 9.13) show the reinforcement measures two days after the storm.

(a) Outer slope reinforcement 1. (b) Outer slope reinforcement 2.

Figure 9.13: Grass revetment reinforcements *Vecht* river (5 January 2018).

9.4. Conclusion technical reliability

Research question five is answered in this chapter: *what is the technical reliability of grass revetment reinforcement measures?*

Four different loads are distinguished that can lead to failure of the grass revetment reinforcement structure:

- Water flow produces a negligible force on the grass revetment reinforcement, based on the consideration that water flow is also neglected in the erosion calculations.
- Wave impact does have a positive effect as it presses the geotextile even more to the dike body.
- Wave run-down:
  - produces a negligible force on the geotextile when it is placed on a clay layer, due to the very low value of the leakage length.
  - can produce a non-negligible force when the geotextile is placed on a sandy soil. An accurate estimate of this force cannot be given based on the analysis presented in this chapter. Two sand bags per meter in the wave run-down area should suffice based on this analysis, this is probably an upper limit because the calculation method is conservative.
- Wind can result in a non negligible load on the geotextile reinforcement, however fixation of the borders of the geotextile to the dike mitigates this load.

The failure probability of the measure (p_m) is determined by the detection (p_d), placement (p_p) and technical failure (p_t) probability. The first two are in the order of 10^{-1} (see Chapter 7 and 8). The technical failure probability will contribute to the failure probability of the reinforcement measure when it is in the same order of magnitude. The technical failure probability is expected to be lower[20] and thereby assumed to be 10^{-3}. This assumption is based on the qualitative and quantitative description of the load and resistance. This conclusion holds for an outer slope grass revetment reinforcement placed on a clay sub soil with a fixed border.

The above described conclusion regarding the technical failure probability holds for the grass revetment reinforcement measure as currently applied. A design question would be to find the optimal grass revetment reinforcement measure: a grass revetment reinforcement measure that requires a short duration to install, is easy to place, is strong enough to prevent failure of the measure itself (p_t) and stops erosion of the grass revetment. A short duration to install means that the likelihood that the measure is installed in time increases.

[19] Mean wind verlocity 10.4 m/s (5 Bft), maximum hourly average wind velocity 15.0 m/s (7 Bft) and maximum wind gust 24 m/s at Marknesse (KNMI, 2018)

[20] This is in line with the findings of Lendering et al. (2014) and Dupuits (2011).

10
Case studies

Chapter 3 to 9 form the input for the effectiveness calculation. These chapters answers all one part of the event tree of Figure 10.1. The effect of the reinforcement measures can be determined based on this complete event tree, which is performed in this chapter for two different cases.

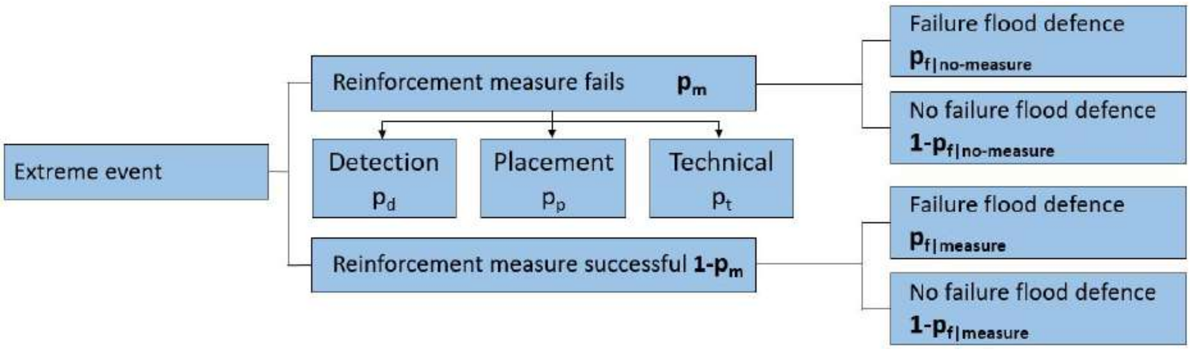


Figure 10.1: Place in reliability framework reinforcement measures.

Two methods are used to calculate and visualize the effectiveness of the reinforcement measures, this can be read in the first section. The second section describes the general starting points of the two cases. The first case (case A) considers the effectiveness of a known weak spot in the flood defence in the third section. In the second case (case B) is the effectiveness for unknown weak spots examined, this can be found in the fourth section. A sensitivity analysis is carried out in the fifth section. The chapter ends, in section six, with conclusions.

10.1. Method

Two methods are used to calculate and visualize the effectiveness of the reinforcement measures:

- A fragility curve, see Section 10.1.1. The fragility curves as deduced for the grass revetment reliability in Section 3.3 are extended with the effect of the reinforcement measures. The fragility curve shows the effect of the measures over the whole range of peak significant wave heights of the storm.
- The failure probabilities calculated with the fragility curve method are used to show the effect of the measures for one particular wave height as function of time, see Section 10.1.2. The main advantage of this method is that it shows the effect of the individual parameters influencing the effectiveness. A disadvantage is that it only gives the effect for one particular wave height only.

10.1.1. Method 1: fragility curve with reinforcement measure

The calculation method for the failure probability of the flood defence with reinforcement measure is visualized on the next page, see Figure 10.2. The calculation method is an extension of the fragility curve method explained in Figure 3.12. This fragility curve is determined by the strength parameters of the grass revetment and clay sub layer and the storm shape and duration as load parameter.

The additional parameters describing the uncertainty of the reinforcement measure are:

- the failure probability of the reinforcement measure p_m;
- the time required to install the reinforcement measure T_{req};
- the effect of the reinforcement measure on the erosion speed, described by the erosion modification factor α_{geo}.

The failure probability of the reinforcement measure is a constant value per case This failure probability is determined by the detection, placement and technical reliability. The time needed to install the measure is approximated by a Gaussian distribution. This total required time is a combination of both the detection and placement phase. The effect of the measure is modelled by a lognormal distribution of the erosion modification factor, see Chapter 4.

The effectiveness of the measure is modelled based on a crude Monte Carlo simulation. The uncertainty of the reinforcement measure is implemented in the model:

- If the randomly generated number is smaller than p_m, then the measure fails. Nothing has changed with respect to the initial erosion resistance. The erosion failure probability of a non-reinforced dike is calculated, according to Chapter 3, Figure 3.12.
- The measure is installed correctly, if the randomly generated number is larger than p_m. However, there is still uncertainty in the time required for the installation and effect of the measure:
  - The erosion speed is modelled based on the erosion formulas until $T = T_{req}$. There is no measure on the revetment until this time, hence the erosion is governed by the initial erosion speed.
  - The modified erosion speed due to the presence of the measure after $T > T_{req}$ is implemented by the erosion modification factor (α_{geo}). This factor reduces the erosion speed.

The general calculation method, for a deterministic case, is explained in Chapter 2.3.

The example of Figure 10.2 shows failure of the revetment for the failing reinforcement measure ($< p_m$) case and no failure for the successful applied reinforcement measure ($> p_m$). However, this is not necessarily the case. Failure of the flood defence can also happen in the case of a successfully installed measure due to a too large value of T_{req} or α_{geo}.

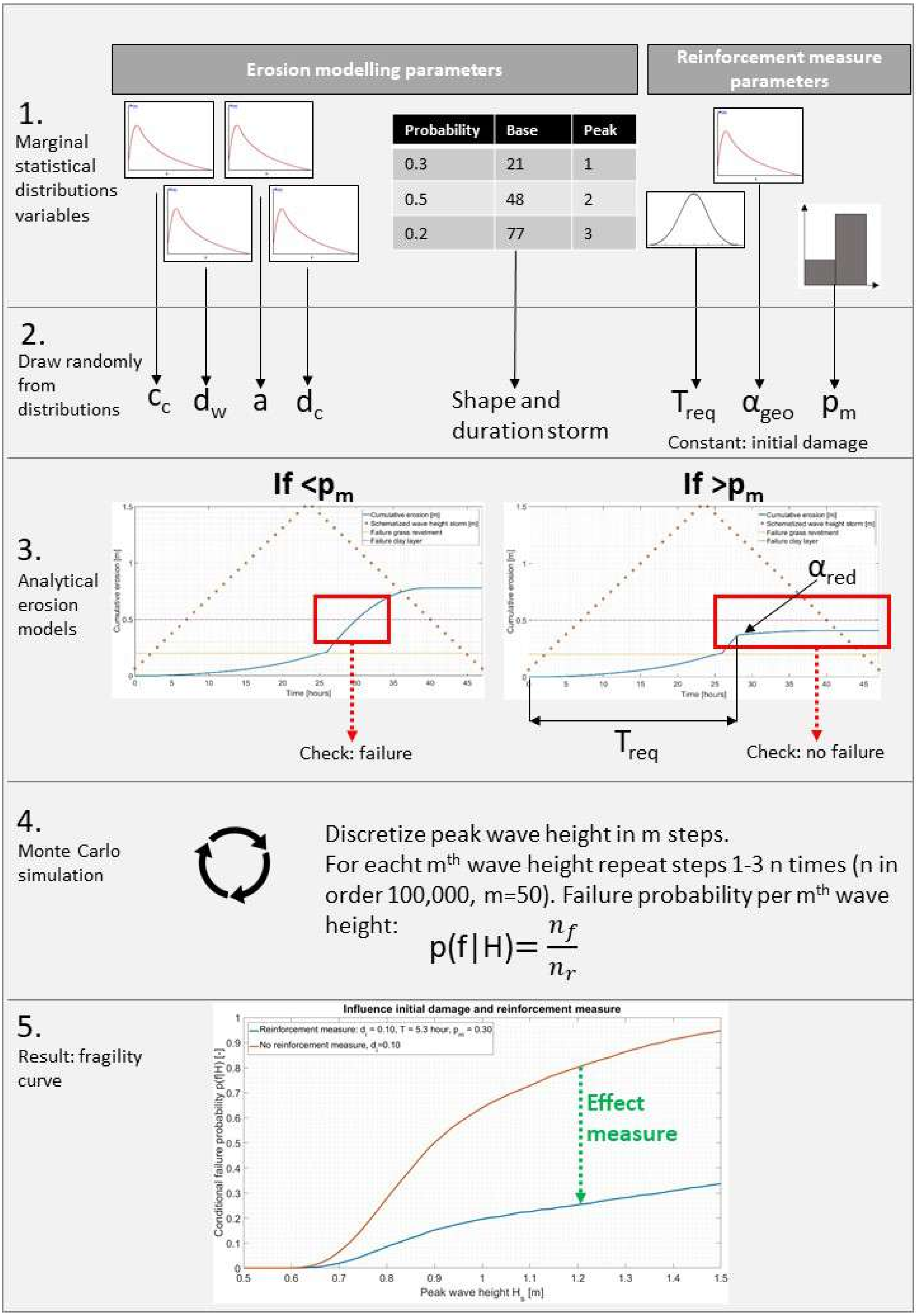


Figure 10.2: Calculation method effectiveness measure.

10.1.2. Method 2: visualization time dependency measures

A visual method is developed to illustrate the effectiveness of the reinforcement measures, see Figure 10.3. The graph shows on the horizontal axis the time needed to install the reinforcement measure. The origin of the axis ($T = 0$) is the start of the schematized storm. The model prescribes a wave height at the start of the storm of zero and increasing linearly to the peak significant wave height. The *start time* of the action chain to install the reinforcement measure is in the negative time domain. The vertical axis represents the conditional failure probability of the flood defence ($p_{f|H}$) due to grass revetment failure, given the peak significant wave height of the storm. The variables that influence the shape of the graph are presented in the figure.

The horizontal part at the right side of the figure ("c") is equal to the failure probability of the flood defence without reinforcement measure ($p_{f|no-measure}$). The graph is horizontal from a specific point in time, because it does not matter how low the failure probability of the reinforcement measure (p_m) is and how positive the effect of the reinforcement measure is (small erosion speed α_{geo}) when the time needed to install the reinforcement measure is too large. The failure probability of the flood defence ($p_{f|H}$) is in this part equal to the failure probability without measure and is therefore determined by the wave height, initial damage depth, clay quality, grass quality and duration of the load.

On the other hand, the reduction in failure probability can be high when the installation time is short (close to $T = 0$, "a" in the graph). The failure probability in this first horizontal part is determined by the failure probability of the measure (p_m) and the erosion modification factor. The length of first horizontal part and the slope of the transition line are a function of the storm duration, storm shape and peak wave height. The line connecting the two horizontal parts is the failure probability influenced by the time needed to install the reinforcement measure. The more time needed the higher the failure probability of the flood defence, eventually arriving at $p_{f|no-measure}$.

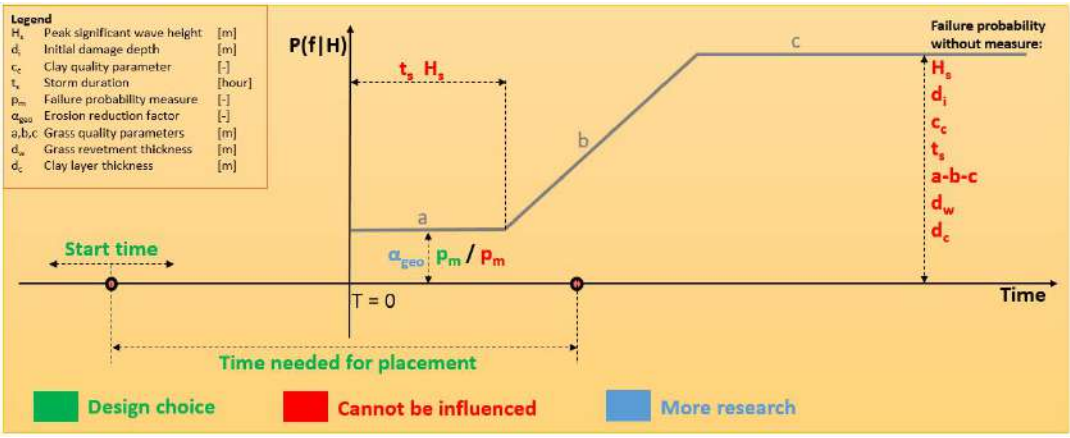


Figure 10.3: Effectiveness of reinforcement measure.

Please notice that the schematization is a simplification of reality. Part "a" and "c" are not completely horizontal and "b" is not exactly linear. An example is given in the sensitivity analysis, see Figure 10.16.
The reinforcement measure is most effective in the bottom left corner. The failure probability is low at this location and the reinforcement measure is installed in time. The shape of the graph is partly a design choice of the crisis organization but several parts cannot be influenced. Influencing factors are:

- External factors, like the weather, are hard to influence but do affect the reliability of the reinforcement measure. On the other hand, time pressure can partly be mitigated by more personnel, therefore is p_m categorized both as *design choice* and *cannot be influenced.*
- The start time is a matter of design, dependent on the predictions. Starting earlier comes with the risk of unnecessary placement of measures, starting late increases the failure probability of the measure.
- The time that is needed to install the reinforcement measure is a design choice; this can be influenced by training sufficient personnel and preparation of the materials.
- A relatively large contribution in the uncertainty is the erosion modification factor (for the sensitivity analysis, see Section 10.5). Large scale tests might prove that the erosion reduction is lower, such research can decrease the uncertainty of the measure. Additional research can also turn out negative and

show that the prediction in this report overestimates the effect of the measure in erosion reduction.

- The clay and grass quality parameters are qualified as *cannot be influenced* in the figure. This qualification holds during a crisis situation, however intensive regular maintenance (design choice) of the dike decreases the probability of having weak spots in the dike.

Example 10.1 Effectiveness measure

The calculation in this example is based on the event tree in Figure 1.7.

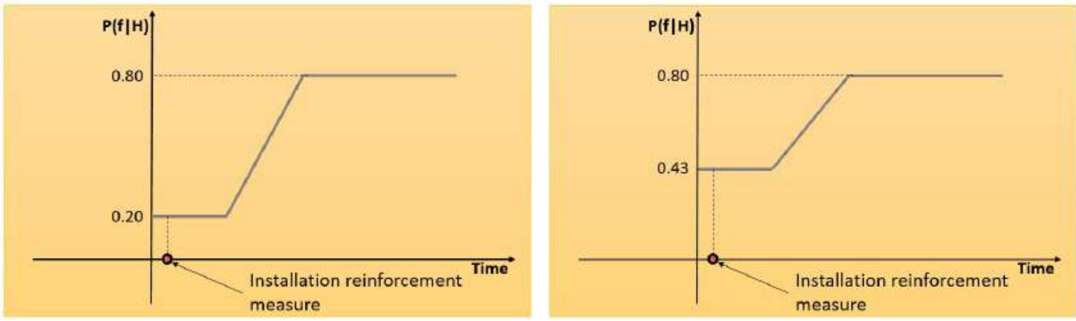
Consider a conditional failure probability of the grass revetment without measure ($p_{f|no-measure}$) equal to 0.80 and the erosion modification factor is equal to 0, the reinforcement measure, when installed correctly, will then stop the erosion, hence $p_{f|measure} = 0$. Furthermore, the installation time is short (close to $T = 0$) and the failure probability of the reinforcement measure (p_m) is 0.25. The failure probability of the flood defence ($p_{f|H}$) in this case is therefore 0.20 according to the calculation below, see Figure 10.4a.

$$p_{f|H} = p_m \cdot p_{f|no-measure} + (1 - p_m) \cdot p_{f|measure} \tag{10.1}$$

$$p_{f|H} = 0.25 \cdot 0.80 + (1 - 0.25) \cdot 0 = 0.20 \tag{10.2}$$

The calculation holds for the case in which the erosion modification factor is equal to zero. Suppose that the erosion modification factor is such that the failure probability of the flood defence with successful applied reinforcement measure ($p_{f|measure}$) is equal to 0.30. The failure probability of the flood defence ($p_{f|H}$) is then equal to 0.43, according to Equation 10.3, this is visualized in Figure 10.4b.

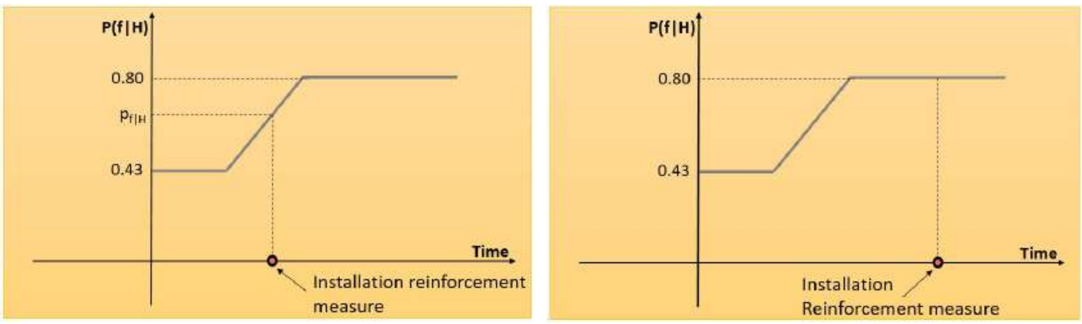
$$p_{f|H} = 0.25 \cdot 0.80 + (1 - 0.25) \cdot 0.30 = 0.43 \tag{10.3}$$



(a) Effectiveness with $p_{f|measure} = 0$. (b) Effectiveness with $p_{f|measure} = 0.30$.

Figure 10.4: Examples failure probability flood defence with reinforcement measure I.

The two examples above are valid for the situation in which the reinforcement measure is installed close to $T = 0$. The effect of delayed placement is illustrated in Figure 10.5a. The failure probability will be, dependent on the specific circumstances, between the two horizontal parts, in this case $0.43 < p_{f|H} < 0.80$.



(a) Delayed installation. (b) Too late installation.

Figure 10.5: Examples failure probability flood defence with reinforcement measure II.

The failure probability of the flood defence is equal to the failure probability of the flood defence without measure ($p_{f|no-measure} = 0.80$) when the placement time is large, see Figure 10.5b.

10.2. Cases

10.2.1. General starting points

The general starting points for the cases are listed below:

1. **Grass revetment reinforcement measure type 2 (installed below the water line)**
   There are two types of reinforcement measures, those installed before the high water (type 1) and reinforcement measures installed during high water (type 2), see Appendix B. Installation before the high water is conservative, because storms cannot be foreseen long in advance. The differentiation between the two types is important as the installation of measure type 2 is more difficult and is not trained at every water board. The installation of reinforcement measure type 2 is studied in this chapter.
2. **Placement of geotextile is impossible during and two hours before and after the storm peak.**
   The placement of the geotextile reinforcement measures is assumed to be impossible during strong wind conditions based on interviews with dike supervisors at the *Rivierenland*, *Drents Overijsselse Delta* and *Vallei en Veluwe* water boards. It is assumed that construction of the reinforcement measure is impossible during the peak of the storm and two hours before and after the storm peak. The required time (T_{req}) is extended when the construction time falls within the boundaries of this criteria.
3. **Expected number and length of weak spots**
   The required time for the construction of the reinforcement measure and thereby the required capacity is determined by the number and length of weak spots. In Chapter 3.2.1 are the possible causes for weak spots listed. Weak spots that are probably limited in length or number are: driving tracks and damage by animals. Damage causes that might be present over larger lengths are: damage by insects and a newly constructed dike with an insufficient grass revetment. The characteristics of the weak spot in combination with the hydraulic conditions determine the need for measures:
   - The wave impact driven failure mechanism does imply that only dikes in the direction of the wind, with a considerable fetch (order 500 meter) and water depth are vulnerable for the erosion failure mechanism.
   - The wave impact locations ($H_s > 0.50$), with initial damage or bad grass quality are potential reinforcement locations.

   The two points above limit the locations where measures are needed. Based on the damage causes is assumed that known weak spots are larger in length than unknown weak spots. The number and length of weak spots will also differ per water board. For the cases is assumed that known weak spots have a length in the order of 500 meter[21] and that weak spots found during high water are smaller in length, order 200 meter, for example damage by driftwood, drivings tracks and damage by animals.

10.2.2. Two different cases

Two cases are examined in this chapter to determine the effectiveness of the reinforcement measure, these two cases are deduced from the way the reinforcement measures are applied in practice[22], see Figure 10.1:

1. As reinforcement measure for **known weak spots**. These measures are installed based on predicted hydraulic conditions. There are two reasons only to reinforce the grass revetment when needed:
   - Geotextiles placed for a long period of time will lead to deterioration of the grass revetment.
   - Unneeded placement of reinforcement measures results in unnecessary costs.
2. As reinforcement measures for **unknown weak spots**. Those weak spots are to be found by inspection of the flood defences during extreme events.

The action chain from the prediction of the hydraulic conditions until the installation of the reinforcement measure is illustrated for the two different cases in Figure 10.6.

Figure 10.6: Chain of actions for the two different cases.

[21] See for example the Rivierenland (Chapter 5.2.4) and Stichtse Rijnlanden case (Chapter 5.2.4)
[22] See Figure :1.4, option B and C.

Table 10.1: Two different cases considered in the effectiveness calculation.

	Case A: known weak spot	**Case B: unknown weak spot**
Start	Start placement based on predetermined hydraulic conditions	Start dike inspection based on predetermined hydraulic conditions.
Detection	No detection needed	Contribution reliability detection
Time pressure	Limited time pressure	Much time pressure
Reinforcement measure	Prepared for site specific conditions	Not prepared for site specific conditions
Logistics	Prepared	Not (completely) prepared

For each case is the effectiveness examined based on the methods developed in this thesis. The effectiveness will be largely determined by the organizational structure of the water board, the local circumstances and experience. Therefore are within each case four options considered. In this way it becomes clear what the effectiveness is, relative to a realistic upper and lower bound. The options are:

1. an optimistic performance;
2. a pessimistic performance;
3. the *Rivierenland* water board;
4. the *Drents Overijsselse Delta* water board.

10.2.3. Available time

An important parameter in the two cases is the available time for the application of reinforcement measures and dike inspection. High water levels in the river system can be predicted days in advance, whereas high wind speeds (storms) are less predictable.
The storm shape is taken as uncertain parameter, according to Geerse (2006). A constant time period of 12 hours before the start of the storm ($T = -12$ hour) is assumed, see Figure 10.7. The time until the peak of the storm is larger, see Table 10.2. The average value of the time before the storm peak is 34 hours[23]. This 12 hour lead prediction time is estimated based on expert judgement. Taking into consideration that the prediction time will be smaller compared to water level driven failure mechanisms. Maaskant et al. (2009) determined the available evacuation time for different hydrological systems, ranging from no available time till 4 days. The expected value of the proposed available time distributions is 1.8 days for the Rhine river and 1.55 days for the Western coast (Maaskant et al., 2009). The 12 hours prediction time in combination with the time till the peak of the storm is therefore assumed to be realistic for grass revetment failure mechanism. The effect of the time parameter will be made clear in a sensitivity analysis.

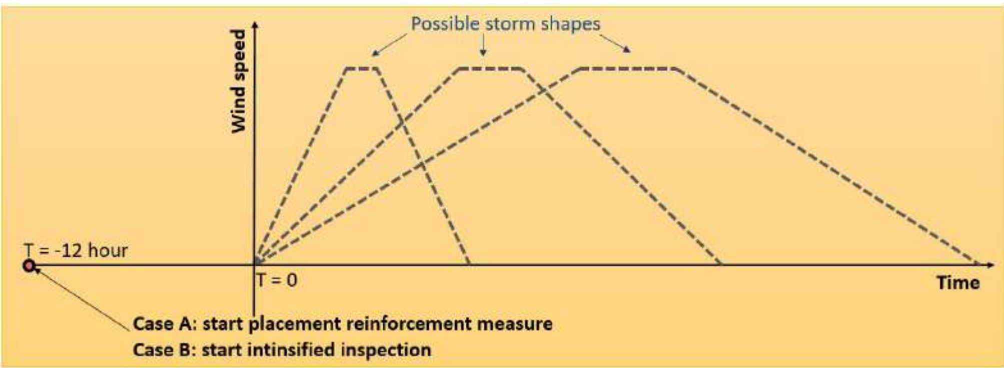


Figure 10.7: Available time.

Table 10.2: Available time before storm peak (time in hours).

Probability	Base duration	Front flank	Prediction time	Time before storm peak
0.3	21	10	12	10+12 = **22**
0.5	48	23	12	23+12 = **35**
0.2	77	37	12	37+12 = **49**

[23] $T_{average} = 0.3 \cdot 22 + 0.5 \cdot 35 + 0.2 \cdot 49 = 33.9 \approx 34$ hour.

10.3. Case A: known weak spots

10.3.1. Relevance scenario

Case A considers the situation in which the weak spot is known based on regular inspection. Grass can be in a non-optimal state due to various reasons, see Figure 10.8:

- a newly constructed dike, this grass revetment is per definition not at its ultimate strength in the first winter (see for example Appendix F.6);
- a fragmented or open grass revetment classification from the WBI-2017 (see Appendix A.2.2);
- insects that damage the grass revetment, possibly at a large scale (see for example Chapter 5.2.2);
- drivings tracks, damage by animals, vandalism etcetera.

(a) Newly constructed dike Lienden (October 2017).
(b) Fragmented sod (Digigids, 2016).
(c) Driving track (Digigids, 2016).
(d) Damage by animals (Digigids, 2016).

Figure 10.8: Illustration different causes damage grass revetment.

10.3.2. Characteristics case A

The motivation of the input parameters can be found in Appendix H. A summary of the time distributions and failure probabilities is given in this section.

The failure probability for the detection and placement phase are based on the methods that are developed in Chapter 7 and 8. The resulting failure probabilities are presented in Table 10.3. The failure probability p_m is calculated based on Equation 1.1.

Table 10.3: Case A: failure probability p_m

	Failure probability			
	Detection (p_d)	Placement (p_p)	Technical (p_t)	**Combined (p_m)**
Optimistic	0.001	0.004	0.001	**0.01**
Rivierenland	0.010	0.008	0.001	**0.02**
Drents Overijsselse Delta	0.010	0.095	0.001	**0.11**
Pessimistic	0.050	0.120	0.001	**0.16**

This case considers a weak spot with a **total length of 500 meters**. The construction time is a function of the number of teams and the construction rate per team. The values for the different scenarios can be found in Table 10.4.

Table 10.4: Potential capacity, construction rate and time needed for installation reinforcement measure. C_p = Potential capacity; n_t = Number of teams; R_t = Construction rate per team; R = Total construction rate; $T_{construction}$ = Construction time.

Performance	C_p **[m]**	n_t **[-]**	R_t **[m/h]**	R **[m/h]**	$T_{construction}$ **[h]**
Optimistic	500	5	40	200	2.5
Rivierenland	500	4	37.5	150	3.3
Drents Overijsselse Delta	500	3	17	50	10
Pessimistic	500	2	20	40	12.5

The construction time is only one part of the total time required for the installation of the reinforcement measure. The required time is modelled with a Gaussian distribution. The action chain starts at $T = -12$ hour, as explained in Section 10.2.3. The reinforcement measure is per definition installed in time when it is placed before the start of the storm ($T = 0$). The required time is modelled with respect to the start of the storm, a time shift of 12 hours is therefore needed[24]. The resulting time distributions can be found in Table 10.5, this table is based on Appendix H.1.4.

Table 10.5: Average and standard deviation required time for placement grass revetment reinforcement. Scaled with respect to start storm. Start action chain at T=-12 hour, start storm at T=0 hour.

	Optimistic	Rivierenland	WDOD	Pessimistic
Average [hour]	5.0	7.7	15.2	22.2
Average scaled with start storm [hour]	**-7.0**	**-4.3**	**3.2**	**10.2**
Standard deviation [hour]	**0.6**	**0.8**	**1.2**	**2.2**

10.3.3. Results

Many parameters are stochastically implemented in the model, however grass revetment quality and initial damage can still be varied. The fragility curve, with and without reinforcement measure for the four options (Optimistic, *Rivierenland*, *Drents Overijsselse Delta* and pessimistic performance) is shown for:

- open sod quality and initial damage depth of 10 centimetre in Figure 10.9;
- an initial damage depth of 30 centimetre[25], see Figure 10.10.

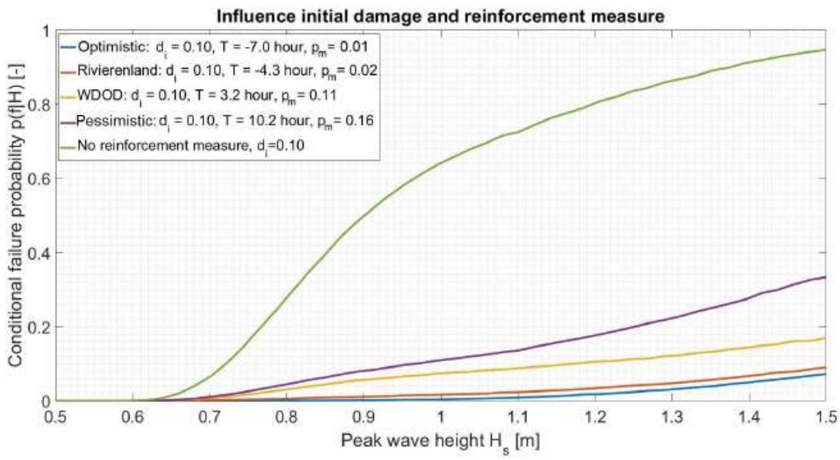


Figure 10.9: Fragility curve: effect of grass revetment reinforcement measure for known weak spot, with open sod quality and 10 cm initial damage.

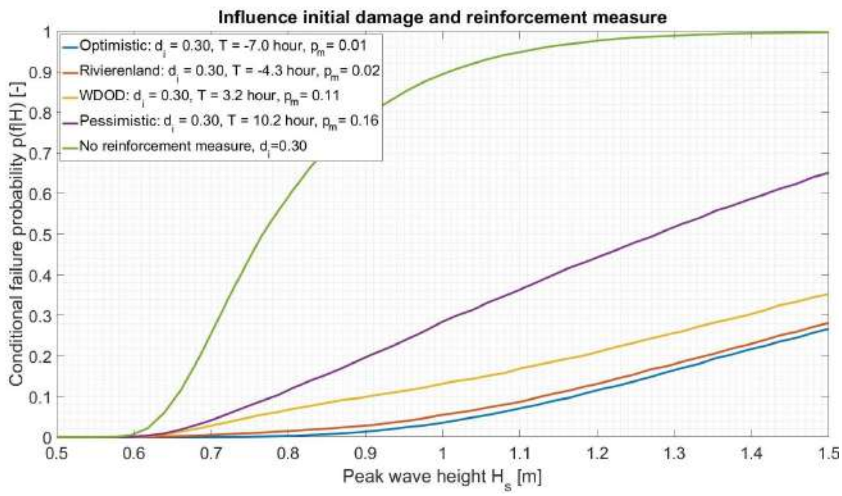


Figure 10.10: Fragility curve: effect of grass revetment reinforcement measure for known weak spot with 30 cm initial damage.

The resulting effectiveness is a function of the initial damage depth and grass revetment quality of which two results are given above. The failure probability reduction has been quantified for a varying H_s (0.8, 1.0, 1.2

[24] If a water board needs 11 hours to place the measure, then it is installed at $T = -1$ hour with respect to the start of the storm at $T = 0$.
[25] The quality of the grass revetment is not applicable, since the initial damage exceeds the thickness of the grass revetment (20 cm).

and 1.4 meter) and a varying damage depth d_i (0.00, 0.10, 0.20, 0.30 and 0.40 meter). The effect in terms of failure probability reduction due to the implementation of grass revetment reinforcement measures can be seen in Table 10.6. An average value for the reduction and the minimum and maximum value are given.

Table 10.6: Reduction factor initial failure probability for varying d_i 0-0.40 [m] and varying peak significant wave height H_s 0.8-1.4 [m]

	Min	Average	Max
Optimistic	1.9	31.8	92.2
Rivierenland	1.9	21.9	49.7
WDOD	1.7	6.5	9.2
Pessimistic	1.2	3.8	6.2

10.3.4. Length effect

The first contribution to the length effect is the time required for installation. The longer the reinforcement measure, the more time needed for installation. The probability of failure of the measure increases. This effect is implemented in the model. In the *conclusions case A* section is elaborated on what the effect is of longer measures than assessed in this case study.

It is assumed that the failure probability of the flood defence does not increase when the total number of reinforcement measures increases (not one weak spot of 500 meter but multiple weak spots but a total of 500 meter). The weak spots are assumed to be dependent and the failure probability is thus equal to the maximum failure probability (Jonkman et al., 2015). This assumption is based on:

- Detection is not needed. The command to install the measure is accounted for in the failure probability, but this failure probability is assumed not to increase for increasing number of weak spots.
- Known weak spots are assumed to be larger in length and less in number (1 or 2).
- The knowledge level of the placement team is assumed to be te same. Mistakes are the result of insufficient preparation, which is the same for the weak spots.

