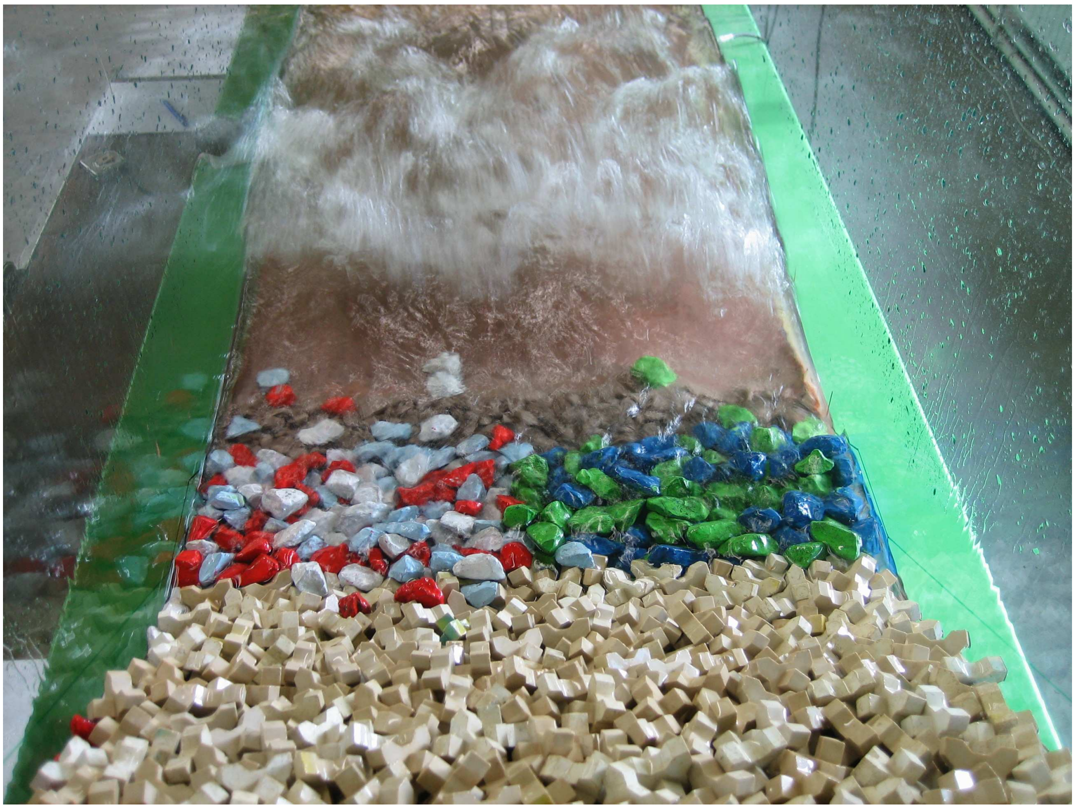
Toe structures of rubble mound breakwaters

Stability in depth limited conditions



Master of Science Thesis

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February 2009

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Toe structures of rubble mound breakwaters

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Preface

This thesis is the final report of a research project to obtain the degree of master of Science in the field of Coastal Engineering at Delft University of Technology. This report is an overview of the results of the investigation to toe stability of rubble mound breakwaters in depth limited conditions.

This study, existing of literature and scale model experiments, is performed in collaboration with the department of coastal engineering of DMC (Delta Marine Consults). DMC is the trade name of BAM Infraconsult bv. The experiments are executed in the laboratory facilities of DMC in Utrecht. I would like to thank DMC for the facilities and support to accomplish this study.

During this period a graduation committee, consisting of the following persons, supervised this thesis, for which I am grateful:

Prof.dr.ir. M.J.F. Stive	Delft University of Technology
Prof.dr.ir. W.S.J. Uijttewaal	Delft University of Technology
Ir. H.J. Verhagen	Delft University of Technology
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Summary

This thesis investigates the stability of toe material for rubble mound breakwaters in depth limited conditions. The present method (Van der Meer, 1998) to calculate the required rock size of the toe gives results for depth limited conditions but is never validated in this area. This design equation is based on physical model tests done by Gerding (1993) and is an empirical relation.

The Van der Meer approach implies deep water situations and breaking waves on the structure slope. However, for shallow water conditions this assumption is not valid anymore. Waves start breaking at the fore shore slope and toe which results in different hydrodynamical wave load at the toe. Toe material is exposed to waves and starts behaving as armour rock.

The transition zone from conventional toe design in deep water to design in shallow water situation introduces a lot of uncertainties for designing rubble mound breakwaters. The objective for this thesis is finding a more reliable design equation in this situation.

In the transition zone it is expected, that there are more parameters of influence than are incorporated in the Van der Meer formula. In shallow water, the fore shore slope is expected of influence, because of the breaking wave climate. The ratio of wave steepness to bottom steepness (Iribarren) is considered as well.

These research questions are answered by performing scale model tests. Toe stability is tested in a two dimensional wave flume for shallow water and different fore shore slopes. The observations during the scale model tests and the analysis of the performed dataset gave the following conclusions:

- The applicability of the Van der Meer design curve for depth limited conditions ($h_t/h_m<0.4$) is confirmed. The new dataset follows the design curve in a correct way.
- Fore shore slope is strongly influencing toe stability. This is not only valid in shallow water but also in deep water. In shallow water, wave steepness influences toe stability as well. Due to a lack in data points, it is not proven for deep water.

- Very shallow water (defined by $h_m/H_s<2.0$), shows significantly different hydrodynamic behaviour. Wave breaking occurs at the fore shore. The toe structure is attacked by breaking or already broken waves. Although a reduced wave height reaches the toe, damage is larger because the toe is exposed to turbulent wave attack.

The dataset from this experiment is used for a new stability equation. Including fore shore slope and wave steepness, results in a more extensive equation for very shallow water. It gives a better fit with less variance than the Van der Meer equation. This relation is like Van der Meer empirical, based on relationships between dimensionless parameters. For this analysis two assumptions are made:

- Scaling of toe rock according to the stability number $H_s/\Delta D_{n50}$ is assumed correct. With help of this ratio, dimensions of the toe rock are related to wave height.
- Influence of wave steepness to toe stability is given as a part of the Iribarren number. $\xi_{op} = \frac{\alpha_{shore}}{\sqrt{H_s / L_0}}$

In this research a different value for damage is suggested by $N_{\%}$. The commonly used N_{od} is defined by the number of displaced rock per strip as wide as D_{n50}. Similar N_{od} values at different stone size, can give different percentages of actual damage. $N_{\%}$ corresponds to the observed damage, does not vary with different stone sizes and is therefore easier to use in design procedures. This damage classification is used in the proposed stability equation. A design value of 10% is given for wind waves (tested $S_{op}={}^{+}/_{-}0.35$) and a design value of 5% for swell waves (tested $S_{op}={}^{+}/_{-}0.01$). The design conditions for swell waves are stricter because of occurrence of upward moving rock for long waves.

The proposed stability equation for very shallow water is the following:

$$\frac{H_s}{\Delta D_{n50}} = 3.0 \cdot \frac{N_{\%}^{1/3}}{\sqrt{\xi_{op}}}$$

Range of validity is: $h_m/H_s<2.0$.

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List of Symbols

A_e	Erosion area	[m^2]
B_{toe}	toe width	[m]
B_{flume}	flume width	[-]
D	particle size or typical dimension of concrete armour unit	[m]
D_{50}	diameter of rock that exceeds the 50% value of sieve curve	[m]
D_n	Nominal block diameter or equivalent cube size	[m]
D_{n50}	median nominal diameter	[m]
E(f)	Energy density	[m^2/Hz]
F	frequency	[Hz]
g	gravitational acceleration	[m/s2]
H	wave height, from through to crest	[m]
$H_{1/3}$	significant wave height based on time domain analysis, average of highest 1/3 of all wave heights	[m]
$H_{2\%}$	wave height exceeded by 2% of waves	[m]
H_s	significant wave height, H_s=$H_{1/3}$	[m]
H_{ns}	significant wave height, near shore	[m]
H_{os}	significant wave height, off shore	[m]
h	water depth	[m]
h_m	local water depth at structure	[m]
h_t	toe depth, water depth above the toe relative to still water level (SWL)	[m]
K_r	wave reflection coefficient, ratio of reflected and incoming wave	[-]
L	particle size or typical dimension of concrete armour unit	[m]
L	length of breakwater section along structure axis (in definition of Nod)	[m]
L	local wave length	[m]
L_0	deep water wave length, L_o=$gT_p^2/2\pi$	[m]
m	mass	[kg]
N_{up}	number of displaced rock (upward)	[-]
N_{down}	number of displaced rock (downward)	[-]
N_{tot}	number of diplaced rock (upward + downward)	[-]
$N_{cum, tot}$	cumulative number of displaced rock (upward + downward)	[-]
$N_{mcum,tot}$	modified cumulative number of displace rock (upward + downward)	[-]
α_{shore}	foreshore slope (gradient)	[-]

$\alpha_{structure}$	armour slope (gradient)	[-]
n	porosity	[-]
N	number of displaced rocks	[-]
N_{od}	damage parameter, average number of displaced toe elements per D_{n50} unit of breakwater length	[-]
N_{odB}	damage parameter, average number of displaced toe elements per D_{n50} unit of top surface of toe structure	[-]
$N_{\%}$	damage parameter, percentage of removed rock from toe profile of volume of toe profile	[-]
N_t	scaling factor for time	[-]
N_l	scaling factor for geometrical parameters	[-]
N_u	scaling factor for speed	[-]
P	notional permeability factor	[-]
R	radius	[-]
S	Damage level, average erosion area per D_{n50} unit of breakwater length	[-]
S	wave steepness, S=H/L	[-]
S_o	wave steepness, for transitional water depth, $S_o=H_s/((gT_p^2/2\pi)\tanh(2\pi h/L))$	[-]
S_{op}	fictitious wave steepness for peak period wave, $S_{op}=H_s/(gT_p^2/2\pi)$	[-]
T	wave period	[s]
$T_{1/3}$	mean period of the highest one-third of waves	[s]
T_m	mean wave period	[s]
$T_{m-1,0}$	wave period based on zeroth and first negative spectral moment, mean energy wave period	[s]
T_p	spectral peak wave period	[s]
U	velocity	[m/s]
V_{tot}	Volume of toe for width B_{flume}	[m^3]
W	weight of a rock	[kg]
W_{50}	Median weight of a rock grading	[kg]
Z_t	toe height	[m]
N	breaker index (H/h)	[-]
Δ	relative density of rock in water	[-]
ξ_0	surf similarity parameter based on calculation with $L_0=gT_p^2/(2\pi)$	[-]
$\rho_{concrete}$	density of rock material	[kg/m^3]
ρ_{water}	density of water	[kg/m^3]

1. Introduction

This master thesis is about toe stability of rubble mound breakwaters. Most breakwater designs contain a toe structure. The toe is located on the sea side of the breakwater and is basically the transition zone from primary armour layer to deeper lying layers. A toe has two main functions:

- The toe supports the above laying armour layer. The horizontal forces generated by the gravitational forces of the primary armour layer need to be absorbed by the supporting underlying structure. The toe gives support to the rock or concrete elements of which the primary armour layer is built.
- The toe prevents erosion of underlying layers. Sub layers are stabilized by putting heavier rock on top of them according to filter rules. This way, smaller stones are not washed out. The toe is often used as part of the filter structure.

