Veiligheidsfactor voor ontwerpen met Steentoets2010 voor betonzuilen

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1206424-010

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Opdrachtgever	**Project**	**Kenmerk**	**Pagina's**
Rijkswaterstaat Waterdienst	1206424-010	1206424-010-HYE-0003	25

Trefwoorden
Veiligheidscoëfficiënt, steenzetting, ontwerp

Samenvatting

Voor het berekenen van de stabiliteit van steenzettingen is al meer dan een decennium het programma Steentoets beschikbaar. Dit programma wordt gebruikt bij de voorgeschreven toetsing van steenzettingen, maar wordt ook gebruikt voor het ontwerpen van steenzettingen. Voor het toetsen is in 2009 aangetoond dat Steentoets voldoende veilige resultaten oplevert (Klein Breteler (2009), validatie). Er is echter behoefte aan een realistische veiligheids-coëfficiënt voor de toepassing van Steentoets bij het maken van een ontwerp. Juist bij het ontwerpen is er behoefte aan een veiligheidsmarge om te zorgen dat er voldoende rekening wordt gehouden met onzekerheden in de uitvoering en dat het ontwerp niet te krap bemeten wordt.

Bij een eerdere poging om de veiligheidscoëfficiënt te bepalen ('t Hart (2012)) bleek dit erg arbeidsintensief te zijn vanwege de complexiteit van Steentoets in combinatie met de complexiteit van probabilistische berekeningen. Deze problematiek is thans het hoofd geboden door gebruik te maken van de vereenvoudigde formules van Klein Breteler & Mourik (2012a) en een Matlab-programma ‘Probabilistic Toolbox’ voor het maken van probabilistische berekeningen uit het onderzoeksprogramma SBW-WTI.

Het huidige onderzoek beperkt zich voorlopig tot steenzettingen van betonzuilen op een talud (niet op een berm) die niet zijn ingegoten met gietasfalt. Dit type steenzetting is het meest gebruikte bij de huidige renovatiewerken.

Het onderhavige onderzoek is uitgevoerd in het kader van het meerjarige project ‘Advisering steenbekledingen Zeeland’ voor het Projectbureau Zeeweringen (PBZ). Dit projectbureau is opgericht ten behoeve van de renovatie van de steenzettingen in Zeeland en is een samenwerking van Rijkswaterstaat Zeeland en het Waterschap Scheldestromen. Contractueel is de Dienst Water, Verkeer en Leefomgeving van Rijkswaterstaat de opdrachtgever namens PBZ voor het onderhavige onderzoek. Het deel van het project dat gericht is op kennisontwikkeling sluit aan op het Onderzoeksprogramma Kennisleemtes Steenbekledingen dat uitgevoerd is in de periode van 2003-2009 in opdracht van de Dienst Weg- en Waterbouwkunde van Rijkswaterstaat namens PBZ.

Hoofdstuk 1 is een uitgebreide Nederlandstalige samenvatting, terwijl de rest van het rapport in het Engels is.

Deltares

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Referenties
Waterdienst zaaknummer 31068749 / 4500196054, van 7 mei 2012
Contactpersoon Waterdienst: dhr. K. Saathof
Contactpersoon Projectbureau Zeeweringen van RWS: dhr. Y. Provoost

Version	Date	Author	Initials	Review	Initials	Approval	Initials
1	sept 2012	Dorothea Kaste		Robert 't Hart		Marcel van Gent	
1	Nov. 2012	Dorothea Kaste		Robert 't Hart		Marcel van Gent	
2	Nov. 2013	Dorothea Kaste		Robert 't Hart		Marcel van Gent	

Status
definitief

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Symbol	Unit	Specification
a_1	[s/m]	Linear resistance coefficient of the first filter layer [s/m]
a_{ftop}	[s/m]	Linear resistance coefficient of the filter layer material directly under the joints [s/m]
a_i	[s/m]	Linear resistance coefficient of the infilling material
A_{ro}	[-]	Part of the top layer which consists of vertical, respectively horizontal, joints [-]
a_s	[s/m]	Linear resistance coefficient of the joints
B	[m]	Width of the blocks
b_1	[s²/m²]	Turbulent resistance coefficient of the first filter layer
b_f	[m]	Thickness of the filter layer
b_{ftop}	[s²/m²]	Turbulent resistance coefficient of the filter layer material directly under the joints
b_i	[s²/m²]	Turbulent resistance coefficient of the infilling material
b_s	[s²/m²]	Turbulent resistance coefficient of the joints
$cot\alpha$	[-]	Cotangent of the slope of the revetment
D	[m]	Thickness of the top layer
D_{f15}	[m]	Grain size of the filter material
D_{i15}	[m]	Grain size of the infilling material
fill	[-]	Indicator of infilling material (1 = yes; 0 = no)
g	[m/s²]	Gravity acceleration
h	[m+NAP]	Water level
h_D	[m+NAP]	Design water level
H_s	[m]	Significant wave height
$H_{s,stab}$	[m]	Admissible wave height calculated with Steentoets
$H_s/(\Delta D)$	[-]	Stability of the revetment calculated with Steentoets
k'	[m/s]	Permeability of the top layer
k_1	[m/s]	Permeability of the first filter layer
k_2	[m/s]	Permeability of the second filter layer (if present)
L	[m]	Length of the blocks
m	[-]	Model factor for the calculation of the failure of the block revetment
N	[-]	Number of waves
n_f	[-]	Porosity of the filter material

Symbol	Unit	Specification
N_{fail}	[-]	Amount of failure points
n_i	[-]	Porosity of the infilling material
N_{calc}	[-]	Amount of calculations in the Monte Carlo simulations
p_f	[-]	Probability of failure
R	[-]	Strength (Resistance)
S	[-]	Load (Solicitation)
s_l	[m]	Joint width of the horizontal joints (langsvoegen)
s_{op}	[-]	Wave steepness
s_s	[m]	Joint width of the vertical joints (stootvoegen)
$stab_F$	[-]	$H_s/\Delta D$ for the design conditions calculated with simplified formulae
$stab_{ST}$	[-]	$H_s/\Delta D$ for the design conditions calculated with Steentoets
$tan\alpha$	[-]	Tangent of the outer slope (average, if there are different slopes)
$tan\alpha_{Bodem}$	[-]	Slope of the foreland
t_{Belast}	[h]	Duration of the load
type	[-]	Type of the blocks (1 = blocks, 2 = columns, 3 = blocks placed on their side)
V	[-]	Variation coefficient of the stochastic parameters
v_t	[m/s]	Filter velocity
Z	[-]	Z-function (if $Z < 0$, failure occurs)
Z_b	[m+NAP]	Upper boarder of the block revetment
z_{Berm}	[m+NAP]	Height of the berm
z_{Bodem}	[m+NAP]	Height of the dike toe
Z_o	[m+NAP]	Lower border of the block revetment
α	[-]	Importance factor
α^2	[-]	Importance ratio
β	[deg]	Angle of the wave direction
Δ	[-]	Relative density of the blocks
γ	[-]	Safety factor
Λ	[m]	Leakage length
ν	[m²/s]	Kinematical viscosity of water
ρ_S	[kg/m³]	Density of the blocks
ρ_W	[kg/m³]	Density of the water
Ω	[-]	Relative open area of the revetment
ξ_{op}	[-]	Breaker parameter

1 Samenvatting

1.1 Inleiding

Voor het berekenen van de stabiliteit van steenzettingen is al meer dan een decennium het programma Steentoets beschikbaar. Dit programma wordt gebruikt bij de voorgeschreven toetsing van steenzettingen, maar wordt ook gebruikt voor het ontwerpen van steenzettingen.
Voor het toetsen is in 2009 aangetoond dat Steentoets voldoende veilige resultaten oplevert (Klein Breteler (2009), validatie). Er is echter behoefte aan een realistische veiligheids-coëfficiënt voor de toepassing van Steentoets bij het maken van een ontwerp. Juist bij het ontwerpen is er behoefte aan een veiligheidsmarge om te zorgen dat er voldoende rekening wordt gehouden met onzekerheden in de uitvoering en dat het ontwerp niet te krap bemeten wordt.

Bij een eerdere poging om de veiligheidscoëfficiënt te bepalen ('t Hart (2012)) bleek dit erg lastig en arbeidsintensief te zijn vanwege de complexiteit van Steentoets in combinatie met de complexiteit van probabilistische berekeningen. Verder was de resulterende veiligheids-coëfficiënt dermate hoog dat nader onderzoek noodzakelijk was.
Deze problematiek is thans het hoofd geboden door gebruik te maken van de vereenvoudigde formules van Klein Breteler & Mourik (2012a) en een Matlab-programma 'Probabilistic Toolbox' voor het maken van probabilistische berekeningen uit het onderzoeks-programma SBW-WTI. Dat Matlab-programma is gemaakt in het kader van de ontwikkeling van het WTI-2017 (wettelijk toetsinstrumentarium), waarbij voorlopig uitgegaan wordt van de overstromingskansbenadering, vooruitlopend op de Deltabeslissing hierover in 2014. Meer informatie hierover is te vinden op:
https://publicwiki.deltares.nl/display/OET/probabilistic (OET (2012)) en in Diermanse et al. (2011).

Het huidige onderzoek beperkt zich voorlopig tot steenzettingen van betonzuilen op een talud (niet op een berm) die niet zijn ingegoten met gietasfalt. Dit type steenzetting is het meest gebruikte bij de huidige renovatiewerken.

Het onderhavige onderzoek is uitgevoerd in het kader van het meerjarige project 'Advisering steenbekledingen Zeeland' voor het Projectbureau Zeeweringen (PBZ). Dit projectbureau is opgericht ten behoeve van de renovatie van de steenzettingen in Zeeland en is een samenwerking van Rijkswaterstaat Zeeland en het Waterschap Scheldestromen. Contractueel is de Waterdienst van Rijkswaterstaat de opdrachtgever namens PBZ voor het onderhavige onderzoek. Het deel van het project dat gericht is op kennisontwikkeling sluit aan op het Onderzoeksprogramma Kennisleemtes Steenbekledingen dat uitgevoerd is in de periode van 2003-2009 in opdracht van de Dienst Weg- en Waterbouwkunde van Rijkswaterstaat namens PBZ.

1.2 Opzet van het onderzoek

In het huidige onderzoek zijn probabilistische berekeningen uitgevoerd voor een aantal voorbeeldconstructies met betonzuilen op een talud, met bovenbegrenzing (overgangs-constructie en/of berm) op 80 cm boven het ontwerppeil. Met deze probabilistische berekeningen zijn diverse ontwerpen gemaakt met precies de juiste faalkans. Door deze vervolgens te vergelijken met de betreffende Steentoetsberekening, is de benodigde veiligheidscoëfficiënt voor Steentoets afgeleid.

Hierbij is impliciet de aanname gedaan dat wanneer de veiligheidscoëfficiënt voor diverse voorbeeldconstructies steeds ongeveer hetzelfde is, of een verklaarbare variatie heeft, het mogelijk is om een conclusie te trekken ten aanzien van de veiligheidscoëfficiënt die algemeen geldig is.