10.3.5. Conclusions case A

The effectiveness of the reinforcement method is visualized according to the method presented in Section 10.1.2. Figure 10.11a shows the effectiveness of the reinforcement measures for the peak significant wave height of the schematized storm of (H_s) of 1.0 meter and an initial damage depth (d_i) of 0.30 meter. These graphs can be made for all combinations of the hydraulic parameters, grass quality and initial damage. Recall that this effectiveness calculation is based on weak spots with a total length of 500 meter. Figure 10.11a shows schematically the failure probability of the flood defence as function of the time needed to install the reinforcement measure. The failure probabilities at $T \approx 0$ are different for the four options because of the differences in level of preparation and organizational structure. The following can be observed in the graph:

- **Optimistic, *Rivierenland* and *Drents Overijsselse Delta* scenario**
  For the optimistic scenario and the two water boards is the failure probability of the flood defence ($p_{f|H}$) determined by the failure probability of the measure (p_m) and the effect of the measure (α_{geo}). The time required to install the measure does not influence the failure probability in this case because all three scenarios are within the first horizontal part of the graph, the measures are even installed before the start of the storm for the *optimistic* and *Rivierenland* case.
- **Pessimistic scenario**
  The failure probability of the flood defence is for the pessimistic scenario also determined by failure probability of the measure. The time needed to install does for this case also contribute to the failure probability of the flood defence, because the time required to place the measure exceeds the first horizontal part of the figure.

Influencing effectiveness: *Drents Overijsselse Delta*

Figure 10.11b shows the same graph of the *Drents Overijsselse Delta* water board with the means to influence the graph included in the figure. For this specific case, based on estimated construction rates and specific length of weak spot, can the effectiveness be increased by:

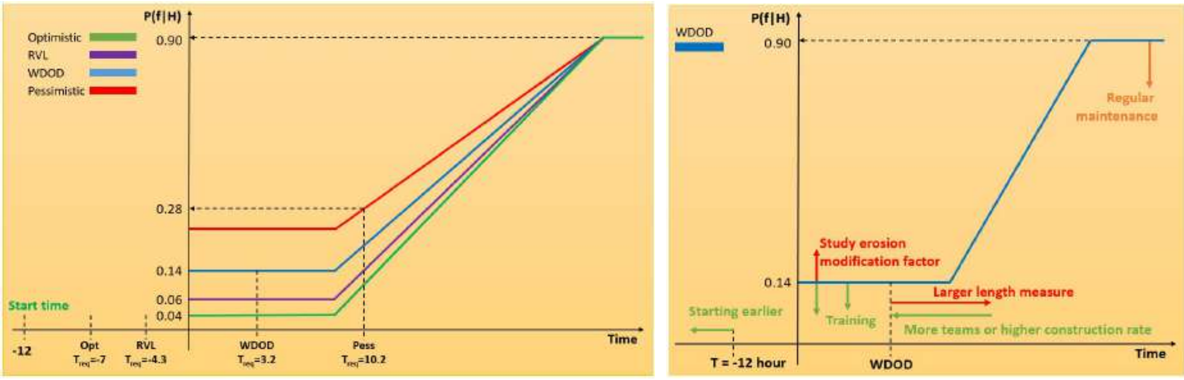
- decreasing the failure probability of the measure (p_m), this can be achieved by (realistic) training, standardized procedures and logistic preparation;

- decreasing the uncertainty around the effect of the measure (α_{geo}) by additional research.

Decreasing the time needed for installation does not have any effect for this case because it would only result in a horizontal shift to the left on the first horizontal part of the graph. However, this reasoning does not hold for increasing lengths of weak spots. The effectiveness will decrease when the required time is longer than first horizontal part of the figure. The failure probability will increase until it reaches $p_{f|no-measure}$. The sensitivity analysis will show that the horizontal part of the figure extends till $T \approx 7$ hours, see Figure 10.16. This means that there is 3.8 hour left (see Table 10.5) for the *Drents Overijsselse Delta* water board without a change in effectiveness of the measure. Based on the assumed construction rates (see Table 10.4) does this result in an additional potential capacity of 190 meter, according to Equation 10.4 .

$$C_p = R \cdot T_a = 50 \cdot 3.8 = 190 \tag{10.4}$$

So, investing in more capacity will have effect for weak spot lengths above approximately 700 meter ($500 + 190 \approx 700$), based on the parameters as used in this calculation. It is assumed that material for this 700 meter of reinforcement measure length is available. In terms of capacity: that the real construction capacity is equal to the potential capacity and thus not limited by material constraints. However, it is advised to check whether this is available for grass revetment reinforcement measure type 2[26].



(a) Interpretation case study for $H_s = 1.0$ m and $d_i = 0.30$ m. (b) Influence effectiveness, example for WDOD.

Figure 10.11: Visualization effectiveness for case A.

Influencing effectiveness: *Rivierenland*

The failure probability of the *Rivierenland* scenario is close to the optimistic scenario (difference in failure probability of 0.02). Furthermore, there is approximately 11 (4+7) hours left for the *Rivierenland* case. This means that the total potential capacity is 1650 meter (see Equation 10.5). In combination with the 500 meter length of this case does this result in 2150 meter. This length is more than the length of available reinforcement measure (l_m) for this water board. The resulting capacity is therefore limited by the material availability for the *Rivierenland* water board in the case of known weak spots see 10.6

$$C_p = R \cdot T_a = 150 \cdot 11 = 1650 \tag{10.5}$$

$$C = \min(l_m, C_p) = \min(1500, 2150) = 1500 \tag{10.6}$$

General influence

Regular maintenance can decrease the failure probability of the flood defence without reinforcement measure $p_{f|no-measure}$. The chance of having a weak spot decreases. However, this cannot always be achieved as grass needs (much) time to recover from damages.

[26]The geotextile availability will not be the limiting factor, the weights to roll down the geotextile down the slope will probably be critical.

10.4. Case B: unknown weak spot

10.4.1. Relevance scenario

Case B considers the situation in which the location and characteristics of the weak spot are unknown. There are various reasons for a grass revetment in bad conditions:

- there is a time gap (months) between regular dike inspections[27] and the high water wave, which means that the failure probability is uncertain in between the inspections (Nicolai, 2018);
- there are damage types that are correlated with high water.
  - damage by animals is probably correlated with increased water levels, as rats, moles and mouses are driven out of their holes by the rising water, they seek higher grounds: the dike (Freriks, 2018);
  - ship collision is at many locations along the river only possible during high water, see Chapter 3.2.

10.4.2. Characteristics case B

The location, characteristics and severity of the weak spot are unknown in advance in case B. Inspection (by volunteers) during high water is needed to find the damaged areas. The reliability of reinforcement measures is in case B, amongst others, influenced by time pressure, an overload of information for the decision makers, incorrect prioritization and placement of multiple reinforcement measures at the same time. These factors are implemented in the reliability model by means of Performance Shaping Factors and distributions for the required time.

The failure probability for the detection and placement phase are based on the methods that are developed in Chapter 7 and 8. The model choices can be found in Appendix H.2, failure probabilities are presented in Table 10.7. The failure probability p_m is calculated based on Equation 1.1.

Table 10.7: Case B: failure probabilities

	Failure probability			
	Detection (p_d)	Placement (p_p)	Technical (p_t)	**Combined (p_m)**
Optimistic	0.03	0.01	0.001	**0.04**
Rivierenland	0.10	0.04	0.001	**0.14**
Drents Overijsselse Delta	0.14	0.28	0.001	**0.38**
Pessimistic	0.42	0.40	0.001	**0.65**

This case considers a weak spot with a **total length of 200 meters**. The construction time is a function of the number of teams and the construction rate per team. The values for the different scenarios can be found in Table 10.8. The motivation of these values can be found in Appendix H.2.

Table 10.8: Potential capacity, construction rate and time needed for installation reinforcement measure. C_p = Potential capacity; n_t = Number of teams; R_t = Construction rate per team; R = Total construction rate; $T_{construction}$ = Construction time.

Performance	**C_p [m]**	**n_t [-]**	**R_t [m/h]**	**R [m/h]**	**$T_{construction}$ [h]**
Optimistic	200	5	40	200	1
Rivierenland	200	4	30	120	1,7
Drents Overijsselse Delta	200	3	10	30	6.7
Pessimistic	200	2	5	10	20

The construction time is only one part of the total time required for the installation of the reinforcement measure. The required time is modelled by a Gaussian distribution. The action chain starts at $T = -12$ hour. The required time is modelled with respect to the start of the storm, a time shift of 12 hours is therefore implemented. The resulting time distributions can be found in Table 10.9, this table is based on Appendix H.2.3.

Table 10.9: Average and standard deviation required time for placement grass revetment reinforcement. Scaled with respect to start storm. Start action chain at T=-12 hour, start storm at T=0 hour.

	Optimistic	Rivierenland	WDOD	Pessimistic
Average [hour]	9.5	17.3	24.8	52.2
Average scaled with start storm [hour]	**-2.5**	**5.3**	**12.8**	**40.2**
Standard deviation [hour]	**1.0**	**1.3**	**1.7**	**4.1**

[27] The inspection interval differs per water board. The *Rivierenland* water board once per year, *Drents Overijsselse Delta* twice per year.

10.4.3. Results

Many parameters are stochastically implemented in the model, however grass revetment quality and initial damage can still be varied. The fragility curve, with and without reinforcement measure for the four options (Optimistic, *Rivierenland*, *Drents Overijsselse Delta* and pessimistic performance) is shown for:

- open sod quality and initial damage depth of 10 centimetre in Figure 10.12;
- an initial damage depth of 30 centimetre, see Figure 10.13.

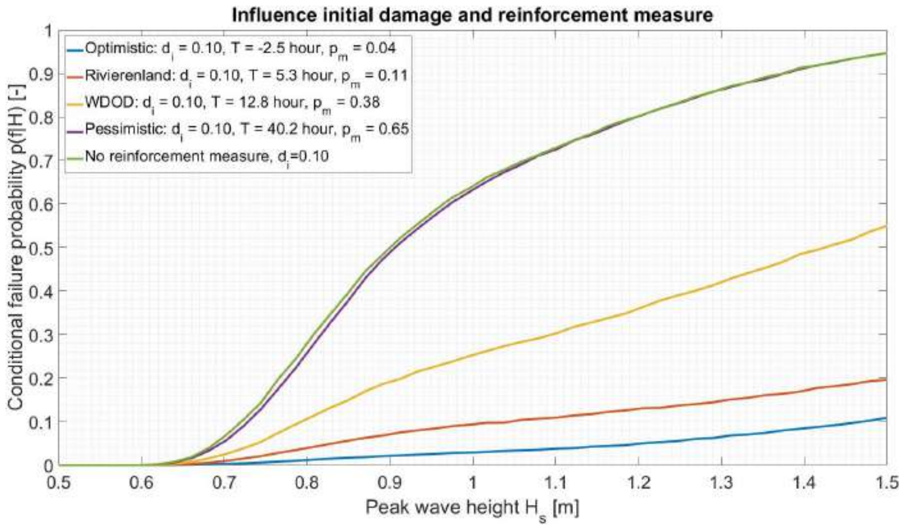


Figure 10.12: Fragility curve: effect of reinforcement measure for unknown weak spot: open sod quality and 10 cm initial damage.

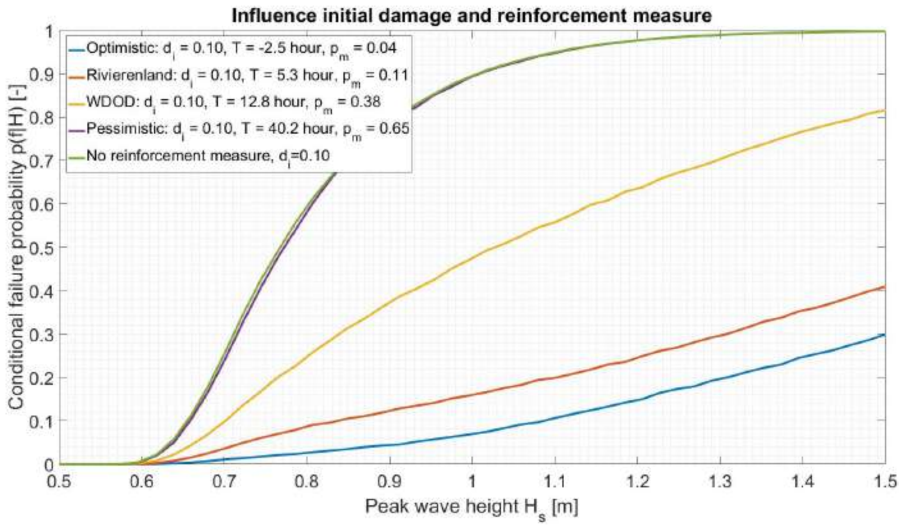


Figure 10.13: Fragility curve: effect of grass revetment reinforcement measure for unknown weak spot with 30 cm initial damage.

The resulting effectiveness is a function of the initial damage depth and grass revetment quality of which two cases are given above. The failure probability reduction has been quantified for a varying H_s (0.8, 1.0, 1.2 and 1.4 meter) and a varying damage depth d_i (0.00, 0.10, 0.20, 0.30 and 0.40 meter). The effect in terms of failure probability reduction due to the implementation of grass revetment reinforcement measures can be seen in Table 10.6. An average value for the reduction and the minimum and maximum value are given.

Table 10.10: [**Without length effect**]Reduction factor initial failure probability for varying d_i 0-0.40 [m] and varying peak significant wave height H_s 0.8-1.4 [m]

	Min	Average	Max
Optimistic	1.8	13.6	24.7
Rivierenland	1.5	5.3	7.3
WDOD	1.1	2.0	2.6
Pessimistic	1.0	1.0	1.2

10.4.4. Length effect

The first source in length effect is the time required for installation. The longer the reinforcement measure, the more time needed for installation. The probability of failure of the measure increases. This effect is implemented in the model. In the *conclusions case B* section is elaborated on what the effect is of longer measures than assessed in this case study (> 200 meter). For the known weak spot case is assumed that the failure probability of the flood defence does not increase when the total number of measures increases. This assumption is not applicable to the unknown weak spot case because:

- The detection reliability is a large contributor to the failure probability of the measure p_m. Detection of multiple smaller weak spots at different locations of the flood defence are independent from each other for this failure mechanism.
- An assessment of whether or not to install a reinforcement measure and the command to install a measure is given independently for each distinct weak spot.
- Multiple placement teams are needed, they work independent.

It is assumed that the weak spots are independent. This is a conservative assumption assumption since some correlation is realistic as the same level of preparation and knowledge level holds for each distinct weak spot. Independence is therefore the lower bound[28]. Assuming independence between the weak spots implies that the failure probability of the flood defence with n weak spots, without taking the reinforcement measures into account, is a function of the failure probability of the individual dike segments, see Equation 10.7.

$$p_{flooding} = 1 - (1 - p_{f|no-measure})^n \tag{10.7}$$

Due to the application of the reinforcement measures can te failure probability of each distinct weak spot be decreased. The failure probability per dike segment is now not $p_{f|no-measure}$ but $p_{f|H}$[29], see Equation 10.8.

$$p_{flooding} = 1 - (1 - p_{f|H})^n \tag{10.8}$$

The average reduction factors in failure probability can be found in Table 10.10. For the optimistic scenario is a reduction factor of the failure probability of a dike segment found of 14. This means that per dike segment $p_{f|H}$ is 14 times lower than $p_{f|no-measure}$. The effect on the flooding probability when the weak spots are larger in number is visualized in Figure 10.14. At n=1 the effectiveness is equal to the table. However, this effectiveness rapidly decreases for increasing number of weak spots. The total length of the weak spots is the same (200 meter), however when there are for example 10 weak spots which are each 20 meter in length is the effectiveness (reduction factor failure probability):

- Optimistic scenario: 3.3
- Rivierenland: 1.5
- Drents Overijsselse Delta: 1.1
- Pessimistic: 1.0

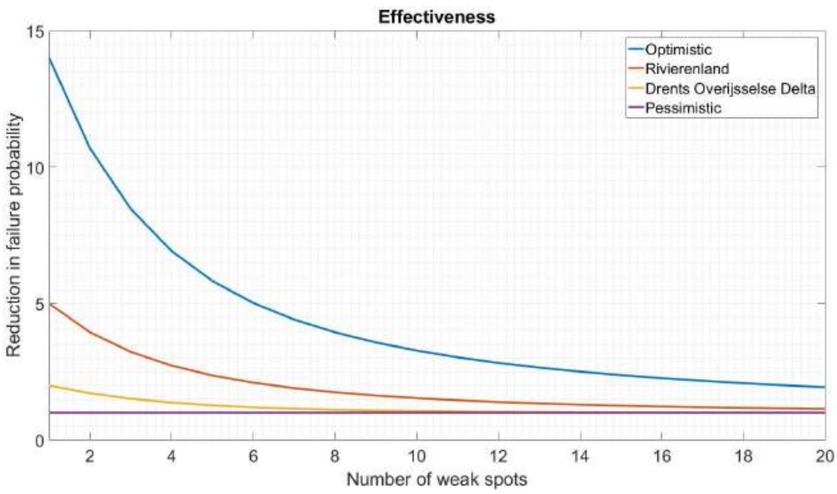


Figure 10.14: Length effect. Effect of multiple weak spots on the effectiveness of the measures.

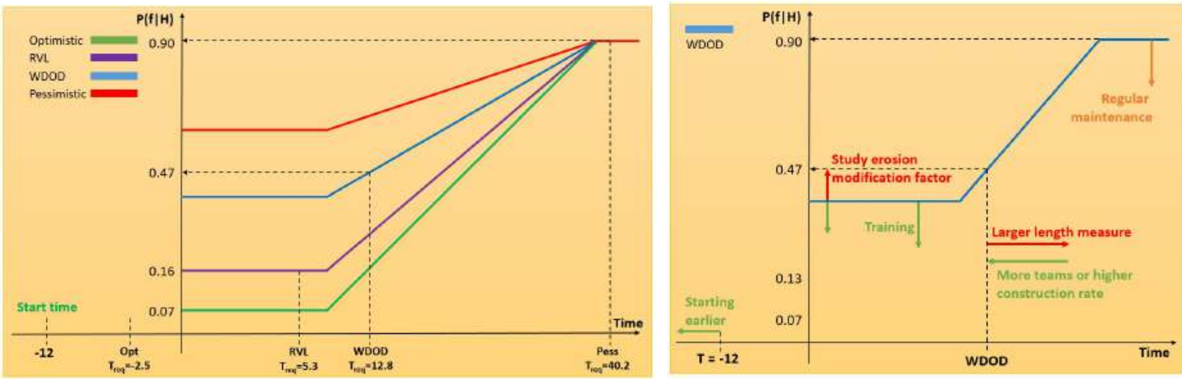
[28] Dependence would be the upper bound, than the failure probability would be equal to the maximum failure probability of all the weak spots.

[29] The failure probability taking into account the measure, see Equation 1.2: $p_{f|H} = p_m \cdot p_{f|no-measure} + (1 - p_m) \cdot p_{f|measure}$

10.4.5. Conclusions case B

The effectiveness of the reinforcement method is visualized according to the method presented in Section 10.1.2. Figure 10.15a shows the effectiveness of the reinforcement measures for case B. This graph is made for a peak significant wave height of the storm of 1.0 meter and an initial damage depth of 0.30 meter. The same graph can be made for other combinations of grass and clay quality, initial damage and hydraulic conditions. The failure probability in the first horizontal part of Figure 10.15a is determined by the failure probability of the reinforcement measure (p_m) and the effect of the measure on the erosion speed (α_{geo}). Right of the first horizontal part is the failure probability also determined by the time needed to install the measure. The measure does not have any effect on the dike safety when T is so large that it enters the second horizontal part of the graph. The following can be observed in the graph:

- **Optimistic scenario and *Rivierenland***
  For the optimistic scenario and the *Rivierenland* water board is the failure probability of the flood defence ($p_{f|H}$) determined by the failure probability of the measure (p_m) and the effect of the measure (α_{geo}). Both scenarios are in the first horizontal part of the graph.
- ***Drents Overijsselse Delta***
  For the *Drents Overijsselse Delta* water board is the failure probability of the flood defence determined by the failure probability of the measure ($p_m = 0.38$) and the time needed to install the measure. This can be seen in the graph because the time needed to install the measure is longer than the first horizontal part of the graph. This time delay results in a failure probability of the flood defence of 0.47.
- **Pessimistic scenario**
  The pessimistic scenario does not have any influence on the failure probability of the flood defence because the time needed to install the reinforcement measure is large (second horizontal part of the graph).



(a) Interpretation case study for $H_s = 1.0$ m and $d_i = 0.30$ m.

(b) Influence effectiveness, example for WDOD.

Figure 10.15: Visualization effectiveness case B.

Influencing effectiveness: *Drents Overijsselse Delta*

How to influence the failure probability of the reinforcement measure is visualized in Figure 10.15b for the *Drents Overijsselse Delta* water board. The *Drents Overijsselse Delta* water board case is in the transition between the two horizontal parts. Therefore can the effectiveness be increased by a combination of reducing the required time (T_{req}), the failure probability of the measure (p_m) and decreasing the uncertainty of the erosion modification factor (α_{geo}).

1. Reduction p_m (WDOD)

The failure probability of the measure p_m is 0.38. All the parts contributing to the failure probability can be found in Appendix H.2.1 and H.2.2. The failure probability can be reduced by:

- increasing the knowledge level of the dike inspectors;
- use damage registration forms;
- standardize and train the procedures at the decision centre (ACW);
- train the placement of grass revetment reinforcement measure type 2;
- prepare the logistics of the reinforcement measures.

The failure probability can be reduced to approximately 0.04, see the optimistic scenario. However, keep in mind that this optimistic scenario is based on large efforts in the crisis organization and that this lower bound is therefore not reached easily.

2. Reduction T_{req} (WDOD)
The total time needed for the installation of the reinforcement measure is approximately 25 hours, 13 hours with respect to the start of the storm (see Table 10.9) for the *Drents Overijsselse Delta* water board. This should be five hours quicker, to arrive in the first horizontal part of the graph, see Figure H.7. For now we only look at the construction time, despite the fact that reductions in the time needed can also be found in the other parts of the action chain. This five hour reduction is reached when the construction rate is equal to 120 m/h. This can be achieved by:

- Quadruple the number of teams. This is however not realistic, as the failure probability will probably increase because 12 teams are then working at the same time. The dike supervisors will not be able to inspect those teams.
- Increase the construction rate per team. This can be achieved by preparation of the materials and training. This would require a construction rate per team (R_t) of 30 m/hour in the case of three teams.
- A combination of the above two options is also possible, where the number of teams and construction rate per team is increased.

Please notice that preparation of the materials will reduce the loading time and thereby require a lower construction rate.

Influencing effectiveness: *Rivierenland*
The *Rivierenland* water board can increase the effectiveness by reducing the failure probability of the measure. The measure is in this case (200 meter) installed before the end of the first horizontal part. There is 1.7 hour left before the failure probability increases. The additional potential capacity is therefore 200 meter, according to Equation 10.9. This potential capacity is equal to the actual capacity (C) because the total length of available reinforcement measure is lower than the length to be installed (200 meter and additional 200 meter), see Equation 10.10.

$$C_p = R \cdot T_a = 120 \cdot 1.7 \approx 200 \tag{10.9}$$

$$C = \min(l_m, C_p) = \min(1500, 200 + 200) = 400 \tag{10.10}$$

10.5. Sensitivity analysis
This section gives insight into the sensitivity of the uncertainty parameters of the reinforcement measure: the required time for installation (T_{req}), the capacity and the erosion modification factor α_{geo}. The strength parameters of the grass revetment and the load parameters do influence the result, however these parameters are part of Chapter 3 (reliability grass revetment).

10.5.1. Time dependency
The required time to install the reinforcement measure is estimated based on the different parts of the action chain of detection and placement. Figure 10.16 shows the influence of the time needed to install the reinforcement measure on the effectiveness of the measure. The figure shows the conditional failure probability given constant initial damage for various peak significant wave heights. The graph shows the same trend as the visualization of the effectiveness in Figure 10.3. However, the two horizontal parts are not connected by a linear line, a stepwise character can be observed. The steps are the result of the discrete stochastic distribution of the storm shape and the condition that the measure cannot be installed during and two hours before and after the storm peak. The storm is schematized in three possible realisations. The steps are exactly at the peak of those storm schematizations. The same graph is determined for case B which shows a similar trend, see Section H.3.1.

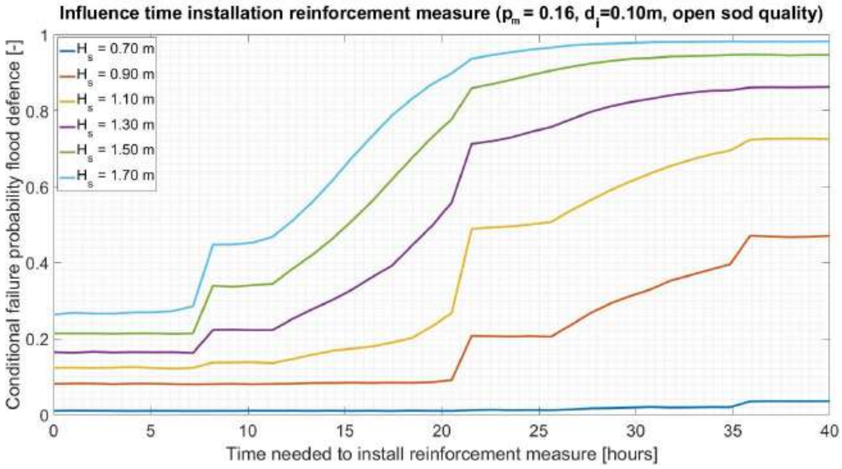


Figure 10.16: Case A: Conditional failure probability for different values of installation time reinforcement measure.

10.5.2. Capacity

The length of reinforcement measure that can be installed is influenced by the construction rate. The construction rate is a design choice in the crisis organization. The capacity can be modified by:

- increasing the construction rate per team (R_t) by training;
- increasing the number of team (n_{teams}) that are deployed during high water;
- having sufficient material in stock or available at the contractors, the total capacity is bound by the length of reinforcement measure (l_m) that is available;
- starting earlier with the installation of reinforcement measures, hence increase in available time (T_a).

The construction chain is assumed to start at $T = -12$ hour. This leads to an available time value of order 14 hours for case A, taking into account a start-up time[30] of a couple of hours. This available time is much smaller for case B in which the weak spot has to be found. It can be seen in Figure 10.16 that the failure probability of the grass revetment is unaltered until $T \approx 7.5$ hours (with respect to the start of the storm).

The construction rates that are needed given a certain length of grass revetment that needs to be reinforced can be seen in the Figure 10.17. Recall that the construction rate is the product of the number of placement teams and their respective construction rates.

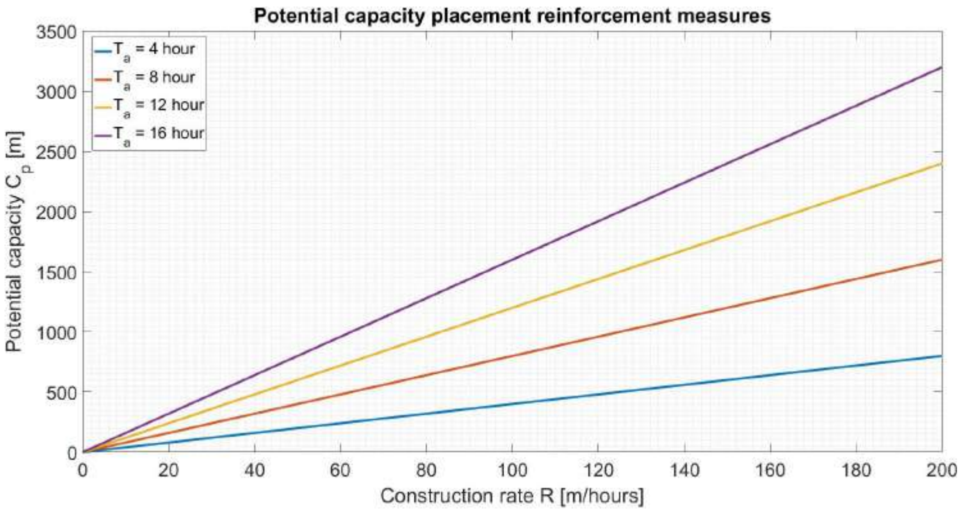


Figure 10.17: Potential placement capacity grass revetment reinforcement measure as function of available time and construction rate.

It is advised to determine the construction rate for the teams during exercises, but taking into account that the production rate is probably smaller during critical events because of bad working conditions. Furthermore

[30] Placement decision, placement command and loading.

is fatigue of importance. This is included in the model by taking more pessimistic construction rates into account in the cases.

10.5.3. Erosion modification factor

The theoretical approach of the erosion modification factor is explained in Chapter 4, a sensitivity analysis of this factor without taking the uncertainty of the placement itself into account can be found in Appendix B.2. The effect of this parameter on the combined reliability assessment of the reinforcement measures is studied in this section.

The contribution of the erosion modification factor to the uncertainty for one specific parameter set is studied. The *Drents Overijsselse Delta* scenario of case B is taken as starting point. The failure probability of the measure (p_m) is equal to 0.38, the time needed for installation is equal to 12.8 hours. The effect is visualized for varying initial damage depths (d_i: 0.00, 0.10, 0.20, 0.30 and 0.0 meter) in Section H.3.2. The graph for case with an initial damage depth of 0.30 meter is given in Figure 10.18. This initial damage depth is chosen because this depth is also used in Figure 10.15.

From the graphs in the appendix can be concluded that::

- The difference in conditional failure probability of the flood defence due to a changing value of α_{geo} is visible in the graph when $p_{f|H} > 0.20$. This value changes for different boundary conditions.
- The effect increases after $p_{f|H} > 0.20$ with increasing significant wave height.
- Initial damage reduces the wave height at which the effect becomes visible, because the conditional failure probability increases with increasing initial damage.
- The effect of the erosion modification factor is negligible for wave heights (H_s) up to 1.0 meter and initial damage of 10 cm. This holds for the studied values of α_{geo}: 0, 0.1 and 0.2.
- The effect is not negligible for larger wave heights or initial damage or modification factors larger than 0.20 (maximum studied value).

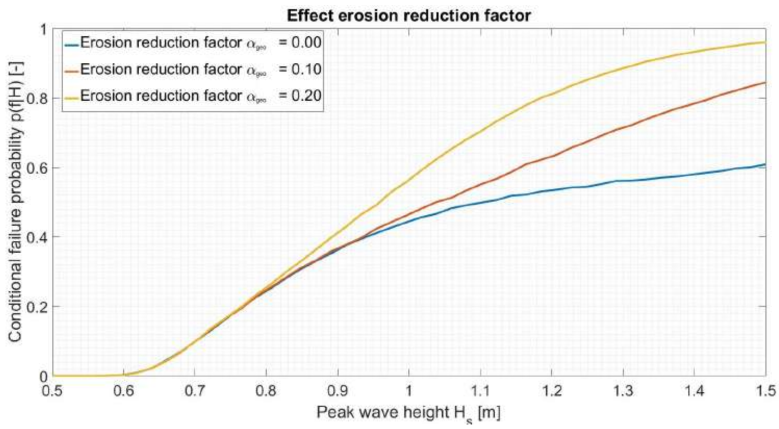


Figure 10.18: Influence erosion modification factor for case B, WDOD ($p_m = 0.38$, $T_{req} = 12.8$ and $d_i = 0.30$).

The effect of the erosion modification factor is given in Table 10.11 for case B with the parameters of the *Drents Overijsselse Delta* water board. A peak significant wave height of the storm $H_s = 1.0$ m and initial damage of $d_i = 0.30$ cm is taken into account.

- The conditional failure probability of the flood defence is 0.47 for the erosion modification factor with a lognormal distribution (mean of 0.10).
- The conditional failure probabilities for three deterministic values of α_{geo} are given in the table. The 0.10 factor does not exactly match the case study result due to the difference in deterministic and stochastic approach.

For this set of parameters is the difference 0.02 between the first two factors, however an increasing factor does have a non-negligible influence on the results as can be seen for $\alpha_{geo} = 0.20$.

Table 10.11: Influence erosion modification factor on case B: WDOD

α_{geo}	$p_{f\|H_s=1.0}$
0.00	0.44
0.10	0.46
0.20	0.56

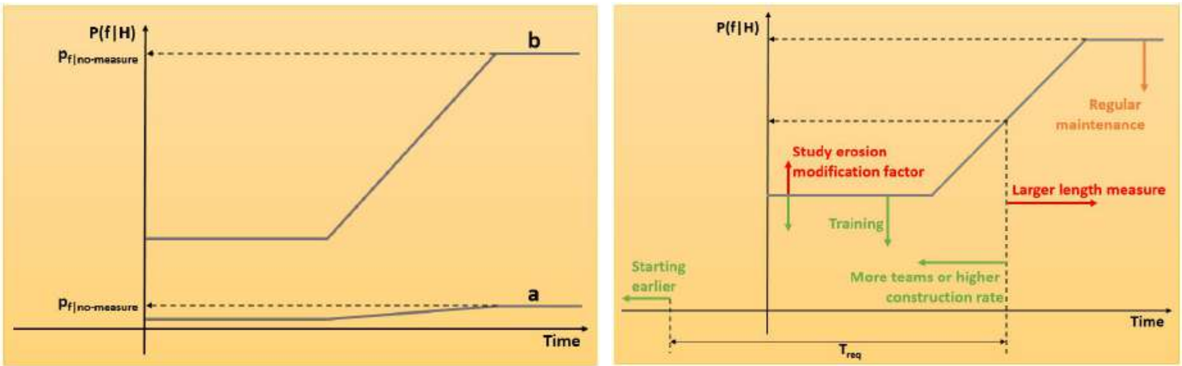
What this sensitivity analysis shows is that the erosion modification factor can have non-negligible influence for high wave heights, larger initial damage depths and high values of the modification factor. Research into this parameter decreases the uncertainty around this parameter.

10.6. Conclusions

The case specific conclusions can be found in Section 10.3.5 for case A and in Section 10.4.5 for case B. General conclusions regarding the two cases are given in this section.

10.6.1. Necessity measures

The cases are based on weak spots with a relatively high initial failure probability ($p_{f|no-measure}$). These weak spots have the potential for a large failure probability reduction. Chapter 3 shows that the resistance of a good quality grass revetment is high and thereby the $p_{f|no-measure}$ low. Figure 10.19a shows two examples of the time dependency for reinforcement measures. Option *a* in the graph represents a lower value for $p_{f|no-measure}$ compared to *b*. The necessity for a reinforcement measure is much higher for option *b* compared to *a*. The figure shows that less urgent locations show the same behaviour over time, however the reduction in failure probability is less.