To be able to design effectively, it is necessary to have knowledge about the hydrodynamics in and around the toe. As this is a difficult process and not fully understood yet, design equations are based on empirical relations found in extensive scale testing.

The research question is to study toe stability in depth limited conditions. At this moment there is no reliable design equation for toe stability in depth limited conditions.

1.1. Problem Description

Breakwaters, built in shallow water, have a toe close to the water surface. Each breakwater has a location with a shallow toe as it approaches the shore. When the whole breakwater is built in shallow water, the toe is built close to the water surface over the full length of the breakwater. In this case, local wave heights are also reduced because of breaking. Nevertheless the reduced wave height causes high wave loads. A very conservative approach is to dimension as primary armour.

Design equations are available for a deep toe and primary armour. However a good design equation for a toe in shallow water is presently not available. This report describes an investigation of toe stability in this region.

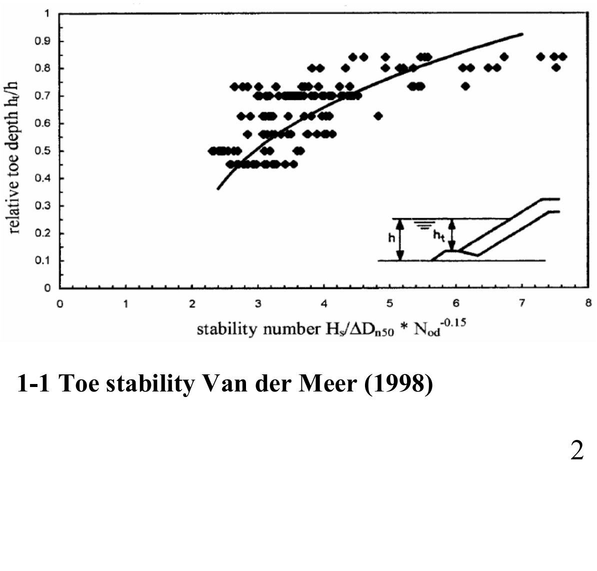
In the past decennia a lot of research is done on the hydrodynamics in and around breakwaters. The goal of these studies is to understand the processes and to design in a proper way. In general, these studies can be divided in two areas of research.

-The first type is fundamental research on physical processes in and around toes. This research gives insight in the local processes and is helpful to understand the hydrodynamics in and around the toe. A lot of the hydrodynamics is still not understood at this moment.
- The second area of research has a more applied character. Often it is not possible to derive a reliable design equation from a theoretical basis. That is why quite some research is done with scale models to derive empirical relationships between dimensionless parameters. From the scale tests, design conditions are derived.

As the hydrodynamics are difficult and not understood yet, it is not possible to describe a stone stability rule on this basis. The second area of research, described above, is still used for stability equations. The main design condition for toe structures is the "Van der Meer" equation. This stability equation is based on scale model experiments performed by Gerding. Gerding gave a first stability equation, based on this dataset, in 1993. See equation (1-1). His data were re-analysed by Van der Meer in 1998 and he derived the currently used design equation (1-2). He mainly adjusted the origin of the curve for h_t/h_m to a damage level corresponding to the damage of primary armour. This is expressed in the constant '2' and a different power function. Both studies are based on regression analysis of the data from experiments.

$$\frac{H_s}{\Delta D_{n50}} = 6.5 \cdot \left(\cdot \frac{h_t}{h_m} \right)^{1.2} \cdot N_{od}^{\;\;0.15} \qquad \textbf{(1-1)}$$

$$\frac{H_s}{\Delta D_{n50}} = \left(6.2 \cdot \left(\cdot \frac{h_t}{h_m} \right)^{2.7} + 2 \right) N_{od}^{\;\;0.15} \qquad \textbf{(1-2)}$$



N_{od}	Damage number
H_s	Significant wave height
h_m	Water depth in front of toe
h_t	Water depth above toe
Δ	Relative density
D_{n50}	Stone diameter

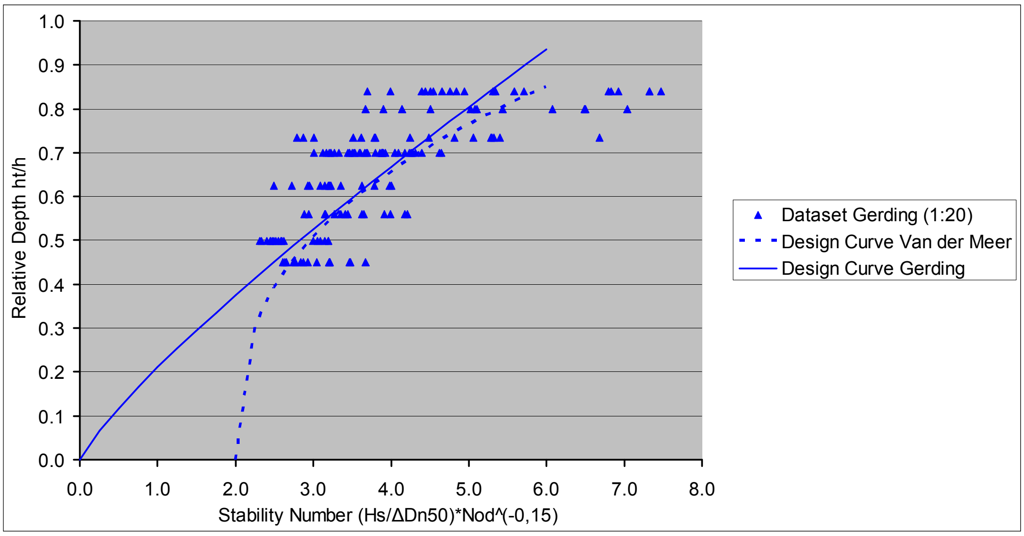
1-1 Toe stability Van der Meer (1998)

The stability equation consists of three dimensionless parts. The first is the stability number that gives a relation between wave load and strength of the toe. The second is the measured damage, expressed in N_{od}. The third is the relative depth, that gives a dimensionless value for water depth.

The design equations have restrictions as no experiments are done in shallow water. In the graph, it is shown that tests are only done in relatively deep water. The design equations are valid for deep water conditions. In formulation $0.4< h_t/h_m<0.9$, h_t/h_m is the dimensionless formulation for water depth.

1.2. Problem Definition

The lack of knowledge for depth limited situations is investigated in this thesis. Objective is to extend the design rule for stability of stones to the depth limited domain. In the graph below is plotted what formulas of Gerding (1993) and van der Meer (1998) predict when they are extended to depth limited conditions. For $h_t t/h_m=0$, the result shows quite some difference.



1-2 Toe stability Van der Meer (1998) & Gerding (1993)

For shallower water conditions, waves are expected to break on the foreshore slope already instead of on the breakwater slope. The wave attack and therefore the hydrodynamics change for lower water depth. Hovestad (2005) already studied the influence of fore shore slope to armour stability of breakwaters and concluded that different kinds of wave breaking effect stone stability. Toe stability in depth limited situation is expected to have similarity with armour stability. The parameters and relations that are used for armour stability are of interest for this research. The Iribarren parameter is a ratio that is often used in armour stability.

The Iribarren number makes a distinction between different kinds of wave breaking.

$$\xi = \frac{\tan\alpha}{\sqrt{H/L_0}} \qquad \textbf{(1-3)}$$

This number gives a relation between fore shore slope and wave steepness to define the breaker type. These two parameters are considered important in stone stability for shallow water.

Besides the blind spot in data points in the Van der Meer curve for shallow water, it is expected that the hydrodynamics are different for shallow water. Therefore it is expected that more variables have an effect on stone stability.

Stone stability in shallow water and the wave attack, that drives the damage development, are subjects for this research.

1.3. Research Question

The two main research questions for this research are:

- Can the existing "Van der Meer" toe stability equation be validated with experimental data in depth limited situations?

- How does toe stability behave in depth limited situations, considering the hydrodynamics to change and the fore shore slope to be important?

1.4. Approach

The first research question is checking the Van der Meer design equation for the area where Gerding did not perform tests. DMC owns a wave flume in which those tests can be executed. With help of the observations during the experiment and analysis of the performed dataset, the research questions are to be answered.

The tests need to be compared with the Gerding's experiment. Therefore it is necessary to investigate the research by Gerding and the analysis by Van der Meer first. When these studies are fully known and understood, a new set of experiments can be prepared and executed. The study from Gerding gives in this sense a practical basis for the execution of this set of experiments as the results need to be compared with his results.

The result of the second research question is the result of the observations and analysis from the experiment. As no literature is available about toe stability in depth limited situation, the result is difficult to predict. From available literature about toe and armour stability, variables are determined that are expected to influence toe stability. These parameters are tested in the experiment, the behaviour is observed during the analysis and mathematically analysed afterwards.

The answer to the formulated research questions is divided in three parts:

- continuation of literature study
- execution of experiment
- analysis of the experiment

These three steps are also found in the continuation of this report.

2. Literature Study to Theory

2.1. Toe Stability

A recent graduation report by Baart (2008) gives a complete overview of the research done until this moment. He has studied and analyzed all research done up to now. Most of the knowledge about toe structures is based on practical knowledge. Last decennia more research is done to the hydrodynamics around breakwaters and more specific to the hydrodynamics around stones.

Shore Protection Manual (1984) gives a first approach for stability definition as it is commonly used. The work of Brebner and Donnelly (1962) is presented in this manual. They tested toes at vertically faced composite breakwaters under monochromatic waves. A relationship is assumed between the ratio h_t/h and the stability number $H/\Delta D$. h_t is water depth at the toe, h is the water depth in front of the toe, D_{n50} is the nominal diameter of toe element and H_s is the significant wave height. Results depend much on the ratio h_t/h. A ratio between 0.3 and 0.5 means that the toe is relatively close to the water surface. Values of about 0.8 represent a relatively deep lying toe.

The British Standards (1991) give a design approach for different circumstances. The present $h_t=2H_s$ as a normative height for the area of influence of the waves. When h_t is higher, the influence of the waves is low and an extension of the underlayer suffices. When h_t is smaller, the toe should be dimensioned as primary armour.

The Rock manual (1991) presents the knowledge about toe stability until that moment. The rock manual refers to the Shore Protection Manual from 1984, to Gravesen and Sørensen (1977) and a more in depth research by Van der Meer was published in this edition of the Rock Manual.

- The contents of the SPM (1984) is already given

- Gravesen and Sørensen (1977) did research to stability of rubble mound breakwaters and included wave steepness in the research. They concluded that high wave steepness gives more damage than low wave steepness. This assumption was based on a few data points and could not be verified on computer aided evaluation.

- The publication by Van der Meer is a more in-depth study to toe stability. Wave boundary conditions were established for which different damage classifications were defined. These are given in below table.

Data from tests at Delft Hydraulics, test results from Danish Hydraulic Institute (DHI) and data from the experiments from Gravesen and Sørensen were used to determine a relationship between ratio h_t/h and the stability number $H_s/\Delta D_{n50}$. For almost all test results counted that the structure is attacked by waves in a more or less depth limited situation, H_s/h is about 0.5 (breaking height).