Om deze probabilistische berekeningen succesvol te kunnen uitvoeren, was het volgende benodigd:

- Een rekenmethode voor het bepalen van de stabiliteit van steenzettingen, die opgenomen kan worden in de SBW-WTI Matlab-programmatuur;
- Een criterium in termen van een faalkans waar de steenzetting aan moet voldoen;
- Informatie over de onzekerheid omtrent de invoerparameters voor het berekenen van de stabiliteit van steenzettingen;
- Informatie over de nauwkeurigheid en impliciete veiligheid in het rekenmodel Steentoets;
- Een aantal representatieve voorbeeldconstructies.

Deze aspecten zijn onderstaand nader toegelicht.

1.2.1 Rekenmethode

Voor het berekenen van de stabiliteit van de steenzetting is gebruikgemaakt van de vereenvoudigde formules van Klein Breteler & Mourik (2012a). Deze formules zijn vermeld in appendix A3. Deze formules zijn toegepast omdat de probabilistische berekeningen daardoor veel sneller verlopen, terwijl de nauwkeurigheid voldoende is voor het berekenen van de veiligheidsfactor.

1.2.2 Toelaatbare faalkans

Het criterium waar de steenzetting aan moet voldoen wordt in dit onderzoek uitgedrukt in een faalkans. 't Hart (2012) heeft hiervoor 5% gekozen, gegeven het optreden van de ontwerp-condities. Deze eis volgt uit de diverse TAW/ENW-leidraden en een schatting van de te verwachten reststerkte.
Bijvoorbeeld in de Leidraad Grondslagen voor Waterkeringen (TAW (1998)) staat het volgende vermeld voor de thans geldende overbelastingsbenadering per dijkvak:

Veiligheidseisen:

1. De kans op overschrijden van het debiet q_t mag voor elk dijkvak niet groter zijn dan de norm die in de Wet op de waterkering voor het betreffende dijkringgebied is genoemd. Daarbij wordt meestal uitgegaan van een ontwerpwaterstand (MHW), waarbij een golf hoort, waaruit weer een golfoploop c.q. golfoverslagdebiet volgt;
2. Bij waterstanden gelijk aan of lager dan MHW mag de kans op falen door andere oorzaken dan overloop/overslag, niet meer dan 10% van de bij punt 1 genoemde norm bedragen.

Voor steenzettingen gaat het om het tweede punt. Daarbij moet meegewogen worden dat er meerdere ‘andere oorzaken’ (bezwijkmechanismen) zijn, zoals piping, macro-instabiliteit,

stabiliteit steenzetting, etc. Daardoor wordt doorgaans per bezwijkmechanisme een faalkans van 1% gehanteerd. Maar gezien het feit dat er een aanzienlijke reststerkte is na de initiële schade aan een steenzetting, kan er een hogere faalkans gehanteerd worden. 't Hart (2012) heeft hiervoor arbitrair 5% gekozen.
In het kader van het thans lopende SBW-onderzoek naar reststerkte wordt onderzocht of deze keuze terecht is.
Het toepassen van een lagere waarde (anticiperen op een kleinere reststerkte) geeft een hogere benodigde veiligheidsfactor.

1.2.3 Onzekerheid van invoervariabelen

Voor de kwantificering van de onzekerheid omtrent de constructie gerelateerde invoervariabelen is gebruikgemaakt van de ervaring van Projectbureau Zeeweringen in Zeeland. Eerst is gewerkt met de standaardafwijking zoals 't Hart (2012) die gebruikt heeft, zodat optimaal aangesloten kon worden op zijn werk, en vervolgens zijn aangepaste waarde gebruikt. Een heranalyse van de beschikbare gegevens heeft aan het licht gebracht dat sommige parameters een lagere standaardafwijking zouden moeten hebben dan was gebruikt door ’t Hart (2012).
In Tabel 1.1 zijn de variatiecoëfficiënten, namelijk de verhouding tussen de standaard-afwijking σ en de verwachtingswaarde μ, van de relevante variabelen gegeven ($V = \sigma/\mu$):

Tabel 1.1 Gebruikte variatiecoëfficiënten voor de constructie gerelateerde parameters

	Variatiecoëfficiënt $V = \sigma/\mu$		
	’t Hart (2012)	Aangepaste waarden	Opnieuw aangepast
Toplaagdikte, D	2,9%	2,9%	2,9%
Open oppervlak, Ω	14%	14%	14%
Soortelijke massa van de beton in de zuilen, ρ_s	2,0%	2,0%	**1,0%**
Korrelgrootte inwasmateriaal, D_{i15}	17%	17%	17%
Filterlaagdikte, b_f	20%	20%	**10%**
Porositeit filter, n_f	14%	**8,6%**	8,6%
Korrelgrootte filter, D_{f15}	5,9%	5,9%	5,9%
Taludhelling, $cot\alpha$	7,1%	**2.9%**	**4,3%**

Voor de soortelijke massa van de zuilen geldt dat de heranalyse laat zien dat de variatiecoëfficiënt ongeveer de helft moet zijn ten opzichte van de waarde die gebruikt is door 't Hart (2012). Verder is er een verschil tussen de waarde die gebruikt wordt in de ontwerpberekeningen (bijvoorbeeld 2300 kg/m^3) en de gemiddelde waarde van de zuilen die de leverancier vervolgens levert (2346 kg/m^3). Dit verschil blijkt doorgaans tweemaal de standaardafwijking te zijn (dus in dit geval 2% van het gemiddelde) (zie paragraaf 4.3).
Ook de standaardafwijking van de filterlaagdikte en porositeit is nu verkleind. De standaardafwijking van de taludhelling ($cot\alpha$) blijkt ook kleiner te zijn dan door ’t Hart (2012) was aangenomen. Die variatiecoëfficiënt van de taludhelling is aanvankelijk sterk verkleind naar 2,9%, maar is in latere berekeningen weer wat verhoogd naar 4,3%.

De variatiecoëfficiënten van de belastingparameters zijn gegeven in Tabel 1.2. Deze waarden zijn hetzelfde als die zijn toegepast door 't Hart (2012).

Tabel 1.2 Gebruikte variatiecoëfficiënten voor de belasting gerelateerde parameters

	Variatiecoëfficiënt $V = \sigma/\mu$
Ontwerppeil, h_D	1,9%
Significante golfhoogte, H_s	5,4%
Golfsteilheid, s_{op}	5,0%
Belastingduur, t_{belast}	14%

1.2.4 Nauwkeurigheid en impliciete veiligheid in Steentoets

Bij het vergelijken van de resultaten van Steentoets met de resultaten van grootschalig modelonderzoek in de Deltagoot blijkt dat Steentoets steeds aan de veilige kant zit, omdat de maximaal toelaatbare golfhoogte volgens Steentoets steeds iets kleiner is dan is gebleken uit de proeven in de Deltagoot. Om dit mee te wegen in de probabilistische berekeningen wordt er een modelfactor aan Steentoets toegevoegd. Deze modelfactor *m* is gelijk aan de verhouding tussen het Steentoetsresultaat en het Deltagootresultaat:

$$m = \frac{\left[H_s / (\Delta D)\right]_{Deltagoot}}{\left[H_s / (\Delta D)\right]_{Steentoets}} \qquad (1.1)$$

't Hart (2012) heeft hiervoor $\mu(m)$ = 1,22 en $\sigma(m)$ = 0,2 (variatiecoëfficiënt V = 16.4%) gehanteerd.
Door dit opnieuw te berekenen, inclusief de recente Deltagootproeven met Basalton, Ronaton en Hillblocks, blijkt de modelfactor als volgt te moeten zijn (zie paragraaf 4.1):

- Gemiddelde: $\mu(m)$ = 1,33
- Standaardafwijking: $\sigma(m)$ = 0,22
- Variatiecoëfficiënt: V = 16.5%

Deze waarden voor de modelfactor zijn ook van toepassing op de vereenvoudigde formules.

1.3 Uitgevoerde berekeningen en resultaten

Doordat de probabilistische berekeningen nu volledig in de computer kunnen worden uitgevoerd met het Matlab-programma en de vereenvoudigde formules, was het mogelijk om een groot aantal voorbeeldconstructies door te rekenen. Dit verhoogt de betrouwbaarheid van het resultaat.

Alle berekeningen zijn uitgevoerd met een vaste waterstand, een vooraf gekozen belastingduur en loodrechte golfaanval. Uiteraard is wel rekening gehouden met de variatiecoëfficiënten zoals vermeld in Tabel 1.2.

Als eerste is een berekening uitgevoerd met exact dezelfde invoer als 't Hart (2012), zie Table 3.1. Hiermee kon de rekenprocedure gecontroleerd worden. Dit leverde een overall veiligheidsfactor van γ_1 = 1,26, terwijl 't Hart 1,25 had gevonden. Dit verschil is klein genoeg om vertrouwen te hebben in de nieuwe rekenmethode.
Om praktische redenen is destijds door 't Hart gekozen voor het berekenen van de veiligheidsfactor als correctiefactor op de ontwerpgolfhoogte. Dat is nu wederom gedaan om goed op zijn werk aan te sluiten en omdat het de berekeningen eenvoudiger maakt. Dezelfde factor kan echter ook gebruikt worden als veiligheidsfactor op de toplaagdikte. Dat komt

omdat bij kleine aanpassingen aan de toplaagdikte de waarde van $H_s/(\Delta D)$ bij begin van schade niet verandert.
Daardoor kan deze overall veiligheidsfactor in het ontwerp van een steenzetting vermenigvuldigd worden met de met Steentoets berekende waarde van de toplaagdikte om de gewenste faalkans te krijgen, terwijl voor alle andere parameters de gemiddelde waarde wordt gehanteerd en voor de soortelijke massa de ontwerpwaarde (rekenwaarde).

Vervolgens is dezelfde berekening uitgevoerd met de verbeterde waarden voor de modelfactor. Omdat deze een grote invloed heeft op de faalkans, is hiermee een veel lagere overall veiligheidsfactor gevonden, namelijk 1,076 (zie paragraaf 4.2).

Daarna zijn berekeningen uitgevoerd met een verkleinde standaardafwijking voor de porositeit en de taludhelling. Met deze waarden zijn 7 verschillende constructie-belasting combinaties doorgerekend, zie paragraaf 4.2. Dit leverde veiligheidsfactoren op in de range van 1,054 tot 1,087.

Verder zijn 4 berekeningen gemaakt met de verbeterde waarden voor de soortelijke massa van de zuilen (standaardafwijking en verschil tussen ontwerpen waarde en gemiddelde waarde) en de standaardafwijking voor de taludhelling en de filterlaagdikte (zie paragraaf 4.3). De resulterende veiligheidsfactoren varieerden voor deze berekeningen van 1,021 tot 1,033. Deze variatie is betrekkelijk klein, waardoor waarschijnlijk dergelijke waarden ook van toepassing zijn voor andere combinaties van de constructie- en belastingparameters.