(a) Necessity reinforcement measure. (b) Influencing effectiveness.

Figure 10.19: Conclusions effectiveness calculation.

10.6.2. Influencing effectiveness

The means to influence the effectiveness is elaborated on in the respective case study conclusions. The influencing parameters are visualized in Figure 10.19b. This graph is valid for both case A (known weak spot) and case B (unknown weak spot). The difference is that the failure probability of the measure (p_m) will be lower for case A (no detection, limited amount of reports of weak spots and less time pressure) compared to case B. Furthermore is the time required (T_{req}) for case A lower (no detection and prioritization time). So in general will the first horizontal part of the figure be lower and the T_{req} shorter for known weak spots. The most effective place in the graph is the bottom left corner. This means a low value of p_m and T_{req}.

11
Discussion

The research results and their implication are discussed in this chapter. The first section concentrates on the interpretations of the results. The seconds section expands on how this research can be used in the broader context of the crisis organization.

11.1. Interpretation of the results

11.1.1. Conservatism in erosion modelling

Uncertain parameters are preferably dealt with stochastically in the calculation of the failure probability. However, three conservative assumptions are made in modelling of the erosion:

1. **Failure definition**
   Failure is defined as erosion of the top 50 centimetre of the revetment. This 50 centimetre consists of a grass layer of 20 cm and a clay sub layer of 30 cm, according to the WBI-2017 schematization (Klein Breteler, 2015). This failure definition is used to compare equal erosion depths and to have no discrepancy between the results. This assumption is conservative when the dike core is made of clay, however probably accurate when the dike core consists of sand. No erosion strength is assigned to a sand core (Steenbergen et al., 2007). On the other hand, the failure probability will be higher when no clay sub layer exist. The calculation procedure as presented in this thesis can be extended by increasing the thickness of the clay layer, when applicable, or incorporating erosion models for the dike core in the limit state function.
2. **Wave impact constantly perpendicular to dike body**
   The waves are assumed to hit the dike constantly perpendicular. This results in the largest erosion rates. Oblique wave attack can be accounted for with a reduction factor in a more detailed assessment. This location specific effect is neglected in this thesis, but can be included in a detailed assessment.
3. **Wave impact constantly at the same level of the dike**
   The water level is not constant during the storm. The water level is taken constant for 12 hours in Hydra-NL (Duits and Kuijper, 2017). The storm duration is in the erosion calculation modelled as 21, 48 or 77 hours, according to Geerse (2006). The water level does certainly change over the course of this time. However, for example a peak significant wave height of 1 meter means that it is already half of the time below 0.5 meter[31]: this is the threshold for erosion of the clay sub layer. Furthermore, the largest wave heights (around) the peak are causing most of the cumulative erosion. Therefore is it justifiable to take the erosion constantly at the same height for this failure mechanism.

Taking the above mentioned effects into account can reduce the probability of failure of the flood defence. Especially the first and second effect can have a large influence on the failure probability, when applicable to the specific dike segment. Taking the effects into account can be used in a more accurate, risk based, analysis of the need for reinforcement measures. The effects are site specific and therefore not included in this thesis, because the goal is to determine the effectiveness of the measures in general.

[31] Linear increase and decrease from zero to peak and vice versa.

11.1.2. *OPSCHEP* model versus field observations

The application of reinforcement measures during critical condition is largely influenced by the performance of human action. Reinforcement measures are probably only needed during extreme water levels, those water levels seldom occur in the Netherlands. No data is available on the performance of humans during those events. Limited data is available of high water exercises, however these practice events are not completely representative for real critical conditions. These events show an order of magnitude of the failure probabilities.

Human Reliability Models exist to deal with the above described problem. These models are deduced from the nuclear industry. The *OPSCHEP* model is used in this research to quantify the Human Reliability. This model is modified in this thesis to make it applicable to the field of temporary reinforcement measures. This is the first time that this model is used in this domain, to the best of the author's knowledge. A base error rate is increased or decreased based on the specific circumstances (by Performance Shaping Factors). The base error rate is a critical factor, because even if those Performance Shaping Factors were certain, the outcome is predominantly determined by the base failure probability. The base error rate is in this research determined based on the *OPSCHEP* model and taking into account that the resulting failure probability should be in the range of failure probabilities as observed during exercises and reference literature. Checking afterwards whether field observations and the *OPSCHEP* model are in correspondence is therefore not possible since they are used in the calibration of the failure probability.

The Performance Shaping Factors make the model flexible. Conditions relevant for the specific cases can be taken into account in the failure probability calculation. The most important parameters are determined based on expert judgement from the experts in the field. Those factors are included in calculation of the failure probability. This flexibility is also the the main weakness of the method, in the end it comes down to expert judgement.

Whatever method is used for the failure probability calculation, assumptions are inevitable due to the lacking data. Although the exact value of the failure probability might be open for discussion, it does provide insight into the relevant factors for the reliability assessment and how to increase the reliability.

11.1.3. Reinforcement measure type

Water boards often train the placement of grass revetment reinforcement measure type 1 (see Appendix B), which can only be installed above the water line. The installation of the type 2 measure taken as starting point in this research because the only relevant condition for the application of the reinforcement measure is when the significant wave height is larger than 0.5 meter. Those waves can only hit the grass revetment when there is water on the flood planes. The installation of reinforcement measure type 1 means that it has to be installed even before the high water wave, however storms cannot be foreseen long in advance. Thus the likelihood of successful application of the reinforcement measure will be much higher for the type 1 method, because installation is easier and more time is available. However, this work method is highly conservative, because the reinforcement measures are then to be installed in the wake of (each) high water wave without knowing whether the reinforcement is actually necessary (presence of waves).

11.1.4. Alternative dike configurations

It is assumed in this research that the revetment sub layer consists of clay. This is most often the case for the Dutch dikes, however there are situations with a sandy sub layer[32]. The theoretical strength of those grass revetments is zero when the grass revetment is of bad quality[33]. This research cannot be applied directly to those cases. The assumption that water flow does not damage the sub layer and that waves with a significant wave height less than 0.5 meter result in no erosion has to be checked for those cases. Furthermore, the technical failure probability is uncertain for geotextiles placed on sandy subsoil, see Chapter 9. In summary: the results of the effectiveness calculation are not valid for geotextiles placed on sandy subsoils, the framework and procedures deduced in this thesis are applicable to other dike configurations, however one has to check the erosion relations and the technical failure probability.

[32] For example the Overijsselse *Vecht* dikes

[33] For example WBI-2017 *fragmented sod* quality or initial damage.

11.1.5. Optimal grass revetment reinforcement structure

There are differences in design of the grass revetment reinforcement measure between the various water boards. The most optimal grass revetment reinforcement structure, applied during critical conditions, is defined in the text box below.

Optimal grass revetment reinforcement measure
An optimal grass revetment reinforcement measure is the one that requires a short duration to install, is easy to place, is strong enough to prevent failure of the measure itself and stops erosion of the grass revetment.

Please notice that the components of the definition are important, but the optimal structure does not exist:

- "strong enough to prevent failure" implies a technical failure probability (p_t) of zero;
- "stops erosion" implies an erosion modification factor (α_{geo}) of zero.

A *short duration to install* means that the likelihood of placement in time increases and that the total length of measures that can be placed is larger. *Easy to place* implies that the placement failure probability is low and less exercises are needed. *Strong enough to prevent failure of the measure* means that the technical failure probability is low. More reliable than 1/1000 is too conservative because the placement and detection failure probability are in an optimistic scenario in the order 1/100. *Stops erosion* describes the effect of the measure. A modification of the design that reduces the technical failure probability (p_t) from 1/100 to 1/1000 at the cost of a far more difficult to install structure does probably not comply to the definition. The placement failure probability and time needed to install will increase.

11.2. Research in broader context

11.2.1. Risk based approach crisis organization

A framework is developed to quantify the contribution of grass revetment reinforcement measures to the reduction in probability against flooding. The three main uncertain parameters are the reinforcement measure failure probability (p_m), the required placement time (T_{req}) and the erosion modification factor of a geotextile measure (α_{geo}). Those factors are implemented in reliability models of the flood defence to:

- quantify the effect of the measures in terms of failure probability reduction;
- to provide insight into the means to influence the effectiveness of the measures, see Figure 11.1.

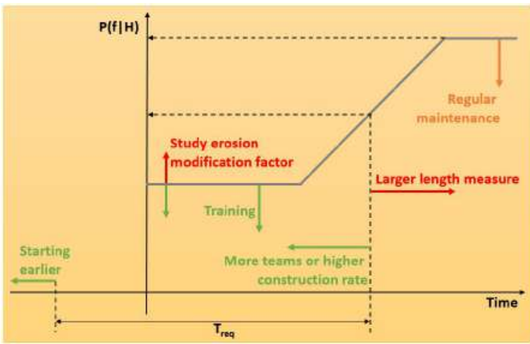


Figure 11.1: Influencing effectiveness of reinforcement measure.

The main goal of the crisis organization is currently often formulated as: *the goal is to prevent or limit harmful consequences* (Rivierenland, 2013). The goal is not made explicit or formulated in terms of desired risk reduction or aim for reduction in the probability against flooding[34]. This observation is supported by the internal evaluation of the *Deining en Doorbraak* exercise of the *Drents Overijsselse Delta* water board, which states that the capacity given certain crisis scenarios is not made explicit (Drents Overijsselse Delta, 2017a).

But why would making the goal of the crisis organization explicit, or a risk based approach on Macro level (see Section 1.3.1) be beneficial?

- The main goal can be made explicit in terms of number or lengths of reinforcement measures that the organization should be able to place during extreme events.

[34] See for examples: exercise goals *Deining en Doorbraak*, Section 5.1.1 and decision not to install reinforcement measures, Section 5.2.4

- This goal can be tested, when made explicit, during high water exercises and by theoretical analysis.
- An explicit goal in combination with an analysis of the effectiveness, as in this study, provides insight into the relevant factors that influences the failure probability. The critical parts can then be distinguished and optimized. The investments in the crisis organization can then be executed more efficient.
- A risk based approach is needed when the measures are implemented in layer one of the multi-layer safety approach, as control measure.

The main difficult part in a risk based approach is that it is unknown how many weak spots will emerge (e.g. sand boils and damages to the grass revetment) during an extreme event. However, this assumption is currently also made, implicitly, by the amount of material in stock, level of training and preparedness. So, basically is the suggested approach one step further compared to the current practice.

11.2.2. Framework applied to other failure mechanisms

This research assesses the effectiveness of one measure: to prevent erosion failure of the outer slope. It is outlined above that this research can be used in a risk based approach of the crisis organization. In this section is explained how the methods, as developed in this thesis, can be applied to other failure mechanisms.

- **Different limit state functions**
  Each failure mechanism has a distinct limit state function, describing the likelihood of failure given the strength and load parameters. This limit state function will be different per failure mechanism.
- **Hydraulic load**
  The relevant hydraulic load is distinctive for each failure mechanism. Piping, macro stability and overflow are governed by extreme water levels, in contrast to erosion of the outer slope, which is governed by waves. This influences the available time to install the reinforcement measures positively, since water levels can be predicted further in advance due to the nature of the systems. On the other hand is the scale of the measures probably larger, piping and overtopping can be a problem along all the river dikes, whereas wave impact can only occur in the direction of the wind and at locations with sufficient water depth and fetch. The water level is governed by the river discharge and the waves by strong wind.
- **Time dependency**
  An important starting point in this research is the time dependency. Erosion evolves over time and can be influenced as long as the revetment has not failed. The more time needed to install the measure the higher the failure probability of the flood defence, see option A in Figure 11.2. Piping and macro stability are potential failure mechanisms with the same behaviour. However, this procedure cannot be applied to overtopping or overflow. The measure does not have any effect as soon as the critical level is exceeded. This phenomenon results in a vertical line combining the two horizontal parts of the time-dependency-figure, see option B in Figure 11.2. The start of overtopping or overflow does not lead to instantaneous failure of the flood defence, however it is assumed that reinforcement measures cannot be installed during overflow or overtopping conditions.

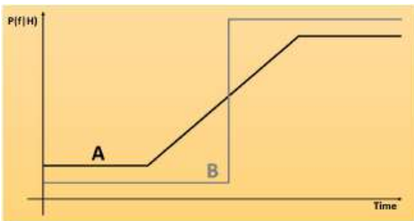


Figure 11.2: Time dependency reinforcement measure.

- **Detection failure probability**
  The detection failure probability and time until successful detection is different per type of weak spot, this is explained in Chapter 7. A sand boil in a soggy hinterland is for example more difficult to observe than damage to the inner slope.
- **Placement failure probability**
  The length effect of the placement failure probability[35] is assumed to be negligible for the grass revetment reinforcement measures. However, this might not be the case for other types of measures.
- **Technical failure probability**
  The technical failure probability is for each type of measure different.

[35] Increasing failure probability of the measure (p_m) with increasing length of reinforcement measure.

12

Conclusion and recommendations

12.1. Conclusions

The goal is to determine to what extent grass revetment reinforcement measures contribute to the safety against flooding. The conclusions of the five sub questions are summarized first, after which the conclusion to the main research question is given.

12.1.1. Main findings sub questions

Question 1. What is the reliability of a grass revetment taking into account initial damage?
Wave impact is the main driving force for outer slope erosion. The threshold for erosion of the clay sub layer is waves with a significant wave height of 0.50 meter. The failure probability of a high quality grass revetment (WBI-2017 classification: closed sod) is high. The failure probability is approximately zero up to a significant wave height[36] of 0.75 meter and the failure probability is 0.08 for a significant wave height of 1 meter. This failure probability rapidly increases for lower quality grass revetments and when initial damage is present.

Question 2. What is the effect of reinforcement measures on the reliability of the grass revetment?
The effect of a correctly placed reinforcement measure is modelled by an erosion modification factor. This factor is assumed to be lognormal distributed with a mean value of 0.10. This factor means a 90% reduction in erosion speed. The presence of the measure does reduce the failure probability of the flood defence significantly. The reliability of a flood defence with initial damage up to 30 centimetre with correctly installed reinforcement measure is more reliable than an open sod grass revetment without measure (for modification factors α_{geo} up to 0.30). Please notice that this statement is valid for the case that the reinforcement measure is installed correctly at the start of the wave impact.

Question 3. What is the reliability of the detection of a weak spot?
The detection uncertainty is modelled based on a failure probability (not finding the weak spot) and the time required for detection. A failure probability per detection round is implemented in the model which takes into account that a weak spot can be found after multiple inspection rounds at the cost of time. The detection failure probability is dependent on numerous factors. The failure probability of detection ranges from 0.03 to 0.31 for outer slope damages, depending on the specific circumstances.

Question 4. What is the placement reliability of grass revetment reinforcement measures?
The placement uncertainty is also modelled based on a failure probability (no correct placement) and the time required for the placement of the measure. In the model is also implemented that a loading mistake will result in a delay rather than a contribution to the failure probability. The placement failure probability ranges from 0.01 to 0.40 depending on the specific circumstances.

Question 5. What is the technical reliability of grass revetment reinforcement measures?
It is assumed, based on the qualitative and quantitative considerations, that the technical failure probability of a correctly installed reinforcement measure is an order of magnitude lower compared to the detection and placement failure probability. The technical failure probability is estimated to be 10^{-3}.

[36]The storm shape and duration is schematized (stochastically), the wave height mentioned corresponds to the peak of the storm.

12.1.2. Conclusion main question

The main research question is: *what is the effectiveness and reliability of grass revetment reinforcement measures for river dikes?*

Wave impact

Grass revetment reinforcement measures can be applied at the outer or inner slope of the river dike. This research focusses on the outer slope measure. The measure can be applied to strengthen the grass revetment by increasing the erosion resistance. Wave impact is the driving force for outer slope erosion. A large fetch and high wind speeds are a necessity for waves to develop. In the riverine does this mean that a (moderate) high water is needed for this failure mechanism to become predominant. The prediction time for wind driven systems is shorter compared to water level dominated mechanisms, due to the nature of the systems. The implication is that the available time will be limited to install the reinforcement measures.

Known and unknown weak spots

Reinforcement measures can be applied at known and unknown weak spots. The measures for known weak spots are applied after reaching a certain threshold in predicted hydraulic conditions. The measure can be prepared for the site specific conditions. Unknown weak spots can be reinforced after detection during critical conditions. Those reinforcement measures cannot be prepared for site specific circumstances. The implication is that the failure probability of the reinforcement measure (p_m) is higher for unknown weak spots due to the contribution of the detection failure probability. The time required for placement (T_{req}) is also higher compared to the situation of a known weak spot, since detection is part of the action chain.

Grass revetment reinforcement measures for known weak spots are only potentially effective when the material, personnel and equipment are prepared and the construction rate is such that the measure can be installed in approximately 10 hours. The reliability is dominated by the placement failure probability and the effectiveness is bound by the placement capacity. The resulting effectiveness is dependent on the level of preparedness, exercises, material availability and time constraints. In the case study are average reduction values for the conditional failure probability of the flood defence found of 32 for an optimistic and 4 for a pessimistic scenario. Be aware that the pessimistic scenario still assumes a certain amount of preparation. Hence, the factor 4 in failure probability reduction is not reached without preparation.

The effectiveness for grass revetment reinforcement measures applied for unknown weak spots is less effective due to a larger value for the failure probability p_m and time required for installation T_{req}. The resulting effectiveness is dependent on, amongst others, the detection phase, prioritization, knowledge level and training. In the case study are average reduction values for the conditional failure probability of the flood defence found of 14 for an optimistic and 1.0 (no reduction) for a pessimistic scenario. However, these values of the effectiveness rapidly decrease when the number of weak spots increase. For example the factor 14 drops to 3.3, when assuming independence, if there are 10 weak spots (with the same total length of 200 meter).

Influencing the effectiveness of the measure

The effectiveness can firstly be increased by decreasing the failure probability of the measure (p_m). This failure probability will in general be higher for the unknown weak spots in contrast to the known weak spots, due to the additional detection uncertainty. Factors influencing this failure probability are amongst others: the knowledge level of inspectors, standardized procedures, logistic preparation and training of the placement. In the case study for the unknown weak spots are failure probabilities of the measure found of 0.65 for a pessimistic and 0.04 for an optimistic scenario. This shows that preparation largely determines the reliability of the measure and thereby the effectiveness. It also reveals a realistic upper bound of the reliability.

The second parameter influencing the effectiveness is the time required for installation T_{req}. This time is important since erosion of the outer slope is a time dependent failure mechanism. Measures can be successful when installed before the cumulative erosion exceeds the critical erosion depth. Up to a certain value of the required time does this duration not influence the effectiveness. This value depends on the hydraulic conditions and the strength of the revetment. Decreasing the time required does therefore not for each case contribute to a more effective measure. When the length of the measure to be installed is high, or the current construction rate is low does decreasing the time required contribute to an increase in effectiveness. In the case studies is found that decreasing the time results in an increased effectiveness for:

- the known weak spot (500 meter) for a pessimistic scenario;
- the unknown weak spot (200 meter) for the *Drents Overijsselse Delta* and pessimistic scenario.

12.2. Recommendations

12.2.1. Recommendations for water boards

Recommendation 1. Adopt a risk based approach

It is explained in the discussion (Section 11.2.1) why a risk based approach is beneficial in the design of the crisis organisation. The main reason is that it provides insight into the performance level of the crisis organization and the critical parts that need to be improved. It is advised to adopt a risk based approach, on macro level (see Section 1.3.1), in which the goal is formulated in terms of risk reduction and the means to reach this goal are made explicit. Figure 12.1 shows a possible path to implement the risk based approach.

Figure 12.1: Road to measurable quality crisis organization water boards.

1. Formulate main goal in terms of risk reduction

The first step is to formulate the main goal quantitatively in terms of risk reduction. This first step cannot be separated from step two and three. Step two and three concern the means to reach the goal and the feasibility of the measures during the extreme events:

- The main goal should be updated if the desired risk reduction is not feasible because the measures cannot be installed during these events (expected conditions).
- The measures that should be taken to reach the goal are not cost effective for each risk reduction goal.

The formulation of the main goal of the crisis organization is therefore determined in an iterative procedure based on, amongst others, cost-benefit considerations and feasibility.

2. Formulate expected conditions during extreme event.

Thinking of the expected conditions, based on experience from the past, expert judgement and experience abroad is important for the design of the crisis organisation. The expected conditions determine the feasibility of the measures, the detection and placement reliability and the number of measures to take. The number of weak spots that are expected determine the quantity of material in stock and the number of personnel that is needed. This is a difficult step, because no one can predict, with certainty, the number of sand boils and grass damages during an extreme event. However, formulating those expected conditions makes the choices in preparation quantifiable. The same consideration is currently also made, because every water board does have a certain amount of material in stock, thereby preparing for a certain number and length of weak spots.

3. Formulate quantitatively measures to achieve the goal

The measures that are necessary to achieve the desired risk reduction should be formulated, taking into account the expected conditions. The number and length of the different types of measures should be made explicit and a plan to install the measures should be made. The required reliability determines the effort to put into the exercises and preparation.

4. Identify needs and critical parts in action chain

The critical parts can be deduced, based on the reliability assessment of the crisis organization. In this step are the expected conditions vital, the needs and critical parts are determined by those extreme conditions.

5. Train crisis organization realistically

The formulated goal and plan should be trained during exercises. The water boards should mimic the expected conditions as realistic as possible during those exercises. It can be tested whether the desired risk reduction is achieved. Those exercises will then probably reveal critical parts that were not foreseen. The plan can then be updated based on those learning points. For each exercise should also be thought of how a real extreme event will differ from the training and what the implications are for the reliability of the organization. Please notice that realistic training does not mean that all high water exercises should be on full scale, this is too expensive. An example of a specific training is given in the box below.

Example 12.1 Prioritization exercise
Critical point: the workshop and high water exercise revealed that prioritization is a critical part.
Expected conditions during high water: the available time during high water threats will be limited and the *Conecto* and *Deining en Doorbraak* exercises show that the number of reports by dike watches far exceeds the number of actual weak spots. Furthermore, the workshop shows that prioritization by the water board supervisors is far from unambiguous.
Training: knowing and being aware of the above described expected conditions can form the input for a specific exercise on the prioritization. The specialists, who are responsible for the prioritization during the real high water threats, should be provided with many fictitious reports of weak spots for a representative period of time (influence fatigue). The specialists need to make a prioritization and the placement decisions, knowing the actual placement capacity of the water board.

A first step in this suggested approach (step 1 to 5) is available at the *Drents Overijsselse Delta* water board (INFRAM, 2012). The need for reinforcement measures is studied based on the "derde toetsronde". In this study are the costs, the types of measures and the need in terms of equipment, personnel and material researched.

The last concluding remark is that there exist not one size fits all for the water boards. The types of threat and thereby the types of measures are different. The recommended procedure, as explained above, should be made for each water board specifically.

Recommendation 2. Study the application of biologically degradable grass reinforcement measures
Grass revetment reinforcement measures are currently not installed long before a (potential) high water wave because that would imply that the geotextile is on the grass for a long period of time. This would make the grass revetment deteriorate even further. From a reliability perspective would a measure installed before the critical event be the preferred solution, option A of Figure 1.4. The *Drents Overijsselse Delta* water board is currently testing biodegradable reinforcement measures and reinforcement measures that do not damage the revetment (Evers, 2018). Those measures have the potential of being more effective than the measures installed during high water. It is recommended to study the performance of these measures as reinforcement measure.

12.2.2. Recommendations for further research

Recommendation 3. Apply effectiveness framework to other types of measures
A framework is developed in this thesis to assess the reliability and effectiveness of temporary reinforcement measures. It is outlined, in the discussion (Section 11.2.2), how other failure mechanisms and respective temporary reinforcement measures differ from the one researched in this thesis. It is recommended to apply this framework to other measures. A comparable geotextile reinforcement measure can be applied to the inner slope to prevent sliding or erosion of the outer slope. The inner slope is subjected to overflow or overtopping.

Recommendation 4. Quantify effect of different measures on system level
It is recommended to perform an integrated study on the effectiveness of all measures taken during critical conditions on the safety against flooding on the water board system level. The focus in this thesis has been on the grass revetment reinforcement measures. However, water boards apply multiple types of reinforcement measures during high water threats. The main goal is part of the macro level of Figure 1.5.

Recommendation 5. Study erosion modification factor
The erosion modification factor for a correctly installed reinforcement measure should be studied. A statistical distribution for the modification factor is assumed in this thesis based on expert judgement. Research can reduce the uncertainty and probably increase the reliability of the reinforcement measure.

Recommendation 6. Research on optimal grass revetment reinforcement structure
The definition of the most optimal grass revetment reinforcement measure is given in Section 11.1.5. The minimum required fixation (nails and sand bags) to withstand the hydraulic and wind forces on the geotextile should be studied and tested. The less fixation the higher the construction rate and cheaper the solution.

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List of observations and interviews

This chapter contains a reference of activities that provided input for this thesis. Interviews, observations during placement of the actual measures and meetings with experts in the field resulted in an understanding of the system and a verification of the used methods.

These logs also show the people involved in this study.

Table 1: Observations during placement reinforcement measures and dike inspection.

Date	Water board	What
16-09-2017	Drents Overijsselse Delta	Theoretical lesson NATRES
16-09-2017	Drents Overijsselse Delta	1x Grass revetment reinforcement measure inner slope
		1x Grass revetment reinforcement measure outer slope
26-09-2017	Drents Overijsselse Delta	1x Grass revetment reinforcement measure outer slope
27-09-2017	Drents Overijsselse Delta	2x Grass revetment reinforcement measure outer slope
27-09-2017	Drents Overijsselse Delta	Dike inspection (exercise)
27-09-2017	Rijn en IJssel	1x Grass revetment reinforcement measure outer slope[37]
30-11-2017	Rivierenland	1x Grass revetment reinforcement measure outer slope
05-01-2018	Drents Overijsselse Delta	Dike inspection *Vecht* river (real high water)

Table 2: Meetings Wiki-Noodmaatregelen measure group

Date	Where	What
23-06-2017	Deltares, Utrecht[38]	Introduction research
10-10-2017	Deltares, Utrecht	Feedback on research proposal
07-12-2017	Deltares, Utrecht	Workshop reinforcement measures
16-03-2018	Deltares, Utrecht	Discussion on workshop reinforcement measures

Table 3: Interviews

Date	Where	Who	What
05-09-2017	Vallei en Veluwe	P. Boone en M. van Betuw	Interview on reinforcement measures and crisis organization.
06-09-2017	Drents Overijsselse Delta	F. Schutte, W. Evers, J. Overman, U. Föster, E. Huijskes, F. Havinga, M. Castelijns	Meeting for preparation Deining en Doorbraak
18-10-2017	Drents Overijsselse Delta	W. Evers en J. Overman, U. Föster, M. Castelijns	Discussion on Deining en Doorbraak exercise
24-10-2017	Deltares	M. Klein Breteler	Input for grass revetment failures
24-10-2017	Rivierenland	H. Knotter, U. Föster, E. Huijskes, M. Castelijns	reinforcement measures and crisis organization
01-11-2017	TU Delft	H.J. Verhagen	Input for grass revetment failures and geotextile reinforcements
21-11-2017	Drents Overijsselse Delta	M. Wit	Explanation reinforcement
06-04-2018	Drents Overijsselse Delta	W. Evers	Discussion research results

[37] Observations by Eric Huijskes

[38] Members wiki-workgroup: Rijkswaterstaat, STOWA, Defensie, Deltares, waterschappen: Hollandse Delta, Rivierenland, Hollands Noorderkwartier, Aa en Maas, Zuiderzeeland, Drents Overijsselse Delta, Vallei en Veluwe, Rijn en IJssel.

Table 4: Workshops reinforcement measures

Date	Where	Who
17-01-2018	Deltares, Utrecht	Waterschap Vallei & Veluwe Waterschap Drents Overijsselse Delta Hoogheemraadschap de Stichtse Rijnlanden Waterschap Rijnland Calamiteiten Team Waterkeren (CTW) Water risk Training & Expertise Centre (WTEC)
24-01-2018	Rivierenland, Tiel	Waterschap Rivierenland Waterschap Aa en Maas

A

Erosion models grass revetment

This appendix contains the background of Chapter 3 and consists of three parts. The first parts describes the hydraulic conditions that can cause failure of the grass revetment of river dikes. The second part gives the models as used in PC-ring and WBI-2017 to analyse the failure mechanism. The last part describes the background information on initial damage caused by floating debris.

A.1. Hydraulic conditions causing grass revetment failure

A.1.1. Waves and water level

Different hydraulic conditions are governing for the various failure mechanisms. Wave impact, overtopping and overflow are regarded relevant for the application of grass revetment reinforcements (see Section 3.1.2). The first two hydraulic conditions require the presence of waves, overflow only occurs when the water level is extremely high. Waves are the result of meteorological conditions (storms) whereas high river discharge is caused by precipitation in the whole catchment area. The time scale of these two phenomena is different, this is schematized in Figure A.1. The duration of the flood wave is in the order of weeks though high waves occur normally with a duration in the order of half a day.

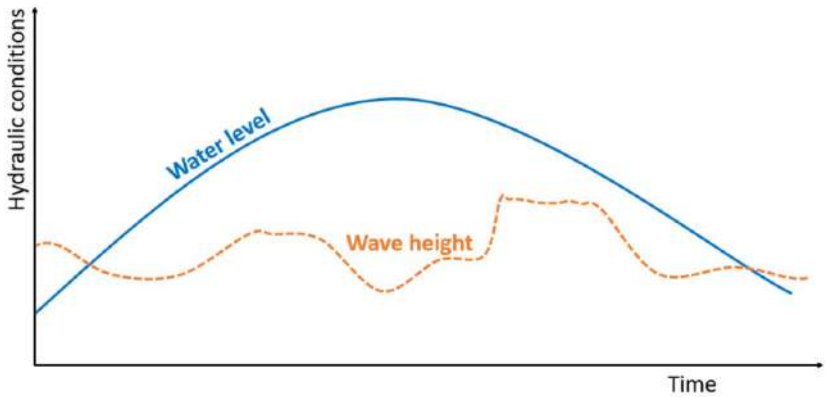


Figure A.1: Wave and water levels over time.

The relation between the river discharge (water level) and wind (waves) is relevant for determining the governing conditions. It is often assumed that there is no correlation between river discharge and waves, see for example Bieman (2015). No correlation between the two parameters means that the likelihood of simultaneous occurrence of both extreme waves and discharge is low. Extreme waves and a normal high water can have the same return period as extreme high water with normal wave conditions. The wave height is the most important parameter for the wave impact (erosion outer slope) situation, but for overflow the discharge (water level) is governing, see Figure A.2. Wave overtopping is possibly due to a combination of a high water level and waves, because waves will not overtop the dike when the distance between still water level and the dike crest is high.

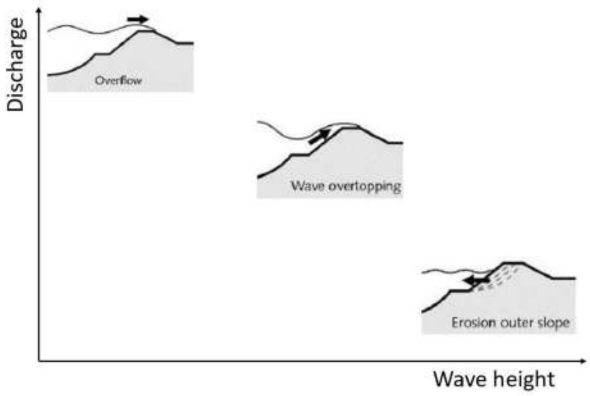


Figure A.2: Governing wave and discharge conditions.

An in depth joint probabilistic analysis for the two hydraulic load parameters (wind and discharge) is beyond the scope of this study, however the concept as discussed above are important to keep in mind.

A.1.2. Storms in the Netherlands

The storms (with peak hourly wind speed above 20 m/s) at measure station Schiphol for the period 1971-2018 can be seen in Figure A.3. The 20 storms are normalized by their corresponding peak so that they have the same scale vertically. The schematization according to the PC-ring method (Geerse, 2011) is also shown in the figure by the red line. The schematization assumes a peak with a duration of 2 hours and a fore and back flank of 23 hours, from zero to the peak.

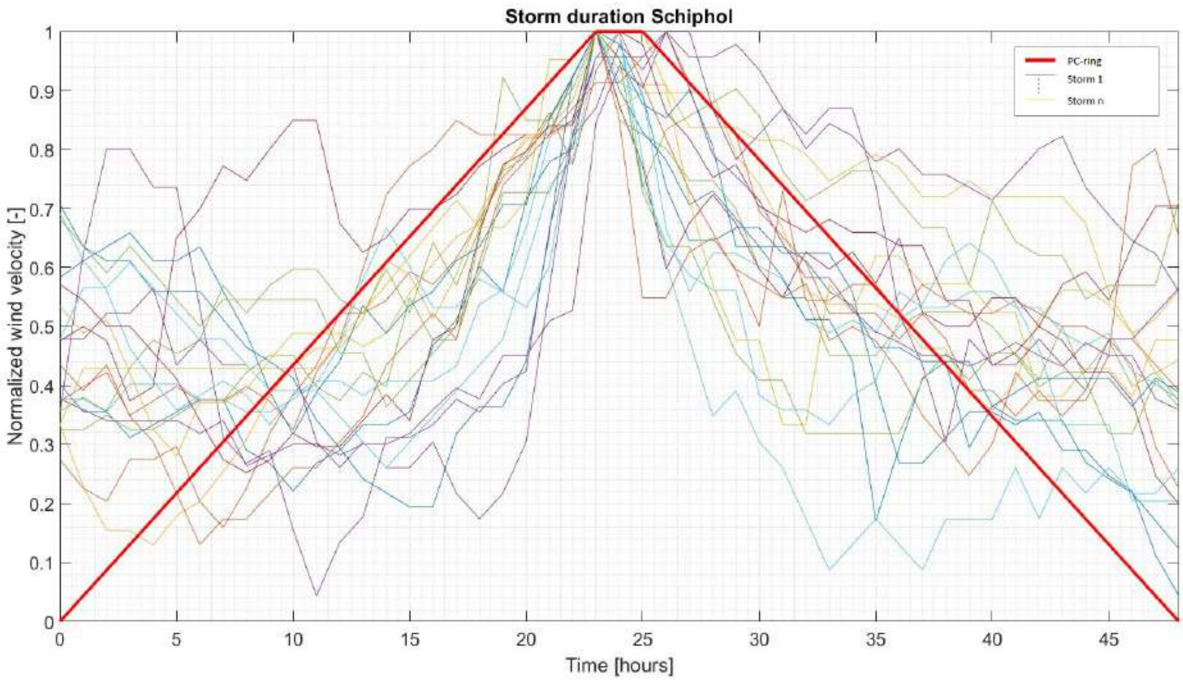


Figure A.3: Storms in the Netherlands (peak hourly wind speed above 20 m/s) 1971-2018. Data by KNMI (2018).