Next table gives design values of the stability number for different water depth.

h_t/h	$H_s/\Delta D_{n50}$
0.5	3.3
0.6	4.5
0.7	5.4
0.8	6.5

The accompanying equation for this table is (2-1). This equation is valid for $h_t/h>0.5$. The curve gives higher stability numbers for deeper lying toes.

$$\frac{H_s}{\Delta D_{n50}} = 8{,}7 \cdot \frac{h_t}{h_m}^{1.43} \tag{2-1}$$

<u>In 1993 Gerding</u> did more experiments on toes within the framework of his graduation thesis. His tests were performed in order to establish the influence of wave height, wave steepness and water depth on toe stability. One of the main conclusions was that wave steepness had no influence. The tests by Gerding showed little to no influence of the width of the toe to damage as well. His analysis resulted in an improved formula with regard to above mentioned formula; he included the damage classification, introduced by Van der Meer, in equation (2-2) and (2-3). However, the mathematical relation is based on a wide scatter of data points and contains quite some dispersion.

$$\frac{H_s}{\Delta D_{n50}} = \left(0.24 \cdot \frac{h_t}{D_{n50}} + 1.6\right) \cdot N_{od}^{\ 0.15} \tag{2-2}$$

$$\frac{H_s}{\Delta D_{n50}} = 6.5 \cdot \left(\cdot \frac{h_t}{h_m}\right)^{1.2} \cdot N_{od}^{\ 0.15} \tag{2-3}$$

The formula with dimensionless parameter h_t/D_{n50} gives the best fit. Both formulas are based on a dimensionless parameter and have a certain range:

- $3 < h_t/D_{n50} < 25$
- $0.4 < h_t/h_m < 0.9$

Gerding gave a classification to N_{od} and assumed $N_{od} = 2$ as an acceptable value for damage. He suggested $N_{od} = 2$ as a design criterion.

% CIRIA (1991)	*description*	N_{od} Gerding (1993)	*description*
0-3 %	no movement of stones (or only a few) in the toe	< 0.5	hardly any damage
3-10 %	toe flattened out a little bit but function is intact and the damage is acceptable	0.5 – 2.0	acceptable damage, design criteria
> 20-30 %	failure; the toe has lost its function and this damage level is not acceptable	> 4	unacceptable damage, toe structure has lost its function

2-1 Overview damage classification

<u>In 1995 Van der Meer</u> presented a paper in which he defined a new stability equation based on the dataset van Gerding. His conclusions were the same but gave a slightly different stability equation for the formula with h_t/h_m as dimensionless parameter.

$$\frac{H_s}{\Delta D_{n50}} = 7.8 \cdot \left(\frac{h_t}{h_m}\right)^{1.43} \cdot N_{od}^{\;0.15} \qquad \textbf{(2-4)}$$

The Van der Meer expression is most widely used. Equation (2-1) containing the dimensionless parameter h_t/D_{n50}, gives the best fit to the data cloud. Unfortunately, this formulation can give negative toe sizes for large values of h_t as shown in the re-drawn equation:

$$D_{n50} = N_{od}^{\;0.15}\frac{H_s}{\Delta} - 0.24h_t \Big/ 1.6 \qquad \textbf{(2-5)}$$

The second parameter h_t/h_m has a more physical background but shows a larger scatter.

<u>Doctors van Leeuwen (1996)</u> checked Gerdings work in her graduation thesis with additional model testing. The damage level she reported was about twice as small as the damage that Gerding reported. The origin of these differences is not found but a few suggestions are done:

- The fore shore slope differs, Gerding tested a 1:20 slope but Doctors van Leeuwen tested a 1:50 slope.

- Doctors van Leeuwen only counted seaward rock displacements while Gerding also counted upward rock displacements.
- There may have been a difference in packing density of the stones or a difference in the angularity of the stones.

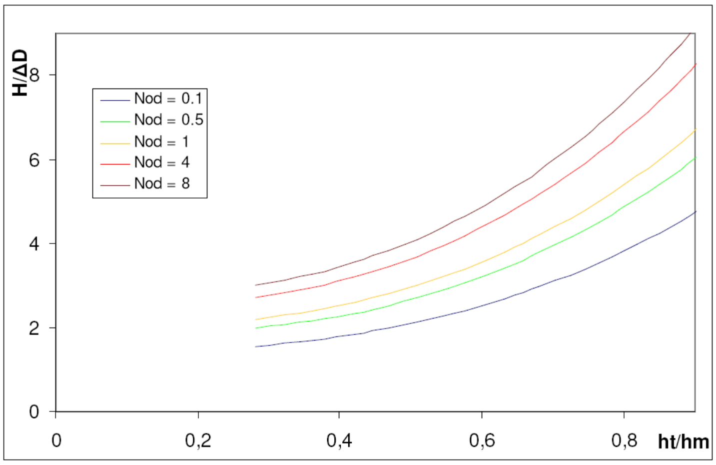
Because of the differences she did not quantify the relations. She concluded that fore shore slope has an influence on stone stability. She recommends more research to velocity fields in and around the toe, more insight in the hydraulic processes will lead to more understanding. She compared two theories about orbital velocities around the toe as well, Shields and Rance Warren.

In 1998 van der Meer gives a new stability formula in "Dikes and Revetments Design" by Pilarczyk. The original formula, given by Gerding and him self, does not contain the water depth in front of the toe structure (hm). This makes it doubtful if this formula can be used for various water depth. He gave an improved formula where toe depth was given as h_t/h_m, h_t/D_{n50} is not used anymore because unrealistic values for D_{n50} were found for deep toe structures. The equation is:

$$\frac{H_s}{\Delta D_{n50}} = 2 + 6.2 \cdot \left(\frac{h_t}{h_m} \right)^{2.7} \cdot N_{od}^{\ 0.15} \qquad \textbf{(2-6)}$$

Baart 2008 did extensive research toe stability within the frame work of his Master Thesis. He studied existing literature about toe stability and derived a new approach for damage description. This approach used the maximum velocities of the incoming waves to relate wave load to damage. Baart used data from Gerding for toes in deep water for his analysis. As this study is about toe stability in shallow water, surging waves do not describe the wave behaviour at the breakwater. Therefore, this approach is not effective for this study

His literature study gave insight in the behaviour of the behaviour of the design equation from Van der Meer (1998). The last parameter in stability equations is damage level, expressed in N_{od}. This number follows from scale tests as this number displays the damage as it is recorded during the experiments. A damage level can be chosen to calculate the stone size for the tolerated damage level. Baart (2008) gave a nice impression of the behaviour of the design curve for varying damage levels, see figure 2-2



2-2 Design curves for various damage levels

The larger the design damage level, the larger stability numbers can be used for determination of the stone size of the toe material. Van der Meer first analyzed the dataset and related the physics to damage in a mathematical way. After he presented his results in a formula, he gave design values of N_{od}. It is important to know that the design curve for a given N_{od} value represents the trend line of the data points for the given N_{od} value. This way, the result of the formula is an average value and it does not represent a limit.

2.2. Influence of shore slope on Stone Stability

Hovestad (2005) en Oortman (2006) both investigated the influence of fore shore steepness on wave attack at breakwaters within the framework of their Master Theses. From experiments follows that steeper fore shores lead to heavier wave attack at the breakwaters slope.

Hovestad mainly focused on the amount of damage with different fore shore slopes. His experiments gave 30% more damage with a 1:8 slope as with a 1:30 slope. This difference was measured while the wave spectrum at the toe was exactly the same for both set ups. The difference in damage, caused fore shore slope, is not described in the formulas of Hudson and Van der Meer. Hovestad suggests a correction factor to implement foreshore steepness of mildness in the mentioned formula. From visual observations Hovestad concludes that the toe suffers a more direct wave attack on steep fore shores due to plunging breakers.

Oortman investigated fore shore steepness on a more process level. He especially looked at the velocities and accelerations occurring at the toe due to wave attack and difference in fore shore.

After testing and analyzing he confirms higher wave loads for steeper slopes. However, because of a wide error band it is not possible to derive a trustworthy relationship. Oortman presents the Morrison approach to explain an increase in velocities and acceleration for waves travelling over steep fore shores. Higher velocities and accelerations coincide with higher damage.

The Rock Manual (2007) gives a lot of information about armour stability. For armour rock stability a different geometrical situation is considered as the rock is placed on a slope. Hudson introduced in 1953 the Hudson formula. Nowadays the formula is used as follows:

$$\frac{H_s}{\Delta D_{n50}} = \frac{\sqrt[3]{K_d \cot\alpha}}{1.27} \qquad \textbf{(2-7)}$$

The stability number is also found in other formula for stone stability. The parameter α is the angle of the breakwater slope. Breakwater slope is considered important.

Van der Meer studied armour stability extensively. Damage is given in terms of erosion area; $S_d = A_e/D_{n50}^2$. Below stability equation are divided for plunging and surging breakers. However they are not the newest stability formula, they give insight in the behaviour of the governing parameters: Equation 2-8 is for plunging breakers and 2-9 for surging breakers.

$$\frac{H_s}{\Delta D_{n50}} = C_{pl} P^{0.18} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \xi_m^{-0.5} \qquad \textbf{(2-8)}$$

$$\frac{H_s}{\Delta D_{n50}} = C_{pl} P^{-0.13} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \sqrt{\cot\alpha} \cdot \xi_m^{p} \qquad \textbf{(2-9)}$$

The range of validity is given as follows:

Parameter	Symbol	Range
Slope angle	$\tan\alpha$	1:6 – 1:1.5
Relative buoyant density	Δ	1 – 2.1 [1)]
Number of waves	N	< 7500
Wave steepness	s_m	0.01 - 0.06
Surf similarity parameter using T_m	ξ_m	0.7 - 7
Relative water depth at the toe	$h_{toe}/H_{s\text{-}toe}$	> 3 [2)]
Notional permeability parameter	P	0.1-0.6
Armourstone gradation	D_{n85}/D_{n15}	< 2.5
Stability parameter	$H_s/\Delta D_{n50}$	1 - 4
Damage – storm duration ratio	$S_d/\sqrt{N}$	< 0.9
Damage level	S_d	$1 < S_d < 20$

2-3 Range of validity of parameters in deep water formula by Van der Meer (1988)

Fore shore slope is not included in stability formula but breakwater slope is considered important.

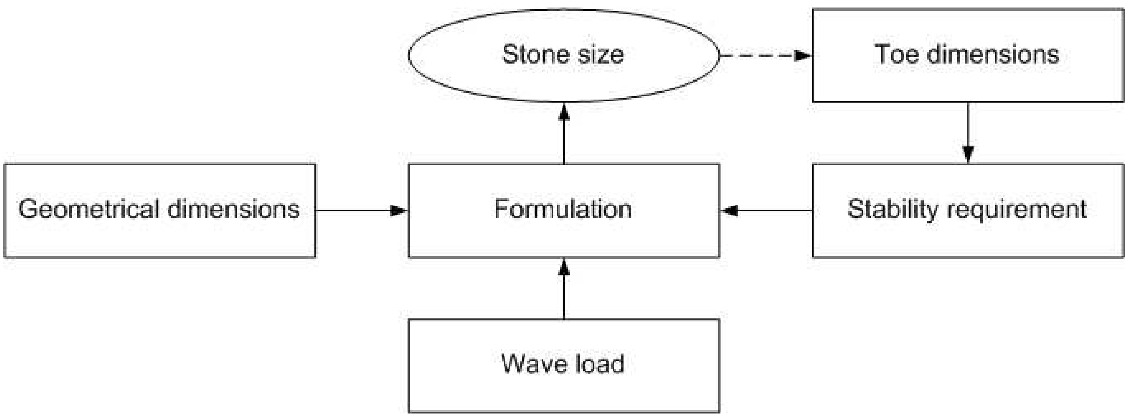
2.3. Toe Design in combination with Xbloc units

Toe Design Procedure

Proper toe design is important for stability of Xbloc units as a fixed location of the units is required. This will be treated in the second part of this paragraph. The stone size of toe rock is normally calculated with Van der Meer design curve. The design procedure is explained below.