Er zijn ook berekeningen uitgevoerd met andere waarden voor de toelaatbare faalkans (van 1% tot 10%). Daaruit blijkt de gevoeligheid van de veiligheidsfactor voor de gekozen waarde. Een kleinere toelaatbare faalkans vereist uiteraard een grotere veiligheidsfactor. Voorlopig wordt aangenomen dat een faalkans van 5% een goede schatting is van de acceptabele faalkans, zie paragraaf 2.1.
Deze schatting kan verbeterd worden aan de hand van het onderzoeksproject WTI-2017, maar dat is nog niet afgerond.

1.4 Conclusies

De nieuwe opzet van de probabilistische berekeningen met het Matlab-programma van het SBW-WTI-onderzoek, in combinatie met de vereenvoudigde formules van Klein Breteler & Mourik (2012a), hebben het mogelijk gemaakt om met minder inspanning veel meer berekeningen te maken. Hierdoor was het mogelijk om een aantal combinaties van steenzettingen en belastingen door te rekenen.

De nieuwe berekeningen hebben geleid tot de conclusie dat de overall veiligheidsfactor veel kleiner moet zijn dan volgens 't Hart (2012). Dit is vooral vanwege het verschil in gemiddelde waarde van de modelfactor. Deze geeft het verschil weer tussen Steentoets en de werkelijkheid (Deltagootresultaten).
In het ontwerp van een steenzetting moet de met Steentoets berekende toplaagdikte met deze overall veiligheidsfactor vermenigvuldigd worden, terwijl voor alle andere parameters de gemiddelde waarde wordt gehanteerd en voor de soortelijke massa de ontwerpwaarde.

Uit de berekeningen is gebleken dat de overall veiligheidsfactor niet erg afhankelijk is van de eigenschappen van de steenzetting of de belasting. Dat maakt het mogelijk om voor alle steenzettingen met geklemde zuilen een waarde voor de overall veiligheidsfactor voor te stellen. Aanbevolen wordt om hiervoor een veilige waarde te hanteren ten opzichte van de berekeningen, namelijk γ = 1,1. Deze veiligheidsfactor moet toegepast worden als toeslag op de benodigde toplaagdikte.

2 Introduction

In the Netherlands block revetments are usually designed with the Excel program Steentoets. This program is also used every six years to carry out the mandatory safety assessment (wettelijke toetsing).
In order to take into account the uncertainties of the characteristics of block revetments, especially those related to the construction of the revetment, a safety margin is necessary.

The research described in this report analyses the necessary safety margin for block revetments on dikes along the sea and large lakes, which are designed with Steentoets. It focuses on block revetments consisting of a top layer of concrete elements with large interaction (ingewassen zuilen met klemming) on a granular filter, geotextiel and a clay layer on the sand core of the dike. This configuration is typical for dikes along the Westerschelde, Oosterschelde, IJsselmeer, Markermeer and some other locations.

The goal of the research is to quantify the safety margin necessary to achieve an acceptable failure probability. The result is a safety factor that can be applied to the block thickness of the revetment.

2.1 Acceptable failure probability

The acceptable failure probability is derived from the criteria given in the former Dutch law on water defences (nowadays these criteria are incorporated in the Dutch law: Waterwet). In Fundamentals on Water Defences (TAW (1998)) these safety requirements for dikes are stated as follows:

> *"Safety requirements:*
> 1. The probability of exceedance of the discharge q_t may for every dike section not exceed the norm mentioned in the Flood Defence Act for the relevant dike ring area. Here a design water level (MHW) is typically assumed, with associated wave climate from which the wave run up or wave overtopping follows on.
> 2. For water levels equal to or lower than MHW the probability of failure due to other factors than wave run up or wave overtopping may not exceed 10% of the norm mentioned in point 1."

For block revetments, the second point is important, as it is one of the "other factors". Since there is more than one failure mechanism, the acceptable probability of failure for just one failure mechanism is much lower than 1/10 of the norm. Considering 10 damage mechanisms it is assumed to be 1/100 of the norm. The norm is defined for the exceedance frequency of the water level, which is given for each region in the law. Most dikes with block revetments can be found in regions where the norm is 1/4000 per year.

For block revetments however, we assume that there is quite some residual strength. This means that after one or more blocks have washed away from the revetment, it will still take a long time before the dike breaches. The probability of a dike breach after initial damage to the revetment is much smaller than 1. In 't Hart (2012) it is chosen for an acceptable probability of failure of the revetment of 5% when the design storm occurs. The design storm has the exceedance frequency equal to the norm (usually 1/4000 per year). This is called the ‘norm storm’.

The 5% probability of failure is assumed to be acceptable because of the expected residual strength. If the block revetment gets damaged, it will take some time before the dike will breach. There is even a fair chance that the dike will not breach at all. That aspect has been included in the assumed acceptable failure probability of 5%.
In the research programme “SBW Reststerkte” Kaste & Klein Breteler (2012) analysed how the residual strength of the dike contributes to the safety of the revetment. Therefore, the failure probability for a dike was calculated, including the failure of the revetment and the residual strength. The results of that research will allow us to verify the assumed 5%. Unfortunately, that research was not finished yet at the moment the present report was finalised.

2.2 Structure of this report

The following chapter (ch. 3) describes the re-calculation of the analysis that was accomplished in 't Hart (2012). This is done to verify the new method of the calculations, that makes use of the Monte Carlo technique and the simplified formulae. Furthermore, the partial safety factors of the variables were determined and finally, the overall safety factor is defined.

In chapter 4 improved values for several parameters are presented and included in the calculations. Several recent available large scale model tests are analysed to enhance the model factor of Steentoets. With this new value for the model factor several calculations were carried out to get the new result for the overall safety factor. Additionally, new values for the mean value and/or the standard deviation of certain input variables are introduced, which are obtained from new measurement data and experiences. With those values the overall safety factor for Steentoets was recalculated.

The 5th chapter provides the conclusions of this report. The most important results are summarized and discussed.

In the appendix the calculations are described in more detail. First, an overview of the necessary input parameters is given (A.1). In section A.2, the probabilistic calculations are explained. All the equations that were taken for the calculation of the failure of the block revetment are presented in section A.3 of the appendix. Appendix B provides the input values for the correction factor of the simplified formulae.

3 Re-calculation of the safety factor for case “zuilen” by 't Hart

3.1 Introduction

Unfortunately, Steentoets2010 is a very complicated program that cannot be easily used in combination with probabilistic tools to carry out probabilistic calculations. A recent attempt to carry out these calculations have been reported by 't Hart (2012). It turned out to be so laborious that only two cases have been evaluated.

Presently a new method to carry out these calculations is used. The safety of the block revetment is calculated with the simplified formulae from Klein Breteler & Mourik (2012a). The formulae are derived from various calculations with the software “Steentoets2010”. For presentation and explanation of the calculations see section A.3. The simplified formulae are derived for two types of revetment, which are rectangular blocks and the here regarded columns with large interaction (ingewassen zuilen). Unfortunately, the results of Steentoets and the simplified formulae are not exactly the same. Therefore, a correction factor is added to the simplified formulae to reduce the error:

$$f_c = \frac{\left[\dfrac{H_s}{\Delta D}\right]_{ST}}{\left[\dfrac{H_s}{\Delta D}\right]_{F}} \qquad (3.1)$$

with:

f_c = correction factor for the simplified formulae [-]

$\left[\dfrac{H_s}{\Delta D}\right]_{ST}$ = stability calculated with Steentoets [-]

$\left[\dfrac{H_s}{\Delta D}\right]_{F}$ = stability calculated with the simplified formulae

The correction factor is multiplied to the result of the $H_s/(\Delta D)$ calculated with the simplified formulae in the probabilistic calculations. A list of the used values for all the calculations is given in appendix B. The factor varies from 0.992 to 1.001.

The simplified formulae are implemented in a Matlab code, which conducts the probabilistic calculations (Open Earth Probabilistic Toolbox, OET (2012)). The failure probability is calculated with the Monte Carlo method (see section A.2 for more details). The simplified formulae are used to create the Limit State Equation (LSE) for the revetment:

$$Z = R - S \qquad (3.2)$$

with:

Z = Z-function (if $Z < 0$, failure occurs)

R = strength function (maximum acceptable $H_s/\Delta D$, result from the simplified formulae)

S = load function (actually occurring $H_s/\Delta D$)

Failure is defined in this report as damage to the block revetment. This means that the residual strength of the revetment, clay layer and sand core are explicitly not taken into account. An acceptable probability of failure of 5% has been chosen, as explained in section 2.1. By using an acceptable probability of failure of 5%, given the occurrence of a norm-storm, the existence of some residual strength is implicitly included.

3.2 Importance of each of the stochastic variables

The safety margin for Steentoets was first derived by 't Hart (2012). To check the present calculation method, a recalculation of the results of that report is the first step. For the here conducted probabilistic calculations, the variables of Table 3.1 are taken, with its given mean value μ and the standard deviation σ. Additionally, the variation coefficients V are given in the last column. The calculations are conducted for a norm storm surge with an exceedance frequency of 1/4000 which gives the water level and the load duration. For these calculations the water level is chosen to be constant over time. The parameters are the same as in 't Hart (2012) to have a good comparison with his results. The calculations are done for a revetment with large interaction between the elements and large open area (geklemde zuilen).

Table 3.1 Input variables and their stochastic parameters

Variable		**Unit**	**Mean value** μ	**Standard deviation** σ	$V = \sigma/\mu$
Duration of the load	t_{Belast}	[h]	10.0	1.43	14.3%
Water level	h	[m+NAP]	5.2	0.1	-
Significant wave height	H_s	[m]	1.865	0.1	5.4%
Wave steepness	s_{op}	[-]	0.040	0.002	5.0%
Wave angle	β	[deg]	0	-	-
Thickness of the blocks	D	[m]	0.35	0.01	2.9%
Width of the blocks	B	[m]	0.30	-	-
Length of the blocks	L	[m]	0.30	-	-
Relative open area of the revetment	Ω	[-]	0.13	0.018	13.8%
Density of the blocks	ρ_S	[kg/m³]	2300.0	46.0	2.0%
Porosity of the infilling material	n_i	[-]	0.70	-	-
Grain size of the infilling material	D_{i15}	[m]	0.006	0.001 (0.002)	16.7%
Thickness of the filter layer	b_f	[m]	0.10	0.02	20.0%
Porosity of the filter layer	n_f	[-]	0.35	0.05	14.3%
Grain size of the filter layer	D_{f15}	[m]	0.0152	0.0009	5.9%
Upper boarder of the block revetment	Z_b	[m+NAP]	6.0	-	-
Lower border of the block revetment	Z_o	[m+NAP]	2.0	-	-
Cotangent of the slope of the revetment	$cot\alpha$	[-]	3.5	0.25	7.1%
Gravity acceleration	g	[m/s²]	9.81	-	-
Viscosity of the water	ν	[m²/s]	$1.2 \cdot 10^{-6}$	-	-
Density of the water	ρ_W	[kg/m³]	1025.0	-	-
Model factor	m	[-]	1.22	0.2	20.0%

A difference is made for the standard deviation of the grain size of the infilling material D_{i15}. As 't Hart (2012) stated in his report, this variable did not influence the calculations much.