A.2. Erosion by wave impact outer slope

A.2.1. PC-ring method

This section is based on the method described in Steenbergen et al. (2007).

Failure of the flood defence is expressed by the limit state function given Equation A.1.

$$Z = t_{RT} + t_{RK} + t_{RB} - t_s \cdot r_h \tag{A.1}$$

Where:	t_{RT}	=	Time needed to damage grass revetment	[s]
	t_{RK}	=	Time needed to damage clay cover	[s]
	t_{RB}	=	Time needed to damage dike body	[s]
	t_s	=	Duration of the storm	[s]
	r_h	=	Reduction factor water level	[-]

The reduction factor water level accounts for different loading locations on the dike slope. The erosion resistance of a dike is higher if the location of the loading changes. For this thesis this parameter is set to one, which is a conservative assumption.

Failure grass revetment

Time till failure of the grass revetment is determined by the thickness of the grass revetment and the erosion speed, see Equation A.2.

$$t_{RT} = \frac{d_w}{E_g} \tag{A.2}$$

The erosion speed is given by Equation A.3.

$$E_g = \frac{r^2 \cdot H_s^2}{c_g} \tag{A.3}$$

Where:	d_w	=	Root depth	[m]
	H_s	=	Significant wave height	[m]
	r	=	Reduction factor wave angle	[-]
	c_g	=	Coefficient erosion resistance grass revetment	[ms]
	E_g	=	Erosion speed	[m/s]

The root depth varies between 0.05 and 0.07 meter, dependent on the location and type of maintenance. The grass quality (c_g) varies between 10^6[ms] (good grass quality) and $3.3 \cdot 10^5$[ms] (bad grass quality). A method to determine the reduction factor for the wave angle is described in Steenbergen et al. (2007). However, this method should be used carefully because the formula is based on experts intuition.

Residual strength clay layer

Time until failure of the clay sub layer is expressed in Equation A.4.

$$t_{RK} = \frac{0.4 \cdot L_K \cdot c_{RK}}{r^2 \cdot H_S^2} \tag{A.4}$$

Where:	L_K	=	Width clay sub layer	[m]
	c_{RK}	=	Coefficient erosion resistance clay	[ms]

L_K is defined in the horizontal plane. c_{RK} varies between $54 \cdot 10^3$ (good quality clay) and $7 \cdot 10^3$ (poor quality clay). The width of the clay layer can be calculated according to Equation A.5 if the thickness of the clay layer (d_k) and the slope of the dike (α_{dike}) are known.

$$d_k = L_k \cdot sin(\alpha_{dike}) \tag{A.5}$$

Residual strength dike body

Two models are available in the PC-ring method to determine the residual strength of the dike body t_{RB}. One model were the degradation of the dike body is influenced by mixing of the core of the dike and the grass revetment. This process is not taken into account in the second (rudimentary) model. For both models reference is made to Steenbergen et al. (2007). The residual strength model is of less importance, because failure is defined as failure of the grass revetment and clay sub-layer.

A.2.2. WBI-2017 method

Grass quality

Three different grass qualities are distinguished in the Dutch safety assessment: closed-, open, and fragmented (Dutch: gesloten, open en fragmentarisch) grass revetments. Examples of these three grass qualities are given in Figure A.4. The grass qualities are assessed visually. Based on the three different grass qualities, critical velocities, erosion model parameters and critical overtopping discharges are assigned. The grass revetments of the Dutch primary flood defences have predominantly the highest quality (closed sod). The erosion resistance of the open sod is approximately 10 to 20% less compared to the closed sod (Rijkswaterstaat, 2016).

(a) Closed sod (b) Open sod (c) Fragmented sod

Figure A.4: Grass revetment quality (Rijkswaterstaat, 2016)

Initial damage grass revetment

For erosion of the top layer, approximately zero till 20 centimetre of the revetment an erosion model is used in the Dutch safety assessment. The erosion model gives the time to failure against the significant wave height, see Figure A.5. (Klerk and Jongejan, 2016). Time to failure of the grass revetment is given as function of the spectral significant wave height. The resistance of the top layer is determined by the grass quality, in the form of model parameters a,b and c.

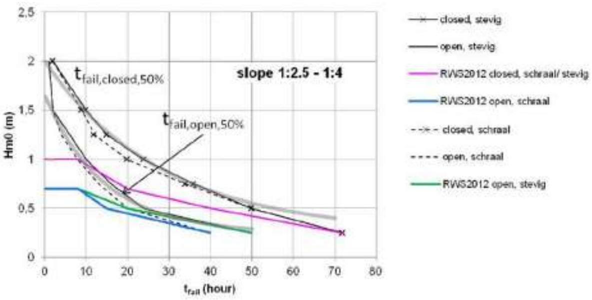


Figure A.5: Erosion model (Klerk and Jongejan, 2016).

The empirical results from Figure A.5, are approximated by Equation A.6. The model parameters a, b and c are given in Table A.1. Note that only closed and open grass qualities are distinguished. Fragmented grass sods have no erosion resistance in the erosion model.

$$H_{m0} = a \cdot e^{b \cdot t_{fail}} + c \tag{A.6}$$

Where:	H_{m0}	=	Spectral significant wave height	[m]
	t_{fail}	=	Time till failure	[hours]
	a, b, c	=	Model parameter	

Table A.1: Erosion model parameters a, b and c (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

The values from Table A.1 are based on data, this same data was used to fit a lognormal distribution, these values can be seen in Table A.2.

Table A.2: Lognormal distribution parameters erosion grass revetment (Klerk and Jongejan, 2016).

Parameter	Closed sod	Open sod
Mean	1.82	1.4
Standard deviation	0.62	0.50

Residual strength

The residual strength of the top 50 centimetre of the clay layer is studied by Klein Breteler (2015). An analytical formula is derived to assess the erosion rate after damage of the top layer (20 centimetre). The initial damage in the model is assumed a small hole with a diameter of 30 centimetre and a depth of 20 centimetre. After initial damage grows to a larger surface and to a larger depth. The formula is derived for depth growth, this is a slower process (Klein Breteler, 2015). The formula shows that there is a threshold for the significant wave above which the erosion starts (Klein Breteler, 2015). The resulting value of the formula is the mean erosion rate. The mean error rate in combination with a standard deviation is used to model the uncertainty of the method based on a normal distribution (Klein Breteler, 2015). The formulas are given below, Equation A.7 and A.8 (Klein Breteler, 2015).

$$R_e = c_c \cdot \frac{(H_s - 0.5)}{f_{NWO}} \tag{A.7}$$

$$t_{RS,grass} = \frac{min(d_c; 0.5) - 0.2}{R_e} \tag{A.8}$$

Where:	R_e	=	Erosion rate (increase of erosion depth per hour)	[m/h]
	f_{NWO}	=	Influence of transition structures and NWO's	[-]
	c_c	=	Constant dependent on the sand content	[hour^{-1}]
	$t_{RS,grass}$	=	Residual strength of the grass and top 50 cm of the clay	[hour]
	d_c	=	Clay thickness	[m]
	F_{sand}	=	Sand content	[%]

The value for c_c can be calculated based on Equation A.9 and A.10 (Klein Breteler, 2015).

Average:

$$c_c = 0.1 + max(0; 1.5 \cdot (F_{sand} - 0.7)) \tag{A.9}$$

5% exceedance level:

$$c_c = 0.2 + max(0; 1.5 \cdot (F_{sand} - 0.7)) \tag{A.10}$$

The values for the NWO factor can be found in Table A.3.

Table A.3: Values for NWO factor (Klerk and Jongejan, 2016)

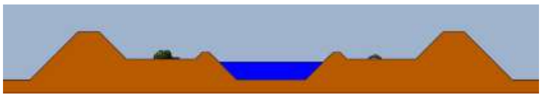
Case	f_{NWO}
Grass along stairs on sand	0.06
Grass along asphalt road on a berg with clay under and along the asphalt	1.0
Grass around a pole with 15 cm diameter	0.94
Grass along a concrete revetment on a slope with poor clay and poor compaction	0.2
Grass along a transition with concrete grass tiles on clay	2.3

The model can be used for (Klein Breteler, 2015):

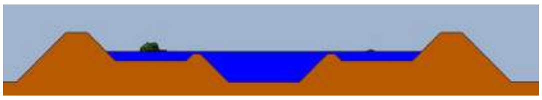
- calculation of the residual strength of the top 50 cm;
- open and closed grass sod qualities;
- significant wave heights larger than 0.5 meter;
- slope steepness of approximately 1:3.

A.3. Initial damage debris and driftwood

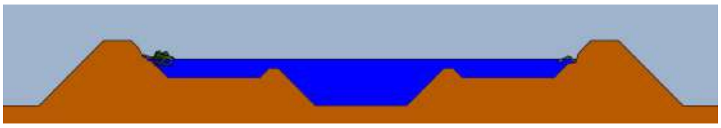
Damage to the grass revetment can happen due to driftwood or floating debris (Niemeijer, 1996). During the high water periods water will flow over the flood planes, through areas that are normally not covered with water. These areas are often nature areas with trees and other vegetation. Water flow through these areas can pick up trees, wood and other debris, this process is visualised in Figure A.6. That this damage mechanism can be a real threat to for the dikes can be seen from the analysis of the 1993 (TAW,1993) and 1995 (TAW, 1995) high water threats. Floating debris and relatively large waves resulted in damage to a dike near Culemborg. This dike was covered by a geotextile to prevent further erosion after damage has occurred (TAW, 1995). That this phenomena is a real threat to the dikes proved the storm in the Netherlands (18-01-2018), see the social media messages of two different water boards in Figure A.7. These damages were not a safety issue as the river water levels were not high.



(a) Phase 0, driftwood or debris in flood planes.



(b) Phase 1, flooding of flood planes..



(c) Phase 2, debris or driftwood damages dike revetment.

Figure A.6: Damage due to driftwood or debris

Water boards try to remove the driftwood as soon as possible during high water situations (Rivierenland, 2012). Damage to the grass revetment due to driftwood can therefore be prevented. The exact location and point in time of damage due to driftwood cannot be foreseen. However locations vulnerable for damage due to driftwood can be predicted, for instance a sharp bend in course of the river (Ciria, 2013).

(a) Statement *Drents Overijsselse Delta* water board.

(b) Statement *Rijn en IJssel* water board.

Figure A.7: Social media messages water boards.

A.4. Sensitivity analysis erosion calculation WBI-2017

The six parameters used in the calculation are studied to qualitatively determine the sensitivity. The erosion lines are calculated for different values of the parameter of interest, while the other parameters are kept constant.

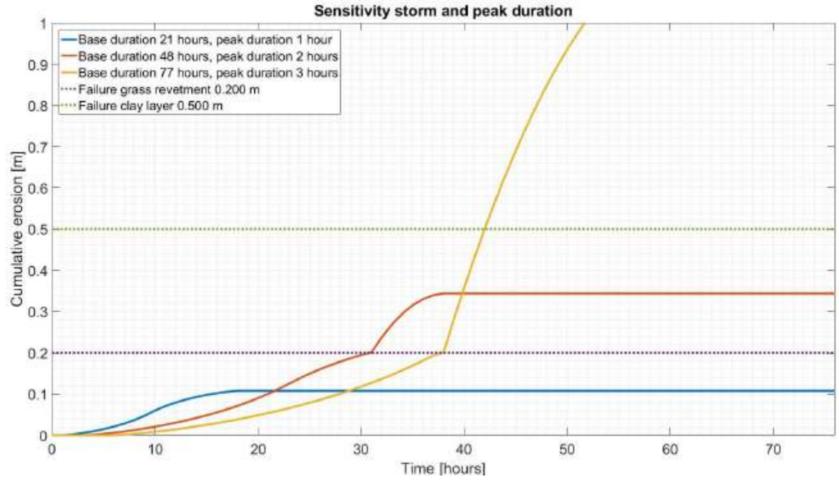


Figure A.8: Cumulative erosion for different storm parameters.

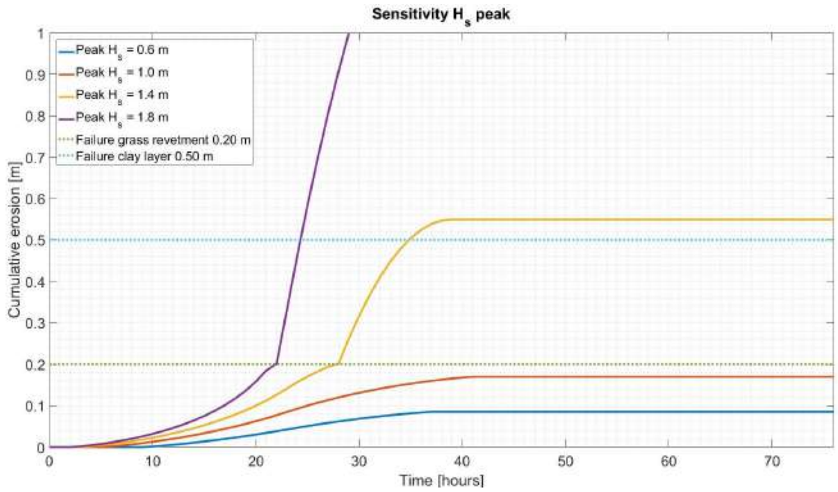


Figure A.9: Cumulative erosion for different peak significant wave heights.

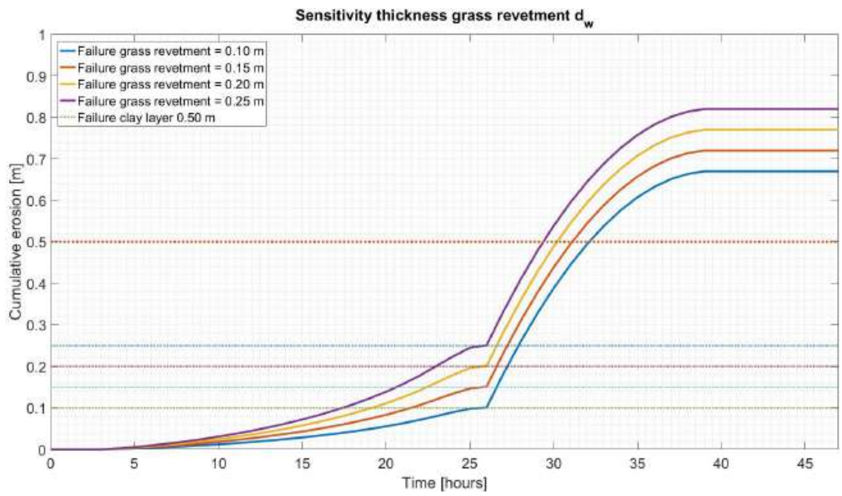


Figure A.10: Cumulative erosion for different grass revetment thickness.

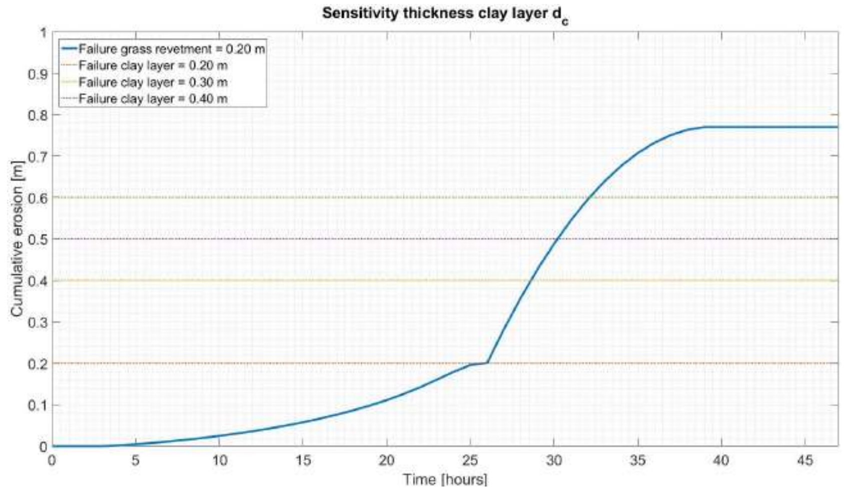


Figure A.11: Cumulative erosion for different clay layer thickness.

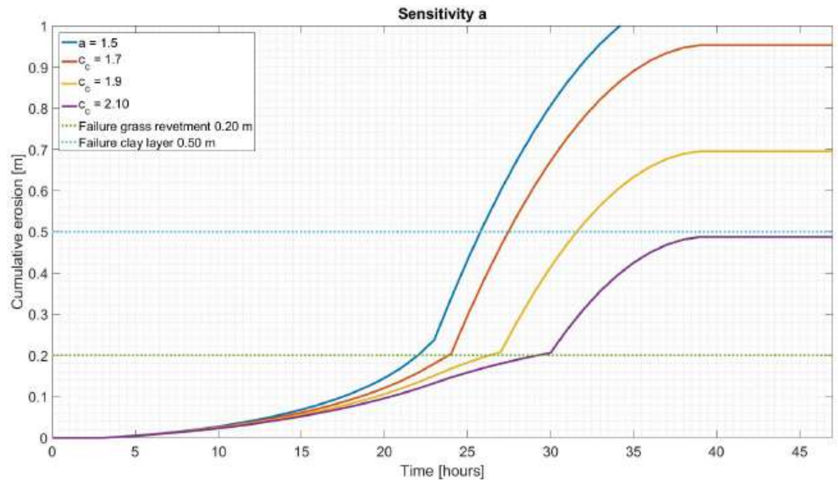


Figure A.12: Cumulative erosion for different grass revetment qualities.

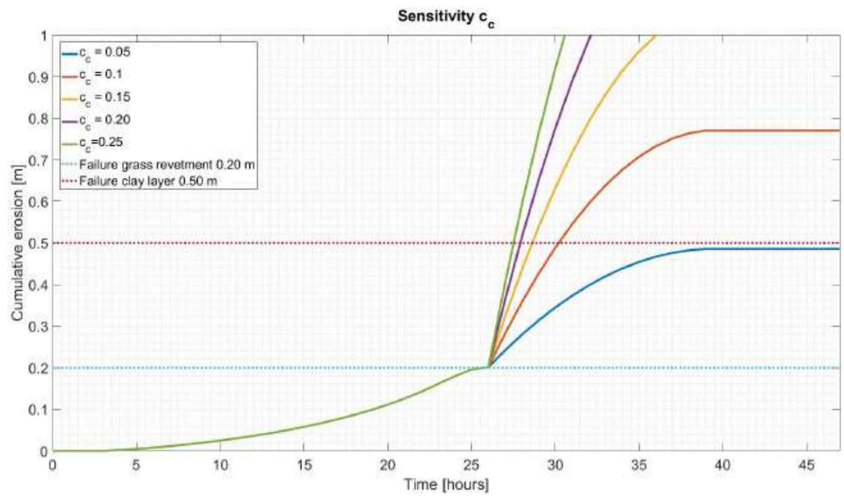


Figure A.13: Cumulative erosion for different clay qualities.

A.5. Sensitivity analysis erosion calculation PC-ring

Four PC-ring parameters used in the calculation are studied to qualitatively determine the sensitivity. The erosion lines are calculated for different values of the parameter of interest, while the other parameters are kept constant.

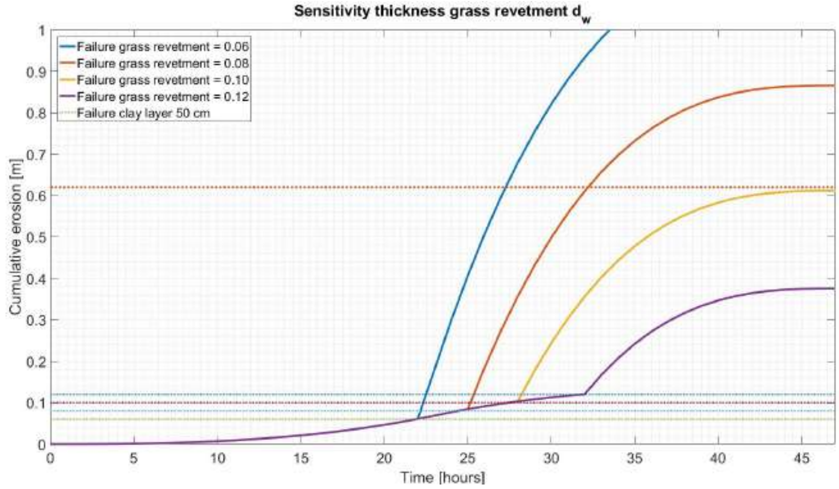


Figure A.14: Sensitivity thickness grass revetment.

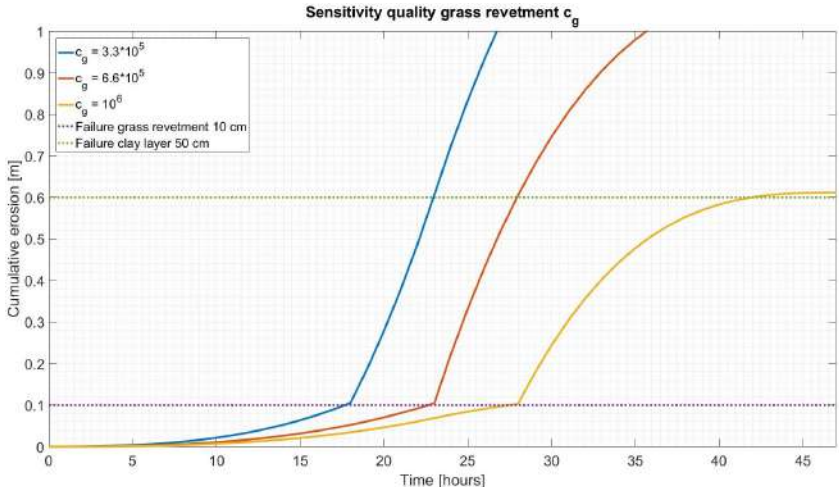


Figure A.15: Sensitivity grass revetment quality.

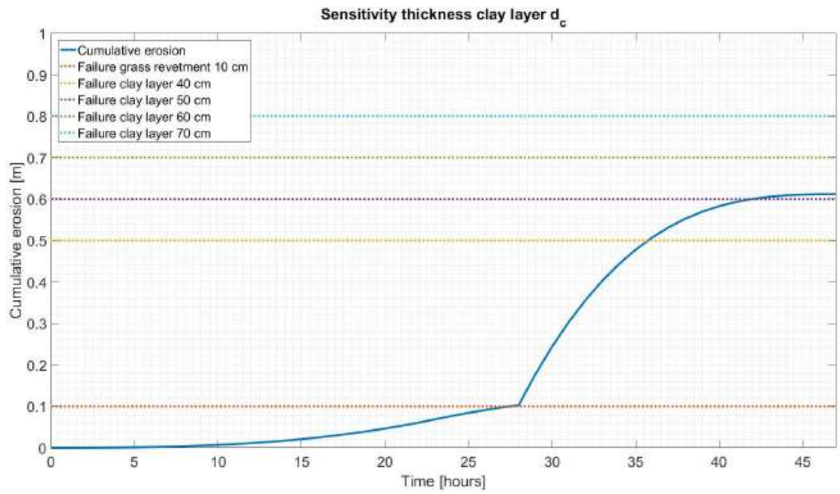


Figure A.16: Sensitivity clay layer thickness.

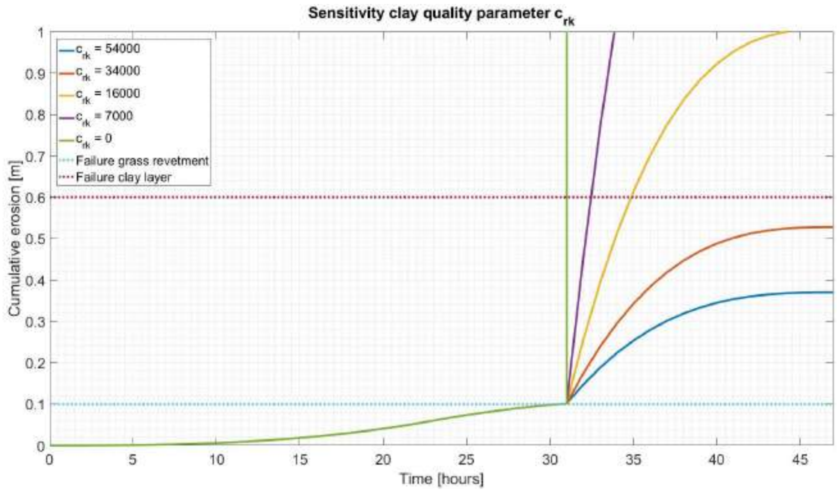


Figure A.17: Sensitivity clay layer quality parameter.

B

Grass revetment reinforcement types

This appendix contains the background of Chapter 4. Two different types of grass revetment reinforcement measures are explained in more detail. Experience with the reinforcement measures during real flood threats is explained in the second part of this appendix. The last part of the appendix describes the placement of the measures during bad weather conditions.

B.1. Types of reinforcement measures

B.1.1. Principle traditional grass revetment reinforcement (type 1)

An example of a traditional reinforcement can be seen in Figure B.1. The different parts of the structure are indicated with A, B, C and D (in order of placement). The different parts are:

A. Geotextile. The geotextile is placed on top of the damaged grass revetment. This is the main part of the structure, and it fulfils the main purpose of the reinforcement measure, which is strengthen the grass revetment. All the other parts of the structure are meant to keep the geotextile in place.

B. Nails. (Dutch: krammen). The nails are designed at certain points to fix the geotextile to the underlying grass revetment.

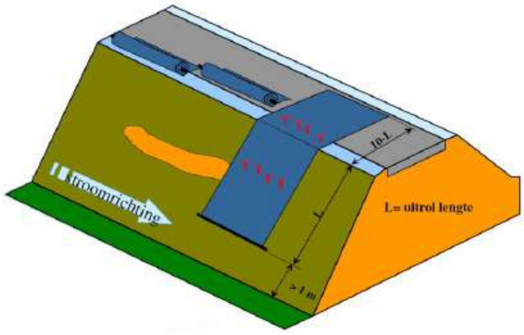
C. Steel cables. The steel cables are not clearly visible in the figure, they are placed between the nails to keep the geotextile close to the soil.

D. Sand bags. Sand bags are placed on the border and on top of the geotextile to keep the borders close to the soil. If there are significant gaps in the dike body, this is filled with sand bags to first level the surface before the geotextile is placed.

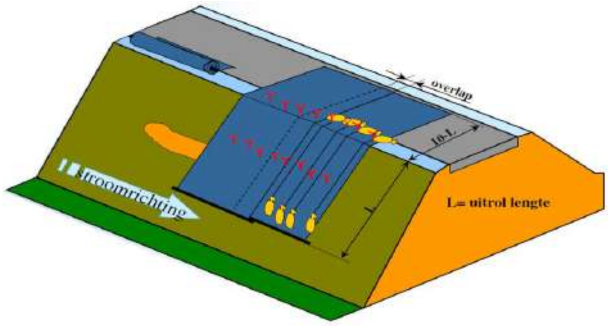
Figure B.1: Example of a grass revetment reinforcement, after Aa en Maas (2016)

B.1.2. Principle grass revetment reinforcement type 2

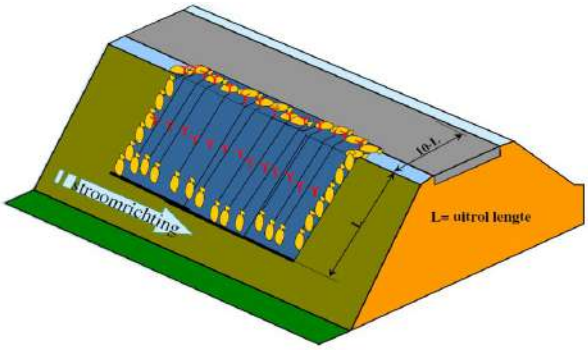
The second grass revetment reinforcement type is used when the geotextile has to be placed below the water line. The placement method is developed by water board Rivierenland, see for an illustration Figure B.2. The permeable geotextiles are initially on a roll, see Figure B.2d. On the downward end of the geotextile a heavy steel pipe is attached. The geotextile can be rolled down the slope due to the weight, see Figure B.2a. An overlap of one meter for the geotextiles is used if multiple rolls are needed. The geotextile is fixated to the dike body at the top of the dike by nails and sand bags (see Figure B.2b). Sand bags are placed at the downward end of the geotextile, these sand bags are kept in place by ropes fixated at the top of the dike. At the water line additional nails are placed,this is the lowest point where the nails can be placed, due to the water flow and waves. In the last stage, stage three (see Figure B.2c, sand bags are placed at the borders of the geotextile, all sand bags are kept in place by a rope.



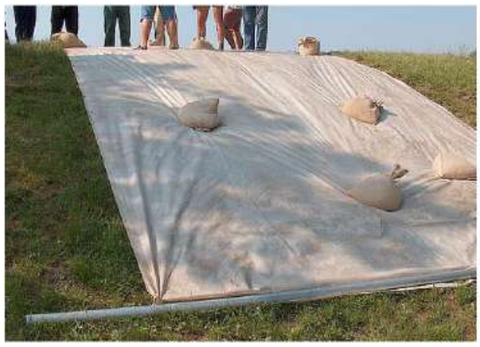
(a) Stage 1.



(b) Stage 2



(c) Stage 3



(d) Example geotextile roll (LHW, 2011)

Figure B.2: Method water board Rivierenland (Rivierenland, 2011).

Other ways of fixating the geotextile to the dike body are used. A grass revetment reinforcement measure applied by water board Rijn en IJssel can be seen in Figure B.3. The geotextile is fixated to the dike body by timber bars. Nails keep these timber bars in place. Sand bags are placed on the slope. Ropes keep these sand bags at the desired location, as can be seen in Figure B.3.

Figure B.3: Grass revetment reinforcement placed by water board Rijn en IJssel (Huijskes, 2017)

B.2. Sensitivity modification factor erosion

Disclaimer: these graphs do show the effect of reinforcement measures on the conditional failure probability without taking the reliability of the detection, placement and technical reliability in account.

The influence of the erosion modification factor α_{geo} on the failure probability of a dike is studied in this section. Five graphs with different values for initial damage are presented. These graph show all:

- The fragility curve for the dike section without damage.
- The fragility curve for the dike section with damage, without reinforcement measure.
- The fragility curve for the dike section with damage, with reinforcement measure that reduces the erosion with a factor 0.10.
- The fragility curve for the dike section with damage, with reinforcement measure that reduces the erosion with a factor 0.20.
- The fragility curve for the dike section with damage, with reinforcement measure that reduces the erosion with a factor 0.30.

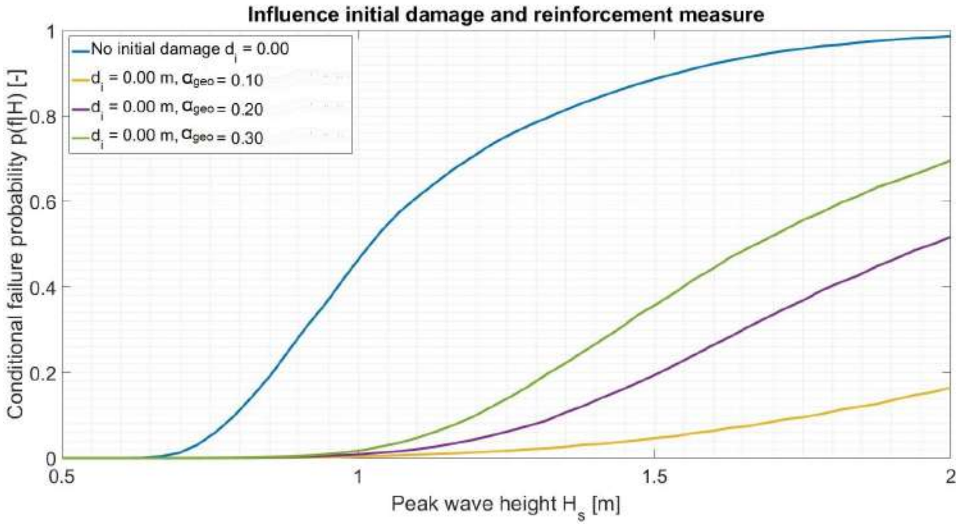


Figure B.4: No initial damage (WBI open sod).

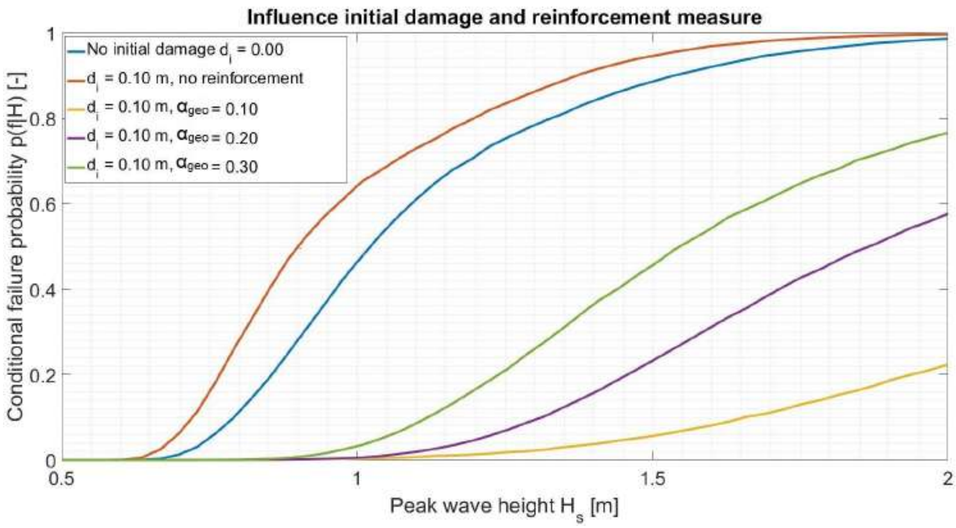


Figure B.5: Initial damage 10 centimetre (WBI open sod).