The N_{od} value represents the accepted damage level in design. As the value N_{od} can be varied for acceptable damage, there is still freedom in the design procedure. The acceptable damage also depends on toe height and width of the toe while this is not included in the design formula. A proper design procedure with this formula is done by iterative calculation.

First a toe profile is designed and an acceptable value for N_{od} is determined, from 0.5 to 2. Acceptable damage is very much related to a specific damage. Secondly the necessary rock size according to van der Meer (1998) is calculated. Third the calculated rock size is compared with the determined toe height and the necessary number of layers is checked. N_{od} = 2 requires a toe of three stones high and five stones wide while for N_{od} = 0.5 two stones in height and 3 in width should be enough. If the result of the calculation does not correspond with this criterion, the toe dimensions should be changed and a new calculation must be done. This iterative design procedure is given in below flow chart.



2-4 Flow chart for design procedure of toe size

Determination of the design value N_{od} is difficult. N_{od} is an easy damage classification in scale tests to use. However for designers, this is an abstract parameter and it is difficult to link acceptable damage to this number.

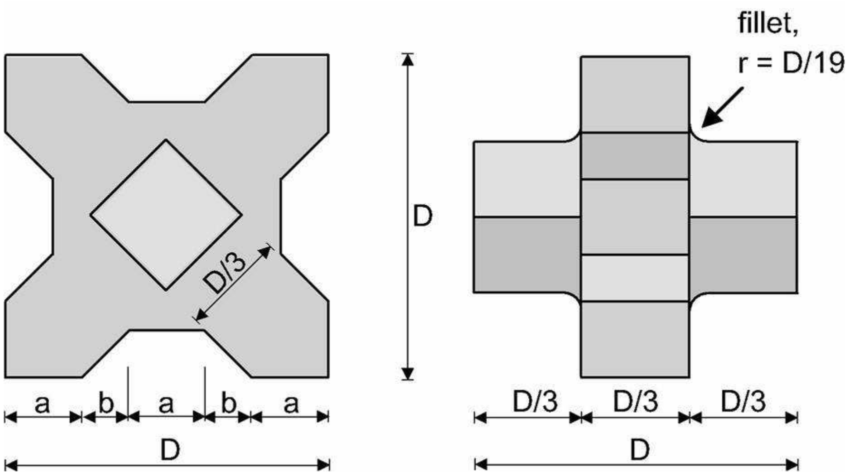
Design in combination with Xbloc units

DMC developed the Xbloc unit. Therefore DMC is interested in the behaviour of toe material in combination with Xbloc units. The toe is the fundament for the position of the Xbloc units.

Single layer armour units, like Xbloc, require a more stable toe than a rock armour layer, does. The main difference in both armour layers is interlocking of single layer armour units. Rock gets its stability mainly from its own mass while single layer armour units get their stability mainly from interlocking.

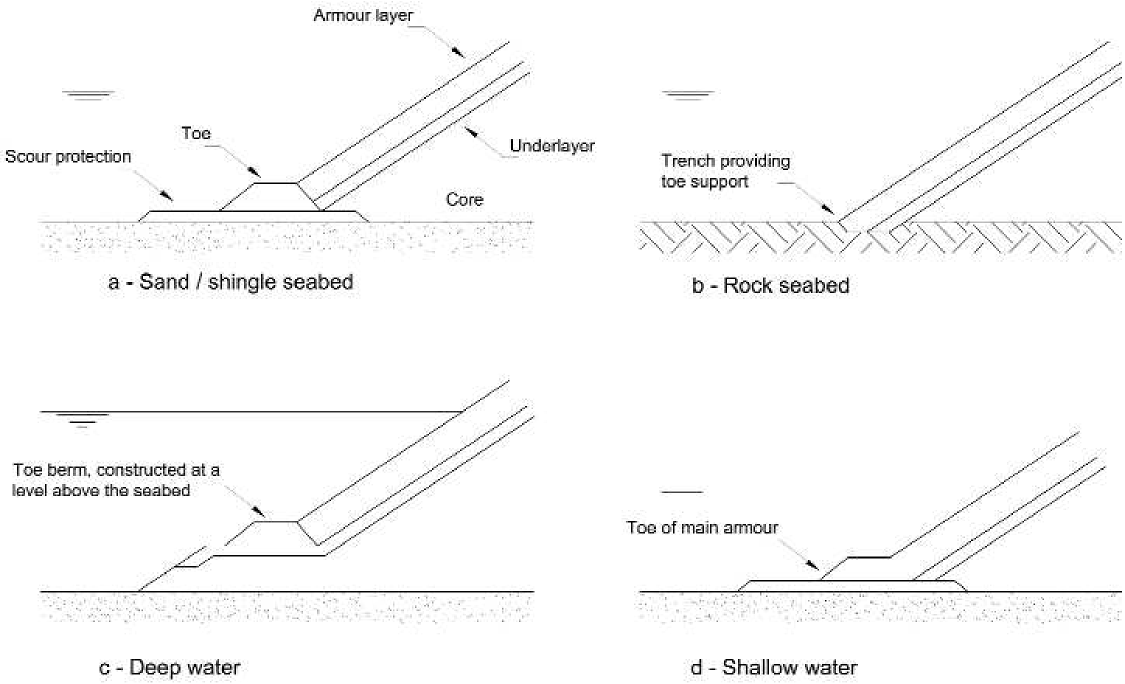
Reshaping of the toe and therefore reshaping of above lying armour, contributes to stability of rock. The rock moves a little and reshapes to a more stable situation. Reshaping of single layer armour units creates gaps in the armour layer, leading to less interlocking and therefore less stability.

Xbloc units require a more stable toe than armour rock does. For this matter a different Xbloc unit is designed, the so called the Xbase unit. A toe on one side of the Xbloc unit has been removed and a flat bottom is created, see picture. This can help to create a stable first layer of Xbloc units. The stability of this unit is not taken into account in this research. An example of Xbloc unit is given below.



2-5 Basic design properties Xbloc units

A stable toe is necessary for a proper design of Xbloc units but designing a stable toe is often a difficult matter, especially in shallow water. Figure 2-6 gives the main design scenarios, as given in Rock Manual (2007).



2-6 Schematic examples of toe details

The picture shows four toe design possibilities, sandy bottom with normal water level, rocky bottom with steep foreshore, deep water and shallow water from rock manual.

- Example A gives a conventional design for toe constructions. A scour layer is constructed on which toe elements are placed. This design is usable for armour rock but also for single layer armour units.
- Example B gives a rock seabed. In reality this is often combined with a steep fore shore. Often a trench is blasted in which the first row of armour is placed. Xbloc units could be placed in a trench. Another option is placing Xbase units on the flat rock seabed. The flat bottom of the Xbase unit is expected to have lots of contact area with the bottom. The Xbloc slope is built from there. As stability of the Xbase units has never been tested so far, extra toe material in front the Xbase units is still required.
- Example C is an example for toe design in deep water. This type of breakwater consists mainly of core material. In this case the toe is the transition zone from the armour layer

toe to underlying layers like the core. Both rock and Xbloc units can be used. It is not logical to use Xbase in this situation as the Xbloc units can be placed in a sort of trench, excavated in the slope.

- Example D gives a toe in shallow water. In this situation the toe rock is in the order of armour rock. When armour rock is used, it is easy to extend the armour layer. Shallow water often requires thin layers because the local water levels do not allow thick layers. Xbloc design is ideal in this situation as armour units are single layered. Xbase units can be used but always in combination with extra toe material in front of it.

The design of breakwater in shallow water in combination with Xbloc units will have most similarity with example A. Toe and armour layer consist of different materials. For shallow water conditions the scour protection on the bottom will be problematic as this washed away in shallow water. The cross section lay out for the experiments, given in next chapter, is much alike this example.

3. Experiment Set-Up

The experiments are done to gain answers to the research questions given in chapter 1. The experiments are executed in depth limited conditions. First an introduction is given to the scaling rules that need to be taken into account for scale test. The experiment set up is explained in next paragraphs.

3.1. Scaling Rules

For practically all coastal engineering problems, the forces associated with surface tension and elastic compression are relatively small and thus, can be neglected. This leaves only a few hydrodynamic scaling laws.

The Froude and Reynolds number are most important to coastal engineers because similarity of one of these numbers, combined with geometric similarity, provides the necessary conditions for hydrodynamic similitude in a majority of coastal models. See reference Hughes (1993).

The Reynolds number Re is a dimensionless number that gives a relation between inertial forces and the viscous forces around a structure. Scaling according to Reynolds means keeping the laminar / turbulent flow the same. Reynolds numbers smaller than 2300 represents laminar flows while Reynolds number larger than 3500 represent turbulent flow. The number is defined as:

$$\mathrm{Re} = \frac{UL}{\nu} \tag{3-1}$$

Scaling to Reynolds gives:

$$\mathrm{Re} = \left(\frac{UL}{\nu}\right)_p = \left(\frac{UL}{\nu}\right)_m \tag{3-2}$$

When viscosity is kept as a constant:

$$N_u = \frac{U_m}{U_p} \quad \& \quad N_L = \frac{L_p}{L_m} \qquad \textbf{(3-3) and (3-4)}$$

Equations (3-3) and (3-4) can be written as:

$$N_u = \frac{1}{N_l} \tag{3-5}$$

$$U = \frac{L}{T} \tag{3-6}$$

When U is rewritten in terms of L and T, the result of scaling to Reynolds gives relation 111, in which N_t is the time and N_l the length scaled to each other. The wave period is scaled to the square root of the geometrical scale.

$$\sqrt{N_t} = N_l \tag{3-7}$$

The Froude number Fr is a dimensionless number that expresses the relative influence of inertial and gravity forces in a hydraulic flow. It gives a ratio between the characteristic velocity V and the characteristic wave propagation speed c. The Froude number is:

$$Fr = \frac{U}{\sqrt{gD}} \tag{3-8}$$

The result of this scaling law is contradicting with the scaling law from Reynolds:

$$N_t = \sqrt{N_l} \tag{3-9}$$

In free surface flow, gravity is considered more important than viscosity. Therefore Froude is used in scaling of waves in a flume in addition to Reynolds. The geometrical dimensions are scaled linearly and time correlated values are scaled with a square root of scale factor (R).

$$L_p = R \cdot L_m \tag{3-10}$$

$$T_p = \sqrt{R} \cdot T_m \tag{3-11}$$

However, in the pores of the scaled structure, this can lead to relatively high viscous forces in under layer and core. Higher viscosities in the pores lead to more laminar flow while the flow in prototype is turbulent. These effects need to be taken into account for scaling of the core, see paragraph 3.4.3

3.2. Damage Recording

Background

At first, the results from the experiment are compared with the experiments by Gerding. The blind spot is tried to be filled to check the current design formula. Besides the correlation with Gerding, a new analysis is done to the dataset, as well qualitatively as quantitatively. This new analysis asks for a general approach for damage correlation.