Nevertheless, the standard deviation is set to σ_{Di15} = 0.001, to avoid negative values and get a more reasonable range of the values.

In 't Hart (2012) the average ratio of the stability (maximum acceptable $H_s/(\Delta D)$) according to Steentoets and the available large scale tests was found to be 1.22 for tests in which damage occurred. This is the implicit safety in Steentoets and has been included in the probabilistic calculations with the model factor m with its mean value μ_m = 1.22 and standard deviation σ_m = 0.2.

Several calculations have been performed to achieve a design with a failure probability of p_f = 5 %. For the probabilistic calculations around 150,000 samples were taken and the failure probability is calculated by dividing the number of failure according to the LSE by the total number of Monte Carlo calculations (see A.1). An accuracy of 5% was achieved. This resulted for the block revetment with the input parameters from Table 3.1 in a design wave height H_s = 1.865 m.

With the calculated failure points and the failure probability, the design point was defined. The reliability index β as well as the importance coefficients α_j are calculated. The reliability index in this case is calculated as β = 1.64 which matches a failure probability of p_f = 5%. The importance coefficients are given in Table 3.2, in the order of importance. A positive value means that increasing the variable also means an increase of the result of the limit state equation and therefore a lower failure probability. Accordingly, the negative values indicate the parameters, which are inversely proportional to the result of the LSE, and thus proportional to the failure probability. Additionally, the α^2-values are given, which are the proportions of the importance of the variables: the larger the value, the larger the influence on the probability of failure.

It is clearly visible that the model factor m has the biggest influence on the results: 93.1%. This is explainable, as it has a large variation and a large influence on the stability: 95% of its values are between 0.82 and 1.62. As it is multiplied directly to the result of the stability, it is obvious that the influence is large. The second most important parameter is the significant wave height H_s, but its influence is small compared to the model factor. It has an importance of only 3.0% on the results. Moreover, the thickness D and the density of the blocks ρ_S have also a small influence on the results: 1.2%. All other parameters have less than 1% and thus have almost no influence on the results.

The results which are presented in 't Hart (2012) are also stated in Table 3.2. Most values for the importance α^2 are in the same order of magnitude as the ones calculated here. On the other hand, more parameters in 't Hart (2012) have apparently almost no influence on the results of the calculations. However, they also have only small influence on the results in the present calculations.

With the analyses described above, it is assumed that the parameters with an α^2-value lower than 1% have a negligible influence on the result. To check this assumption a new calculation is made with some variables set deterministic (σ = 0). This is done for the grain size of the filter layer D_{f15}, the grain size of the infilling material D_{i15} and the porosity of the filter layer n_f. The other variables, which have also a small importance, are kept to their stochastic values. With these adjustments the failure probability changes only slightly to 4.9%, which is not a substantial difference.

Table 3.2 The stochastic parameters and their importance coefficients

		Present calculations		't Hart (2012)
Variable		α	α^2	α^2
Model factor	m	0.965	0.931	0.903
Significant wave height	H_S	-0.173	0.030	0.048
Thickness of the blocks	D	0.109	0.012	0.014
Density of the blocks	ρ_S	0.107	0.012	0.023
Relative open area of the revetment	Ω	0.061	0.004	0.000
Duration of the load	t_{Belast}	-0.055	0.003	0.002
Thickness of the filter layer	b_f	-0.054	0.003	0.000
Cotangent of the slope of the revetment	$\cot\alpha$	0.054	0.003	0.008
Grain size of the infilling material	D_{i15}	0.039	0.002	0.000
Porosity of the filter layer	n_f	-0.032	0.001	0.000
Wave steepness	s_{op}	0.022	0.001	0.002
Water level	h	-0.018	0.000	-
Grain size of the filter layer	D_{f15}	-0.015	0.000	0.000

3.3 Partial safety factors

Partial safety factors can be quantified for each stochastic variable. With the results presented above, the partial safety factors can be calculated with the following equations (e.g. 't Hart (2012)):

- For the parameters describing the strength:

$$\gamma_{R,j} = \frac{\mu(R_j) - k_j \sigma(R_j)}{\mu(R_j) - \alpha_{R,j} \beta \sigma(R_j)} \tag{3.3}$$

- For the parameters describing the load:

$$\gamma_{S,j} = \frac{\mu(S_j) - \alpha_{S,j} \beta \sigma(S_j)}{\mu(S_j) - k_j \sigma(S_j)} \tag{3.4}$$

Therein k is a factor to describe the difference between the characteristic value of the variable and the mean value. As for the present calculations the characteristic values equal the mean values, it is $k = 0$. For example, if the characteristic value would have an exceedance probability of 95%, the k-factor would be $k = 1.645$. If the exceedance probability of the characteristic value would be 90% the factor would be $k = 1.28$.

The equations used here with the factor $k = 0$ are thus as follows:

- For the parameters describing the strength:

$$\gamma_{R,j} = \frac{\mu(R_j)}{\mu(R_j) - \alpha_{R,j} \beta \sigma(R_j)} \tag{3.5}$$

- For the parameters describing the load:

$$\gamma_{S,j} = \frac{\mu(S_j) - \alpha_{S,j}\beta\sigma(S_j)}{\mu(S_j)} \quad (3.6)$$

With equation (3.5) the partial safety factors of the stochastic variables can be calculated for the parameters describing the strength. Equation (3.6) gives the partial safety factors for the loading parameters.

In Table 3.3 the partial safety factors for the strength and the load parameters are given. Because the model factor *m* has the biggest influence, it has a relative high partial safety factor, with $\gamma_m = 1.199$. This partial safety factor was originally 1.463, because it was calculated with the probabilistic calculations in which the implicit safety of Steentoets was removed by introducing a model coefficient. To obtain a partial safety factor for Steentoets, it is divided by the mean value of the model coefficient: γ_m = 1.463/1.22 = 1.199.
This value is approximately the same the partial safety factor that was calculated in the same way in 't Hart (2012) $\gamma_{m,Hart}$ = 1.191.
Because both results for the partial safety of the model factor are approximately the same, it is concluded that the present method to quantify the safety factor is equally reliable. The advantage of this method is that it is much easier to do a number of calculations with various example revetments.

In the 4th column the partial safety factors from the calculations of 't Hart (2012) are given. As also described for the results of the importance of the variables, some parameters have only a small influence and therefore a safety factor near to 1.0. The differences between the results of 't Hart (2012) and the present calculations are only small.

Table 3.3 Partial safety factors of the stochastic input variables

Strength			
Variable		γ_R	γ_R **'t Hart (2012)**
Model factor	m	1.199	1.191
Grain size of the infilling material	D_{i15}	1.022	1.000
Relative open area of the revetment	Ω	1.014	1.000
Cotangent of the slope of the revetment	$\cot\alpha$	1.006	1.010
Thickness of the blocks	D	1.005	1.006
Density of the blocks	ρ_S	1.004	1.005
Wave steepness	s_{op}	1.002	1.004
Load			
Variable		γ_S	γ_S **'t Hart (2012)**
Thickness of the filter layer	b_f	1.018	1.000
Significant wave height	H_S	1.014	1.000
Duration of the load	t_{Belast}	1.013	1.018
Porosity of the filter layer	n_f	1.008	1.010
Grain size of the filter layer	D_{f15}	1.001	1.000
Water level	h	1.001	-

3.4 Overall safety factor

For practical calculations, the partial safety factors can be combined into one overall safety factor. This is recommended because most of the partial safety factors are almost 1.0. Therefore, an overall safety factor is determined to include the uncertainties of the input parameters. The factor is defined with the same method as in 't Hart (2012) to have a good comparison. There it is defined as the ratio between the wave height $H_{s,pf}$, that corresponds with a probability of failure of 5% according to the probabilistic calculations, and the maximum significant wave height according to Steentoets $H_{s,ST}$ (with mean values as input). That ratio is the safety margin of the calculations, as it gives the factor for which the wave height should be increased:

$$\gamma = \frac{H_{s,ST}}{H_{s,pf}} \tag{3.7}$$

with:

γ = safety factor
$H_{s,ST}$ = maximum wave height calculated with Steentoets [m]
$H_{s,pf}$ = wave height that results in the target failure probability of 5% [m]

The implicit safety which is in the model factor is not included in the calculation of the overall safety factor. This is because this implicit safety is already included in the maximum wave height calculated with Steentoets.

Thus, the overall safety factor is determined to $\gamma_1 = 1.263$. The safety factor determined in 't Hart (2012) is $\gamma_{Hart} = 1.25$, which is only slightly lower than the safety factor determined here. This shows a good resemblance.

The safety factor is calculated as the ratio between the wave heights, while the wave steepness was constant. This is done for practical reasons. The same safety factor can in practice also be applied on the thickness of the blocks *D*, because the parameter $H_s/(\Delta D)$ at the start of damage is constant for small variations of *D* and H_s. The safety factor can either be applied on the design wave height (with constant wave steepness), or it can be applied to the design block thickness to increase it by multiplying it with the safety factor.

4 Improved values for certain parameters

A number of example revetments have been used to calculate the safety factor in this chapter, after improving the mean value and standard deviation of the model factor first.
New results from large scale model tests were available to improve the value of the model factor for the uncertainties in Steentoets (section 4.1). With the new values the calculations are repeated to investigate the influence of the new model factor (section 4.2). These calculations have been carried out with improved values of the standard deviation of certain parameters. This has been done in two steps, to show the influence of it. First, the standard deviation for the porosity of the filter layer n_f and slope angle $\cot\alpha$ have been changed (section 4.2). Secondly, the parameters of the density of the blocks ρ_S and the standard deviation of the slope angle $\cot\alpha$ and the filter layer thickness b_f were changed (section 4.3).
Each time a number of calculations have been carried out in which the mean value of the most important parameters have been changed to check the influence on the safety factor.

4.1 Improved value for the model factor for the uncertainties in Steentoets

The model factor was calculated as the ratio between the results of the large scale model tests (at start of damage) and the results of Steentoets calculations (maximum acceptable $H_s/(\Delta D)$). Shortly after the publication of 't Hart (2012) the report on the validation of Steentoets2010 (Klein Breteler & Mourik (2012a)) was published, where more large scale tests were described and their results presented. Table 4.1 shows the results of the failure calculated with the model Steentoets as well as the large scale tests. The number of the figures in this table refer to the above stated validation report. The upper part of the table refers to the tests used by 't Hart (2012). The mentioned ratio is the ratio between the Steentoets results and the large scale test results.

In the recently published validation report for Steentoets2010 (Klein Breteler & Mourik (2012b)), additional failure points are presented which are added to Table 4.1 (lower part). The mean value and standard deviation of the ratio between all the Steentoets calculations and the test results are calculated and given in the last two rows of the table. Thereby, the grey filled rows are not considered. The Basalton (first grey row) is not taken into account, because the joints were not filled with gravel material. The shaded Hydroblocks result is not considered, because the blocks that had failed already in a previous test seem to have a lower stability after the repair.