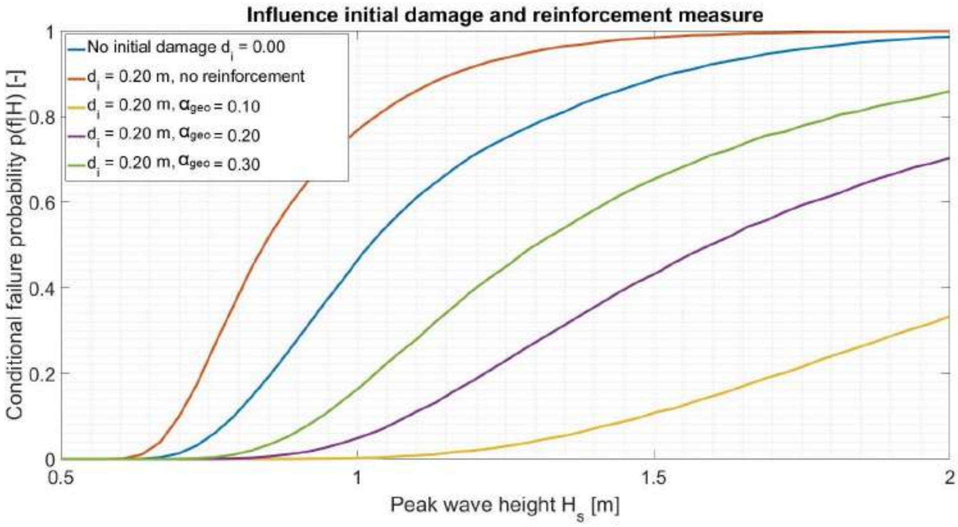


Figure B.6: Initial damage 20 centimetre (WBI open sod).

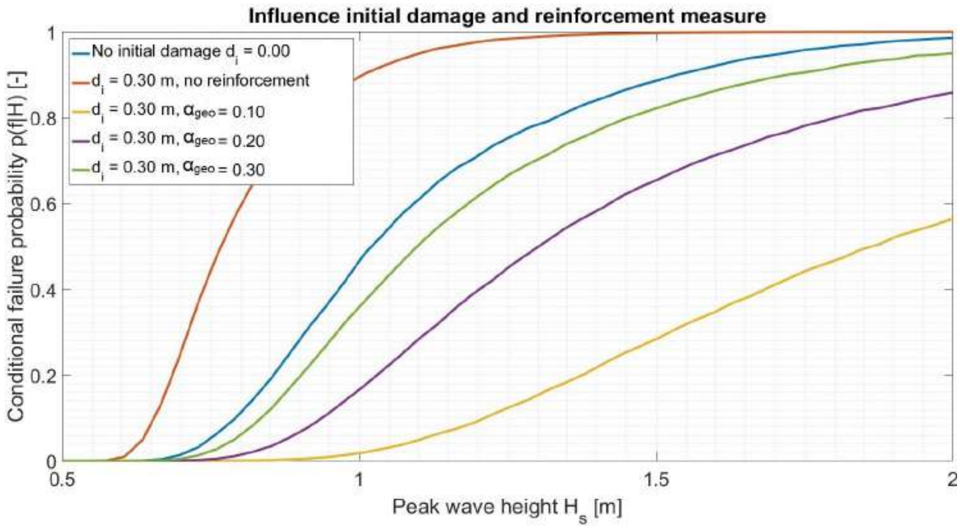


Figure B.7: Initial damage 30 centimetre (WBI open sod).

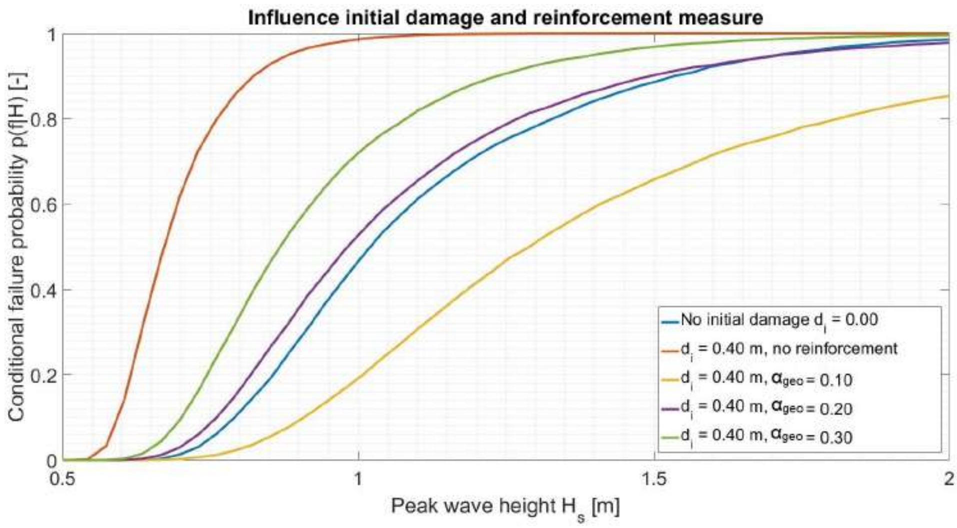


Figure B.8: Initial damage 40 centimetre (WBI open sod).

B.3. Monte Carlo Analysis

```
%Define distribution d_w
dw_mu = 0.20;
 dw_sig = 0.1*dw_mu;
 dw_mu_scaled = log(dw_mu^2/sqrt(dw_mu^2+dw_sig^2));
 dw_sig_scaled = sqrt( log(( dw_mu^2 + dw_sig^2 ) / dw_mu^2 ));

%Define distribution d_c
dc_mu = 0.30;
 dc_sig = 0.1*dw_mu;
 dc_mu_scaled = log(dc_mu^2/sqrt(dc_mu^2+dc_sig^2));
 dc_sig_scaled = sqrt( log(( dc_mu^2 + dc_sig^2 ) / dc_mu^2 ));

%Define distribution a
a_mu = 1.4;
 a_sig = 0.5;
 a_mu_scaled = log(a_mu^2/sqrt(a_mu^2+a_sig^2));
 a_sig_scaled = sqrt( log(( a_mu^2 + a_sig^2 ) / a_mu^2 ));

%Define distribution cc
cc_mu =0.1;
 cc_sig = 0.052;
 cc_mu_scaled = log(cc_mu^2/sqrt(cc_mu^2+cc_sig^2));
 cc_sig_scaled = sqrt( log(( cc_mu^2 + cc_sig^2 ) / cc_mu^2 ));

number = 100;        %number of iterations per wave height
di = 0.0;            %Initial damage

for k = 1:50
    Hs_peek(k) = 0.45+0.031*k;
    failure = 0;
        for j = 1:number
            d_w = exp(dw_mu_scaled + dw_sig_scaled*normrnd(0,1));
            d_c = exp(dc_mu_scaled + dc_sig_scaled*normrnd(0,1));
            aa = exp(a_mu_scaled + a_sig_scaled*normrnd(0,1));
            cc = exp(cc_mu_scaled + cc_sig_scaled*normrnd(0,1));
            %Account for initial damage
            if di<=d_w
                d_w = d_w - di;
            else
                d_c = d_c - (di-d_w);
                d_w = 0;
            end
            %%Define storm
            Random = rand;
            if Random<0.3
                peak = 1;
                base = 21;
            elseif Random>0.3 && Random<0.8
                peak = 2;
                base = 48;
            else
                peak = 3;
                base = 77;
            end
```

```
            flank = (base-peak)/2;
            T = [0:base-1];
            H = zeros(1,length(T));
            H(flank+1:flank+1+(peak-1)) = Hs_peek(k);
            for i = 1:flank
                H(i) = (Hs_peek(k)/(flank+1))+Hs_peek(k)/(flank+1)*(i-1);
                H(flank+peak+i) = Hs_peek(k)-H(i);
            end
            sum_erosion = 0;
            for r = 1:length(H)
                if sum_erosion<=d_w;
                    if H(r) >0.25
                        d_e(r) = 1/(log((H(r)-0.25)/aa)/-0.035)*0.20;
                        if d_e(r)<0
                            d_e(r) = d_w-d_e(r-1);
                        end
                    else
                        d_e(r) = 0;
                    end
                    sum_erosion = sum_erosion + d_e(r);
                    Cumulative_erosion(j) = sum_erosion;
                    continue
                elseif sum_erosion>d_w
                    if H(r)>0.5
                        d_e(r) = (H(r)-0.5)*cc;
                    else
                        d_e(r) = 0;
                    end
                    sum_erosion = sum_erosion + d_e(r);
                    Cumulative_erosion(j) = sum_erosion;
                end
            end
            if Cumulative_erosion(j)>(d_w+d_c)
                failure = failure + 1;          %Counter failures
            end
        end
        Failure_per_H(k) = failure / number;        %Failure probability calc.
end
```

B.4. Experience during flood threats

The flood threat of 1993 and 1995 in the Dutch river system resulted in large scale evacuations and applications of reinforcement measures. The hydraulic conditions and reinforcement measures applied are well described by the Dutch technical committee for flood defences (Dutch: Technische Adviescommissie voor de Waterkeringen TAW). They reported multiple applications of geotextile reinforcements as reinforcement measure during the 1993 and 1995 events:

Near flooding 1993 (TAW, 1993)

- Where: next to the river Waal in the polder district Betuwe
  What: grass revetment damaged on outer slope by wave attack, grass cover was in bad condition due to shadow of trees.
  Measure: during high water a nylon cover is placed to prevent further damage.
- Where: Gewande, next to the river Maas
  What: erosion of the slope
  Measure: slope covered

Near flooding 1995 (TAW, 1995)

- Where: water board Salland aan de IJssel (currently water board Drents Overijselse Delta) multiple damaged spots
  What: damage grass revetment due to wave run-up
  Measure: Damaged spots covered with nylon cover to prevent further erosion of the slope
- Where: Dike segment Oeffelt next to the river Maas, water board De Maaskant (currently water board Aa en Maas)
  What: due to recent dike reinforcement no sufficient grass cover was present
  Measure: geotextile placed to prevent erosion of the dike cover.
- Dijkpaal 213 at the river Lek (close to the railway bridge in Culemborg) at hoogheemraadschap De Stichtse Rijnlanden.
  What: damage of the outer slope due to heavy wave attack and driftwood. The dimensions of the damage were large, depth 0.5 meter, length 15 meter and width 2 meter.
  Measure: geotextile placed to prevent erosion of the dike cover.

All these measures were successful, since no flooding occurred during these events. This does not imply that every weak spot would have resulted in failure of the dike body.

B.5. Placement during bad weather conditions

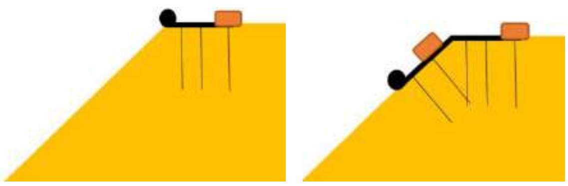
Placement of a large geotextile during windy conditions might be a problem. Relatively mild conditions can already expose the geotextile when wind can come under the geotextile, see for example Figure B.9.

Figure B.9: Placement geotextile outer slope during exercise NATRES and water board Drents Overijsselse Delta during relatively mild wind conditions 2 Bft, 1.8 m/s measures at De Bilt (KNMI, 2018) (16 September 2017).

Water board Drents Overijsselse Delta also exercised the placement of a geotextile during more windy conditions, see Figure B.10. The video footage of this event (Drents Overijsselse Delta, 2011) shows that there is no problem as long as the geotextile is close to the ground.

Figure B.10: Placement geotextile inner slope during exercise water board Drents Overijsselse Delta (Drents Overijsselse Delta, 2011) during relatively windy conditions 5 Bft, 8 m/s measures at De Bilt (KNMI, 2018) (7 December 2011).

Geotextiles are often stored on rolls. The geotextile will not be exposed to the wind as long as the geotextile is on the roll. It is therefore advised to unroll the geotextile incrementally and fix it directly to the dike body, see Figure B.11. In this way it is prevented that wind exposes the geotextile.



(a) Phase 1 placement. (b) Phase 2 placement.

Figure B.11: Placement procedure during windy conditions.

C
Grass revetment reinforcement inner slope

Grass revetment reinforcement measures can be placed both on the outer and inner slope. The focus in this thesis is on the reinforcement measures applied at the outer slope. This appendix describes the reinforcement measure types, the effect on the dike performance for the inner slope measures.

C.1. Current practice grass revetment reinforcement design inner slope

C.1.1. Impermeable geotextile

An impermeable geotextile is most often used as reinforcement measure on inner slope of the dike. Blocking of the water is needed as infiltration in the inner slope is undesirable. Infiltration can lead to sliding of the inner slope. The placement difficulties holding for placement on the outer slope are not present at the inner slope, because no water is permanently at the outer slope. Leakage is also not a huge problem as water will flow quickly over the slope.

C.1.2. Reinforcement measure inner slope

An example of a reinforcement measure (in this case impermeable geotextile) is given in Figure C.1. A weak spot on the inner slope for wave overtopping and overflow is at the transition from the slope and the toe (Le Trung et al., 2014). The inner slope reinforcement should cover this part of the slope to increase the strength of the slope.

Figure C.1: Inner slope reinforcement at water board Drents Overijsselse Delta (September 16, 2017).

C.2. Influence geotextile reinforcement on dike performance inner slope

The influence of a reinforcement measure on the inner slope is visualized in Figure C.2.

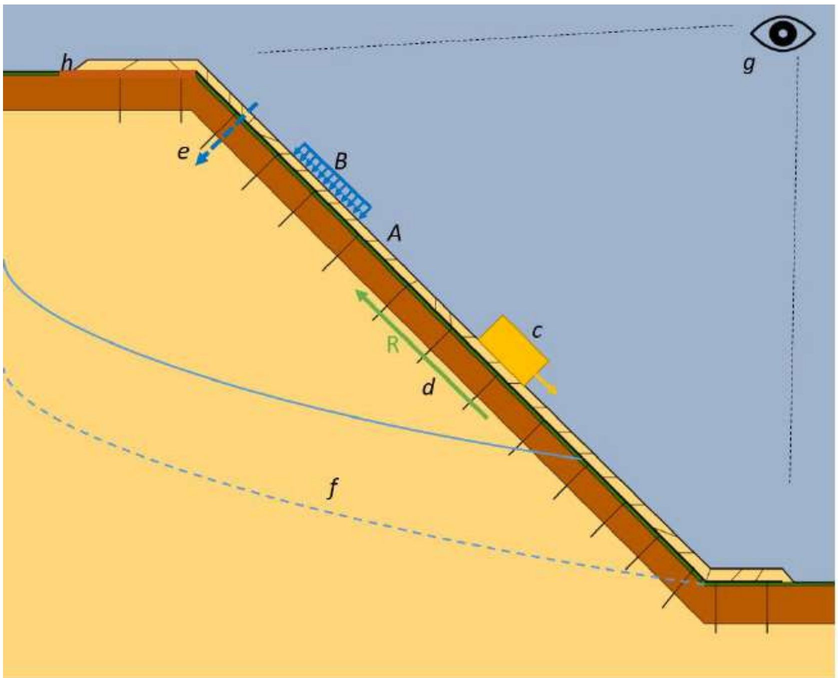


Figure C.2: Influence grass revetment reinforcement measure inner slope on dike performance (Not To Scale).

Main function

A. **Erosion resistance**
Phenomenological description
Overtopping and overflow can result in initial damage to the grass revetment, this damage is enlarged when overtopping or overflow continuous (Le Trung et al., 2014). Damage is likely to happen around irregularities in the grass revetment: objects, trees and initial damages. Water flow will enhance the load on for example damaged areas due to flow concentration. Erosion due to wave overtopping or overflow is often modelled in a cumulative overload method, see Appendix A. An overtopping wave contributes to erosion when the flow velocity exceeds the critical flow velocity, which is a soil parameter (Rijkswaterstaat, 2016). A correctly placed geotextile smoothens the slope and prevents flow concentration at the damaged spots.
Modelling of effect
Based on the above described erosion process it is assumed that erosion is stopped at the inner slope when a grass reinforcement structure is placed correctly. In terms of Equation 4.1: $\alpha_{geo} = 0$. The grass revetment or clay sub layers are not exposed to the (turbulent) water flow any more when the grass revetment is covered.

B. **Infiltration inner slope** [Positive, main function]
Phenomenological description
Infiltration in the inner slope does have a negative influence on the stability of the inner slope and micro instability. Infiltration into the dike body is decreased, provided an impermeable geotextile is placed. A permeable geotextile will decrease the infiltration to a certain extent, but will not lower it to zero. However, water will flow down the slope with a relatively high speed, the amount of water infiltrating through a permeable geotextile will therefore also be limited. This reasoning is different in the case of overflow. Water is constantly present on the slope and will therefore infiltrate. In the case of impermeable geotextiles this will also result in infiltration at the overlapping parts.
Modelling of effect
The effect can be modelled as a percentage of the initial infiltration (without measure) that is able to enter in the dike body. This will be 0% when an impermeable geotextile is functioning correctly.

Side effects

c. **Weight sand bags** [Negative, side effect]
Phenomenological description
The weight on the inner slope does have the same effect as described for the outer slope situation. However, macro stability is a more relevant problem for the inner slope during high water conditions.
Modelling of effect
The effect of the additional weight will be modelled as an extra weight on the outer slope for the stability calculations.

d. **Resistance steel nails** [Negligible]
Phenomenological description
The effect of on the resistance against sliding is the same as described for the outer slope situation. The influence is neglected based on the same reasoning.

e. **Infiltration at nails** [Negligible]
Phenomenological description
Water can possibly infiltrate into the dike body at the location of the nails. The nails should extend to the dike body for this phenomenon to occur. However, as can be seen in Figure C.3, the number of nails is limited and water will flow easily over the smooth geotextile (no water will accumulate on the dike slope). Furthermore, wet clay will probably seal off the water entry point. This process is neglected based on the above.

f. **Drainage dike body** [Negligible]
Phenomenological description
Drainage of the lower part of the inner slope is a way to limit the likelihood of the micro-instability mechanism (Jonkman et al., 2017) and macro-instability problems. Placement of an impermeable geotextile on the inner slope can possibly limit the permeability of the lower part of the slope. This is in conflict with the principles of dike design (Wiki Noodmaatregelen, 2017b). The impermeable geotextile is placed on the inner slope, fixated with nails at the border, as can be seen in Figure C.3. The geotextile is not tightened to the dike body at the water exit point. The water can easily exit the dike body at this location. The negligible influence does not hold if sand bags are covering the water exit point completely. It is assumed that placement of a (impermeable) geotextile on the inner slope will not limit the seepage of water out of the dike body.

g. **Effect on further visual inspection** [Negative]
Phenomenological description
Visual inspection of the dike during high water is negatively influenced by a dike revetment cover. This problem is especially relevant for the inner slope (in contrast to the outer slope) because of the macro- and micro instability problems. Micro instability cannot be observed because the inner slope is covered and cracks in the crest are also difficult to detect.

h. **Deterioration grass revetment** [Negligible / negative]
Phenomenological description
The same reasoning as for the outer slope revetment holds, see Figure 4.5. The influence is negligible for reinforcement measures, as they are on the dike body for a short period of time. This deterioration is a relevant problem when the geotextile is on the dike for a longer period of time, as control measure.

Figure C.3: Influence inner slope reinforcement measure on exit water. Impermeable geotextile loosely present at the water exit point. Chance of blocking the water and therefore raising the phreatic level in the dike is limited.

C.3. Failure inner slope reinforcement measure

The likelihood of failure of the outer slope grass revetment reinforcement is discussed in this section. First the loads that can damage the structure are discussed, secondly the resistance of the structure and lastly the combination of load and resistance determines the likelihood of failure. The grass revetment structure for the inner slope can be seen in Figure C.4, the impermeable geotextile is fixated with nails and sand bags.

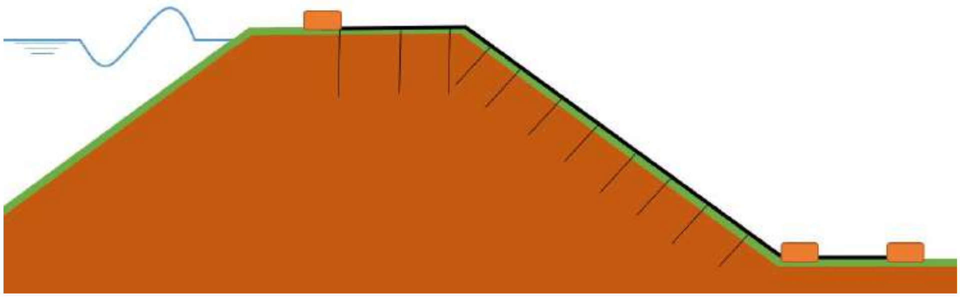
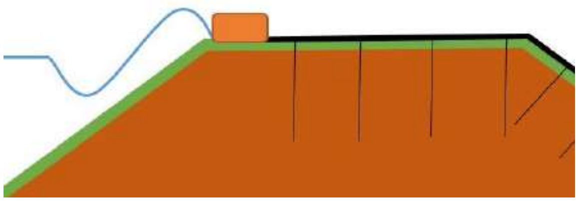


Figure C.4: Inner slope grass revetment reinforcement measure.

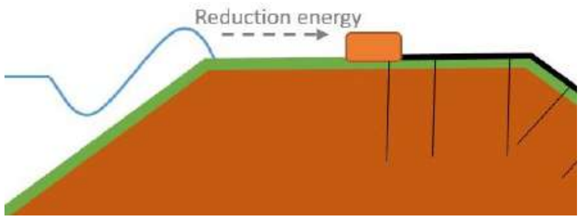
C.3.1. Load inner slope reinforcement

The inner slope grass revetment reinforcement is subjected to the following loads:

- **Overtopping**
  Overtopping exerts a load on the inner slope grass revetment and on the fixation (sand bags). The larger the distance between the outer slope side of the crest and the sand bags, the more the wave energy will be reduced, this principle is illustrated in Figure C.5.



(a) At outer slope side dike crest.



(b) At distance from outer slope.

Figure C.5: Location fixation sand bag.

- **Overflow**
  Overflow is a more static load compared to the cyclic character of wave overtopping. The load on the sand bag on top of the crest is subjected to the water flow over the dike, this flow velocity is dependent on the head difference.
- **Seepage**
  Seepage through the river dike could potentially damage the grass revetment reinforcement due to the water pressure increase under the geotextile, because the geotextile is impermeable. This principle is illustrated in Figure C.6.

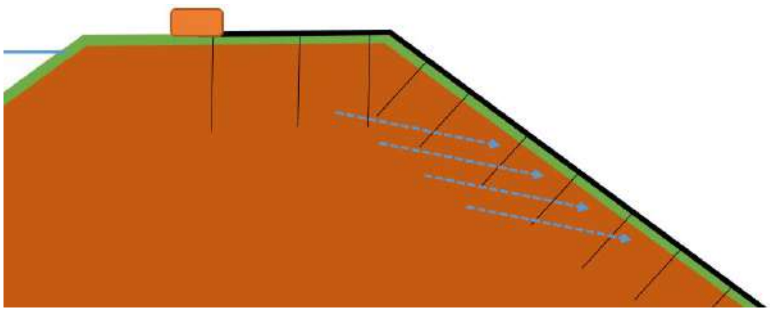


Figure C.6: Seepage through dike as potential load.

Seepage as damaging load for the geotextile is however neglected. It is true that pressure built up can occur when the inner slope is impermeable, however the geotextile is not tightened to the grass revetment, it is loosely present on the soil. Water can easily escape downward over the grass revetment, because seepage is not a constant severe water flow but just a limited amount of water. Even if the pressure built up occurs, would it probably not lead to much of a problem, because the nails would be lifted out of the soil over a short distance in order to provide pressure relief, without failure of the reinforcement.

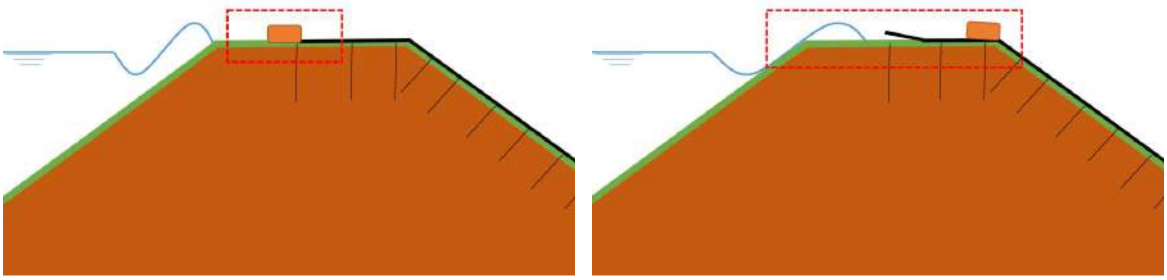
- **Wind**
  The same wind load as discussed for the outer slope grass revetment reinforcement is relevant for the inner slope reinforcement.

C.3.2. Resistance

Failure definition

Failure of the grass revetment reinforcement is, in accordance to Figure 9.6, defined as failure of the fixation or rupture of the geotextile.

It is assumed that the fixation on the dike crest, see Figure C.7a, is vital for correct functioning of the grass revetment reinforcement. Failure of the sand bag, see Figure C.7b, can lead to water flow under the geotextile with erosion as result.



(a) Pressure distribution permeable geotextile. (b) Failure sand bag.

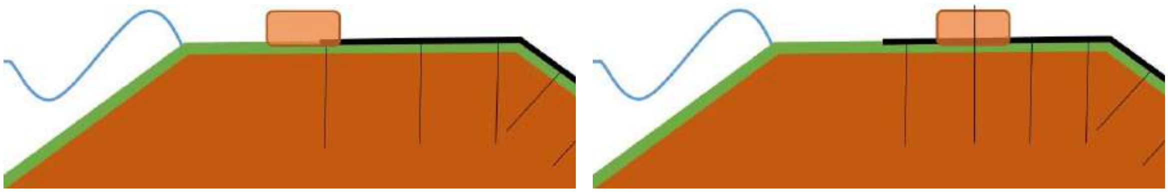
Figure C.7: Schematization load and resistance.

Lendering et al. (2014) concluded that the technical failure probability of a sand bag as overtopping measure is negligible compared to the failure probability of the detection and placement phase. Important parameter in this calculation is the friction coefficient, which was taken equal to 0.25 in this computation, this results in a Safety Factor of 1.5 in the case of only hydrostatic water pressure (Dimensions sand bag: 0.15x0.30x0.4m, weight: 20 kg). The friction factor will certainly reduce when the sand bag is placed on top of the geotextile, this friction factor will even more reduce when there is water in between the sand bag and the geotextile. Without determining the exact value of the friction factor can be concluded that the safety against sliding can become problematic in this situation. Because the Unity Check fails for the hydrostatic load situation when the friction factor drops below 0.17.

C.3.3. Conclusion: failure probability inner slope grass revetment structure

It is concluded, based on the analysis, that the failure probability of the inner slope grass revetment reinforcement is negligible provided that:

- The front border, which is prone to overtopping and overflow, is fixated correctly. If the sand bag is placed according to Figure C.8a does it result in the same situation as heightening of the dike by sand bags, for which is concluded that the technical failure probability is negligible, see Lendering et al. (2014).
  Based on the basic calculation as presented in this chapter is concluded that placement of the sand bag on top of the geotextile can result in failure due to sliding of the sand bag. The sand bag can be fixed by hammering a nail through the sand bag (see Figure C.8) if one, for some reason, want to place the sand bag on top of the geotextile.



(a) Fixation with sand bag.

(b) Fixation with sand bag and nail.

Figure C.8: Recommended fixation inner slope reinforcement.

- The borders of the geotextile are tightened to the grass revetment, by sand bags or nails. This will prevent the wind from getting *grip* on the geotextile.

D

Crisis organization water boards

This appendix describes the crisis organization of two different water boards in the first three sections. The fourth section discusses the different types of personnel that water boards deploy during high water events.

D.1. Important terms

WBT (Waterschap Beleidsteam): responsible for general operating water board. Policy oriented management team, also responsible for coordination between different water boards and other governmental organizations
WOT (Waterschap Operationeel Team): The WOT team is responsible for the impact control and determines a crisis fighting strategy. WOT is the link between WAT and WBT.
WAT (Waterschap Actieteam): coordination team for the people working on the dikes and dike posts. Coordinates measures taken in the field.
ACW (Actiecentrum Water): teams (WBT, WOT and WAT) are working together at one location.

D.2. Crisis organization water board Drents Overijsselse Delta

This section is based on (Drents Overijsselse Delta, 2016).
Dike inspection starts after reaching a certain threshold in the water level. Water board employees (experts) inspect the dikes as long as the water level is not too high. Inspection by own personnel has two advantages. First, dike managers know the weak spots, for example the dike sections vulnerable for piping. The second advantage is that dike managers have large general knowledge about failure mechanisms and dike characteristics. In summary, they have a high knowledge level. A disadvantage is that the number of experts is limited and thereby the lengths of the dikes that can be inspected. The crisis organization is visualized in Figure D.1. The dike inspectors report their findings to the Water Board Action team, then there will be decided whether or not to apply an reinforcement measure.

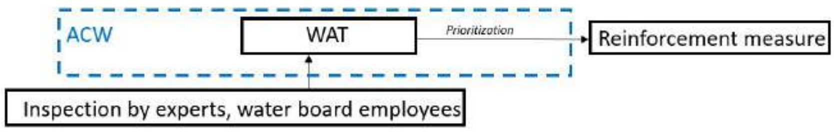


Figure D.1: Crisis organization water board Drents Overijsselse Delta phase 1.

The dike inspection is intensified when the water levels become more severe. Dike inspection will be done by volunteers. During the most profound inspection dike watches will start their inspection every four hours, they walk their dike segment back and forth. The knowledge level of the dike watches is low, based on observations during the *Deining en Doorbraak* exercise in 2017 and based on observations by Lendering et al. (2014). The crisis organization is visualized in Figure D.2. Dike watches report their findings to the dike posts, which is managed by a dike post supervisor. All these observations are forwarded to the Head Central Dike Post (HCD). Dike watches, dike post managers and HCD are all volunteers. The WAT decides where to place reinforcement measures based on the information provided by the HCD. The WBT and WOT decide on a more general level what the strategy for flood fighting is. This provides input for the WAT for prioritization of the measures to be taken.

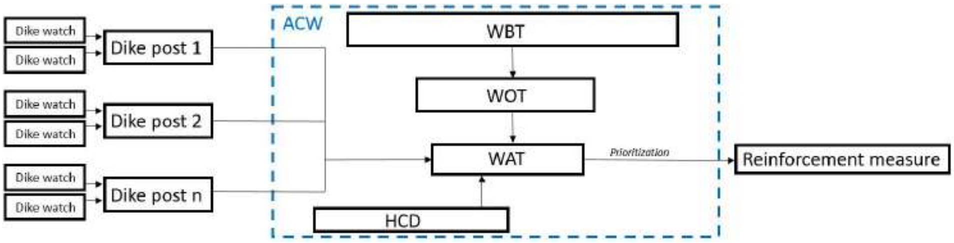


Figure D.2: Crisis organization water board Drents Overijsselse Delta phase 2.

D.3. Crisis organization water board Rivierenland

The crisis organization of water board Rivierenland is slightly different compared to water board Drents Overijsselse Delta. The total area of water board Rivierenland is divided into six sections. These six districts are managed by dike posts. When the decisions regarding reinforcement measures have little consequences (e.g. financial, legal), they can decide for themselves whether or not to apply reinforcement measures. Every dike post has their own contractors to place the measures.

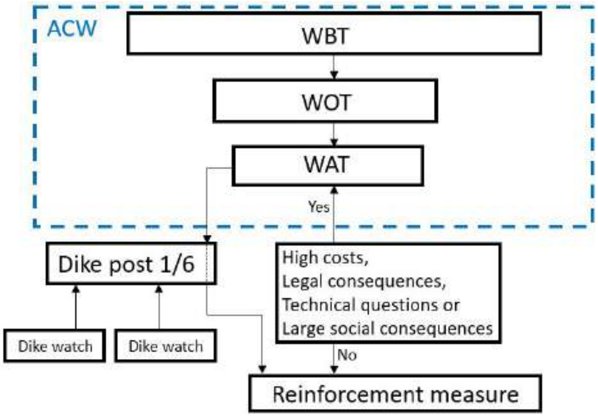


Figure D.3: Crisis organization water board Drents Overijsselse Rivierenland.

D.4. Crisis personnel

- **Water board personnel** is experienced in the application of reinforcement measures and the general characteristics and failure mechanisms of flood defences. Water board personnel also have site specific knowledge of the accessibility of specific locations. In the water boards organization there is also a differentiation in knowledge level between employees. The number of people available for the placement of reinforcement measures is however limited during high water threats.
- The **military**, genie or National Reserve (Dutch: NATRES), can be deployed in the case of imminent flood threats. An advantage of the military is that a relatively large amount of man power can be deployed in a short period of time. However, this number can also be limited when the flood threat takes place in a large area of the Netherlands, which is likely to be the case with river floods. Differentiation should be made between the genie and the National Reserve. The latter one is less trained and less specialized in hydraulic engineering related tasks.
- **Contractors** reinforce and repair the flood defences on a regular basis. During flood threats they can also be deployed to install reinforcements. Water boards often have agreements with contractors to guarantee their availability in the case of calamities (Dutch: waakvlam contracten). Contractors have the advantage that they have personnel and equipment available in the threatened areas.
- **Volunteers** can be deployed to install temporary defences or reinforcement measures. The temporary flood defence in Kampen is an example of a flood defence that is placed, in the case of a flood threat, by volunteers. The 1993 and 1995 flood threat in the Netherlands shows that people in the threatened area are willing to contribute to the flood fighting. The experience and knowledge level of these people is low, so for tasks like the distribution of sand bags they can be helpful. However, the placement of grass revetment reinforcement measures is a relatively difficult task and is therefore problematic to delegate to volunteers.

E

Monte Carlo analysis detection and placement reliability

This appendix contains the Matlab scripts of the Monte Carlo analysis for the detection (first section) and placement phase (second section).