Damage is mainly influence by the following three aspects:

- The wave load is the hydraulic forcing at the structure, wave height and wave period
- The stability of the toe material is defined by its strength, its stone size and density
- Geometrical variables do influence the amount of damage development.

$$Damage = f(Waveload, Strength, Geometry)$$

This is the general description for damage, and is kept in mind for the analysis of the data from this experiment. The Hudson stability number, given in paragraph 2.2, is a widely used relation between wave load and strength. For this study, this relation is assumed correct. The general description for damage can be re-written to:

$$Damage = f\left(\frac{WaveLoad}{Strength}, (Geometry)\right) \qquad \textbf{(3-12)}$$

Damage is described by a relation of wave load and strength of the toe material. Damage development is influenced by geometrical factors.

In order to measure damage, it needs to be specified. In other studies, damage is specified in various ways. For example, The Rock Manual (1991) used damage as a percentage of the whole toe structure as can be read in the literature study. It is based on the number of removed stones expressed as a percentage of the total number of stones.

In 1993 Gerding introduced the damage number N_{od}. This is the number of stones moved, in a strip, as wide as the nominal diameter of the stones, perpendicular to the breakwater.

$$N_{od} = \frac{N}{B/D_{n50}} \qquad \textbf{(3-13)}$$

Gerding used this number in his design formula. Van der Meer (1995) and Docters van Leeuwen (1996) carried on using this damage number and based their design formula on this number as well. N_{od} is a number which is introduced for doing scale tests, in reality this number is less representative. It is tried by Gerding and Van der Meer to find a representative value of N_{od} for design of a breakwater. Gerding gave an acceptable design value of 2 for N_{od} and Van der Meer said that N_{od} should not be higher than 0,5 for safe design. As long as N_{od} is given in the design formula, a user of the design equation can make a proper choice for the acceptable damage.

A problem for the N_{od} number is that the actual damage for different stone sizes cannot be compared. As more stones fit in a strip of the toe profile for smaller stone sizes than for larger stone sizes, the same N_{od} value represents smaller percentage of damage for smaller stone sizes in comparison with the larger stone sizes.

Baart (2008) introduced a modified number in which the width of the toe is taken into account:

$$N_{odB} = \frac{N}{B_{flume} / D_{n50} \cdot B_{toe} / D_{n50}} \qquad \textbf{(3-14)}$$

Baart gives the following definition:
"The damage number N_{odB} is the amount of elements that have actually displaced from top surface layer of the toe bund with respect to the amount of elements that were lying in this layer before the test."

This number tries to give the number of stones displaced from the top surface layer as the number of the total number of stones in the top surface layer. This seems incomplete for two reasons:

- First, in real it is not the case that stones are only displaced from the top layer of stones.
- Second and more important, D_{n50} is not the right parameter to scale rock within the profile because the porosity between the stones is not included.

N_{od} or N_{odB} are both artificial numbers to give a relation between the rock size and the number of removed stones. N_{od} is in this case the best option because it is a simple number. N_{odB} seems to give the percentage of stones displaced from the top layer while this is not the case. Therefore this is an improper way of describing damage.

A better approach of linking the N_{od} number to the percentage of damage is multiplying the damage number N with $(D_{n50})^3$ and dividing this with the total stone volume. The total stone volume is the toe volume minus porosity

$$DamagePercentage = 100 \cdot N \cdot \frac{(D_{n50})^3}{(1-n)V_{tot}} \qquad \textbf{(3-15)}$$

In fact, this gives the percentage of damage, calculated from the number of displaced stones. This damage classification requires knowledge about porosity within the toe structure and the exact dimensions the toe profile. This makes the percentage of damage more difficult to calculate.

A last way of damage determination is profile measuring. The Berm Breakwater formula of Van der Meer is based on profile measurements. They measure the eroded profile area (A_e), next this eroded area is transformed to damage (S) in the following way:

$$S = \frac{A_e}{D_{n50}{}^2} \qquad \textbf{(3-16)}$$

Profile measuring is used for determination of large scale damage. This counts for berm breakwaters where reshaping of the top layer is part of the design. This method has one big disadvantage because. It is difficult to measure the mean profile. The envelope is more convenient to measure. At the start of the test, slope is smooth. When stones start moving, the profile gets more edgy and bumps and gaps occur. When the envelope is used for the measured profile, the profile seems to grow while this is physically not possible.

This Research

With respect to this research damage is one of the most important parameters because this is the only unregulated result of the tests. The damage development determines the result of this research. However, damage is a debatable parameter as well. In previous studies damage is defined by number of stones moved or the percentage of stones moved.

Counting the number of displaced stones can be done in several ways. A division can be made in stones moving downwards (away from the breakwater), stones moving upwards (to primary armour layer) and movind within the toe profile (more than its own diameter). This is easily done with digital image processing. Digital image processing is simply comparing a picture before with a picture after the test.

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Gerding mentioned in his report “This damage was obtained by counting and weighing the total number of stones removed out of the original bed of the toe structure,” while Docters van Leeuwen mentioned in her report (p36) “The damage was obtained by counting the number of stones removed seaward on or over a white painted line at the bottom of the flume.”

Despite the fact that the damage number N_{od} has disadvantages, it is used in this research to be able to relate it in a correct way with studies done by Van der Meer. Other displays of damage are investigated during analysis like the damage description in terms of percentages.

3.3. Wave Conditions

3.3.1. Wave spectrum

Tests are done with irregular wave fields. A Jonswap spectrum is used which represents a young sea state. This spectrum is the most widely used spectrum and is more peaked in comparison with a normal Pierson Moskowitz spectrum.

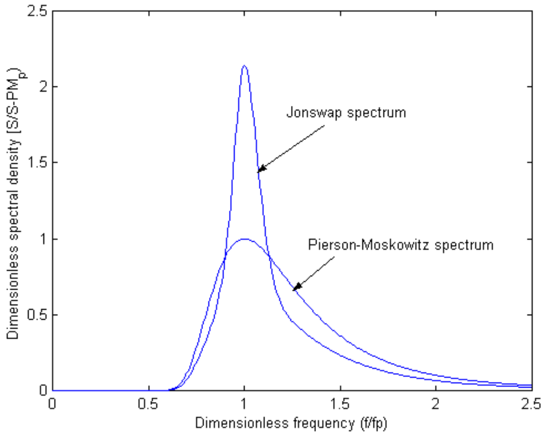
$$E(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left(-\frac{5}{4}\left(\frac{f}{f_m}\right)^{-4}\right) \gamma_0^{\exp\left(-\frac{1}{2}\left(\frac{f-f_m}{\sigma f_m}\right)\right)} \qquad \textbf{(3-17)}$$

E	Spectral energy density [m2/Hz]
α	Scaling parameter (Pierson-Moskowitz) [-]
f	Frequency [Hz]
f_m	Peak frequency [Hz]
γ_0	Scaling parameter (Jonswap peak-enhancement factor) [-]
σ	Scaling parameter (Jonswap peak enhancement factor) [-]

The peak enhancement factors are:

- $\gamma_0 = 3,3$
- $\sigma_a = 0,07$
- $\sigma_b = 0,09$

Figure 3-1 gives a representation of a Jonswap and a Pierson Moskowitz spectrum. Jonswap is more peaked in comparison with Pierson Moskowitz, leading to more energy in one wave period.



3-1 Comparison between Pierson Moskowitz and Jonswap spectrum

3.3.2. Wave generation and Wave analysis

The wave spectrum, generated in the experiments, is expected to be similar with the theoretical Jonswap wave spectrum. The wave fields, that are generates in the experiments, recorded with wave gauges. The wave records are analyzed according to a frequency domain analysis and a time domain analysis.

From the frequency domain analysis follows the frequency-spectral density curves and the values for the significant wave height H_{mo}, peak wave period T_p, the moments of the spectrum and the reflection coefficients. From the time domain analysis follows a Rayleigh distribution of the incoming waves and different values for wave height, wave period and reflection coefficients. Two examples of wave analysis are given in appendix G.

For analysis of the experiment, the significant wave height H_{m0} and the peak period T_p are used to do the analysis of the experiment. The use of different values for wave height and the peak period is restricted to these two parameters from practical points of view.

The objective of this research is deriving a mathematical relationship for toe stability in shallow water. If this objective is achieved, it will be used for design of real breakwaters. For these projects the available wave data is often limited and a designer is helped by the use of easy parameters for wave height and peak period.

Some of the parameters like $T_{m-1,0}$ and $H_{2\%}$ from the reflection analysis are stored in Appendix G.

3.4. Fore Shore and Cross Section

3.4.1. Facility

The 2D physical experiments are carried out in the wave flume of DMC. This flume is located in the laboratory of DMC in Utrecht. The coastal engineering department of DMC uses this facility for commercial projects and research.

The flume has a length of 25m, a width of 60cm and the height is 1m. It is brought into use in July of 2008. The wave paddle can generate regular and irregular wave fields and contains automatic reflection compensation. This compensator measures the pressure of the reflected wave and takes this into account for the waves to be generated.

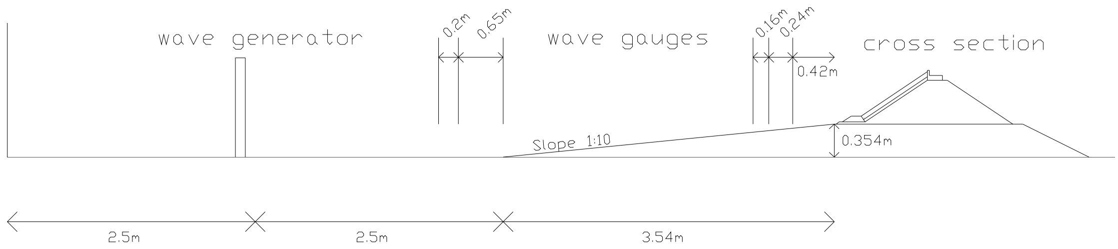
Wave data capturing is included in the operation software, the available 8 wave gauges were enough to use multiple gauges (three each) near the paddle and near the construction. With the help of three closely located wave gauges, it was possible to derive the incoming wave height and reflected wave height. This was done off shore and near shore.

3.4.2. Flume Lay out

The flume lay out consists of four parts:

- Wave generator, the front of the generator is located 2.5m from the side wall. The front of the paddle is a vertical sheet moving horizontally. In fact the paddle creates long waves as water is moved from the bottom until the water level. The wave needs some space to move into a correct orbital moving wave.
- Fore shore, each of the three fore shores starts at 5m from the side wall. This means that a smaller section of the flume is used for a steeper fore shore slope. Each fore shore goes until a height of about 35 cm. There are some small variations in the height of the fore shore as the exact height depended on the pattern of the frame work under the fore shore. These variations occurred between 33 and 36cm. These variations are expected not to be of influence.
- Near the paddle and near the structure, wave gauges are placed. They are placed in sets of three to be able to derive the incoming and reflected wave form the captured data. Off shore, the gauges are place 2.5m from the paddle. The measured wave has already adapted to the local circumstances. Near shore, the gauges are still located quite far from

the structure as a certain water level is required. These are not present just above the toe in shallow water. For the different fore shore, the distance from the structure varies. But the local water level at the location of the first wave gauges from the structure is the same (4.2cm bottom level drop from the structure). The structure is built on a horizontal platform, on which the fore shore slope ends. The structure lay out is explained in next paragraph. Figure 3-2 gives a schematization of the flume lay out for a 1:10 fore shore.