The overall results show different values than the ones calculated with the upper part of the table. This is caused mostly by the two high additional results for Basalton and RonaTon+. The value of the standard deviation is only slightly raised. With the additional results, the model factor of the Steentoets2010 model is calculated to have a mean value $\mu = 1.33$ and the standard deviation $\sigma = 0.22$.

The subsequent calculations described in this chapter are conducted with the new model factor. Therefore, the variables are adjusted to $\mu_m = 1.33$ and $\sigma_m = 0.22$. The same calculation as before is conducted, with the same input variables (see Table 3.1), except for the wave height, which is adjusted to $H_s = 2.190$ to achieve the failure probability of 5%. For this calculation the overall safety factor is determined to be $\gamma_2 = 1.076$. The safety factor calculated with the new model factor is significant lower than the one derived in 't Hart (2012) because of the difference in the mean value of the model factor.

Table 4.1 Calculation of the model factor from 't Hart (2012) and new values for infilled column revetment

Type of revetment	Figure	Comment	$H_s/\Delta D$		Ratio test / calculation
			Failure in Steentoets calculations	Failure in large scale tests	
Basalton	B.15	not infilled	4.45	4.72	1.061
Hydroblocks	B.16		6.12	7.34	1.199
			5.11	6.29	1.231
			3.81	4.08	1.071
		reused	5.01	4.71	
			4.94	5.04	1.020
C-Star en Pit-Polygoon	B.18		4.69	6.10	1.301
			5.00	6.10	1.220
			3.93	6.48	1.649
Results 't Hart		**Mean value of the ratio**			1.22
		Standard deviation of the ratio			0.20
Additional results					
Basalton	B.15		4.76	7.68	1.613
RonaTon+	B.19		4.00	6.54	1.635
			5.04	6.47	1.284
Hillblocks	B.19		3.78	5.19	1.373
		Mean value of the ratio (overall)			1.33
		Standard deviation of the ratio (overall)			0.22

Note that some types of block revetments fail consequently at a lower value of $H_s/(\Delta D)$ than others. Since presently it is assumed that in the design stage it is not yet known which type of block revetment will be built, it is reasonable to calculate the model factor without taking this difference into account.

4.2 First phase of calculating the safety factor for various block revetments

A series of calculations are conducted to investigate the range of the values of the safety factors. Therefore, in each calculation, one variable is changed from its original parameters (see Table 3.1). When the mean value μ is changed, the standard deviation σ is changed proportional in the present report to keep the variation coefficient $V = \sigma/\mu$ constant.

A reanalysis of the information available about the porosity of the filter layer n_f and the cotangent of the slope of the revetment $cot\alpha$ has led to the conclusion that the standard deviation should be reduced compared to the values of 't Hart (2012). The standard deviation of the porosity is reduced to σ_{nf} = 0.03 and the standard deviation of the cotangent of the slope is reduced to $\sigma_{cot\alpha}$ = 0.1. Table 4.2 shows all the varied variables with the chosen input parameters.

Table 4.2 Varied variables and the changed values

Variation	Changed variable		Mean value μ	Standard deviation σ	V $= \sigma/\mu$
all variations	Porosity of the filter layer	n_f	0.35	0.03	8.6%
	Cotangent of the slope of the revetment	$cot\alpha$	3.5	0.1	2.9%
Var1	Duration of the load	t_{Belast}	5.0	0.715	14.3%
Var2	Wave steepness	s_{op}	0.02	0.001	5.0%
Var3	Thickness of the blocks	D	0.45	0.013	2.9%
Var4	Density of the blocks	ρ_S	2600	52.0	2.0%
Var5	Thickness of the filter layer	b_f	0.2	0.04	20.0%
Var6	Cotangent of the slope of the revetment	$cot\alpha$	3.0	0.086	2.9%
Var7	Water level	h	3.5	0.067	-

The results of the calculations are presented in Table 4.3 with the importance ratio α^2 for every variable. *Var0* is the same calculation as the previous section, but with updated standard deviation for n_f and $cot\alpha$. The variable, which is changed in the certain variation, is marked in bold. It can be seen that for most variations the values are similar for each variable. Variations 4-6 are highlighted as they show the most differing results. The varied variables in these calculations are the density of the blocks ρ_S, the thickness of the filter layer b_f and the cotangent of the slope of the revetment $cot\alpha$. The higher value for the thickness of the filter layer shows a large increase in the importance ratio of Ω, D_{f15}, n_f and b_f. It also resulted in a lower influence factor of the model factor. For this particular calculation the stability is determined by the first part of the simplified formulae (see section A.3), containing the influence of the leakage length Λ. That explains the large influence of these variables.

For most of the cases the stability is determined by the maximal stability $[H_S/(\Delta D)]_{max}$ (see section A.3, equation (A.31)). The maximal value $[H_S/(\Delta D)]_{max}$ is only calculated with the influence of the breaker parameter, and thus the wave steepness s_{op}, and the number of waves, which is defined by the duration of the load t_{Belast}. The angle of the wave direction β is also included in the equation, but in this report the wave attack is assumed to be perpendicular, which means no attenuating influence from it. In the highlighted calculations, the stability is calculated with equation (A.39) (section A.3), which includes the influences of all of the parameters. Therefore, almost all of the variables gain more influence in these calculations, whereas the model factor has its lowest influence.

Table 4.3 Importance ratio of the variables α^2 derived from the varied calculations

	t_{Belast}	H_S	$cot\alpha$	D	Ω	ρ_S	D_{i15}	b_f	n_f	D_{f15}	s_{op}	h	m
Var0	0.003	0.030	0.003	0.012	0.004	0.012	0.002	0.003	0.001	0.000	0.001	0.000	0.931
Var1	**0.002**	0.031	0.002	0.017	0.001	0.023	0.000	0.001	0.000	0.000	0.001	0.000	0.922
Var2	0.003	0.040	0.000	0.017	0.003	0.025	0.000	0.003	0.001	0.000	**0.000**	0.000	0.907
Var3	0.003	0.040	0.000	**0.017**	0.003	0.025	0.000	0.003	0.001	0.000	0.000	0.000	0.907
Var4	0.007	0.021	0.003	0.021	0.012	**0.021**	0.004	0.017	0.005	0.001	0.001	0.000	0.887
Var5	0.011	0.052	0.003	0.024	0.024	0.016	0.009	**0.049**	0.012	0.001	0.000	0.002	0.796
Var6	0.006	0.041	**0.003**	0.018	0.011	0.021	0.004	0.015	0.005	0.000	0.000	0.000	0.876
Var7	0.002	0.034	0.002	0.015	0.000	0.022	0.000	0.000	0.000	0.000	0.001	**0.000**	0.925
aver.	0.005	0.037	0.002	0.018	0.008	0.022	0.003	0.013	0.003	0.000	0.000	0.001	0.888

Table 4.4 shows the partial safety factors for the variables for these calculations. As it is highly dependent on the importance factors, the results show the same behaviour as the

above presented table. The average of the partial safety factor for each variable is calculated. The results for *Var0* are almost the same as in section 3.3, from which we can conclude that the influence of standard deviation of n_f and $cot\alpha$ is small.

Table 4.4 Partial safety factors derived from the varied calculations

	t_{Belast}	H_S	$cot\alpha$	D	Ω	ρ_S	D_{i15}	b_f	n_f	D_{f15}	s_{op}	h	m
Var0	1.016	1.013	1.006	1.007	1.022	1.005	1.027	1.033	1.008	1.002	1.002	1.000	1.346
Var1	**1.011**	1.012	1.005	1.006	1.007	1.005	1.008	1.010	1.003	1.000	1.003	1.000	1.354
Var2	1.012	1.016	1.000	1.006	1.013	1.005	1.009	1.018	1.004	1.001	**1.001**	1.001	1.350
Var3	1.012	1.011	1.000	**1.006**	1.013	1.005	1.009	1.018	1.004	1.001	1.001	1.001	1.350
Var4	1.019	1.009	1.006	1.007	1.026	**1.005**	1.037	1.043	1.010	1.002	1.002	1.001	1.345
Var5	1.024	1.021	1.007	1.007	1.036	1.004	1.055	**1.073**	1.015	1.004	1.002	1.002	1.321
Var6	1.018	1.016	**1.003**	1.006	1.024	1.005	1.036	1.040	1.010	1.001	1.002	1.001	1.342
Var7	1.010	1.013	1.002	1.006	1.002	1.005	1.000	1.000	1.001	1.000	1.002	**1.000**	1.355
aver.	1.015	1.014	1.003	1.006	1.017	1.005	1.022	1.029	1.007	1.001	1.002	1.001	1.345

For each variation calculation the overall safety factor is calculated as described in section 3.4 and presented in Table 4.5. Note that the variations 4-6 give slightly higher results than the other calculations. This is already explained above as the safety factors depend on the influences of the variables. The average value is comparable to the value calculated in section 3.4 (see last row).

Table 4.5 Overall safety factor of the variation calculations

Variation	**Overall safety factor γ**
Var0	1.076
Var1	1.058
Var2	1.058
Var3	1.054
Var4	1.082
Var5	1.079
Var6	1.087
Var7	1.056
average	1.066

As the safety factor should include all of the uncertainties, the resulting safety factor is defined to be γ_3 = 1.09 after these calculations. This value is remarkably lower than the factor calculated with the original value of the model factor (section 3.4). The variation of the safety factor is small, which gives the confidence that this safety factor can be applied to all revetments of this type.

4.3 Second phase of calculating the safety factor for various block revetments

In this section some key parameters have been changed again to show the influence on the safety factor. The parameters of the density of the blocks ρ_S and the standard deviation of the cotangent of the slope of the revetment $cot\alpha$ and the thickness of the filter layer b_f are adapted.

A reanalysis of the available data from the Rijkswaterstaat concerning measurements of the density of the blocks, has led to the conclusion that the standard deviation should be reduced compared to ‘t Hart (2012) and the mean value lies higher than the design value. Table 4.6 is derived from the measurements of the density of the blocks, in specific on Hydroblocks. Four sets of measurements have been carried out and the mean value and the standard deviation of the measurements are given in the table.

It can be clearly seen that the blocks have a larger density in average than the design values. With the measured values, the variation coefficient can be calculated, which is given in the last column of the table. Hence, the average variation coefficient results in 1%. Furthermore, it is determined that the design density of the stones is approximately $\rho_{S,D} = \mu - 2\sigma$. Therefore, the corrected parameters for the density of the stones are defined to $\mu_{\rho s}$ = 2346 kg/m³ and $\sigma_{\rho s}$ = 23 kg/m³, while the design of the revetment is calculated with $\rho_{S,D}$ = 2300 kg/m³. This provides some extra safety, which is taken into account in the safety factor.