E.1. Reliability detection phase

```
%Failure probabilities
p1=0.0; p2=0.05; p3_day=0.05; p3_night=0.5; p4=0.0225; p5=0.045; p6=0.50;

%Time related paramters
t_int       = 4;        %Inspection interval (WDOD)
time_light  = 0;        %Sunrise at 08:00
time_dark   = 16;       %Dark at 16:00 (inspection till 20:00!)
time_start  = 0;        %Start at 00:00 hour
p3 = p3_night;          %If start 00:00, 04:00, 16:00, 20:00

NoInsp = 0;Insp = 0; %Counting successful inspections versus failures
Nit = 1000000;  %Number of iterations

for i = 1:Nit
    time = time_start;
    T = 0;                      %Day time per iteration
    X = 0;                      %Stop parameter while-loop
    if p1 - rand >= 0           %Failure no inspection
        NoInsp = NoInsp + 1;
        continue
    else
        T = T + normrnd(5,1);
    end
    p3i = p3;
    if p2 - rand >= 0
        NoInsp = NoInsp + 1;
        X = X + 1;
    end
    while X==0
        if p3i - rand >= 0
            T = T + t_int;
            p3i = p3i;
        else
```

```
            X = X + 1;
            T = T + t_int/2;
            if p4 - rand >= 0           %Failure (incorrect report)
                if p6 - rand >=0
                    NoInsp = NoInsp + 1;
                else
                    Insp = Insp + 1;
                    T = T + normrnd(0.5,0.25);
                    InspT(Insp) = T;
                end
            else
                if p5 - rand >= 0       %Failure (no placement request)
                    NoInsp = NoInsp + 1;
                else
                    Insp = Insp + 1;    %Successful placement request
                    T = T + normrnd(0.5,0.25);
                    InspT(Insp) = T;
                end
            end
        end
        time = time + t_int;
        if time>23.59
            time = time - 24;
        end
        if (time>=time_light) && (time<time_dark)
            p3i = p3_day;
        else
            p3i = p3_night;
        end
    end
end
```

E.2. Reliability placement phase

```
p1 = 0.075; p2 = 0.075;  p3 = 0.015;
NoPlace = 0; Place = 0;
Nit = 100000;

for i=1:Nit
        T = 0; x = 1;
    if p1 - rand >=0
        NoPlace = NoPlace + 1;
        continue
    end
    if p2 - rand >=0
        x = normrnd(2,0.2);
    end
    T = T + normrnd(1,0.1);
    T = T + x*normrnd(0.75,0.075);
    if p3 - rand >=0
        NoPlace = NoPlace + 1;
        continue
    else
        Place = Place + 1;
        InspT(Place) = T;
    end
end
```

E.3. Emperical and theoretical fit detection phase

Empirical cumulative probability function and Gaussian approximation (p_{d1} = 0.06;p_{d2} = 0.05;$p_{d3,day}$ = 0.05;$p_{d3,night}$ = 0.5;p_{d4} = 0.225;p_{d5} = 0.45;p_{6} = 0.045; start at 08:00).

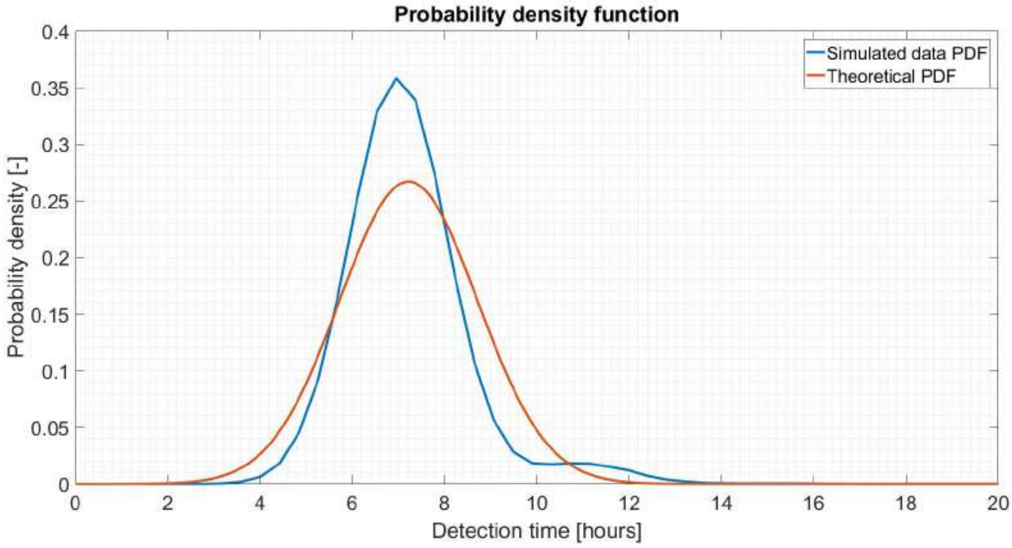


Figure E.1: Probability density function.

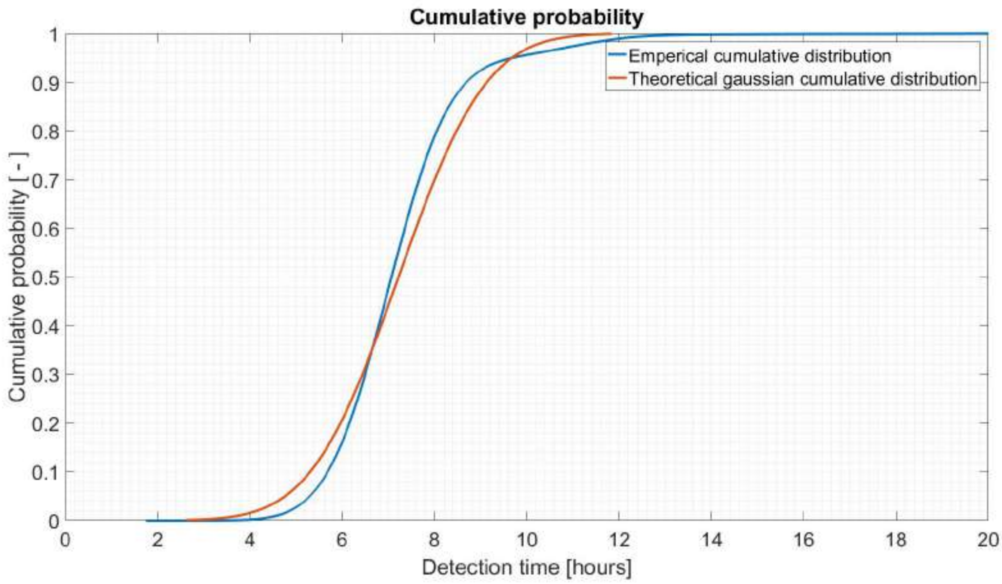


Figure E.2: Cumulative probability function.

F

Data placement phase

This appendix contains the details of the placement of six distinct grass revetment reinforcement measures as training at three different water boards.

F.1. Zendijk IJsselmuiden September 16, 2017

The first reinforcement measure can be seen in Figure F.1. The data on this placement can be seen in Table F.1. The material is transported to the site by tractor over the crest of the dike. The material used is: sand bags, steel wire, steel nails and geotextile. The reinforcement measure was placed by the NATRES, the Dutch national reserve.

Figure F.1: Reinforcement measure Zendijk

Table F.1: General information reinforcement measure Zendijk.

Location	Zendijk, IJsselmuiden	
Water board	Drents Overijsselse Delta	
Weather	Rain	Little
	Wind	Little
	View	clear
Location damage	Outer slope	
Dimensions damage	25 x 10 meter	
Revetment type	Grass	
Reinforcement measure	Type 1, see Appendix B	
Placement team	Supervisors	4
	Placement	16
Duration	1 hour	

General observations
General observations are:

- the placed geotextile was damaged, gaps were present in the textile;
- a certain number (estimated 5%) of the sand bags were damaged and still placed;
- equipment was driving on the dike crest.

F.2. Zalkerdijk, Zalk September 26, 2017

The grass revetment reinforcement measure placed on the outer slope of a grass revetment in Zalk can be seen in Figure F.2. The general information is given in Table F.2.

Figure F.2: Reinforcement measure Zalkerdijk, Zalk

Table F.2: General information reinforcement measure Zalkerdijk, Zalk.

Location	Zalkerdijk, Zalk	
Water board	Drents Overijsselse Delta	
Weather	Rain	No
	Wind	Light
	View	Clear
Location damage	Outer slope	
Dimensions damage	10x10m	
Revetment type	Grass	
Dimensions reinforcement measure	10x10m	
Reinforcement measure	Type 1, see Appendix B	
Placement team	Water board personnel	5
Duration	Loading material	15:35-16:05
	Driving time	16:10-16:35
	Placement traffic control measures	16:40-16:50
	Placement geotextile	16:50-17:00
	Placement nails and steel wire	17:00-17:20
	Placement sand bags	17:20-17:50

General observations
General observations are:

- five men to place the reinforcement measure is too little. The work is hard (placement sand bags), if more measures have to be placed during high water this might become a problem;
- personnel decide in the field how big the overlapping part should be.

F.3. Camping Haven Severingen Kampen September 27, 2017

The grass revetment reinforcement measure placed for a damaged spot nearby Kampen can be seen in Figure F.3. The specific conditions and the performance can be seen in Table F.3.

Figure F.3: Reinforcement measure Camping Haven Severingen Kampen

Table F.3: General information reinforcement measure Camping Haven Severingen.

Location	Camping Haven Severingen, Kampen	
Water board	Drents Overijsselse Delta	
Weather	Rain	No
	Wind	No
	View	Foggy
Location damage	Outer slope	
Dimensions damage	40 x 100 cm	
Revetment type	Grass	
Dimensions reinforcement measure	9 x 5 meter	
Reinforcement measure	Type 1, see Appendix B	
Placement team	Personnel water board	7
	NATRES	7
Duration	Placement team informed	06:00
	Start loading material	06:30
	Arrived at location	08:45
	NATRES arrived	09:05
	Placement textile	09:10
	Ready	10:05

General observations

General observations are:

- Water board personnel (placement team) decide for themselves whether they are allowed to drive on the crest of the dike.
- The equipment, material and personnel for the placement was based on a reinforcement measure of 100 meter due to miscommunication.

F.4. Zalkerveer, Zalk September 27, 2017

The grass revetment reinforcement measure placed for a damaged spot nearby Zalk can be seen in Figure F.4. The specific conditions and the performance can be seen in Table F.4.

Figure F.4: Reinforcement measure Zalkerveer Zalk

Table F.4: General information reinforcement measure Camping Haven Severingen.

Location	Zalkerveer, Zalk	
Water board	Drents Overijsselse Delta	
Weather	Rain	No
	Wind	No
	View	Sunny
Location damage	Outer slope	
Dimensions damage	20x5 meter	
Revetment type	Grass	
Dimensions reinforcement measure	20x5 meter	
Reinforcement measure	Type 1, see Appendix B	
Placement team	Water board personnel	5
	NATRES	10
Duration	Arrival NATRES	13:00
	Arrival WDOD personnel	13:20
	Placement geotextile	13:45
	Placement nails and steel wire	14:00
	Placement sand bags	14:35

General observations

General observations are:

- equipment standing at outer slope of the dike (normally covered with water);
- damaged sand bags are still placed (estimation 5%).

F.5. Eefde September 27, 2017

The grass revetment reinforcement measure placed for a damaged spot nearby Eefde can be seen in Figure F.5. The specific conditions and the performance can be seen in Table F.5. Observations by Eric Huijskes.

Figure F.5: Reinforcement measure Eefde

Table F.5: General information reinforcement measure Eefde.

Location	Eefde	
Water board	Rijn en IJssel	
Weather	Rain	No
	Wind	No
	View	Sunny
Location damage	Outer slope	
Dimensions damage	12x15 m, depth: 0.5 meter	
Revetment type	Grass	
Dimensions reinforcement measure	12x15 m	
Reinforcement measure	Type 1, see Appendix B	
Placement team	Water board personnel	6
Duration	Logistics material	10:30-11:45
	Start work	12:00
	Ready	13:10

General observations

General observations are:

- geotextile fixated to the dike body by sticks;
- fence poles removed before placement geotextile.

F.6. Lienden October 30, 2017

The *Rivierenland* water board exercised the placement of a grass revetment reinforcement on the outer slope of a river dike in Lienden. This river dike is recently constructed and the grass revetment is not at its desired strength. The water board and contractor exercised the placement of a grass revetment reinforcement, this measure should be placed above the water line, so before the water level rises. General information about this training can be found in Table F.6 and Figure F.6.

Figure F.6: Reinforcement measure Lienden

Table F.6: General information reinforcement measure Lienden.

Location	Lienden	
Water board	Rivierenland	
Weather	Rain	No
	Wind	No
	View	Sunny
Location damage	Outer slope	
Dimensions damage	Not applicable	
Revetment type	Grass	
Dimensions reinforcement measure	Not applicable	
Reinforcement measure	Geotextile fixated by nails	
Placement team	Contractor	7

General observations

General observations are:

- The grass revetment reinforcement measure was only fixated with nails, no sand bags were used.
- Construction from the dike crest with use of hydraulic hammers is a very quick method, however it is only possible when the dike crest is accessible with equipment.

G

Technical failure reinforcement measure

This appendix contains the derivation of the wave run down pressure force on the grass revetment reinforcement.

G.1. Wave run-down mechanism

The wave run-down on the outer slope results in an outward directed wave pressure, which can cause failure of the reinforcement measure.

G.1.1. Wave run-down

The wave run-down, see Equation G.1 is a function of the wave height and Iribarren number, see Equation G.2 (Battjes, 1974). The run-down is not very accurate, as it is ill-defined and measurements are scarce, according to Battjes (1974). The wave run-down according to the equations below is valid for individual waves.

$$R_d = H \cdot (1 - 0.4 \cdot \xi) \cdot \xi \tag{G.1}$$

$$\xi = \frac{tan\alpha}{\sqrt{H/L_0}} \tag{G.2}$$

$$L_0 = \sqrt{\frac{g \cdot T^2}{2 \cdot \pi}} \tag{G.3}$$

Where:	Rd	=	Run-down	[m]
	H	=	Wave height	[m]
	ξ	=	Iribarren number	[-]
	α_{dike}	=	Slope angle	[-]
	L_0	=	Deep water wave length	[m]
	g	=	Gravitational acceleration	[m/s^2]
	T_w	=	Wave period	[s]

G.2. Derivation water pressure

The definition of the horizontal and vertical axis can be seen in Figure G.1. The origin is situated at the dike body and point of maximum wave run-down.

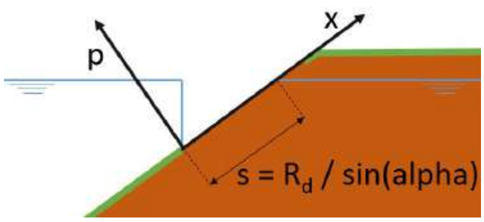


Figure G.1: Definition axis

The water pressure at the point $x = 0$ is the maximum water pressure (max wave run-down) and is equal to Equation G.4, the water pressure at point $x = s$ (still water level) is zero. The distribution of the water pressure is visualized in Figure G.2. Please notice that this is the water pressure without reduction because of leakage.

$$p_{max} = R_d \cdot g \cdot \rho_w \tag{G.4}$$

Where:				
	p_{max}	=	Maximum water pressure	[N/m^2]
	R_d	=	Wave run-down	[m]
	g	=	Gravitational acceleration	[m/s^2]
	ρ_w	=	Water density	[kg/m^3]

The distribution of the water pressure is described by the linear function given in Equation G.5 for the limits $0 < x < s$.

$$p = p_{max} - \frac{p_{max}}{s} \cdot x \tag{G.5}$$

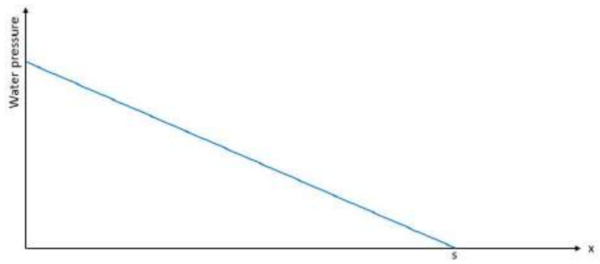


Figure G.2: Water pressure

The water pressure will in the case of a permeable geotextile not be like Figure G.2. The water pressure reduction is given by Equation G.6. The distribution of the reduction factor in x-direction can be seen in Figure G.3.

$$\alpha = exp\left(\frac{-x}{\Lambda}\right) \tag{G.6}$$

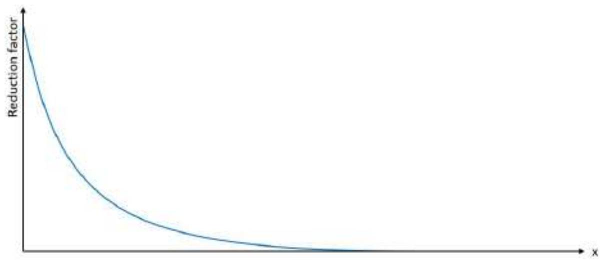


Figure G.3: Reduction factor water pressure

The resulting water pressure is the multiplication of the not reduced water pressure (Equation G.5) and the reduction factor (Equation G.6), see Equation G.7.

$$p = (p_{max} - \frac{p_{max}}{s} \cdot x) \cdot exp\left(\frac{-x}{\Lambda}\right) \tag{G.7}$$

The integration of the wave pressure gives the wave force per unit width (kN/m). The integration can be seen step by step in Equations G.8, G.9 and G.10.

$$F_{rw} = \int_0^s p dx = \int_0^s exp\left(\frac{-x}{\Lambda}\right) \cdot \left(p_{max} - \frac{p_{max}}{s} \cdot x\right) dx \tag{G.8}$$

$$F_{rw} = \left[\frac{\Lambda \cdot p_{max}}{s} \cdot (x - s + \Lambda) \cdot exp\left(\frac{-x}{\Lambda}\right)\right]_0^s \tag{G.9}$$

$$F_{rw} = \frac{\Lambda^2 \cdot p_{max}}{s} \cdot exp\left(\frac{-s}{\Lambda}\right) - \frac{\Lambda \cdot p_{max}}{s} \cdot (\Lambda - s) \tag{G.10}$$

H

Case study input

This appendix forms the basis for the case studies of Chapter 10. This appendix consists of four parts:

- In Section H.1 the input for case A.
- In Section H.2 the input parameters for case B.
- In Section H.3 more details and background on the sensitivity analysis that is carried out in Chapter 10.

H.1. Case A: known weak spot

H.1.1. General input considerations case A

The location, dimensions and characteristics of the weak spot are known in case A. Regular inspection by water board supervisors provides this information[39]. The following boundary conditions are used in case A:

Weak spot

- The known weak spot is in this case taken as 500 meter in length, a relatively large length because of the mentioned causes in Section 10.3.1. The construction rates for the four options, based on expert judgement, are given in Table H.1.

Table H.1: Potential capacity, construction rate and time needed for installation reinforcement measure. C_p = Potential capacity; n_t = Number of teams; R_t = Construction rate per team; R = Total construction rate; $T_{construction}$ = Construction time.

Performance	C_p **[m]**	n_t **[-]**	R_t **[m/h]**	R **[m/h]**	$T_{construction}$ **[h]**
Optimistic	500	5	40	200	2.5
Rivierenland	500	4	37.5	150	3.3
Drents Overijsselse Delta	500	3	17	50	10
Pessimistic	500	2	20	40	12.5

The values for the construction rates and number of teams are based on expert judgement and based on observed construction rates during exercises, see Appendix F. Please notice that only observations are available on the installation of grass revetment reinforcement measure type 1. Type 2, installed below the water line, is more difficult and less practised at the water boards. Therefore are the construction rates in this table lower than can be seen in the appendix. The difference between the *Rivierenland* and *Drents Overijsselse Delta* water board is the result of a difference in level of preparedness and exercises.

First the number of teams is estimated, a team will in general consist of 5-10 peoples. The construction rates per team are estimated based on the level of preparation and observed construction rates. The total construction rate per hour is the product of the rate per team and the number of teams.

A sensitivity analysis at the end of this case will show the importance of the numbers and how it affects the reliability of the reinforcement measures.

[39] Most of the water boards register their weak spots in an online application, the *Rivierenland* and *Aa en Maas* water board use *Vizier* as online application.

Detection phase

- Most of the detection phase is not important as the weak spot is already known. However, the decision to start the placement of the reinforcement measure has to be made, which failure probability is treated the same as the decision to start the intensified dike inspection (failure probability p_{d1} from the detection phase).
- The indications for action are considered weak for the *Rivierenland* and *Drents Overijsselse Delta* water board and for the pessimistic scenario because thresholds for inspection and installation of reinforcement measures are in most cases set for the water level, however not for the wind (waves).
- The remainder of the detection phase is not relevant (not applicable: n.a.) for case A, because the weak spot is already known. Failure probability p_{d2} till p_{d6} are therefore zero.

Placement phase

- The differences between the *Rivierenland* and *Drents Overijsselse Delta* water board are the result of the fact that placement of grass revetment reinforcement measures in the water line is practised and prepared for the *Rivierenland* water board and not at the *Drents Overijsselse Delta* water board.
- The time pressure for case A is assumed to be limited. There is time pressure because the storm is predicted and the available time is finite, however it is assumed to be manageable because the measures are probably prepared and the time pressure is more severe if the weak spot is not found yet (case B).

Required time

- The time required to install the reinforcement measure is for case A dependent on the: decision time, command time, loading time, delay time, transport time and construction time. Especially the construction time is highly dependent on the size of the damage and can thereby differ per situation. Realistic values for the time are assumed, these values can be seen in Figure H.3 and Table 10.4 . A sensitivity analysis will show for what values of the required time the effectiveness is still high.
- The difference between the *Rivierenland* and *Drents Overijsselse Delta* water board are only found in the construction time. This time is lower for the *Rivierenland* water board, because they train this measure more often and the heavy weight at the bottom end of the geotextile is already prepared to be able to roll down the geotextile down the slope.

The most important considerations for case A are listed above, the specific Performance Shaping Factors or boundary conditions can be found in Section H.1.2, H.1.3 and H.1.4 for the detection phase, placement phase and the required time respectively.

H.1.2. Detection phase

The detection phase considerations for the four different qualities are shown in Figure H.1:

Phase		Optimistic	Rivierenland	WDOD	Pessimistic
Inspection	**Decision start inspection**				
	Indications for action are weak or bad instructions	No	Yes	Yes	Yes
	Competition with other actions	Yes	Yes	Yes	Yes
	No training	No	No	No	Yes
	Relatively limited time availble for recovering of actions	Yes	Yes	Yes	Yes
	Counter intiutive action	No	No	No	No
	Bad physical condition	No	No	No	No
	Availability inspectors				
	Volunteers	n.a.	n.a.	n.a.	n.a.
	Water board personnel	n.a.	n.a.	n.a.	n.a.
	Failure comminucation				
	Communication neccesary	n.a.	n.a.	n.a.	n.a.
Detection	**Knowledge level inspector**				
	Supervisor	n.a.	n.a.	n.a.	n.a.
	District	n.a.	n.a.	n.a.	n.a.
	Dike watch	n.a.	n.a.	n.a.	n.a.
	Type of weak spot				
	Damage grass inner slope	n.a.	n.a.	n.a.	n.a.
	Damage grass outer slope	n.a.	n.a.	n.a.	n.a.
	Piping	n.a.	n.a.	n.a.	n.a.
	Macro instability	n.a.	n.a.	n.a.	n.a.
	Dimensions weak spot				
	Large	n.a.	n.a.	n.a.	n.a.
	Small	n.a.	n.a.	n.a.	n.a.
	Conditions during inspection				
	Night	n.a.	n.a.	n.a.	n.a.
	Day light, bad conditions	n.a.	n.a.	n.a.	n.a.
	Good conditions	n.a.	n.a.	n.a.	n.a.
Reporting	**Knowledge level inspector**				
	Supervisor	n.a.	n.a.	n.a.	n.a.
	District	n.a.	n.a.	n.a.	n.a.
	Dike watch	n.a.	n.a.	n.a.	n.a.
	Damage registration forms				
	Yes	n.a.	n.a.	n.a.	n.a.
	Yes but not correctly	n.a.	n.a.	n.a.	n.a.
	No	n.a.	n.a.	n.a.	n.a.
	Time pressure				
	No	n.a.	n.a.	n.a.	n.a.
	Limited	n.a.	n.a.	n.a.	n.a.
	Much	n.a.	n.a.	n.a.	n.a.
Placement decision	**Knowledge level decision maker**				
	Supervisor	n.a.	n.a.	n.a.	n.a.
	District	n.a.	n.a.	n.a.	n.a.
	Dike watch	n.a.	n.a.	n.a.	n.a.
	Standardized procedures				
	Yes	n.a.	n.a.	n.a.	n.a.
	Yes but not correctly	n.a.	n.a.	n.a.	n.a.
	No	n.a.	n.a.	n.a.	n.a.
	Time pressure				
	No	n.a.	n.a.	n.a.	n.a.
	Limited	n.a.	n.a.	n.a.	n.a.
	Much	n.a.	n.a.	n.a.	n.a.
	Failure probability detection	**0.001**	**0.01**	**0.01**	**0.05**

Figure H.1: Case A: specification detection phase.

H.1.3. Placement phase

The placement phase considerations for the four different qualities are shown in Figure H.1:

		Optimistic	Rivierenland	WDOD	Pessimistic
Placement command	**Formal procedures or work instructions are used**				
	Yes	x			
	Yes, but not correctly		x	x	
	No				x
	Complexity of the task				
	Not a complex task	x	x	x	
	The use of multiple systems at the same time				
	Multiple persons work on the same system				x
	Time pressure				
	No time pressure				
	Limited time pressure	x	x	x	x
	Much time pressure				
Loading error	**Specification of materials**				
	Type of material and quantity specified	x	x	x	
	Type of material specified				
	Type of reinforcement measure specified				x
	Time pressure				
	No time pressure	x			
	Limited time pressure		x	x	
	Much time pressure				x
	Experience and skills				
	Sufficient experience	x	x		
	Some experience			x	x
	No experience				
Construction	**Knowledge level**				
	Good	x	x		
	Average				x
	Bad			x	
	Work instructions				
	Yes	x	x		
	Yes, but not correctly				
	No			x	x
	Time pressure				
	No time pressure				
	Limited time pressure	x	x	x	x
	Much time pressure				
	Failure probability placement	**0.004**	**0.008**	**0.095**	**0.12**

Figure H.2: Case A: specification placement phase.

H.1.4. Required time

		Optimistic	Rivierenland	WDOD	Pessimistic
Detection	**Mobilisation time (t_mob)**				
	Mean	n.a.	n.a.	n.a.	n.a.
	Standard deviation	n.a.	n.a.	n.a.	n.a.
	Detection time (t_detec)				
	Inspection interval	n.a.	n.a.	n.a.	n.a.
	Number of inspections until success	n.a.	n.a.	n.a.	n.a.
	Reporting time (t_report)				
	Mean	n.a.	n.a.	n.a.	n.a.
	Standard deviation	n.a.	n.a.	n.a.	n.a.
	Decision time (t_dec)				
	Mean	0	1	1	2
	Standard deviation	0	0.2	0.2	0.4
Placement	**Command time (t_command)**				
	Mean	0.5	1	1	2
	Standard deviation	0.1	0.2	0.2	0.4
	Loading time (t_loading)				
	Mean	1	1	2	4
	Standard deviation	0.5	0.5	0.5	0.5
	Delay time (t_delay)				
	Factor (if failure p2)	2	2	2	2
	Transport time (t_transport)				
	Mean	1	1.25	1.25	1.5
	Standard deviation	0.3	0.3	0.3	0.3
	Construction time (t_construction)				
	Mean	2.5	3.5	10	12.5
	Standard deviation	0.2	0.5	1	2
	Mean (combined)	5	7.7	15.2	22.2
	Standard deviation (combined)	0.60	0.80	1.20	2.20

Figure H.3: Case A: specification time.

H.2. Case B: unknown weak spot

The location, characteristics and severity of the weak spot are unknown in advance in case B. Inspection (by volunteers) during high water is needed to find the damaged areas.

The following considerations, that influence the failure probability, are used in the effectiveness quantification in case B:

Weak spot

- A weak spot of 200 meter in length is taken for the unknown weak spot case (case B). The construction rates for the four options, based on expert judgement are given in Table H.2. The construction rate per hour (R) is assumed to be lower compared to case A because multiple smaller weak spots take more time compared to one big weak spot. Furthermore, the case B reinforcement measures are installed during more hectic conditions with probably less skilled personnel (for example contractors with limited supervision due to capacity problems).

Table H.2: Potential capacity, construction rate and time needed for installation reinforcement measure. C_p = Potential capacity; n_t = Number of teams; R_t = Construction rate per team; R = Total construction rate; $T_{construction}$ = Construction time.

Performance	C_p **[m]**	n_t **[-]**	R_t **[m/h]**	R **[m/h]**	$T_{construction}$ **[h]**
Optimistic	200	5	40	200	1
Rivierenland	200	4	30	120	1,7
Drents Overijsselse Delta	200	3	10	30	6.7
Pessimistic	200	2	5	10	20

Detection phase

- Thresholds in water level are fixed for the start of intensified dike inspection. However, the relevant scenario for grass revetment reinforcement measures is not dominated by the water level. Therefore is the indicator for failure probability p_{p1} (detection phase) *indications for actions weak* applicable.
- The conditions during inspection are probably bad, because storm is expected.
- The inspection is carried out under time pressure by dike watches (volunteers), those have a low knowledge level.
- The *Rivierenland* water board uses damage registration forms, whereas the *Drents Overijsselse Delta* water board does not.

Placement phase

- The complexity and time pressure of the task for the placement command is both for the *Rivierenland* and *Drents Overijsselse Delta* water board set to the most unfavourable conditions (Performance Shaping Factor). High water exercises show that the number of reports far exceeds the number of actual weak spots, see Chapter 5. Furthermore, the workshop revealed that water board supervisors are not in agreement on the prioritization of weak spots.
- The knowledge level of the placement team is assumed to be lower for case B compared to case A. Water boards outsource the placement of the reinforcement measures to contractors without intensive supervision of own personnel during busy conditions.
- No work instructions exist for the placement of the grass revetment reinforcement measure below the water line for the *Drents Overijsselse Delta* water board, whereas the *Rivierenland* water board does have work instructions, exercises the placement of this type of measure and have all materials prepared in one container.

Required time

- The mobilisation time, detection time[40] and reporting time are estimated based on observations at the exercises (e.g. Deining en Doorbraak).
- The fact that the prioritization is prone to errors is accounted for by taking a relatively high value for the decision and command time.
- Failure probability p_{p2} determines the failure probability of loading. A doubled transportation time is assumed if mistakes are made in the loading of materials.

The most important considerations for case A are listed above, the specific Performance Shaping Factors or boundary conditions can be found in Section H.2.1, H.2.2 and H.2.3 for the detection phase, placement phase and the required time respectively.

[40] Dependent on the detection interval and the failure probability per detection round.

H.2.1. Detection phase

Phase		Optimistic	Rivierenland	WDOD	Pessimistic
Inspection	**Decision start inspection**				
	Indications for action are weak or bad instructions	No	Yes	Yes	Yes
	Competition with other actions	Yes	Yes	Yes	Yes
	No training	No	No	No	Yes
	Relatively limited time availble for recovering of actions	No	Yes	Yes	Yes
	Counter intiutive action	No	No	No	No
	Bad physical condition	No	No	No	No
	Availability inspectors				
	Volunteers		X	X	X
	Water board personnel	X			
	Failure comminucation				
	Communication neccesary	X	X	X	X
Detection	**Knowledge level inspector**				
	Supervisor	X			
	District				
	Dike watch		X	X	X
	Type of weak spot				
	Damage grass inner slope				
	Damage grass outer slope	X	X	X	X
	Piping				
	Macro instability				
	Dimensions weak spot				
	Large	X	X	X	X
	Small				
	Conditions during inspection				
	Night				
	Day light, bad conditions	X	X	X	X
	Good conditions				
Reporting	**Knowledge level inspector**				
	Supervisor	X			
	District				
	Dike watch		X	X	X
	Damage registration forms				
	Yes	X	X		
	Yes but not correctly				
	No			X	X
	Time pressure				
	No				
	Limited				
	Much	X	X	X	X
Placement decision	**Knowledge level decision maker**				
	Supervisor	X	X	X	
	District				X
	Dike watch				
	Standardized procedures				
	Yes	X	X		
	Yes but not correctly			X	
	No				X
	Time pressure				
	No				
	Limited				
	Much	X	X	X	X
	Failure probability detection	**0.031**	**0.100**	**0.140**	**0.420**

Figure H.4: Case B: specification detection phase.

H.2.2. Placement phase

		Optimistic	Rivierenland	WDOD	Pessimistic
Placement command	**Formal procedures or work instructions are used**				
	Yes	X	X		
	Yes, but not correctly			X	
	No				X
	Complexity of the task				
	Not a complex task	X			
	The use of multiple systems at the same time				
	Multiple persons work on the same system		X	X	X
	Time pressure				
	No time pressure				
	Limited time pressure				
	Much time pressure	X	X	X	X
Loading error	**Specification of materials**				
	Type of material and quantity specified	X	X		
	Type of material specified			X	
	Type of reinforcement measure specified				X
	Time pressure				
	No time pressure				
	Limited time pressure				
	Much time pressure	X	X	X	X
	Experience and skills				
	Sufficient experience	X			
	Some experience		X		
	No experience			X	X
Construction	**Knowledge level**				
	Good	X			
	Average		X		
	Bad			X	X
	Work instructions				
	Yes	X	X		
	Yes, but not correctly				
	No			X	X
	Time pressure				
	No time pressure				
	Limited time pressure				
	Much time pressure	X	X	X	X
	Failure probability placement	**0.010**	**0.035**	**0.280**	**0.399**

Figure H.5: Case B: specification placement phase.

H.2.3. Required time

The *detection* and *placement* phase both result in a normal distributed value for the required time. These two Gaussian distributions are summed, assuming independence between these two distributions. The resulting combined mean value and standard deviation can be seen in Equation H.1 and H.2 (Dekking et al., 2005).

$$\mu_{combined} = \mu_1 + \mu_2 \tag{H.1}$$

$$\sigma_{combined} = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{H.2}$$

		Optimistic	Rivierenland	WDOD	Pessimistic
Detection	**Mobilisation time (t_mob)**				
	Mean	4	8	8	16
	Standard deviation	1	1	1	2
	Detection time (t_detec)				
	Detection time	2	2.5	2.5	4
	Reporting time (t_report)				
	Mean	0	0.5	0.5	1
	Standard deviation	0	0.1	0.1	0.2
	Decision time (t_dec)				
	Mean	1	2	2	4
	Standard deviation	0.1	0.5	0.5	1
	Mean	7	12.3	12.3	23.6
	Standard deviation	1	1.2	1.2	2.5
Placement	**Command time (t_command)**				
	Mean	0.5	1.5	2.5	4
	Standard deviation	0.1	0.3	0.5	1
	Loading time (t_loading)				
	Mean	0.5	0.5	2	3
	Standard deviation	0.1	0.1	0.2	0.3
	Delay time (t_delay)				
	Factor	2	2	2	2
	Transport time (t_transport)				
	Mean	0.5	1	1	1.5
	Standard deviation	0.05	0.1	0.1	0.2
	Construction time (t_construction)				
	Mean	1	2	7	20
	Standard deviation	0.2	0.5	1	3
	Mean	2.5	5	12.5	28.6
	Standard deviation	0.25	0.6	1.15	3.2
	Mean (combined)	9.5	17.3	24.8	52.2
	Standard deviation (combined)	1.03	1.34	1.66	4.06

Figure H.6: Case B: specification time.

H.3. Sensitivity analysis

H.3.1. Time dependency

Section 10.5.1 elaborates on the sensitivity of the time required to place the reinforcement measure on the failure probability of the flood defence. In the main report is an example calculation presented for case A. Case B shows the same phenomenon and is as additional background included in this appendix. See Figure H.7.