3-2 Schematization of flume lay out for 1:10 fore shore

The lay out for different fore shores is about the same and is given in Appendix G.

An additional remark is made about the materials used in the flume. The fore shore is made of wood. A framework of wood is built on the bottom floor of the flume. This frame is aggravated with tiles. On top of the frame work a wooden plate is attached which forms the fore shore. The plates are strengthened with beams in length direction and are connected to the underlying frame each 60cm. This lead to a floor in which the plates hardly moved by the force of the wave. However, Gerding used a concrete fore shore in his experiments. This is expected to be more stiff than wood.

3.4.3. Structure Dimensions

The cross section highly corresponds with the cross section that Gerding (1993) used for his research to toe stability. Sub question 1 is about extension of the Van der Meer design formula of toe rock. This formula is based on the test from Gerding. To be able to compare, the cross section is kept as similar as possible. In next paragraphs, the dimensions of armour layer, first underlayer, core and toe are discussed.

Armour layer

The armour layer is made of Xbloc single layer armour units. The units have a D of 40mm and weigh 49gr. According to the design rules of Xbloc the significant wave height H_s is 10cm. In fact, the whole experiment set up is based on the design wave height of this size Xbloc unit.

First Under layer

Design of the Xbloc under layer totally depends on the size of the above laying Xbloc® unit. "Specifications for Application of Xbloc" (May 2008) prescribes:

- W_{85} is equal or smaller than $W_{Xbloc}/11$
- W_{50} is equal or larger than $W_{Xbloc}/7$
- W_{50} is equal or smaller than $W_{Xbloc}/9$
- W_{15} is equal or smaller than $W_{Xbloc}/5$

This gives a W_{50} of 5.0gr and a D_{n50} of 12.4mm with a grade of 1.29.

Core

The core is not scaled geometrically like the armour layer and under layer. The viscous forces in the pores are too large here in relation with the inertial forces leading to too low Reynolds numbers in comparison with prototype. The related increase in flow resistance reduces the flow in and out of under layer and core. This again causes relatively larger up-rush and down-rush velocities. As a result run-up levels will be too high and armour stability too low. Different scaling laws are needed to maintain the right viscous flows inside the breakwater leading to corresponding Reynolds numbers.

The method of Burcharth 1999 is used to scale the core of the breakwater. This formula, together with the Forchheimer equation can be used for estimation of pore velocities in cores. The diameter of the core material in models is chosen in such a way that the Froude scale law is valid for a characteristic pore velocity.

The principle in the proposed scaling procedure is to base the scaling on knowledge about the wave induced pore pressure distribution in the prototype core. The wave induced pore pressure is given by the horizontal pressure gradient I_x. The Burcharth formula reads:

$$I_x = -\frac{\pi H_s}{L'} e^{-\delta \frac{2\pi}{L'}} \left[\delta \cos\left(\frac{2\pi}{L'} x + \frac{2\pi}{T^p} t \right) + \sin\left(\frac{2\pi}{L'} x + \frac{2\pi}{T^p} t \right) \right] \qquad \textbf{(3-18)}$$

δ	Damping coefficient which is given by $\delta = 0{,}0141 \frac{n^{1/2} L_p^2}{H_s b}$
H_s	Significant wave height
b	Core width
T_p	Wave Period
L'	Wave length in the core $L' = L / \sqrt{D}$ valid for h/L<0.5
L	Wave length (incident)
D	coefficient to account t for seepage length as a result of the deviation of the flow path caused by the grains (1.4 -1.5).

And Forchheimers equation:

$$I_x = \alpha \left(\frac{1-n}{n} \right)^2 \frac{\nu}{g d_{50}^2} \left(\frac{U}{n} \right) + \beta \frac{1-n}{n} \frac{1}{g d_{50}} \left(\frac{U}{n} \right)^2 \qquad \textbf{(3-19)}$$

- n Porosity
- ν Kinematic viscosity taken as 1.1 10^{-6} m^2/s
- U Pore velocity

α and β are coefficients dependent on the Reynolds number and the grain shape and grading.

Burcharth gives a method for determination of the horizontal pressure gradient in a breakwater. This is done for six different points in the breakwater. With the help of the Forchheimer equation the characteristic pore velocities between the stones is calculated. In model size the same calculation is done to find the right D_{n50} for the same characteristic pore velocity.

A scale of 1:40 is applied and a significant wave height of 0.10m with a wave period of 10 seconds. This results in a D_{n50} of 11.1mm (3.6grams). The available stones are available with a certain sieve size. The relation between D_{n50} and sieve size is given by a rule of thumb. A multiplication of 1.2 times D_{n50} is used for the accompanying sieve size to let the stone fall through. A grading of 1.5 is used. this leads to broken stones with a sieve size of 11/16. This is a standard stone grading which can be delivered by the quarry.

A grading of 1.5 turned out to be quite narrow in the end. Stone size is important but grading is just as important. High grading creates a thicker packing density because small stones fill the pores of the larger stones and has in this sense a big influence in pore pressures as well. During the experiments, reflections were quite small. A wider grading (+/- 2.5) would enlarge wave reflection on the breakwater slope until more realistic values.

Toe

The size of the toe material is of course determined with the Van der Meer toe formula. Stone sizes are determined for 70%, 80% and 100% of the design wave height (H_s). This leads to a nominal diameter of 1.88cm, 2.15cm and 2.68cm. The grading is kept narrow with a maximum of 1.5 for the stone mass.

Each test two different fractions of toe material are used to obtain more data points for the same amount of tests. Damage results with different configurations are comparable according to the assumption that scaling is possible with the stability number:

$$\frac{H_s}{\Delta D_{n50}} \qquad \textbf{(3-20)}$$

3.4.4. Structure Lay Out

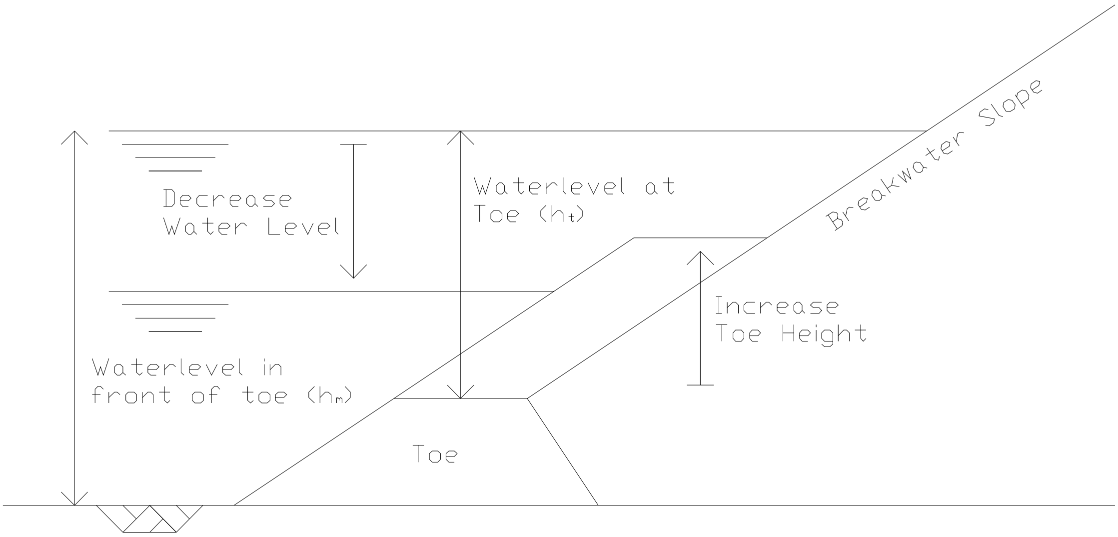
Some additional knowledge about the research of Gerding is presented in this paragraph. It is mainly focused on the use of the dimensionless parameter h_t/h_m from which the stability equations is built up.

Behaviour of relative depth, h_t/h_m, in the experiments from Gerding

The analysis done by Van der Meer is based on tests of Gerding (1993). These tests were done in deep and shallow water. Below a remark is made about how the water level is created and how the relative depth, h_t/h_m, is derived from this.

The water level, given in terms of relative depth, is between 0.4 and 0.9. These relative water depths are obtained by variation in the water level but also by variations in the toe height. As the relative depth is a ratio of the water depth at the toe divided by the water depth before the toe, it can be obtained in different ways.

A very high located toe with a high water level can give the same number for relative depth as a very low located toe with a very low water level as well. Expressed in terms of relative depth, this ratio can express totally different hydro dynamical situations. The possible variations in water level and toe height are schematized in figure 3-3.



3-3 Differences in test program of Gerding and this research

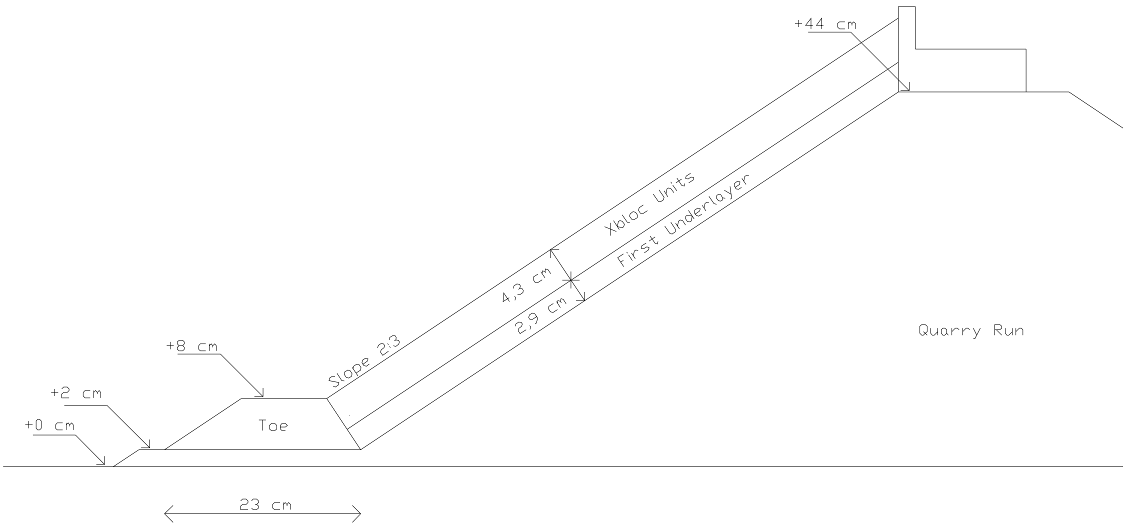
Gerding lowered the toe height but also increased the toe height. As the water level was not lowered very much, wave breaking occurred at the structure slope and the hydrodynamics kept the same for his set of experiments.