Table 4.6 Measured values for the density of the blocks

Measure-ments	**Date of measure-ment**	**Design density $\rho_{S,D}$**	**Number of measured items**	**Measured density ρ_S**		
				Mean value μ	**Standard deviation σ**	**Variation coefficient**
Hydro 1	1998	2700	161	2753	49	0.018
Hydro 2	2002	2300	12	2361	16	0.007
Hydro 3	2007	2400	20	2449	21	0.009
Hydro 4	2008	2400	25	2450	18	0.007
					Average:	0.010

For the angle of the slope, the standard deviation of the cotangent is adjusted to meet more realistic values. The mean value is left to be $\mu_{cot\alpha}$ = 3.5. By changing the standard deviation from 0.25 to $\sigma_{cot\alpha}$ = 0.15, the 95% range lies between 3.2 and 3.8, which are considered realistic values.

The thickness of the filter layer b_f had in the previous sections also a slightly too high standard deviation. With the mean value μ_{bf} = 0.1 m, the standard deviation is changed from 0.02 to σ_{bf} = 0.01. This gives a 95% range from 0.08 m to 0.12 m.
With these new values, several calculations are conducted to show the influence on the safety factor. According to the results of the previous sections, some variables can be set to deterministic values. The influences of those variables were negligibly small and therefore it is not necessary to calculate with their stochastic distributions. The variables that are set to their mean values as their deterministic values are the grain sizes of the filter layer D_{f15} as well as the infilling material D_{i15} and the porosity of the filter layer n_f.
The stochastic input parameters are given in Table 4.7 and the deterministic input parameters in Table 4.8. For each stochastic parameter the mean value μ, the standard deviation σ as well as the variation coefficient V is given in the table. With those values the subsequent calculations are carried out.

A series of calculations were made with the improved values. At first, a calculation is made with the new values. Additionally, some variables are varied to achieve more results to compare. The thickness of the filter layer b_f, the cotangent of the slope of the revetment $cot\alpha$ as well as the thickness of the blocks D are changed according to Table 4.9.

Table 4.7 Input values for the stochastic parameters for the calculations with the improved values

Stochastically distributed variables					
Variable		**Unit**	**Mean value μ**	**Standard deviation σ**	**V $= \sigma/\mu$**
Duration of the load	t_{Belast}	[h]	10.0	1.43	14.3%
Water level	h	[m+NAP]	5.2	0.1	-
Significant wave height	H_s	[m]	1.865	0.1	5.4%
Wave steepness	s_{op}	[-]	0.040	0.002	5.0%
Thickness of the blocks	D	[m]	0.35	0.01	2.9%
Relative open area of the revetment	Ω	[-]	0.13	0.018	13.8%
Density of the blocks (design $\rho_{S,D}$ = 2300)	ρ_S	[kg/m³]	2346.0	23.0	1.0%
Thickness of the filter layer	b_f	[m]	0.10	0.01	10.0%
Cotangent of the slope of the revetment	$cot\alpha$	[-]	3.5	0.15	4.3%
Model factor	m	[-]	1.33	0.22	16.5%

Table 4.8 Input values for the deterministic parameters for the calculations with the improved values

Deterministic variables			
Variable		**Unit**	**Value**
Porosity of the filter layer	n_f	[-]	0.35
Grain size of the filter layer	D_{f15}	[m]	0.015
Porosity of the infilling material	n_i	[-]	0.70
Grain size of the infilling material	D_{i15}	[m]	0.006
Width of the blocks	B	[m]	0.30
Length of the blocks	L	[m]	0.30
Upper boarder of the block revetment	Z_b	[m+NAP]	6.0
Lower border of the block revetment	Z_o	[m+NAP]	2.0
Wave angle	β	[deg]	0
Gravity acceleration	g	[m/s²]	9.81
Viscosity of the water	ν	[m²/s]	$1.2 \cdot 10^{-6}$
Density of the water	ρ_W	[kg/m³]	1025.0

Table 4.9 Variations of the variables for the calculations with the improved values

Variation	**Changed variable**		**Mean value μ**	**Standard deviation σ**
Var2.1	Thickness of the filter layer	b_f	0.20	0.02
Var2.2	Cotangent of the slope of the revetment	$cot\alpha$	3.00	0.086
Var2.3	Thickness of the blocks	D	0.45	0.013

The importance ratio of the variables α^2 are presented in Table 4.10. The variable, which is changed in the certain variation, is marked in bold. These calculations give for most of the variables similar results to the previous calculation conducted in section 4.2. The previous calculations were done with 13 input variables with stochastic distributions. In the current calculations, three of them were set to deterministic values, as explained above. Still, the results are roughly the same, as these three variables had only a small importance of 0.1% or even 0%. Therefore, a comparison of the results of the two different calculations is still possible.

However, a difference is notable in the importance of the density of the blocks ρ_S. This is because the mean value of the density is increased and the standard deviation changed a lot: it is now only half of the previous value. Therefore, the influence of the density of the blocks is now smaller, but more realistic.

Another difference lies in the importance of the thickness of the filter layer b_f. As the standard deviation was changed to half the size as before, its influence is not as big as before. Also in the case of variation *Var2.1*, in which the mean value as well as the standard deviation of b_f is doubled, the importance parameter for b_f is only 1.5%, as before it was raised to even 4.9% (*Var5* in Table 4.3).

Table 4.10 Importance ratio of the variables α^2 derived from the varied calculations and the actual values

	t_{Belast}	H_s	$\cot\alpha$	D	Ω	ρ_S	b_f	s_{op}	h_w	m
Var2.0	0.003	0.032	0.005	0.018	0.004	0.006	0.001	0.001	0.000	0.930
Var2.1	0.011	0.051	0.007	0.024	0.031	0.006	**0.015**	0.001	0.003	0.852
Var2.2	0.003	0.035	**0.005**	0.019	0.008	0.006	0.002	0.000	0.000	0.921
Var2.3	0.002	0.018	0.005	**0.009**	0.000	0.006	0.000	0.001	0.000	0.958
average	0.005	0.034	0.005	0.018	0.011	0.006	0.005	0.001	0.001	0.915
previous values	0.004	0.036	0.002	0.018	0.007	0.022	0.011	0.001	0.001	0.893

The overall safety factor is calculated for the new set of input variables as before (see section 3.4). The results are presented in Table 4.11. The safe upper limit for the overall safety factor is determined to be γ_4 = 1.03 for these structures.

Table 4.11 Results for the overall factor for the actual values

Calculation	**Overall safety factor**
Var2.0	1.021
Var2.1	1.033
Var2.2	1.026
Var2.3	1.008
Average	1.022

4.4 Influence of the acceptable failure probability

In order to get an impression of the influence of the value of the acceptable failure probability, more calculations were performed in the range of 1% to 10%. For the calculation, the default case with the improved values (second phase) were taken (*Var2.0*). The results are presented in Table 4.12.

The results in the table show a considerable influence of the value of the acceptable failure probability. An acceptable failure probability of 1% means that there is no residual strength assumed and also 9 other relevant damage mechanisms that are a threat to the safety. In that case, a safety factor of 1.22 is required. When we assume an acceptable failure probability of 10%, which would mean a big residual strength or no other damage mechanisms that jeopardize the dike, the overall safety factor would be below 1 (cover layer thickness can be smaller than calculated by Steentoets).

Table 4.12 Overall safety factor for different values of the acceptable failure probability

Acceptable failure probability	**Overall safety factor**
1%	1.22
2%	1.14
5%	1.02
10%	0.94

The additional calculations show that the value of the safety factor for block revetments is very much depending on the assumed acceptable failure probability. This is itself depending on the residual strength of the dike, after the failure of the block revetment.

In the research programme “SBW Reststerkte” Kaste & Klein Breteler (2012) analysed how the residual strength of the dike contributes to the safety of the revetment. Therefore, the failure probability for a dike was calculated, including the failure of the revetment and the residual strength. The results of that research will allow us to verify the assumed 5% in this report. Unfortunately, that research was not finished yet at the moment the present report was finalised.

5 Conclusions

To calculate the safety factor for the design of block revetments several probabilistic calculations have been performed. Because of the complexity of Steentoets it was necessary to use the simplified formulae of Klein Breteler & Mourik (2012a). The safety factor is determined for one specific type of block revetment: those with large interaction between the blocks and a relatively large open area (in Dutch: zuilen met klemming).

The first calculation was based on the report of 't Hart (2012) where the safety of Steentoets has been determined. Therefore, the safety factor for Steentoets was calculated with probabilistic calculations for the norm-case of a storm with the probability of exceedance of 1/4000 years. For this norm-storm, a failure probability of 1% is allowed for the failure of the dike due to the failure of the block revetment. As there is still residual strength present after the revetment failed, which is not further calculated here, the aimed failure probability is 5%. To verify the calculation method with the simplified formulae the same input parameters as in 't Hart (2012) were applied. The resulting overall safety factor is γ_1 = 1.263, which is close to the one derived by 't Hart (2012): γ_{Hart} = 1.25. Therefore, it is concluded that the new method is sufficiently precise. With this new method it is much easier to carry out a lot of calculations to investigate a large variety of structures.

Since there are now more results of large scale model tests available, the model factor of 't Hart (2012) is revised to $\mu(m_0)$ = 1.327 and $\sigma(m_0)$ = 0.22. With this new model factor the calculation is repeated, which results in a safety factor of γ_2 = 1.076.

Based on a re-analysis of the information from Projectbureau Zeeweringen it was possible to improve the input values for the density of the stones, the slope of the revetment and the thickness of the filter layer. With these values the safety factor was γ_4 = 1.03. The decrease to the previous calculations is explainable, because it includes the fact that the density of the blocks have a higher mean value than the design value (mean = design + 2σ), but a lower standard deviation than before. The adapted values result in a lower overall safety factor for the failure probability of 5%.

There were also calculations done with another acceptable failure probability than 5%, ranging from 1% to 10%, to analyse the influence of this aspect. As could be expected, the safety factor is dependent on the acceptable failure probability. This means it is dependent on the amount of residual strength and/or the number of other relevant failure mechanisms that jeopardise the dike. This is further analysed in the scope of the research project WTI-2017 in Kaste & Klein Breteler (2012). Unfortunately, that research was not finished yet at the moment the present report was finalised. However, the here used value of 5% for the acceptable failure probability is presently considered to be a reasonable value for a common dike profile.

Although the calculations (chapter 4) result in γ_4 = 1.03, it is recommended to apply a higher value to take other structure-load combinations into account that have not been included in the present research. Therefore, it is recommended to apply a safety factor of γ = 1.1. This recommendation will be checked in the coming years in the framework of the research programme WTI-2017. The here determined safety factor can be applied to the design value of the block thickness of the revetment, in the way that the calculated block thickness is multiplied by the safety factor.

6 References

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A Description of the calculations

This section describes the calculations for deriving the failure probability of the block revetment induced by waves. In the first section of this chapter, all the input parameters are presented that are needed for the calculations. The structure of the calculations is described in the following sections.

A.1 Input Parameters

A simplified geometry of the block revetment is chosen, as shown in Figure A.1. All the input parameters needed to calculate the failure of the block revetment are presented in Table A.1. Besides the parameters of the block revetment, also the sea state has to be described.