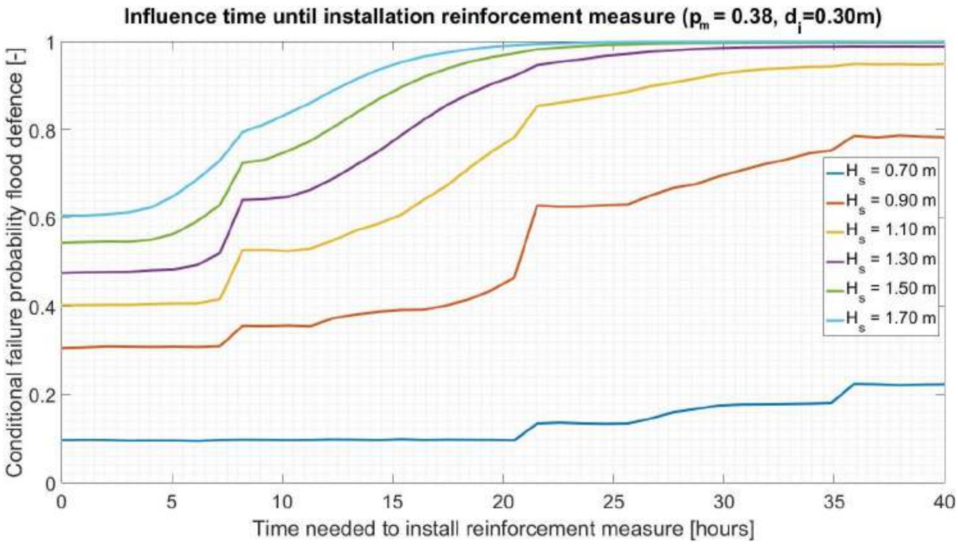


Figure H.7: Case B: Conditional failure probability for different values of application time reinforcement measure, with discretized wave height.

H.3.2. Erosion modification factor

The effect of the erosion modification factor is studied in this section. The five graphs in this section show the effect of an erosion modification factor (α_{red}) of 0, 0.10 and 0.20. Those factors do physically mean stopping of the erosion, 90% reduction and 80% reduction of the erosion speed.

The examples are based on the parameters of the *Drents Overijsselse Delta* water board scenario of case B. The failure probability of the measure (p_m) is equal to 0.38, the time needed for installation is equal to 12.8 hours. The five graphs show the result for varying initial damage depths (d_i: 0.00, 0.10, 0.20, 0.30 and 0.0 meter).

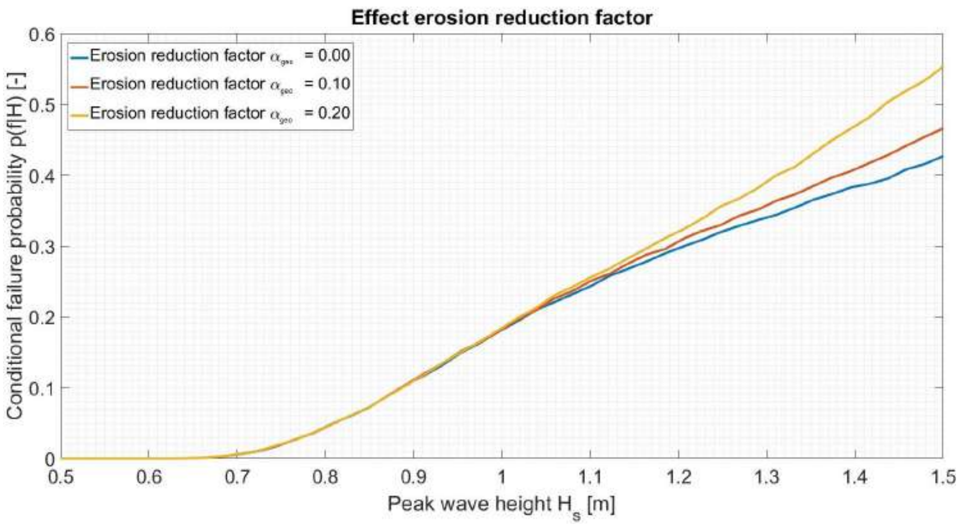


Figure H.8: Influence erosion modification factor for case B, WDOD (p_m = 0.38, T_{req} = 12.8 and d_i = 0.0).

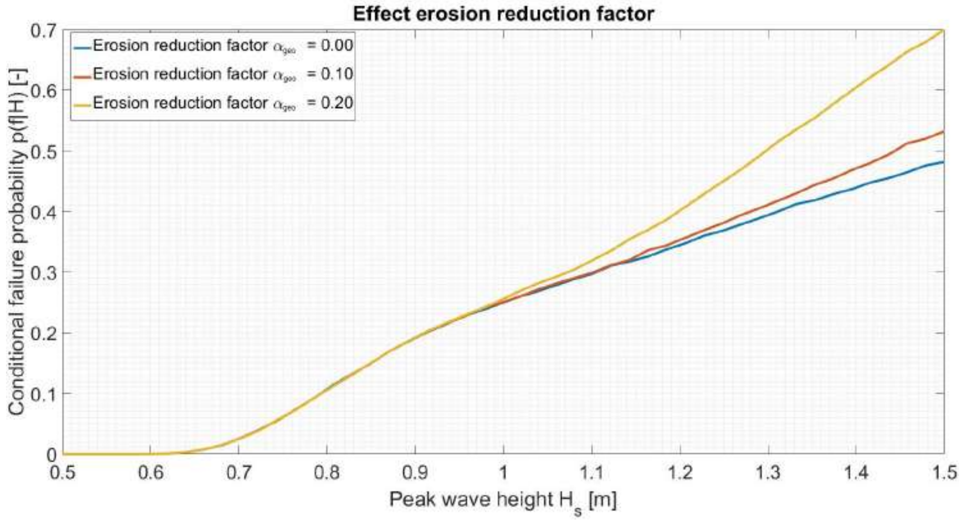


Figure H.9: Influence erosion modification factor for case B, WDOD (p_m = 0.38, T_{req} = 12.8 and d_i = 0.10).

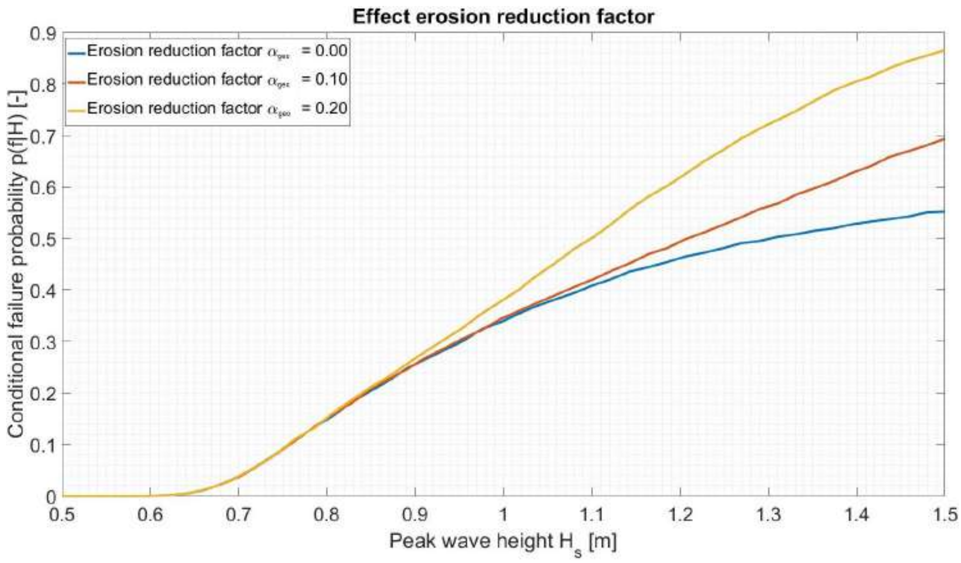


Figure H.10: Influence erosion modification factor for case B, WDOD (p_m = 0.38, T_{req} = 12.8 and d_i = 0.20).

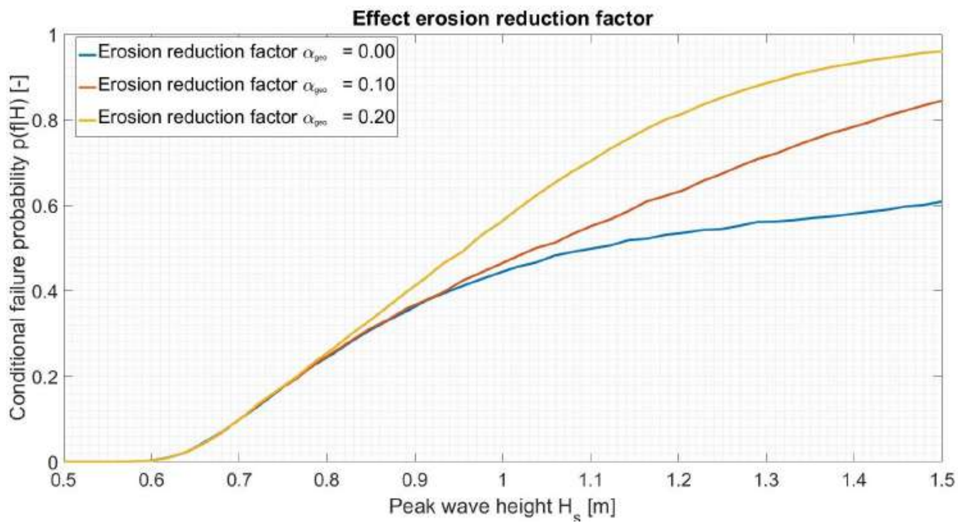


Figure H.11: Influence erosion modification factor for case B, WDOD (p_m = 0.38, T_{req} = 12.8 and d_i = 0.30).

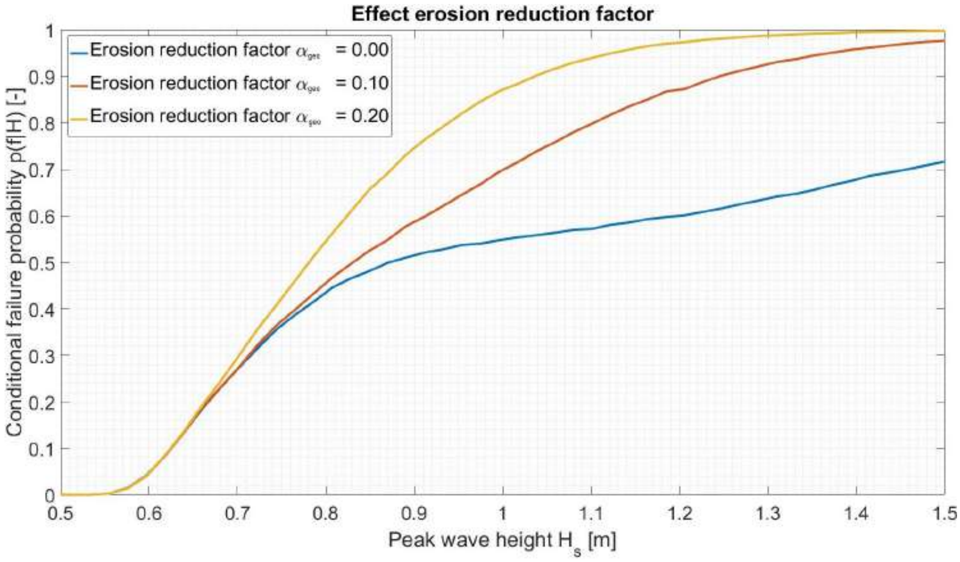


Figure H.12: Influence erosion modification factor for case B, WDOD (p_m = 0.38, T_{req} = 12.8 and d_i = 0.40).

I

Workshop reinforcement measures

This appendix consists of two parts:

- The fictitious case with questions that was used in the workshop with the water boards.
- The results of the workshop.

The participants of the workshop were:

- A01: Hoogheemraadschap De Stichtse Rijnlanden (group I)
- A02: Hoogheemraadschap Van Rijnland
- A03: Hoogheemraadschap De Stichtse Rijnlanden (group II)
- A04: Calamiteiten Team Waterkeringen (group I)
- A05: Waterschap Vallei en Veluwe
- A06: Waterschap Drents Overijsselse Delta en WTEC
- A07: Calamiteiten Team Waterkeringen (group II)
- B01: Waterschap Rivierenland
- B02: Waterschap Aa en Maas

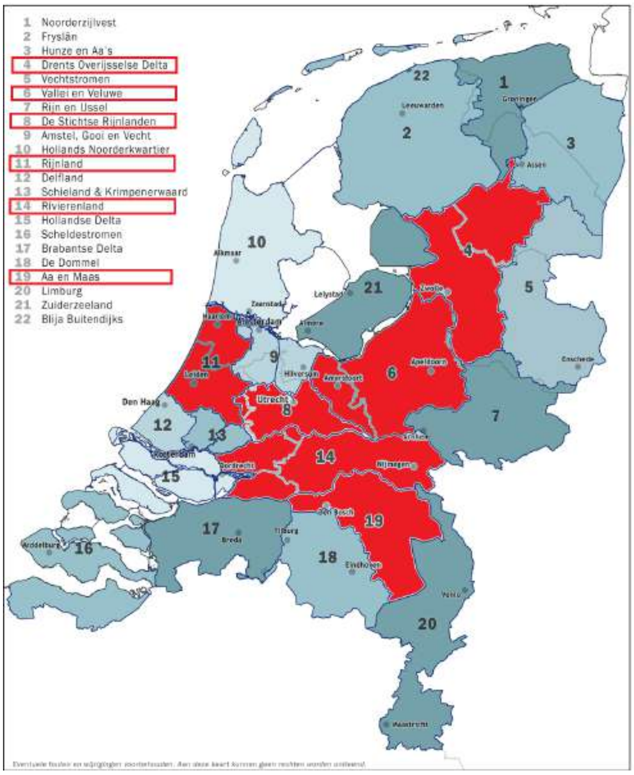


Figure I.1: Water boards that participated in the workshop.

Workshop Piping & Bekrammingen

Van elkaar leren - BEKRAMMINGEN

Workshop januari 2018

DUUR OEFENING CIRCA 1,5 uur

Deltares

Rijnland

Drents Overijsselse Delta

vallei veluwe

Aa en Maas

1

Algemene informatie

- Waterschap:……………………………………………………
- Deelnemer 1
  Naam: ……………………………………….
  Functie binnen waterschap: ……………………………………….
  Aantal jaar in dienst: ……………………………………….
- Deelnemer 2
  Naam: ……………………………………….
  Functie binnen waterschap: ……………………………………….
  Aantal jaar in dienst: ……………………………………….
- Deelnemer 3
  Naam: ……………………………………….
  Functie binnen waterschap: ……………………………………….
  Aantal jaar in dienst: ……………………………………….

2

Algemene opmerkingen voor begin workshop

- Schroom niet additionele informatie te verstrekken als bepaalde aspecten volgens u ontbreken in de vraagstelling maar wel van belang zijn.
- Gedurende 'echte' hoogwaterdreigingen zal de informatie waarop u uw keuzes baseert niet perfect zijn, dit is in de workshop ook (bewust) het geval. Denk u echter toch dat essentiele informatie ontbreekt: vraag dit dan. Deze informatie wordt met alle workshopdeelnemers gedeeld als dit nodig is.
- De incidenten in deze case zijn fictief, neem de locale omstandigheden niet mee in uw overwegingen als u deze kent.
- Houd strikt de volgorde van de slides aan! Vooruitblikken kan uw antwoorden op de vragen beinvloeden.
- Succes!

3

Inhoud workshop

1. Situatieschets
   – Verhaallijn
   – Verwachtte waterstanden
   – Weer
2. Detectiefase
   – Mobiliseren inspectieteams
   – Fysieke inspectie
   – Prioritering en beslissing plaatsing noodmaatregel
3. Plaatsingsfase
   – Opdracht tot noodmaatregel
   – Fysieke plaatsing noodmaatregel

4

Situatieschets

- Verhaallijn
- Verwachte waterstanden
- Weer (afgelopen week en voorspelling)

Voortgang – Slide 2 min – Totaal 2/90 min

Situatieschets:
verhaallijn – verwachtte waterstanden – weer

Het is 24 januari 2018.

Het is al dagen noodweer in het Rijnstroomgebied. Vooral in Duitsland regent het heel hard en dit leidt mede door de bevroren ondergrond tot snelle afstroming, toenemende rivierafvoeren en daardoor ook zeer hoge waterstanden. Verwacht wordt dat dit minimaal vergelijkbaar is met de situatie uit 1995. Daarnaast is er ook stevige wind uit zuidelijke richting, tot maximaal windkracht 8, mogelijk ook draaiend naar zuid-west.

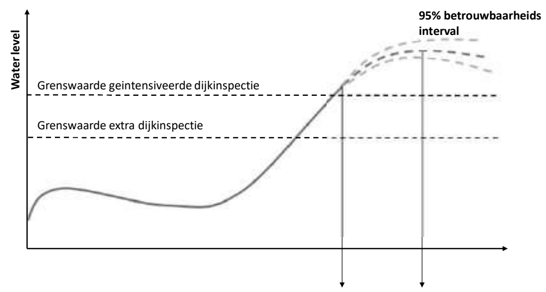
Dit heeft ook voor uw waterschap grote gevolgen. De (verwachtte) waterstanden geven voor jullie beheersgebied aanleiding tot opschalen naar de hoogste staat in (vrijwillige) dijkinspectie.

Uw waterschap heeft geen getijdeinvloed.

6

Voortgang – Slide 1 min – Totaal 3/90 min

Situatieschets:
verhaallijn – verwachtte waterstanden – weer



7

Voortgang – Slide 1 min – Totaal 4/90 min

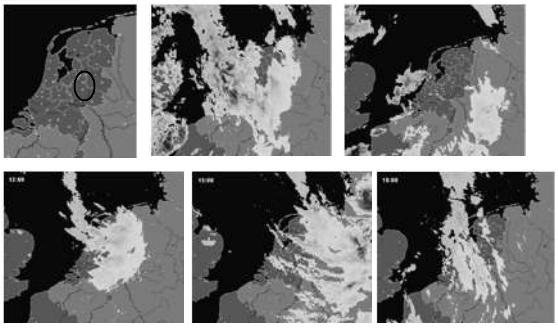
Situatieschets:
verhaallijn – verwachtte waterstanden – weer

	Do 18 Jan	Vr 19 Jan	Za 20 Jan	Zo 21 Jan	Ma 22 Jan	Di 23 Jan	Vandaag Wo 24 Jan	Do 25 Jan	Vr 26 Jan	Za 27 Jan	Zo 28 Jan
Min (°C)	1	2	2	-1	-1	0	-1	1	3	4	5
Max(°C)	5	4	5	6	6	3	2	5	2	4	2
Wind (max) Bft	2	3	3	4	6	2	8	7	6	3	2
Neerslag mm	20	5	3	15	5	4	10	8	7	2	8

8

Voortgang – Slide 1 min – Totaal 5/90 min

Situatieschets:
verhaallijn – verwachtte waterstanden – weer



9

Detectiefase

- Mobiliseren inspectieteams
- Fysieke inspectie
- Prioritering en beslissing plaatsing noodmaatregelen

10

Voortgang – Slide 3 min – Totaal 8/90 min

Detectiefase:
Mobiliseren – fysieke inspectie – prioritering + beslissing

Beslissing intensieve dijkinspectie

Op basis van welke informatie maakt u de keuze om de dijkinspectie te intensiveren? Zowel waterstanden als golfcondities kunnen van belang zijn, hier zijn veel verschillende combinaties van mogelijk. Heeft u de waardes exact bepaald of wordt op basis van engineering judgement / ervaring tijdens hoge rivierafvoeren bepaald door experts wanneer er opgeschaald wordt?

……
……
……
……
……
……
……
……
……
……

11

Voortgang – Slide 2 min – Totaal 10/90 min

Detectiefase:
Mobiliseren – fysieke inspectie – prioritering + beslissing

Uw waterschap besluit de hoogste staat in dijkinspectie uit te voeren (al dan niet met vrijwilligers).

Wie zijn uw inspecteurs? (vrijwilligers/experts/…)
……

Hoe mobiliseert u de vrijwilligers / inspecteurs? (sms, mail, …)
…………………………………………………………………………………………

Noem twee factoren die fout zouden kunnen gaan met de gebruikte methode?
1…………………………………………… 2……………………………………………

Hoe lang denkt u dat de mobilisatietijd is?
………………………………………………………

Zijn er weersomstandigheden waarbij u het risico voor de inspecteurs te groot acht ten opzichte van de baten (het opsporen van zwakke plekken) en dijkinspectie daarom annuleert?
……

12

Voortgang – Slide 2 min – Totaal 12/90 min

Detectiefase: Mobiliseren – fysieke inspectie – prioritering + beslissing

Beschikbaarheid dijkinspecteurs
Noem redenen die ervoor zouden kunnen zorgen dat uw inspecteurs niet beschikbaar zijn in uw waterschap gedurende een extreme gebeurtenis en geef een schatting van de kans dat dit voorkomt gegeven hoog water [0-100%] (expert judgement):

Oorzaak	Kans
1. Evacuatie in waterschapgebied	……….
2. Geen motivatie	……….
3. Beschermen eigen huis	……….
4. ………………………………………	……….
5. ………………………………………	……….

Voortgang – Slide 2 min – Totaal 14/90 min

Detectiefase: Mobiliseren – fysieke inspectie – prioritering + beslissing

Uw waterschap besluit de hoogste staat in dijkinspectie uit te voeren (al dan niet met vrijwilligers).
(expert judgement vraag)
Elk waterschap zal zijn eigen procedures hebben voor het mobiliseren van de dijkinspectie. Externe omstandigheden, foutieve voorspellingen of menselijke fouten kunnen leiden tot vertraging van het mobiliseren. Hoe groot acht u de kans dat er geen, 4, 8 of 16 uur vertraging ontstaat?

Vertraging [uur]	0	4	8	16
Kans [-]	……	……	……	……

Voortgang – Slide 3 min – Totaal 17/90 min

Detectiefase: Mobiliseren – fysieke inspectie – prioritering + beslissing

Extra vragen:
- Gaat u gegeven de (beperkte) informatie die u nu heeft 's nachts ook inspecteren?
  Ja / Nee
  Toelichting:
  ………………………………………………………………………………………………
  ………………………………………………………………………………………………
- Als u op basis van deze informatie deze vraag moeilijk kunt beantwoorden: wanneer wel en wanneer niet 's nachts inspecteren?
  ………………………………………………………………………………………………
  ………………………………………………………………………………………………
  ………………………………………………………………………………………………
  ………………………………………………………………………………………………
- Wat is voor uw waterschap het inspectieronde-interval (tijd)? Als dit geen vaststaand interval is, waarvoor kiest u in deze situatie?
  ………………………………………………………………………………………………
- Hoeveel km is het inspectietracject per inspectieteam?
  ………………………………………………………………………………………………

Voortgang – Slide 3 min – Totaal 20/90 min

Detectiefase: Mobiliseren – fysieke inspectie – prioritering + beslissing

Welke factoren beinvloeden volgens u de kwaliteit van de inspectie? We hebben zelf ook wat punten genoemd. Vul deze aan geef het belang aan met een score tussen 1 en 10):

- Het weer
- Tijdstip van de dag (donker of licht) → …..
- Communicatiemiddelen → …..
- Schaderegistratieformulier → …..
- Kennisniveau / ervaring → …..
- ………………………………. → …..
- ………………………………. → …..
- ………………………………. → …..
- ………………………………. → …..
- ………………………………. → …..
- ………………………………. → …..

Voortgang – Slide 3 min – Totaal 23/90 min

Detectiefase: Mobiliseren – fysieke inspectie – prioritering + beslissing

Het is 12:00 en de dijkpost is bemand en de dijkwachten beginnen te lopen.

Wat geeft de dijkpostleider aan de dijkwachten mee met betrekking tot waar ze naar moeten kijken:
- ……………………………………………..
- ……………………………………………..
- ……………………………………………..
- ……………………………………………..
- ……………………………………………..

Voortgang – Slide 4 min – Totaal 27/90 min

Detectiefase: Mobiliseren – fysieke inspectie – prioritering + beslissing

We zoomen nu in op de fysieke inspectie, in welke mate beinvloeden volgens u de onderstaande factoren of een zwakke plek wel of niet gevonden wordt? (Vul aan en geef het belang aan met een score tussen 1 en 10):
- Kennisniveau/ervaring → ………………………………………………
- Type zwakke plek → ………………………………………………
- Werkcondities (bijv. het weer) → ………………………………………………
- ………………………… → ………………………………………………
- ………………………… → ………………………………………………

Als de zwakke plek gedetecteerd wat is volgens u van belang voor een succesvolle communicatie van de observaties naar de verantwoordelijken? (vul aan en geef het belang aan met een score tussen 1 en 10):
- Kennisniveau/ervaring → ………………………………………………
- Schaderegistratieformulieren → ………………………………………………
- Tijdsdruk → ………………………………………………
- ………………………… → ………………………………………………
- ………………………… → ………………………………………………

Voortgang – Slide 3 min – Totaal 30/90 min

Detectiefase:
Mobiliseren – fysieke inspectie – prioritering + beslissing

We zoomen verder in op de typen zwakke plekken. Niet elke zwakke plek zal dezelfde moeilijkheidsgraad hebben van detectie. Verdeel 100 punten over de onderstaande typen zwakke plekken naar moeilijkheid van detecteren gegeven de weersomstandigheden (van de voorgaande dagen).

- Lokale schade aan bekleding binnentalud → ....
- Lokale schade aan bekleding buitentalud → ....
- Piping → ....
- Macro instabiliteit → ....
- Micro instabiliteit → ....

19

Voortgang – Slide 1 min – Totaal 31/90 min

Detectiefase:
Mobiliseren – fysieke inspectie – prioritering + beslissing

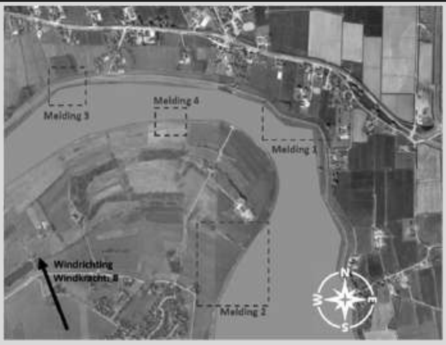
Voor een kaart met de meldingen: zie volgende pagina.

- Melding 1.
  - Golven slaan tegen dijk. Grote stukken graszode weggeslagen over 100 meter lengte op het buitentalud. Geen zandkern zichtbaar.
- Melding 2.
  - Overslag over een traject van ongeveer 200 meter. Hele kleine volumes, we kunnen er nog prima lopen. Wel wat beginnende schade (10 cm breedte) langs een trap in het binnentalud.
- Melding 3.
  - Boomstam beschadigt talud, te zwaar om te verwijderen door de vrijwilligers.
- Melding 4.
  - Dierschade, graving 40 bij 40 cm. Gedeeltelijk onder waterlijn, diepte moeilijk in te schatten, lijkt zand uit te spoelen.

20

Voortgang – Slide 1 min – Totaal 32/90 min

Detectiefase:
Mobiliseren – fysieke inspectie – prioritering + beslissing



21

Voortgang – Slide 5 min – Totaal 37/90 min

Detectiefase:
Mobiliseren – fysieke inspectie – prioritering + beslissing

Maak een prioritering, geef het faalmechanisme aan en motiveer je keuze:

Prioritaire locatie 1: ....
....
....

Prioritaire locatie 2: ....
....
....

Prioritaire locatie 3: ....
....
....

Prioritaire locatie 4: ....
....
....

22

Plaatsingsfase

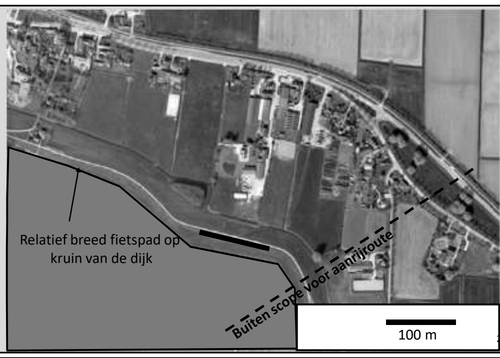
- Opdracht tot noodmaatregel
- Fysieke plaatsing noodmaatregel

Het voorgaande vraagstuk diende om het aspect prioritering te beschouwen. In het vervolg van deze casus gaat u verder met melding 1, ongeacht uw prioritering om een uniforme casus te houden voor alle deelnemende partijen.

23

Voortgang – Slide 1 min – Totaal 38/90 min

Plaatsingsfase:
Extra informatie melding 1



24

Voortgang – Slide 1 min – Totaal 39/90 min

Plaatsingsfase: Extra informatie melding 1

Voortgang – Slide 2 min – Totaal 41/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

Melding 1 wordt nu behandelt. Schadebeeld en bijbehorende faalmechanisme zijn hiervoor dus vastgesteld. Welke factoren spelen nu een rol om er voor te zorgen dat de juiste maatregel wordt vastgesteld?

- ………………………………………………………………………………………………………
- ………………………………………………………………………………………………………
- ………………………………………………………………………………………………………
- ………………………………………………………………………………………………………
- ………………………………………………………………………………………………………
- ………………………………………………………………………………………………………

Voortgang – Slide 4 min – Totaal 45/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

Kies de maatregel. Beschrijf in detail wat de maatregel is? Maak eventueel schetsen)

……
……
……
……
……
……
……
……

Voortgang – Slide 2 min – Totaal 47/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

Welke factoren spelen nu een rol om er voor te zorgen dat deze maatregel vervolgens snel en effectief wordt ingezet?En welke zijn met name van doorslaggevende aard vul aan en geef het belang aan met een score tussen 1 en 10:

- Invloed op mogelijk andere faalmechanismen → …..
- Beschikbaarheid van de maatregel → …..
- Bereikbaarheid → …..
- Tijd om het te realiseren (beschikbaar vs nodig) → …..
- ………………………………………… → …..
- ………………………………………… → …..
- ………………………………………… → …..
- ………………………………………… → …..
- ………………………………………… → …..

Voortgang – Slide 2 min – Totaal 49/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

U geeft opdracht tot het plaatsen van de noodmaatregel.

Wie plaatst voor uw waterschap de noodmaatregel? Ga ervan uit dat de werkdruk voor uw waterschap hoog is)

a. een aannemer, dit is normale procedure
b. een aannemer, omdat de werkdruk hoog is
c. eigen (buiten)personeel, dit is normale procedure
d. vrijwilligers
e. andere optie, namelijk:……………………………….

Hoe schat u de kennis en ervaring van degenen die de maatregel plaatsen in?

……
……
……
……

Voortgang – Slide 2 min – Totaal 51/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

Hoe is de communicatie tussen degenen die beslissen tot het plaatsen van een noodmaatregel en uitvoerenden?

……
……
……
……

Noem de factoren die van belang zijn voor een succesvolle communicatie

……
……
……
……

Voortgang – Slide 2 min – Totaal 53/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

U geeft opdracht tot het plaatsen van de noodmaatregel.

Wie heeft de supervisie gedurende de plaatsing?

a. een aannemer, dit is normale procedure
b. een aannemer, omdat de werkdruk hoog is
c. één van de keringsbeheerders, maar hij is niet continue aanwezig
d. één van de keringsbeheerders, en hij is continue aanwezig
e. andere optie, namelijk:……………………………

Hoe schat u de kennis en ervaring van de supervisie in?
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………

31

Voortgang – Slide 4 min – Totaal 57/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

In welke mate specificeert u als *opdrachtgever voor het plaatsen van de noodmaatregel* de volgende aspecten en hoe verhoudt zich dit met de kennis en ervaring van het plaatsingsteam/supervisors (Opmerking: u hoeft wellicht minder te specificeren als er veel ervaring aanwezig is bij het plaatsingsteam)

1. Het materieel en materiaal dat meegenomen moet worden voor het plaatsen van de maatregel?
(Voorbeeld: alleen maatregel gespecificeerd / maatregel + materialen en hoeveelheden gespecificeerd etc.)
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
2. De route naar de plaatsingslocatie
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
3. Werkwijze voor de plaatsing
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………

32

Voortgang – Slide 3 min – Totaal 60/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

Wat heeft u met betrekking tot de door u gekozen maatregel voorbereid in de *koude fase*?
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………

Wat gaat u tijdens het hoogwater bepalen?
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………

33

Voortgang – Slide 5 min – Totaal 65/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

Welke materialen en in welke hoeveelheid heeft u nodig voor het plaatsen van de noodmaatregel?
- ……………………… Hoeveelheid ………………………
- ……………………… Hoeveelheid ………………………
- ……………………… Hoeveelheid ………………………
- ……………………… Hoeveelheid ………………………
- ……………………… Hoeveelheid ………………………

Hoeveel en welke personen mobiliseert u in een realistisch optimaal scenario gegeven deze case?
- ……………………… Taak ……………………… Aantal ……..
- ……………………… Taak ……………………… Aantal ……..
- ……………………… Taak ……………………… Aantal ……..
- ……………………… Taak ……………………… Aantal ……..

34

Voortgang – Slide 5 min – Totaal 70/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

Met betrekking tot de materialen die u zojuist heeft gespecificeerd. Hoeveel heeft u daar nu van in voorraad en hoeveel verwacht u dat externe partijen u kunnen leveren tijdens extreme gebeurtenissen.