As the toe is placed high on the construction and closer to the water level, it begins to behave like a berm. At a certain moment it should not be designed as a toe anymore, but as a berm breakwater. Van der Meer has developed another design equation for berm breakwaters as well. However this is based on different experiments and uses different kind of damage classification, they are comparable and both use the stability number as basis. These two stability equations seem to have some overlap. When the toe stability formula is not valid anymore, the armour formula can be used. However, this is only valid for situations with relatively deep water.

Another way of creating a shallow toe is by lowering the water level and keeping the toe at the same spot. This is the other way around. The same values for the relative depth are found but the setting is different. Because of the shallow water, waves starts feeling the bottom already on the fore shore and start breaking. This depth limited situation happens quite often in prototype. The incoming waves are breaking and thus wave height is reduced, but due to breaking the damage can be worse.

Overview of cross section

In this research, the toe has a fixed low location. The relative depth is obtained by lowering the water level. This concept, in combination with the dimensions from previous paragraph, leads to the following cross section.



3-4 Cross section of structure for model tests

The main part of the breakwater is the core. Most of the time this is quarry run in reality. The core layer is deposited until the seaward edge of the structure. On top of this layer the toe, under layer and armour layer are placed. On the crest a L-wall is placed to simplify the cross section. The rear side is not of interest and this L-wall is the transition from front side to rear side. The height of the crest is chosen in such way that no overtopping took place.

The design of the toe is exactly the same as Gerding (1993). It is 6cm high and 10 cm wide. It has as 2:3 slope on the front and a 1:3 slope at the rear. Under layer is dumped against the toe material on top of the core. On top of this under layer the Xbloc units are placed. Notice is made to the extended core layer on sea side. This layer, representing scour protection is glued, to prevent erosion of this layer in the experiments.

3.5. Structure of Test Program

The test program is built up in such way that the toe is tested on stability with an increasing load. The first series of experiments is executed with the mildest slope, succeeded by the steeper slopes. It is expected that the wave force on toe material is larger for shallower water levels than for deep water conditions. The experiment set up is varied by lowering the water level and raising the wave load. The details of the test program are given per parameter.

Number of waves

The influence of number of waves, hitting the structure is not taken into account, in the test program. The storm duration is set at 1000 waves. In prototype, 1000 waves represent a storm of three hours when a mean wave period of 10 seconds is assumed. As the toe is a small structure, it is assumed that most of the damage has occurred after 1000 waves. In the experiment, the number of waves turned out to be more, about 1100 waves.

The influence is not mathematically taken into account. Because cumulative testing is executed, the measured damage is the result of many tests behind each other. This schedule is explained extensively further on in this paragraph.

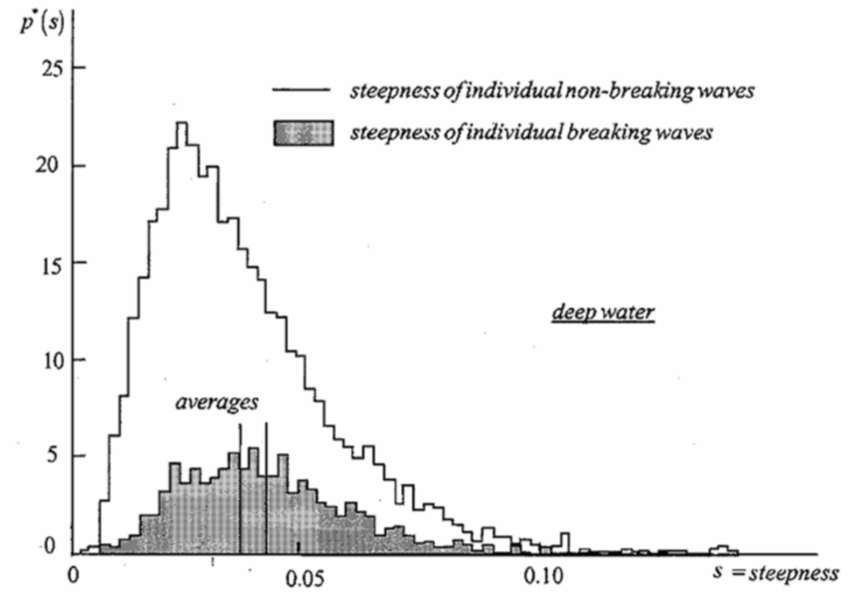
Wave height

The wave height H_s is 6cm and is raised with 2cm until 12cm, in total 4 different wave heights. This is the significant wave height of the wave height developed by the generator. How the waves shoal and deform is not taken into account in the test program. The wave generation is determined at the paddle and development of the wave height through the flume is measured each test. The result of the wave height at the structure is investigated as the effect of fore shore slope.

The test program depends for a certain part on the possibilities of the flume. Wave spectra with a significant wave height of 12 cm and a period of 3 seconds are possible to generate within the safe range of the flume. The scale for the tests is 1:40. The significant wave height for the heaviest wave load is 5m and about 15sec in prototype.

Wave steepness

In the experiment waves are made with wave steepness between 0.02 and 0.04. The wave steepness is determined near the paddle. In reality wave steepness between 0.02 and 0.04 are very common as they are observed under high wind conditions in deep water, see picture 3-5 from Waves in oceanic and coastal water by Holthuijsen (2006).



3-5 Distribution of observed off shore wave steepness (S=H/L) by Holthuijsen (2006)

The input in the wave maker is wave period and not wave length. For this reason the wave length is transformed in right wave period, using shallow-, deep- or transitional wave equations. Because of the relatively shallow water level conditions, the transitional wave theory is the most suitable theory to use. Equation (3-13) is used to calculate the wave period for each test:

$$S_0 = \frac{H_s}{L} = H_s \Bigg/ \frac{g T_p^{\ 2}}{2\pi} \tanh\left(\frac{2\pi}{L} h\right) \qquad \textbf{(3-21)}$$

This is done for the conditions just before the wave generator, assuming the wave steepness to be still linear at this location.

However, this is not the conventional way of calculating the wave steepness. Gerding (1993) used the formulae for fictitious wave steepness S_{op} and calculated this for the waves near shore, see:

$$S_{op} = \frac{2\pi \cdot H_s}{g \cdot T_p^{\ 2}} \qquad \textbf{(3-22)}$$

This is called fictitious steepness as real wave steepness near shore because is not representative because of shoaling. This parameter is used as a fixed ratio between wave height and wave period. The calculation from wave period to wave length is done to make it dimensionless. Besides that, the deep water theory does not hold near shore. This formulation only gives a fixed ratio between S_{op}, H_s and T_p.

In this report steepness for transitional water depth is given by S_0 and the fictitious wave steepness by S_{op}. This is the formulation how it is used from now on in this report.

The result of both calculation methods leads to different wave periods. The wave periods for this research are far larger, representing lower wave steepness. Gerding (1993) and Van der Meer (1995) claimed that wave steepness is not of big influence on toe stability. It is interesting to check if this conclusion also holds for this research.

Water level

Tests are done at seven different water levels. The four lowest water levels are the main four water levels, representing the depth limited conditions. The tests at the highest three water levels are calibration tests to check this dataset to the Gerding dataset.

A difference in wave steepness is made between the main tests and the calibration tests. For the calibration tests only a wave steepness of 0.03 is maintained. For each water level, this means four runs per water level. The main tests contain two different wave steepness, S=0.02 and S=0.04. This means eight runs per water level.

For each water level the damage after a run is not rebuilt, leading to cumulative damage. Before each change in water level, the toe structure is rebuilt. For the calibration runs, four tests are done without rebuilding. For the main test, eight tests are done without rebuilding. The cumulative character of damage development differs from most other studies.

Fore shore slope

In this depth limited situations fore shore slope is expected to be an important geometrical parameter. Therefore the set of experiments explained above is repeated three times with a different fore shore slopes to find the influence of fore shore slope angle.

The mildest slope is a 1:50 fore shore. This is the same fore shore slope as Docters van Leeuwen (1996) used in her research to toe stability for breakwaters. The second slope is a 1:20 slope, similar to the slope Gerding used in his research. The steepest slope is a 1:10 slope. This steepest fore shore slope seems too steep but does occur in rocky environments and is interesting in this sense.

Test Schedule

The set of variations, described in above paragraph leads to a set of 3*44 runs. This is given in matrix form. A distinction is made between tests in deep water, corresponding with the experiment from Gerding and the tests in shallow water. The two columns in the matrix show this difference in parameters used.

Matrix of Runs	Calibration Runs (deep water) h_t (8.0, 13.0 & 18.0cm)	Main Runs (shallow water) h_t (0, 2.0, 4.0 & 6.0cm)
S_{op} (0.02, 0.03 & 0.04)	0.03	0.02 &0.04
α_{shore} (1:50, 1:20, 1:10)	1:50, 1:20, 1:10	1:50, 1:20, 1:10
H_s (6.0, 8.0, 10.0 & 12.0cm)	6.0, 8.0, 10.0 & 12.0cm	6.0, 8.0, 10.0 & 12.0cm

Besides that extra tests are done for the 1:20 slope in deep water. For three water level in deep water, tests are done with wave steepness 0.02 and 0.04. These runs are done to compare with the experiment from Gerding in a better way. These extra tests contain 24 runs.

The calibration tests in relatively deep water are done with only one wave steepness. For each fore shore slope 12 runs are done. Below table shows the tests for one water level:

H_s (m)	S_{op} (m/m)	T_p (s)
0.06	0.03	1.15
0.08	0.03	1.3
0.10	0.03	1.5
0.12	0.03	1.65

The main tests in relatively shallow water are done for two wave steepness, for each fore shore slope 32 tests are done. Below table shows the tests for one water level.

H_s (m)	S_{op} (m/m)	T_p (s)
0.06	0.04	1
0.06	0.02	1.5
0.08	0.04	1.15
0.08	0.02	2
0.10	0.04	1.3

0.10	0.02	2.4
0.12	0.04	1.5
0.12	0.02	2.8

An extra remark is made to the sequence of tests for the eight runs. It is tried to create a test program with increasing wave load. Each wave height is tested twice with varying wave steepness. This schedule has a very practical character. The toe profile is not rebuilt after each test and the wave load is enlarged by raising/varying the wave height and wave steepness in turn.

In prototype, this is likely to happen as well because large storms occur more rarely and thus after a sequence of smaller storms when the toe has already reshaped a bit. This test program has lots of similarity with test programs for scale tests of breakwater projects.

4. Experiment observations, analysis and results

This chapter presents observations made during the experiments, analysis of the obtained dataset and presentation of results from the experiment.

4.1. Observations

An overview of the most interesting observations is given first:

- Damage development, caused in depth limited situations ($h_t h_m$<0.4), is influenced by the fore shore slope. As the slope got steeper the observed damage got worse.
- Different fore shore slopes caused different kinds of wave breaking on the fore shore slope. These observed breaker types corresponded with the expected breaker types according to the Iribarren number.
- Breaking waves, like spilling and plunging waves, caused more damage to the toe than surging waves.
- Water level decrease leads to a more exposed toe, increase of wave breaking at the fore shore but also to a reduced wave height. This interaction of three influences determined the rate of damage development. An optimum in damage development for this interaction was observed.
- Wave steepness is an important parameter in damage development as well. Long waves caused more damage than short waves. Damage increase with lower wave steepness. As both parameters were varied in turn in the test program, damage level could be compared easily by observations but was difficult to interpret from experimental data.
- Rock was pushed in upward direction for long waves ($S_{op}={}^{+}/_{-}0.01$) in combination with an exposed situation of the toe. They were taken with the wave and were put on top of the structure slope. The rock was smashed on top of the Xbloc layer. The steeper waves ($S_{op}={}^{+}/_{-}0.35$) lead mainly to downward moving of stones.