The input *type* and *fill* are indicators for the type of revetment, respectively if there is infilling material or not. For the joints there is either the joint widths s_s and s_l or the relative open area of the revetment Ω needed. In this case, which is a revetment made of columns, the open area is given. The parameters $stab_{ST}$ and $stab_F$ are as well needed for the calculation of the failure of the revetment and described in section A.3 in Step 1.

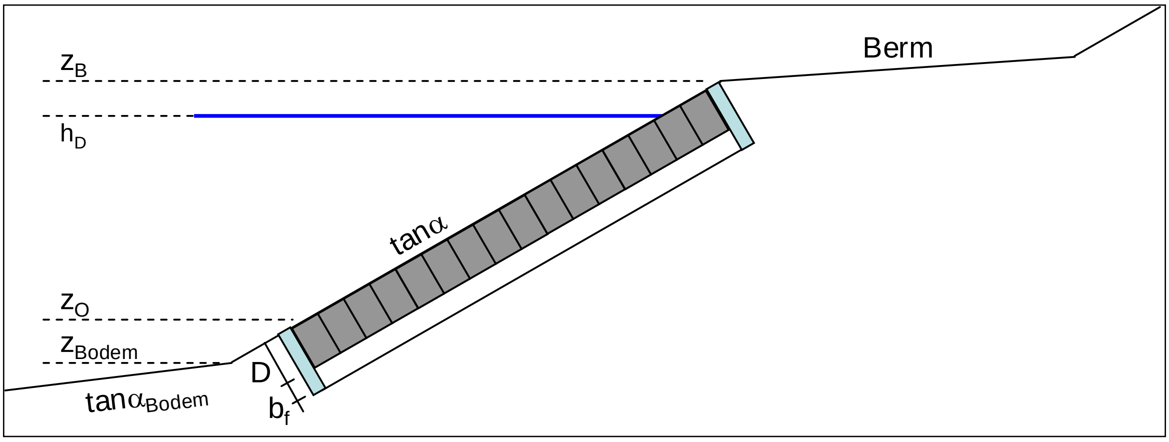

Figure A.1 Simplified geometry of the revetment as input for the calculations

For the sea state parameters, either the wave steepness s_{op} or the wave peak period T_p is needed, as they can be derived from each other. In this report, it is chosen to set the wave steepness as the input parameter and the wave peak period is calculated with it in the script.

A.2 Probabilistic calculations

There are several methods to estimate multivariate probabilities, like the probability of failure of a dike. In Diermanse et al. (2011) a description of the most common probabilistic sampling methods are given, such as the Crude Monte Carlo method, FORM (First Order Reliability Method), Directional Sampling and Monte Carlo with Importance Sampling. It is also stated that FORM usually is the most efficient probabilistic simulation method, but the method may not converge when there are discontinuities in the results. There are discontinuities in the present calculations, for example the stability of the block revetment is either a maximum value, defined only by a few variables or calculated with different parameters (see appendix A.3). The leakage length induces also discontinuities, as the current around the blocks is either laminar or turbulent.

Table A.1 All needed input parameters

General parameters		
g	[m/s²]	gravity acceleration
Parameters describing the sea state		
t_{Belast}	[h]	duration of the load
h_D	[m+NAP]	design water level
H_s	[m]	significant wave height
s_{op}	[-]	wave steepness
β	[deg]	angle of the wave direction
ρ_W	[kg/m³]	density of the water
ν	[m²/s]	kinematical viscosity of water
Parameters describing the revetment		
type	[-]	type of the blocks (1 = blocks, 2 = columns, 3 = blocks placed on their side)
fill	[-]	indicator of infilling material (1 = yes; 0 = no)
s_s	[m]	joint width of the vertical joints (stootvoegen)
s_l	[m]	joint width of the horizontal joints (langsvoegen)
Ω	[-]	relative open area of the revetment
B	[m]	width of the blocks
L	[m]	length of the blocks
D	[m]	thickness of the top layer
ρ_S	[kg/m³]	density of the blocks
n_f	[-]	porosity of the filter material
D_{f15}	[m]	grain size of the filter material
b_f	[m]	thickness of the filter layer
n_i	[-]	porosity of the infilling material
D_{i15}	[m]	grain size of the infilling material
$tan\alpha$	[-]	tangent of the outer slope (average, if there are different slopes)
z_{Berm}	[m+NAP]	height of the berm
Z_b	[m+NAP]	level of the top border over NAP
Z_o	[m+NAP]	level of the low border over NAP
$tan\alpha_{Bodem}$	[-]	slope of the foreland
z_{Bodem}	[m]	height of the dike toe over NAP
$stab_F$	[-]	$H_s/\Delta D$ for the design conditions calculated with simplified formulae
$stab_{ST}$	[-]	$H_s/\Delta D$ for the design conditions calculated with Steentoets
Model factor for the calculation		
m	[-]	model factor for the calculation of the failure of the block revetment

Furthermore, it is stated in Diermanse et al. (2011) that the Crude Monte Carlo method is very robust, accurate and simple, but is not very efficient, as a large amount of calculations are needed to get a reliable result. In the present report, the aimed failure probability is 5% and thus not very low, so the Monte Carlo method is efficient enough. It is also very simple and straightforward to implement the time dependent calculations. Another advantage of the

Monte Carlo method is that it is very transparent and simple. That makes it easy to check the steps in the calculations, which is important in the development phase of the research. Therefore, it is chosen for the Monte Carlo method in this research.

In a crude Monte Carlo simulation there are random samples chosen out of the range of the distribution of the variables, taking into account their probability of occurrence. With these input variables, the failure is calculated with the limit state equation (LSE):

$$Z = R - S \tag{A.1}$$

with:
R = Strength (Resistance)
S = Load (Solicitation)

The LSE describes if there occurs failure or not in a simple way. When the load is bigger than the strength and thus Z results in a negative value, failure occurs.
For $Z = 0$, the LSE describes the border between failure and non-failure. But in the most cases, the load and the strength are not specified by one number. They mostly are dependant on many variables as they consist of an equation or calculation. In the report at hand, the resistance consists of the stability of the block revetment $H_{s,stab}/(\Delta D)$ according to Steentoets, respectively of the admissible wave height resulting from it: $H_{s,stab}$. This wave height is calculated with the method described in section A.3. The model factor m to include uncertainties of the calculations is multiplied to it to take the implicit safety into account, which is calculated with Steentoets. The load is defined by the occurring wave height H_s. Thus, the following LSE for the failure of the block revetment is applied:

$$Z_{BR} = H_{s,stab} \cdot m - H_s \tag{A.2}$$

with:
$H_{s,stab}$ = calculated admissible wave height [m]
H_s = occurring wave height [m]
m = model factor to include uncertainties and implicit safety in Steentoets [-]

The amount of the failure points, the number of negative Z-values, is divided by the amount of the calculations to obtain the failure probability.

$$p_f = \frac{N_{fail}}{N_{calc}} \tag{A.3}$$

with:
p_f = probability of failure [-]
N_{fail} = amount of failure points [-]
N_{calc} = amount of calculations [-]

Therefore, a large amount of samples is needed for a reliable result. Especially when the failure probability is very small, it often takes many samples to obtain only a single failure point.

The probabilistic calculations are accomplished with the program “Matlab” and using the probabilistic toolbox of the OpenEarth Tools (OET (2012), described in Diermanse et al.

(2011)). The probabilistic toolbox of the OpenEarth Tools provides the Matlab routine for a Monte Carlo simulation.

A.3 Calculation of the stability of the block revetment

The software named "Steentoets2010" was developed to calculate the stability of block revetments. The calculation time of Steentoets2010 is rather long and not suitable to perform probabilistic calculations with some thousands of samples. Therefore, simplified formulae to calculate the stability of the block revetment were derived in Klein Breteler & Mourik (2012a). With these simplified formulae, the stability of the block revetment can be estimated in shorter calculation time. The accuracy of these formulae is slightly lower than Steentoets calculations, but sufficient for the probabilistic calculations.

In this report the focus lies on the block revetment build with columns with infilling material and thus large interaction between the blocks. The here presented equations are only applicable for columns. It has to be noticed that the equations are presented here for explanation, but are derived from Klein Breteler & Mourik (2012a).

The overall calculation consists of the following three steps:

1. Preparation for the probabilistic calculations
2. Calculate the leakage length
3. Deterioration of the block revetment and the filter layer in each time step

Step 1: Accommodation for the probabilistic calculations
For the probabilistic calculations a correction factor is added to the simplified formulae for calculating the stability $H_s/(\Delta D)$. The factor is chosen to decrease the inaccuracy of the simplified equations compared to Steentoets. Therefore, calculations with the design values of the input parameters are conducted, once in Steentoets and once with the simplified formulae. With this correction factor f_c, the results of the simplified formulae are adjusted to the Steentoets calculations.

$$f_c = \frac{\left[\frac{H_s}{\Delta D}\right]_{ST}}{\left[\frac{H_s}{\Delta D}\right]_{F}} = \frac{\text{stability calculated with the design values with Steentoets [-]}}{\text{stability calculated with the design values with the simplified formulas [-]}} \tag{A.4}$$

Step 2: Calculate the leakage length
In the second step the leakage length Λ is calculated as follows:

Equivalent joint width
For revetments build with columns, usually the relative open area is given instead of the joint width. An equivalent joint width can be calculated with the following formula:

$$s_s = s_l = -\frac{1}{2}(B+L) + \sqrt{\frac{\Omega \cdot B \cdot L}{1-\Omega} + \frac{1}{4}(B+L)^2} \quad \text{(A.5)}$$

with:
s_s = width of the vertical joints (stootvoegen) [m]
s_l = width of the horizontal joints (langsvoegen) [m]
Ω = relative open area of the revetment [-]
B = width of the blocks (use for Basalton B = 0.3 m) [m]
L = length of the blocks (use for Basalton L = 0.3 m) [m]

Permeability of the filter layer
The permeability of the filter layer can be calculated with the following equations, which are applicable for the first and the second filter layer. In the here regarded calculations is only one filter layer present.

$$a_1 = 160 \frac{\nu \left(1-n_f\right)^2}{g \cdot n_f^{\,3} \cdot D_{f15}^2} \quad \text{(A.6)}$$

$$b_1 = \frac{2.2}{g \cdot n_f^{\,2} \cdot D_{f15}} \quad \text{(A.7)}$$

$$k_1 = \frac{-a_1 + \sqrt{a_1^2 + 1.2 \cdot b_1}}{0.6 \cdot b_1} \quad \text{(A.8)}$$

with:
a_1 = linear resistance coefficient of the first filter layer [s/m]
b_1 = turbulent resistance coefficient of the first filter layer [s²/m²]
k_1 = permeability of the first filter layer [m/s]
ν = $1.2 \cdot 10^{-6}$ m²/s = kinematical viscosity of water
g = gravitational force [m/s²]
n_f = porosity of the filter layer [-]
D_{f15} = grain size of the filter layer [m]

Permeability of the infilling material
For the infilling material, if present, the permeability can be calculated as follows. (Equation (A.10) differ from equation (A.7)!)