Waterschap
- ……………………… Hoeveelheid ………………
- ……………………… Hoeveelheid ………………
- ……………………… Hoeveelheid ………………
- ……………………… Hoeveelheid ………………
- ……………………… Hoeveelheid ………………

Externe partijen
- ……………………… Hoeveelheid ………………
- ……………………… Hoeveelheid ………………
- ……………………… Hoeveelheid ………………
- ……………………… Hoeveelheid ………………
- ……………………… Hoeveelheid ………………

35

Voortgang – Slide 4 min – Totaal 74/90 min

Plaatsingsfase: Opdracht tot noodmaatregel – fysieke plaatsing

Wat is volgens u van belang om zeker te zijn dat de juiste materialen getransporteerd worden naar de locatie waar de noodmaatregel geplaatst wordt?
(geef het belang aan met een score tussen 1 en 10):

- Materialen+hoeveelheden gespecificeerd → ………………
- Kennis+ervaring → ………………
- Tijdsdruk → ………………
- ………… → ………………
- ………… → ………………
- ………… → ………………
- ………… → ………………
- ………… → ………………
- ………… → ………………

36

Voortgang – Slide 3 min – Totaal 77/90 min

Plaatsingsfase:
Opdracht tot noodmaatregel – fysieke plaatsing

Hoe transporteert u de materialen naar de locatie? (gegeven de case en de extra informatie m.b.t. melding 1) Vermeld in ieder geval met welk materieel u over welke wegen rijdt.
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………

Voortgang – Slide 5 min – Totaal 82/90 min

Plaatsingsfase:
Opdracht tot noodmaatregel – fysieke plaatsing

Beschrijf in detail hoe u de maatregel aan gaat brengen, welke personen dit doen en welk materieel ze gebruiken. Maak eventueel schetsen.
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………

Voortgang – Slide 2 min – Totaal 84/90 min

Plaatsingsfase:
Opdracht tot noodmaatregel – fysieke plaatsing

Vragen

1. Hoe wordt gecommuniceerd dat de maatregel (succesvol) geplaatst is?
   ……………………………………………………………………………………………
2. Wordt de maatregel gecontroleerd? En zo ja: door wie?
   ……………………………………………………………………………………………
3. Als de maatregel geplaatst is: waar let u op als u de maatregel inspecteert? Of geeft u de (vrijwillige) dijkinspectie instructies om te letten op bepaalde aspecten?
   ……………………………………………………………………………………………

Voortgang – Slide 2 min – Totaal 86/90min

Plaatsingsfase:
Opdracht tot noodmaatregel – fysieke plaatsing

Hoeveel tijd denkt u nodig te hebben voor:

1. Het laden van de materialen nodig voor de plaatsing van de noodmaatregel?…………………………………………………………………
2. Het transport naar de locatie (neem een voor uw waterschap realistische afstand tussen de locatie waar de materialen opgeslagen liggen en een locatie op een dijk)……………………………………………
   ……………………………………………………………………………………………
   ……………………………………………………………………………………………
3. De plaatsing van de noodmaatregel……………………………………………
   ……………………………………………………………………………………………
   ……………………………………………………………………………………………
   ……………………………………………………………………………………………

Voortgang – Slide 4 min – Totaal 90/90min

Plaatsingsfase:
Opdracht tot noodmaatregel – fysieke plaatsing

Vul de onderstaande tabel in met uw kwalitatieve inschatting: hoog/middel/laag/geen (*Ga uit van hoogwater in het gehele rivierengebied*)

	Waterschap personeel	Militairen		Aannemers	Vrijwilligers
		NATRES	GENIE		
Betrouwbaarheid beschikbaarheid tijdens hoogwater					
Aantal beschikbaar tijdens hoogwater					
Kennis noodmaatregelen					
Gebiedsspecifieke kennis					
Algemene kennis waterbouwkunde					

Resultaten

Deelvraag 1. Beslissing intensieve dijkinspectie: Op basis van welke informatie maakt u de keuze om de dijkinspectie te intensiveren?

A01	A02	A03	A04	A05	A06	A07	B01	B02
1.Waterstand Conform CBP (Lobith en lokaal). 2. Toestand van de keringen. 3. Expert Judgement	1.Verwachtingen 2. Neerslag. 3. Singalen uit veld of burgers 4. Calamiteitenplan (opschaalcriteria).	1.Standaard Lobith peil. 2. Indien nodig wordt hiervan afgeweken.	1.Draaiboek. 2.Risicoinschatting. 3.Verwachting-En. 4. Situatie binnenwater-stand	1.Ccriteria in CBP, Hoogwater-erwachting Lobith. Grip 1. Beperkt Grip 2. Volledig. Randmeren: Oploop-verwachting	1.Websites RWS / Rijn Duitsland. 2. In gecoordineerd overleg wordt bepaald of opgeschaald wordt. 3.Als het overzicht weg is.	1.Exacte waarden Expert judgement 2.Speciale aandacht nieuwe dijken die nog niet op sterkte zijn. 3.Beheer-aandachts-locaties	Hoogwaterstanden conform calamiteiten plan hoogwater rivier.	1.De niveaus waarop wordt opgeschaald zijn numeriek vastgesteld. 2.Oren en ogen op de dijk. 3.Gegeven weerprognose

Deelvraag 2. Uw waterschap besluit de hoogste staat in dijkinspectie uit te voeren (al dan niet met vrijwilligers).

Vragen	A01	A02	A03	A04	A05	A06	A07	B01	B02
Wie zijn uw inspecteurs?	Medewerkers zonder crisis-rol	Waterkeringsysteembeheerder	Getrainde collegas	Vrijwilligers, objectdeskundigen en experts	Medewerkers beheer&onderhoud + kantoorpers.	Vrijwillige dijkwacht	Eigen mensen en vrijwilliger	Vrijwilligers+ eigen personeel	≈100 mede-werkers. 25 burgers en 6 experts.
Hoe mobiliseert u de inspecteurs?	Mail, met spoed bellen	Mail + telefoon en voorwaarschuwingen	Mail of telefoon	Bellen	App allarmeringen + bellen	SMS	Whatsapp	Mail/telefoon.	Mail, eventueel telefoon.
Noem twee factoren die fout zouden kunnen gaan met de gebruikte methode?	Te weinig mensen beschikbaar of mail niet lezen	1.Grootschalige uitval energie of netwerk	Geen reactie of telefoon niet aan.	Bereikbaarheid mensen.	1.Deskundigheid kantoorpersoneel. 2.Ijzel en files	1.Te late berichtgeving. 2.Systeem behelst met oproepen werkt niet mee	1.Geen verbinding	Verkeerd telefoobnnummer. Uitval telefoonnet.	Uitval ICT. Mensen op vakantie.
Hoe lang denkt u dat de mobilisatietijd is?	4 uur	2 uur	2(4 teams)-24 (volledig dijkleger) uur	6 uur	4 uur	1 dag	4 uur	c.a. 4 uur.	Tussen de 3 en 24 uur. 3=20%. 24=80%.
Zijn er weersomstandig-heden waarbij u niet inspecteert gezien het risico?	Onweer of hevige storm	Extreme wind of neerslag	Onweer of zware storm 9+	Niet veilig kunnen werken of er niet kunnen komen	Onweer, extreme ijzel	Bij slechte omstandigheden met defensie. Nog niet meegemaakt	Ja, extreme wind en onweer	Windkracht orkaan/storm, geen lopende inspectie.	Nee, tenzij veiligheidsregio bepaalt dat het te gevaarlijk is.

Deelvraag 3: Beschikbaarheid dijkinspecteurs.Noem redenen die ervoor zouden kunnen zorgen dat uw inspecteurs niet beschikbaar zijn in uw waterschap gedurende een extreme gebeurtenis en geef een schatting van de kans dat dit voorkomt gegeven hoog water [0-100%] (expert judgement):

Oorzaken	A01	A02	A03	A04	A05	A06	A07	B01	B02
Evacuatie waterschapsgebied		1%	10%	5%	10%	10%	5%	10%	10%
Geen motivatie	1%	5%	70%	0%	1%	40%	10%	0%	5%
Beschermen eigen huis		<5%	40%	20%	10%	5%	5%	30%	10%
Vakantie					10%				
Beschikbaarheidsregeling					10%				
Andere werkzaamheden				20%					
Beschermen dierbaren			60%	10%-40%					
Epidemie	1%		30%					10%	
Inzet bij andere waterschappen		5%							
Verkeer					15%		5%	10%	5%

Deelvraag 4: Elk waterschap zal zijn eigen procedures hebben voor het mobiliseren van de dijkinspectie. Externe omstandigheden, foutieve voorspellingen of menselijke fouten kunnen leiden tot vertraging van het mobiliseren. Hoe groot acht u de kans dat er geen, 4, 8 of 16 uur vertraging ontstaat?

Vertraging	A01	A02	A03	A04	A05	A06	A07	B01	B02
0 uur	0%	100%	80%	10%	95%	70%	50%	90%	20%
4 uur	0%	<10%	10%	60%-80%	90%	20%	10%	10%	50%
8 uur	0%	<1%	5%	30%-50%	25%	5%	5%	0%	20%
16 uur	0%	<1%	0%	10%-50%	5%	0%	1%	0%	10%

Deelvraag 5: vragen dijkinspectie

Vertraging	A01	A02	A03	A04	A05	A06	A07	B01	B02
Gaat u 's nachts inspecteren?	Ja	Nee	Ja	Ja/nee	Ja	Ja	Ja	Alleen per auto, niet te voet.	Ja, nadruk op monitoren.
Waarom?	Rijdende inspectie	Te weinig zicht. Alleen plekken waar acuut gevaar is.	Alleen specifieke plekken	Aleen serieuze dreigingen die bekend zijn monitoren	Met name bekende schades monitoren	Voor helder beeld	De baten zijn groter dan de kosten		
Inspectie interval?	4x per dag	Continue, voor dit waterschap slechts enkele locaties	Rijdend 2x-4x-6x per dag. Lopend 1x-2x-4x per dag	1-4 overdag	2 a 3 uur	2x daags	1a2x per 24 uur	12 uur	Nu 12 uur, toekomst 8 uur.
Aantal km inspectietraject per team	2.5x2 heen en weer	n.v.t.	2.5-3 km heen en terug	Niet gedefinieerd	2km	2x5 heen en weer	10km per dag	10 km rivier. 5 km delta	c.a. 10 km

Deelvraag 6: vragen dijkinspectie: Welke factoren beinvloeden volgens u de kwaliteit van de inspectie? We hebben zelf ook wat punten genoemd. Vul deze aan geef het belang aan met een score tussen 1 en 10):

Vertraging	A01	A02	A03	A04	A05	A06	A07	B01	B02
Weer	7.5	6	4	9	9	3	6	8	7
Tijdstip vd dag (donker/licht)	9	8	8	9	10	5	8	9	10
Communicatiemiddelen	9	2	9	8	8	7	8	9	6
Schaderegistratieformulieren	8	2	4	6	6	6	7	10	8
Kennisniveau/ervaring	7	8	8	8	7	7	8	9	9
Bereikbaarheid locatie	7.5 (?)			9			8		
Conditie inspecteur	7.5			8		6			
Gebiedskennis					5				
Waterstanden rivier	4.5								
Beschikbaarheid dijkwachten + leiders	8								
Eten en drinken	9								

Deelvraag 7: Het is 12:00 en de dijkpost is bemand en de dijkwachten beginnen te lopen. Wat geeft de dijkpostleider aan de dijkwachten mee met betrekking tot waar ze naar moeten kijken:

A01	A02	A03	A04	A05	A06	A07	B01	B02
Reeds geconstateerde schades	Overslag	Locatie Specifieke zaken	Eigen veiligheid	Veiligheid	Erosiebestendig-heid grasmat	Kritische aspecten uit verleden	Historische punten.	Weer
Faalmechanismen	Piping		veiligheidsmiddelen	Traject	Grasmat kwaliteit	Info vanuit omgeving/derden	Inspectie monitoring eventueel schadebeelden.	Veiligheid
Veiligheidsinstructie	Vervorming		Te verwachten faalmechanismen	Waar op te letten	Uittredend waterr	Hele profiel inspecteren	Veiligheid.	Aandacht spunten
Communicatie do's en don't	Verweking		Te inspecteren vakken	Omstandigheden		Risicovolle zaken direct melden	Communicatie	
Communicatie media/omgeving	Waterstand		Hoe registreren, wat ze moeten meleden en hoe	Ontwikkelingen		Veiligheid	Huidige en toekomstig waterbeeld.	
				Hoe laat terug melden				

Deelvraag 8. We zoomen nu in op de fysieke inspectie, in welke mate beinvloeden volgens u de onderstaande factoren of een zwakke plek wel of niet gevonden wordt? (Vul aan en geef het belang aan met een score tussen 1 en 10):

Aspect	A01	A02	A03	A04	A05	A06	A07	B01	B02
Kennisniveau / ervaring	9	8	7	10	8	8	8	9	10
Type zwakke plek	9	8	8	8	7	8	6	8	7
Werkcondities	8	6	4	9	10	6	7	9	8
Begroeiing of bebouwing	9						8		
Dag/nacht			8						7
Waterstand/golven					9				
Hulpmiddelen (digigids					6				
Gebiedskennis						8			
Bereikbaarheid							8		7

Als de zwakke plek gedetecteerd wat is volgens u van belang voor een succesvolle communicatie van de observaties naar de verantwoordelijken?

Aspect	A01	A02	A03	A04	A05	A06	A07	B01	B02
Kennisniveau / ervaring	8	8	10	10	9	9	8	9	10
Schaderegistratieformulieren	5	7	3	8	6	9	8	10	10
Tijdsdruk	7	7	7	6-9	8	6	6	8	10
App	9								
Middelen	9								
Eenduidige termen		7							
Comm. midellen		7			7				7
Terugkoppeling				10					
Hulpmiddelen					10		9		
Uniformiteit							8		

Deelvraag 9. We zoomen verder in op de typen zwakke plekken. Niet elke zwakke plek zal dezelfde moeilijkheidsgraad hebben van detectie. Verdeel 100 punten over de onderstaande typen zwakke plekken naar moeilijkheid van detecteren gegeven de weersomstandigheden (van de voorgaande dagen).

Aspect	A01	A02	A03	A04	A05	A06	A07	B01	B02
Locale schade bekleding binnentalud	5	10	0	15	15	20	5	10	10
Locale schade bekleding buitentalud	20	10	10	40	25	10	15	20	20
Piping	50	20	20	20	20	30	35	10	40
Macroinstabiliteit	20	30	50	20	15	30	25	40	10
Microinstabiliteit	5	30	20	5	25	10	20	20	20

Deelvraag 10. Maak een prioritering, geef het faalmechanisme aan en motiveer je keuze:

Aspect	A01	A02	A03	A04	A05	A06	A07	B01	B02
Prioriteit 1	4	4	4	1	4	1	2	1	4
	Zanduit-spoeling onduidelijk wat gaande is	Piping	Uitspoeling zand	Flinke beschadiging en hoogste waterstand moet nog komen.	Graverij, macrostabiliteit zandkern loopt vol, buitentalud schuift af.	Zode is al weg, geen bekleding. Verdere afslag talud.	Stabilteit en erosie bij overlsag. Dichtst bij doorbraak is grote gevolgen.		Stabiliteit
Prioriteit 2	2	3	1	4	1	4	1	3	1
	Veel tijd nodig voor maatregelen en wanneer spoelgat ontstaat gaat het snel	Macro buiten	Buitentalud bekleding beschadigd	Grote strijklengte, HW neemt toe (rest toelichting onleesbaar)	Golven schade grasmat, macrostabiliteit : talud erodeert.	Afslag van het talud, het is niet zichtbaar dus lastig.	Erosie buitentalud, grote schade.		Erosie buitentalud + afschuiving
Prioriteit 3	1	1	2	2	3	2	4	4	2
	Actie gewenst maar nog wat kleidek over	Macro buiten	Tijd om overslag te verminderen met zandzak ophoging		Boomstam, kale plek, schade grasmat, erosie talud.	Bij trap erosiebestendigheid kwetsbaarder.	Erosie buitentalud, beperkte locale schade.		Erosie buitentalud
Prioriteit 4	3	2	3	3	2	3	3	2	3
	Zolang hij geen schade oplevert niet acute prio	OVerslag	Later op de dag met kraan verwijderen	Verhoogte freatische lijn.	Kleine schade trap, locale schade. Binnentalud, erosie.	Talud beschadigd.	Erosie buitentalud, beperkte schade, nog geen gat.		Overslag erosie binnentalud

Deelvraag 11. Melding 1 wordt nu behandeld. Schadebeeld en bijbehorende faalmechanisme zijn hiervoor dus vastgesteld. Welke factoren spelen nu een rol om er voor te zorgen dat de juiste maatregel wordt vastgesteld?

A01	A02	A03	A04	A05	A06	A07	B01	B02
In hoeverre sprake is van	Goede waarneming,	Bereikbaarheid	Bereikbaarheid ter plaatse	Kennis dijkopbouw	Je kunt niet alles goed zien.	Bereikbaarheid materieel en materialen	Inschatting afmetingen scahde en eventuele gevolgen.	Afmetingen
	Kennis inspecteur	Omvang schade	Materieel voorhanden.	Snelheid verergering	Watesrtabdeb.	Weersomstandigheden		Locatie

zuiduit-spoeling								
In hoeverre sprake is van verweking	Kennis over opbouw van kering	Peilsteiging waken	Materiaal voorhanden,.	Weers-verwachting	Bereikbaarheid rijplatenbaan deel zode weggeslagen	Omvang schade.	Opbouw materialen kering.	Dijkopbouw
	Toetsresultaten		Mensen gewend om in omstandigheden veilig te werken,	Bereikbaar-heid	Of bekramming voorradig is.			Bereikbaarheid
	Eenduidige overdracht inspectieresultaat				Type dat met gewicht omdat het onder de waterlijn moet uitkomen			Weersomstandig heden.

Deelvraag 12: kies de maatregel. Beschrijf in detail wat de maatregel is? Maak eventueel schetsen)

A01	A02	A03	A04	A05	A06	A07	B01	B02
Met dicht zeil inpakken, zandzakken in grate gaten, afdekken met landbouwfolie en dichtkrammen. Versterken met zandzakken en balk onder zandzakken voor stevigheid.	Verzwaard (onderzijde) doek aanbregen vanaf kruin, afrollen over buitentalud. Verzwaren met zandzakken tegen wegwaaiien. Vastzetten met pennen/krammen .	Opvullen gaten met zakken. Doek verticaal aanbrengn. Overlappen doek. Doek vastzettten met balken en krammen. Verwaren met zandzakken. Vastzetten met krammen.	Geotextiel + rocks 10-60 kg.	Steunberm aanbrengen en inpakken buitentalud.	Bekramming met buizen aan onderzijde in talud waar graszode weg is kan men geen pennen slaan doek moet door gewicht omlaag hangen van bovenaf met pennen vastzetten.	Aanbrengen doek incl verzwaring (zandzakken + stortsteen. Dakpansgewijs aanbrengen.	Aanbrengen waterdoorlaten doek met dijkpennen en zandzakken. Onderin doek zit stalen pijp.	Om de beschadigde kleilaag te beschermen. Om erosie te voorkomen: grof puin storten. Indien ontoereikend: binnendijks een berm tot kruin.

Deelvraag 13: welke factoren spelen nu een rol om er voor te zorgen dat deze maatregel vervolgens snel en effectief wordt ingezet?En welke zijn met name van doorslaggevende aard vul aan en geef het belang aan met een score tussen 1 en 10:

Aspect	A01	A02	A03	A04	A05	A06	A07	B01	B02
Invloed op andere faalmech.	9	4	3	9	9	5	8	2	7
Beschikbaarheid vd maatregel	7	8	6	7	8	8	8	8	10
Bereikbaarheid	8	10	4	9	6	8	8	9	9
Realisatietijd	9	8	7	9	10	6	9	9	8
Werkinstructie		7							
Kennis/ervaring		7			7		8		
Veilige werksituatie		8							
Weersomstandigheden		6				5	8	9	
Effectiviteit				10					
Tijdstip van de dag							6		
Contactpersoon die verantwoordelijkheid en mandaat heeft							8		

Deelvraag 14: u geeft opdracht tot het plaatsen van de noodmaatregel. Wie plaatst voor uw waterschap de noodmaatregel? Ga ervan uit dat de werkdruk voor uw waterschap hoog is) a. een aannemer, dit is normale procedure; b. een aannemer, omdat de werkdruk hoog is c. eigen (buiten)personeel, dit is normale procedure d. vrijwilligers e. andere optie, namelijk:……………………………… Hoe schat u de kennis en ervaring van degenen die de maatregel plaatsen in?

	A01	A02	A03	A04	A05	A06	A07	B01	B02
Wie	Eigen personeel + aannemers.	Eigen personeel + aannemers.	Aannemer onder aansturing eigen personeel.	Aannemer of anders de genie	Aannemer onder aansturing eigen personeel	Eigen buitenpersonee l	Aannemer en eigen personeel	Een aannemer, normale procedure	Een aannemer, normale procedure
Kennis/ervaring	Wisselend, oude garde veel ervaring. Nieuwe personeel valt tegen.	Ervaring eigen personeel minimaal. Ervaring aannemer ook minimaal.	Personeel redelijk, aannemer matig.	Kennis oke, ervaring onder goede omstandighede n.	Redelijk grote kennis ervaring met maatgevense situatie is alag	Oefent jaarlijks	Hoog	Kennis redelijk op niveau dmv jaarlijkse oefening (uitvoeren maatregel).	Voor taken prima, altijd dijkinspecteur aanwezig.

Deelvraag 15: Hoe is de communicatie tussen degenen die beslissen tot het plaatsen van een noodmaatregel en uitvoerenden? En noem de factoren die van belang zijn voor een succesvolle communicatie

	A01	A02	A03	A04	A05	A06	A07	B01	B02
Hoe	Hoofd veld coordineert en heeft contact met HDP via hem naar ACW	Via telefoon, LMCS, fysiek en whatsapp.	Mondeling op dijkpost en via mobiel en portofoon.	Een persoon gaat ter plaatse.	Wachtcomman dant, wat + hoe geeft instructie en houdt toezicht.	Ter plekke wordt de situatie bekeken met uitvoerenden	Overleg op dijkpost, ter plaatse bij opstarten en controle achteraf.	Telefonisch, mondeling	Goed, telefonisch.
Factoren	Comm. Middelen. Comm. Tijd en rolvastheid.	Systemen moeten het doen.	Hoe hectisch de situatie is. Kennis en ervaring		Voldoende tijd, elkaars taal spreken vaste termen en gebiedskennis		Na afloop afspraken samenvatten.	Duidelijkheid, training, het spreken van dezelfde taal en gebiedskennis.	Spreken van dezelfde taal, dwz kennis van mechanismen en maatregelen

Deelvraag 16: U geeft opdracht tot het plaatsen van de noodmaatregel. Wie heeft de supervisie gedurende de plaatsing? a. een aannemer, dit is normale procedure; b. een aannemer, omdat de werkdruk hoog is; c. één van de keringsbeheerders, maar hij is niet continue aanwezig; d. één van de keringsbeheerders, en hij is continue aanwezig ; e. andere optie, namelijk:………………………… Hoe schat u de kennis en ervaring van de supervisie in?

	A01	A02	A03	A04	A05	A06	A07	B01	B02
Wie	Hoofd veld	Senior, + C watersysteemb eheerder.	Hoofd incident is op locatie afhankelijk hoe druk het is.	Wij	Een van de keringsbeheerders maar is niet continue aanwezig.	Een van de keringsbeheerd ers maar is niet continue aanwezig.	Een van de keringsbeheerd ers maar is niet continue aanwezig.	Een aannmer, met keringbeheerde r.	Keringbeheerde r (1) en aannemer (2)
Kennis/ervaring	Wisselend heeft ook te maken met kennis/ervaring en acceptatie	Minimaal, komt niet voor bij Rijnland.	Wisselend wie het is, matig tot goed.	Voldoe nde	Voldoende over faalmechanismen maatregel en gebiedsspecifiek.	Jaarlijks wordt er geoefend. Dijkwachten monitoren dagelijks.	Goed	Op niveau	Goed

Deelvraag 17: In <u>welke mate</u> specificeert u als *opdrachtgever voor het plaatsen van de noodmaatregel* de volgende aspecten en hoe <u>verhoudt zich dit met de kennis en ervaring</u> van het plaatsingsteam/supervisors (Opmerking: u hoeft wellicht minder te specificeren als er veel ervaring aanwezig is bij het plaatsingsteam)?

1. Het materieel en materiaal dat meegenomen moet worden voor het plaatsen van de maatregel?
   (Voorbeeld: alleen maatregel gespecificeerd / maatregel + materialen en hoeveelheden gespecificeerd etc.)
2. De route naar de plaatsingslocatie

Werkwijze voor de plaatsing	A01	A02	A03	A04	A05	A06	A07	B01	B02
1	Behoefte aan richtlijn, nu op inschatting en ervaring technisch team.	100%	Hoeveel heid, indicatie van de omvang.	Ponton, licht vaartuig en geotextiel/stenen.	Materiaal en hoeveelheden. Materiaal, rijroutes en inschating H-veld. Afhankelijk van omstandigheden	Bij dijkmagazijn weet men wat men moet meenemen voor bv. 100m bekramming. Hier zijn werkinstructies voor uitvoerder of beheerder dijkmagazijn	Materie el: niet. Materia al: niet	Maatregel en materialen en hoeveelheden gespecificeerd.	Wij doen handreiking / voorstel
2	N.v.t. = bekend	0%	Door superie uren.	Via het water.	Supervisor bepaald	Wordt ter plekke gekeken.	In overleg	Afhankelijk van loactie.	Dijkbeheerder bepaald obv instructie.
3	Uniformering is belangrijk. Nu nog niet goed geregeld bij HDSR.	80%	Supervis or	Storten bovenstrooms. Haaks op de dijk. Korte stukjes vanaf dijk naar beneden direct gooien	Supervisor bepaald.	Er is een werkinstructie en personeel oefent zodat het makkelijk gaat	In overleg	Werkinstructies en locaties.	Dijkbeheerder bepaald in afstemming met clusteroverleg.

Deelvraag 18: Wat heeft u met betrekking tot de door u gekozen maatregel voorbereid in de *koude fase*? En wat gaat u tijdens het hoogwater bepalen?

	A01	A02	A03	A04	A05	A06	A07	B01	B02
Koude fase	Materiaal op voorraad. OTO. Vedeeld over depots. Goede CBP's	Materiaal voorhanden. Werkwijze voor handen.	Doek. Lege zandzakken. Krammen.	Geotextiel en stenen zijn in voorraad.	Nog niets. Na afkeur wel beheermaatreg elen uitwerken	OTO met eigen personeel en defensie. Up to date dijkmagazijn, beheerder is verantwoordelij k.	Kennis over dijk / areaal. Werkinstructie. Materialen in voorrad en contract met aannemer.	Voorraad materiaal/mate rieel oefening waakvlamovere enkomsten.	Waakvlam, draaiboekinstru cties. OTO. Zwakke plekken.
Tijdens HW	Hoeveelheid materiaal en personeel/aan nemer.	Locatie en noodzaak voor maatregel.	Zandzakken vullen. Doek op lengte maken en erop monteren.	Of de maatregelen nodig zijn.	Schades en scenario's	De afmetingen van de te leggen bekramming. Aanrijroute mbt transport.	Type maatregel. Afmetingen. Haalbaarheid. Route en bereikbaarheid welke personen worden ingezet.	Windrichting, stroomrichting, windkracht, aanrijroute, hoeveelheden en veiligheid.	Wie wat en waar.

Deelvraag 19. Welke materialen en in welke hoeveelheid heeft u nodig voor het plaatsen van de noodmaatregel? En hoeveel en welke personen mobiliseert u in een realistisch optimaal scenario gegeven deze case?

	A01	A02	A03	A04	A05	A06	A07	B01	B02
Doek	400m landbouwfolie.	500m2	20x30m doek 100m 53 recht	2x100x5	1005mx	120x5	40 rollen, breedte 4m	1 container, 48 rollen.	Genoeg.
Zandzakken	3400 a 4000	500	5000			200	1000	1000 22	
Stenen 10/60 kg				2000ton					
Ijzeren balken	200	100	200m						
Tie rips		1000							
Krammen	800	500	3000			150	Niet gespecificeerd	1 container.	
Touw						350m			
Platenbaan					300m				
Zand					400m3				
Afzettingen					2x				
Aanlijnen					2x			4x	
Personen	40	12	20	50	22	10	10 a 15 pers.	10pers.	10 pers.

Deelvraag 20. Met betrekking tot de materialen die u zojuist heeft gespecificeerd. Hoeveel heeft u daar <u>nu</u> van in voorraad en hoeveel verwacht u dat externe partijen u kunnen leveren tijdens extreme gebeurtenissen.

	A01	A02	A03	A04	A05	A06	A07	B01	B02
Doek	Zelf: 10 rollen Ext. ?	Zelf: 200m Ext: voldoende	Zelf: 35x5x100	Zelf: 2 rollen Heel rws: 2 rollen	Zelf: 15x100x5m Ext: 100xk 10000m3 veel)	Zelf: 5km	Heeft benodig ede hoeveel heden voor deze schade op voorraa d. 1000 Niet gespecif iceerd 10 a 15 pers.	600 op rol	Zelf: niks Externe n alles
Zandzakken	Zelf: 20.000 Ext: 20.000	Zelf: 500 gevuld	Zelf: 20 …	300000 (RWS)				200000	
Steen				Zelf: 2000 ton RWS: heel veel.					
Big bag			Zelf 50 vol.						
Krammen	Zelf: 7kisten a 500	Zelf: 0				Zelf: 2000		10000	
zand			Ext: oneindig.		Zelf: 30000 st	Zelf: 20000 gevuld, 80000 leeg			
Buizen		Zelf: 50m							
Tie wraps		Zelf: 1000 st Ext: voldoende							
aanlijnen					Zelf: 6x	Zelf: 6x			
platenbaan					Zelf: 0				
Personen									
Touw								12	

Deelvraag 21. Wat is volgens u van belang om zeker te zijn dat de juiste materialen getransporteerd worden naar de locatie waar de noodmaatregel geplaatst wordt? (geef het belang aan met een score tussen 1 en 10):

	A01	A02	A03	A04	A05	A06	A07	B01	B02
Materialen+hoeveelheden gespecificeerd.	9	10	8		10	9	8	9	10
Kennis+ervaring	6	8	6		5	7	8	9	10
Tijdsdruk	8	7	4		7	7	8	10	9
Transportmiddelen	7								
Verkeersdrukte	8								
Tijdeig beginnen met vullen zandzakken	9								
Materieel		8							
Personeel		7							
Toegang/transportroute				X		7	8		7
Materieel /ontheffingen				x	8				
Instructie/beggeleiding					9				
Terugkoppeling/bevestiging					6				
Situatie ter plekke						8	8		

Deelvraag 22. Hoe transporteert u de materialen naar de locatie? (gegeven de case en de extra informatie m.b.t. melding 1) Vermeld in ieder geval met welk materieel u over welke wegen rijdt.

A01	A02	A03	A04	A05	A06	A07	B01	B02
Is afhankelijk van verweking kering. Breed fietspad, geasfaleerd dan kan je lang blijven rijden. Niet geasfalteerd, dan niet. Auto met aanhanger of trekker met kieper.	Tracktor met aanhanger, mobiele kraan en hi-lux	Auto + aanhanger. Trekker + aanhanger. Aanhanger met kraan en minigraver.	Over water	Berm: platenbaan binnendijks tbv transport shovel voor versprijding. Bekramming: 4x4 auto over de dijk.	Route via oprijlaan boerenbedrijf, dus aantal rijplaten leggen. Dus Tot binnenberm rijden, hekken_wagen en mobiele kraan.	M.b.v. kleine vrachtauto over het fietspad. Optie: via perceel ter hoogte van schade, dam in sloot maken. Voor definitieve keuze meer info noodzakelijk.	Met vrachtwagen naar losplaats, verder met traktor met aanhanger of andere klein materiaal naar locatie ivm fietspad, met mobiele kraan shovel of heftruck	Per as, rups of boot.

Deelvraag 23: Beschrijf in detail hoe u de maatregel aan gaat brengen, welke personen dit doen en welk materieel ze gebruiken.

A01	A02	A03	A04	A05	A06	A07	B01	B02
UV met aannemer of defensie. 4 banen met 1 meter overlap. Zandzakken om de 10 meter enzijdig. Elke m2 4 krammen.	Zie slide 27	Doek uitrollen, bekrammen, zandzakken aanbrengen, gaten opvullen met zandzakken	Letten op beneden en bovenstrooms.	Berm: vrachtauto's zandzaktransport over baan, shovel verdeling + aanrijden. Bekramming: kraan+evenaar voor afrollen mensen met hamer aanlijnen krammen aanbrengen zandzakken 4x4 aanvoer krammen +zandzakken	Trekker met wagen met materiaal, mobiele kraan. Om bakken op te zetten. 12 man om bekramming aan te brengen.	Afrollen van boven naar. Doek incl verzwaring aan onderzijnde. Zandzakken aanbrengen. Overlap tussen baan ca 1meter. Tegen richting stroming. Ivm afmeting meer dan 100 meter, te groot voor eigen mensen.	Zie vorige vraag.	Aannemer en waterschap. Kraanwagen lader buldozer en vrachtwagens.

Deelvraag 24: (1) Hoe wordt gecommuniceerd dat de maatregel (succesvol) geplaatst is? (2) Wordt de maatregel gecontroleerd? En zo ja: door wie? (3) Als de maatregel geplaatst is: waar let u op als u de maatregel inspecteert? Of geeft u de (vrijwillige) dijkinspectie instructies om te letten op bepaalde aspecten?

	A01	A02	A03	A04	A05	A06	A07	B01	B02
1	Hoofd veld > hoofd dijkpost > ACW	Terugkoppeling via telefoon/lmcs	Met mob/porto aan hoofd dijkpost	Bellen	Controle terugkoppeling door wachtcommandant.	Telefoninsch dat de werkzaamheden klaar zijn	Aannemer doet terugmelding	Via telefoon/app naar hoofd dijkpost.	Per telefoon.
2	Hoofd veld	Ja cpi	Ja door dijkleger	Ja, wij zijn terplaatse	Idem tijdens dijkinspectie.	Opzichter waterkeringen.	Controle door ws / eigen personeel.	Ja door wachtcommandant en dijkwachten.	Ja, waterschap.
3	Blijft het doek heel en goed liggen? Blijven zandzakken liggen? Verweekt de dijk niet verder? Dit geven we de dbo ook mee?	Dat alles blijft liggen en werkt, niet wegwaait of spoelt.	Kijken of constructie intact is. Geen opbollingen in doek.	Onderloopsheid + overgangen geotextiel + overgang geotextiel dijk.	Blijft alles op zijn plek. Berm: scheurvorming bovenlangs + uittredend water in talud of teen berm.	Zijkanten van doek dat zandzakken hierop liggen. Zakken op goede wijze dakpansgewijs over elkaar liggen	Stopt het de erosie, randen overlappen binnen talud in de gaten houden.	Of alles nog intact is en eventuele uitbreiding probleem.	ja

Deelvraag 25: Hoeveel tijd denkt u nodig te hebben voor: (1) Het laden van de materialen nodig voor de plaatsing van de noodmaatregel? (2) Het transport naar de locatie. (3) De plaatsing van de noodmaatregel?

	A01	A02	A03	A04	A05	A06	A07	B01	B02
1	3 a 4 dagen? Kan sneller, maar veel personeel nodig?	30 min	2 dagen	1 dag	0.5 uur	1 uur	½ dag	1 uur	3 uur
2	30 min	1,5 uur	4 uur	2-4 uur per boot	5-25km = 1 uur	1uur	1 uur	45 min	1uur
3	1 dag	6 uur (??)	1-2 dagen.	1 dag	4-5uur	1,5 tot 2 uur.	1.5 dag	4 uur	3 a 24 uur.