$$a_i = 160 \frac{\nu \left(1-n_i\right)^2}{g \cdot n_i^3 \cdot D_{i15}^2} \quad \text{(A.9)}$$

$$b_i = \frac{0.10}{g \cdot n_i^5 \cdot D_{i15}} \quad \text{(A.10)}$$

with:
a_i = linear resistance coefficient of the infilling material [s/m]
b_i = turbulent resistance coefficient of the infilling material [s²/m²]

n_i = porosity of the infilling material [-]
D_{i15} = grain size of the infilling material [m]

Permeability of the top layer
To calculate the permeability of the top layer, several steps have to be followed.
Beginning with the calculation of the permeability of the filter material, which is positioned directly underneath the joints.

$$a_{ftop} = 160 \frac{\nu \left(1 - n_f - 0.1\right)^2}{g(n_f + 0.1)^3 D_{f15}^2} \qquad \text{(A.11)}$$

$$b_{ftop} = \frac{0.14}{g(n_f + 0.1)^5 D_{f15}} \qquad \text{(A.12)}$$

with:
a_{ftop} = linear resistance coefficient of the filter layer material directly under the joints [s/m]
b_{ftop} = turbulent resistance coefficient of the filter layer material directly under the joints [s²/m²]

In the next step, the permeability of the joints is calculated. The same process has to be performed for the vertical as well as for the horizontal joints. The difference is the calculation for the part of the top layer, consisting of the ratio of the joints A_{ro} and the modified joint width *s*:

- for the permeability of the vertical joints (k'_s) with $s = s_s + 0.3 \cdot 10^{-3} m$ and

$$A_{ro} = \frac{s_s + 0.3 \cdot 10^{-3}}{L + s_s + 0.3 \cdot 10^{-3}} \qquad \text{(A.13)}$$

- for the permeability of the horizontal joints (k'_l) with $s = s_l + 0.3 \cdot 10^{-3} m$ and

$$A_{ro} = \frac{s_l + 0.3 \cdot 10^{-3}}{B + s_l + 0.3 \cdot 10^{-3}} \qquad \text{(A.14)}$$

with:
A_{ro} = part of the top layer which consists of vertical, respectively horizontal, joints [-]

The following steps are the same for the vertical and horizontal joints.
For the first estimation it is assumed that the current in the joints is laminar. The calculation of the permeability of the joints is then calculated:

$$a_s = \frac{12\nu}{g \cdot s^2 \cdot A_{ro}} \qquad \text{(A.15)}$$

$$b_s = 0 \qquad \text{(A.16)}$$

with:
a_s = linear resistance coefficient of the joints [s/m]
b_s = turbulent resistance coefficient of the joints [s²/m²]

With that, the first estimation of the permeability of the joints is calculated as follows. The calculations are performed with the characteristics of the first filter layer (D_{f151}, n_{f1}) and the following:

$$e = \exp(1) \tag{A.17}$$

$$r_{\min} = \max\left(0.8 \cdot D_{f15}; 0.5 \cdot s\right) \tag{A.18}$$

$$n_{in} = 0.6 \tag{A.19}$$

If there is infilling material: $n = n_i = 0.7$; else: $n = n_{in}$ (A.20)

$$a_{spleet} = a_s + \frac{s \cdot a_{ftop}}{\pi \cdot D \cdot A_{ro}} \cdot ln\left(\frac{s}{\pi \cdot e \cdot A_{ro} \cdot r_{\min}}\right) + \frac{a_i}{2 \cdot A_{ro}} \tag{A.21}$$

$$\begin{aligned} b_{spleet} = b_s &+ \frac{1}{g \cdot D \cdot A_{ro}^2}\left(1 - \frac{1}{n} + \frac{1 - A_{ro}^2}{2n_{in}^2}\right) + \frac{1}{g \cdot D}\left(1 - \frac{1}{A_{ro}}\right) + \\ &+ \frac{s \cdot b_{ftop}}{\pi \cdot D \cdot A_{ro}}\left(\frac{s}{\pi \cdot r_{\min} \cdot A_{ro}} - 2\right) + \frac{b_i}{2A_{ro}^2} \end{aligned} \tag{A.22}$$

$$k' = \frac{-a_{spleet} + \sqrt{a_{spleet}{}^2 + 4b_{spleet}}}{2b_{spleet}} \tag{A.23}$$

With this first estimation of $k_t = k'$, the filter velocity is calculated:

$$v_t = \frac{k_t}{A_{ro}} \tag{A.24}$$

If $\frac{v_t \cdot s}{\nu} \leq 5000$: the first estimation is right and no changes have to be made.

If $\frac{v_t \cdot s}{\nu} > 5000$: the current is turbulent and the permeability has to be calculated again with the equations (A.21), (A.22) and (A.23), considering the following changes:

$$a_s = 0 \tag{A.25}$$

$$b_s = \frac{2}{s \cdot C^2 \cdot A_{ro}^2} \tag{A.26}$$

with: $C = 18 \cdot \log\left(\frac{6s}{1 \cdot 10^{-4}}\right)$ (A.27)

When the permeability is determined for the vertical as well as for the horizontal joints, the overall permeability of the top layer is summed:

$$k' = k'_s + k'_l \tag{A.28}$$

Leakage length
Eventually, the leakage length can be calculated:

$$\Lambda = \max\left(\sqrt{\frac{D \cdot \left(b_{f,1} \cdot k_1 + b_{f,2} \cdot k_2\right)}{k'}};\ 0.5 \cdot D\right) \tag{A.29}$$

with:
$b_{f,1}$ = thickness of the first filter layer [m]
k_1 = permeability of the first filter layer [m/s]
$b_{f,2}$ = thickness of the second filter layer (if present) [m]
k_2 = permeability of the second filter layer (if present) [m/s]
k' = permeability of the top layer [m/s]

Step 3: Calculation of the stability of the block revetment
In this step the stability of the block revetment $H_s/(\Delta D)$ is calculated. As the water level does not change in the present calculations, the stability of the block revetment can be calculated with the here presented way. For other cases it is referred to Klein Breteler & Mourik (2012a).

At first, the influence factor of the load duration is calculated:

$$f_{sfront} = \max\left(1 - c_1 \cdot \log\left(\frac{N}{1000}\right);\ c_2\right) \tag{A.30}$$

with:
c_1 = 0.15; c_2 = 0.85 (for columns)
N = number of waves

$$N = \frac{t_{Belast} \cdot 3600}{T_p / 1.1}$$

t_{Belast} = duration of the load [h]

$$T_p = \sqrt{\frac{H_s}{1.56 \cdot s_{op}}} \text{ [s]}$$

With that factor, the maximal value of the stability $[H_s/(\Delta D)]_{max}$ can be calculated:

$$\left[\frac{H_s}{\Delta D}\right]_{max} = \frac{\left(7\left(\min\left(\xi_{op};2\right)\right)^{-1/3} + \max\left(0.5\left(\min\left(\xi_{op};5\right)-2\right);0\right)\right)}{\max\left((\cos\beta)^{2/3};0.4\right)} \cdot f_{sfront} \qquad \text{(A.31)}$$

with:

ξ_{op} = breaker parameter [-] $\xi_{op} = \frac{\tan\alpha}{\sqrt{s_{op}}}$

β = wave angle [deg]

To calculate the stability $H_s/(\Delta D)$ several parameters need to be calculated first. Each parameter reflects the influence of a certain aspect of the revetment. The equations depend on the type of the revetment. For revetments with columns (with large interaction between the blocks such as Basalton and Hydroblocks), the equations are presented here.

- relative density of the blocks Δ:

$$p_\Delta = 0.25 \cdot \left(\Delta - 1.5\right)^2 + 0.99 \qquad \text{(A.32)}$$

with:

$$\Delta = \frac{\rho_S - \rho_W}{\rho_W}$$

ρ_S = density of the blocks [kg/m³]
ρ_W = density of the water [kg/m³]

- number of waves N:

$$p_N = \max\left(4.52 \cdot N^{-0.19};\ 0.7\right) \qquad \text{(A.33)}$$

- slope of the revetment $\tan\alpha$:

$$p_{\tan\alpha} = 0.53 \cdot \tan\alpha^{-0.49} \qquad \text{(A.34)}$$

- angle of the waves β:

$$p_\beta = \min\left(10^{-6} \cdot \beta^{3.29} + 1; 0.063 \cdot D^{-2.4} + 1\right) \qquad \text{(A.35)}$$

- leakage length Λ:

$$p_\Lambda = 0.42 \cdot \left(\frac{\Lambda}{D}\right)^{-2.4} + 0.65 \qquad \text{(A.36)}$$

- upper boarder of the revetment Z_b:

$$p_{Z_b} = \max\left[\begin{array}{l} 0.99\cdot\left(\max\left[\dfrac{Z_b-h}{H_s};-0.6\right]+0.6\right); \\ 5\cdot\left(\min\left[\dfrac{Z_b-h}{H_s};-0.2\right]+0.2\right)^4+0.87 \end{array}\right] \tag{A.37}$$

- steepness of the waves s_{op}:

$$p_{s,op} = \max\left(0.29\cdot \mathrm{s_{op}}^{-0.29}; 1.73\cdot \mathrm{s_{op}}^{0.17}\right) \tag{A.38}$$

This results in the stability $H_s/(\Delta D)$ with the additional correction factor as explained in Step 1:

$$\left[\frac{H_s}{\Delta D}\right] = \min\left[6.16\cdot p_\Delta\cdot p_N\cdot p_{\tan\alpha}\cdot p_\beta\cdot p_\Lambda\cdot p_{Z_b}\cdot p_{s_{op}}\ ;\left[\frac{H_s}{\Delta D}\right]_{\max}\right]\cdot f_c \tag{A.39}$$

With the stability of the revetment, the admissible significant wave height $H_{s,stab}$ can be calculated:

$$H_{s,stab} = \left[\frac{H_s}{\Delta D}\right]\cdot\Delta\cdot D \tag{A.40}$$

B Correction factor for the simplified formulae

In appendix A.3 it is explained that an additional factor is added to the simplified formulae (*Step 1: Accommodation for the probabilistic calculations*). With this factor, the results of the simplified formulae are adjusted to the Steentoets calculations to decrease possible uncertainties. Table B.1 gives a list of the results and the factor used in the certain calculations.

Table B.1 Values for the stability of the design values calculated with Steentoets and the simplified formulae

	$H_s/(\Delta D)$ Simplified formulae (*F*)	**$H_s/(\Delta D)$ Steentoets (*ST*)**	**Correction factor *ST/F***
Chapter 3			
Recalculation	5.414	5.412	1.000
Chapter 4.2			
Var0	5.446	5.412	0.994
Var1	5.741	5.718	0.996
Var2	4.991	4.992	1.000
Var3	5.503	5.466	0.993
Var4	5.489	5.446	0.992
Var5	4.507	4.493	0.997
Var6	5.162	5.144	0.997
Var7	5.450	5.412	0.993
Chapter 4.3			
Var2.0	5.457	5.412	0.992
Var2.1	4.505	4.493	0.997
Var2.2	5.173	5.144	0.994
Var2.3	5.514	5.522	1.001