In the performed experiments a wide variation of types of waves occurred. They developed from smooth surging waves into plunging waves right above the toe of the structure. For a surging wave the toe is only attacked by the orbital motion of the incident and reflected wave. In the shallowest situation the toe was exposed and attacked by plunging waves right above the toe. This is a turbulent process and difficult to describe. Because of these different kinds of wave breaking, at this moment it is not possible to describe this from a hydro dynamical point of view. Defining a stability condition is a matter of logical reasoning and relating the different parameters with each other.

4.2. Analysis of observations

4.2.1. Behaviour of waves in depth limited conditions

For the behaviour of waves in depth limited conditions, observations are combined with theoretical background. The theoretical basis for describing the breaker types is explained. This is done because the theoretical basis describes the observed breaking wave climate in a correct way.

Wave load, Breaker type & Breaker depth

In the depth limited situations, in which the tests are done, wave breaking is dominating the wave attack. Wave breaking reduces the wave height. However during breaking, wave attack can be more aggressive. The amount of wave attack at the toe depends mainly on four items:

- The available wave energy in a wave. The local circumstances determine to which extent the wave energy is able to reach the structure.
- Reflection of the wave energy on the breakwater structure.
- Breaker types, the type of wave breaking contributes to the impact of the wave on the toe. This is described by the Iribarren number.
- The location of breaking, this depends on the ratio between water level and wave height. The interaction between both determines the location of breaking.

The first item is a boundary condition for wave attack at the structure. A wave needs a certain amount of wave energy to be able to attack the toe structure. The available wave energy depends on wave height and wave length. Higher and longer waves contain more energy. In shallow water waves are breaking on the fore shore and toe structure. This breaking situation, dissipating their wave energy, creates extra damage as observed in the experiment. When waves are higher or longer, more energy can be dissipated and more damage is expected. In this research, wave energy is only discussed in a qualitative way and no formulation is considered.

Reflection depends on wave energy dissipation on the breakwater structure. Permeability of the rock influences energy dissipation in a high rate. Open structures dissipate more energy than impermeable structures and thus cause lower reflections. Larger reflection leads to heavier down rush and more wave attack to the toe. The measured reflection is calculated with a spectral analysis. Reflection is measured for each test and given in the attached dataset. Values are between 0.1 and 0.5. The extent of impact on the toe depends on the other two items. This paragraph continues with an explanation of the other two items.

Because of these shallow water conditions wave breaking occurs. The Iribarren number gives a common used approach for describing the different kinds of wave breaking. The different breaker types have occurred during the tests from surging to collapsing to plunging to spilling waves. The Iribarren number is given as follows:

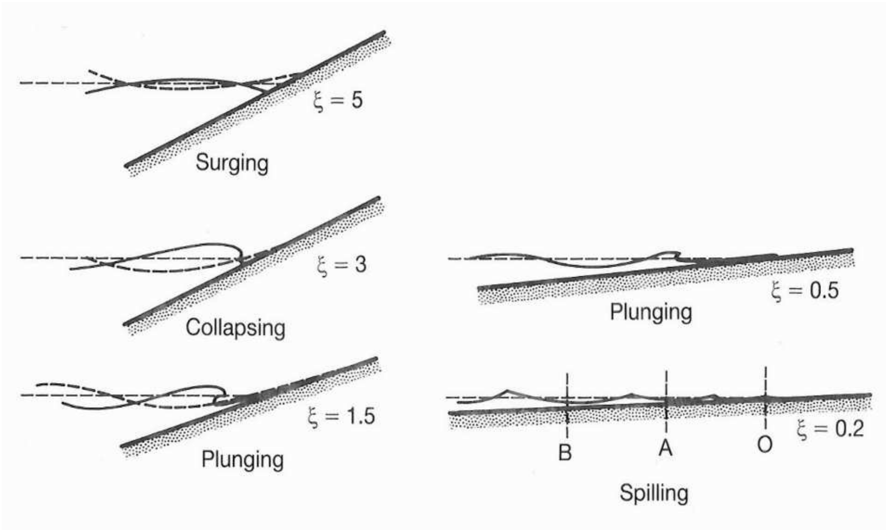
$$\xi_{op} = \frac{\tan\alpha}{\sqrt{H/L_0}} \tag{4-1}$$

The Iribarren number is a ratio between bottom slope (tan α) and value for the wave steepness (H/L_0). Iribarren used the local wave height for wave height H_s and the deep water wave length L_0. L_0 is calculated according to equation (4-1), using the deep water peak period T_p of the wave.

$$L_o = \frac{2\pi}{g \cdot T_p^{\ 2}} \tag{4-2}$$

The breaker type is a combination of wave height, wave length (= wave steepness) and bottom slope. During the experiments, two locations of wave breaking were present, breaking at the fore shore and breaking at the slope of the structure. The location of breaking depended on the ratio of wave height and water level. For relatively high water level in comparison to the wave height, the waves were able to reach the structure without breaking. For lower water levels in comparison to the wave height, the waves already broke on the fore shore slope.

The kind of breaking was totally different for both locations. This is mainly caused by the slope angle. The Iribarren number turned out to be a good way of describing the different breaker types. The different breaker types are shown in figure 4-1. This figure is given in the Rock Manual (2007). Two columns are given, the left gives a nice representation of breaking waves at a rather steep slope (slope structure). The right column give a nice representations of breaking waves on rather mild slope (slope fore shore).



4-1 Examples of Iribarren breaker types

To start with the left column, breaking on a relatively steep slope is presented. These breaker types have been observed at the structure slope. Mention that kind of wave breaking happened for relatively small wave heights in relation to the water level at the structure. The most decent kind of wave breaking is a surging wave. Breaking is not visible but the wave is partly dissipated and partly reflected on the slope by up wash and down rush of the wave. This is no real wave breaking but the wave is interacting with the underlying bottom slope and is looses and reflecting its energy this way.

Larger waves lead to a change in wave breaking, also presented in the picture. In one test series of eight tests for a fixed water level, the wave height and wave period were increased. In the sequence of tests, heavier wave attack was visible. First surging waves, next collapsing and plunging waves hit the structure.

From the interpretation of the Iribarren number this was unexpected while for every single tests the same wave steepness S_{op} was used. As the wave steepness is kept the same, the breaker type should be the same as well. It did not turn out to be this way.

The reason for this can be found in the shoaling and deformation of the wave. As the wave shoals, propagating to shallower water, it deforms and the wave energy is concentrating in the peak of the waves. A larger wave contains more energy. Unless the wave steepness is the same, this larger wave is concentrating more energy in the peak of the wave during shoaling. The peak of the wave has a different steepness, when hitting the structure, and breaks in a different way.

Besides that a breaking wave is a turbulent process and has more impact than water velocities and pressures of surging waves. When individual waves are observed with about the same local wave height H_s, but different breaker types, surging wave turned out to be less vulnerable. Plunging waves at the toe created most damage while collapsing wave attack was something in between. This was also concluded by Hovestad (2006)

A last remark is made for the difference in wave steepness, executed in the test program. As the Iribarren number prescribes, a difference in wave steepness leads to a different kind of wave attack. Shorter waves (S_0 = 0.04) were breaking sooner than longer waves (S_0 = 0.02).

To continue with the second column in figure 4-1 breaking on a mild slope is presented. This type of wave breaking occurred in the later part of the test program. After lowering the water level each eight tests with 2cm wave breaking at the fore shore slope started to occur. From observations the breaker types were spilling and plunging. There was a clear difference in wave breaking for the three different fore shore slopes. As Iribarren prescribes the fore shore slope in relation to the wave steepness determines the breaker type.

Wave breaking for the 1:50 slope was mainly spilling. The waves break at a certain spot and propagate as turbulent spilling waves. As these spilling waves reach the structure, the turbulent motion of the broken wave hits the structure. For a 1:20 slope the breaking waves are a combination of spilling and plunging waves. For a 1:10 slope the breaking is predominantly plunging. After the wave has plunged, the reduced wave propagates.

Slope Wave Steepness	2:3 (structure)	1:50 (shore)	1:20 (shore)	1:10 (shore)
S_0 = 0.02	5.54	0.14	0.35	0.7
S_0 = 0.04	3.92	0.10	0.25	0.5

These are the calculated Iribarren numbers for the desired wave steepness near the paddle and design wave height of 10 cm. The values correspond with the breaker types as were observed in the experiments

Here above a division is made between breaking on the structure slope and breaking on the foreshore slope. This division was a big difference in physical processes that was seen during the experiment. The transition zone from breaking at foreshore to breaking at the structure is around the toe. Especially these waves hit the toe hardest because they break just before or on top of the toe and can dissipate their wave energy on the toe.

Wave impact at toe

The combination of wave load, breaker type and breaker depth determine the wave load of the incident wave. To understand what happens around the toe, the hydrodynamical processes were studied to a smaller scale first.

<u>Small scale processes</u>
Wave attack on the breakwater is a difficult process. The incoming wave hits the structure and the wave energy is partly dissipated. The other part of the wave energy is reflected on the slope of the structure. This reflected wave propagates in opposite direction and is influencing the next incoming waves. The reflected wave increases the total wave height, which is a combination of the incoming and reflected wave. The incoming wave can break spontaneously because of the influence in total wave height of the reflected wave.

The interaction of incoming and reflecting waves can also lead to more vulnerable situations at the structure itself. After the wave retreats from the structure, the local water levels vary and can contribute positively and negatively to the toe.

If the second wave comes in, when the first one has just retreated it can hit the toe harder. When waves follow too soon after each other, the second wave is influenced negatively because the water has not retreated yet. The phase difference between two sequent waves is an important parameter in this interaction between waves. As the water level was decreased in the flume, this behaviour became more significant.

For situations when relatively low water level and a favourable phase difference occurs, the attack of the second wave appeared as a volume of water rushing over the exposed toe structure. For the extreme situation, the water rushing over the toe material looked like a bore of water.

These local processes are interesting but for the objective of this research not relevant. With this research it is tried to find relations for toe stability in depth limited conditions. As the hydrodynamics on this small scale vary too much for all the different kinds of wave attack, the processes are studied at a larger scale.

Large scale processes

As described before, wave load and there fore wave attack to toe material is influenced by the breaker height, the ratio of wave height to water level. Picture 4-2 shows a water depth characterization, given by the Rock Manual (2007). This representation is used for the armour stability formulas of Van der Meer. A separation is made for different ratios of $h_{toe}/H_{s\text{-}toe}$. From the physical processes observed in the experiment, this separation seems plausible.

Parameter	Water depth characterisation		
	Very shallow water	**Shallow water and shallow foreshore**	**Deep water**
Relative water depth at the toe: $h_{toe}/H_{s\text{-}toe}$	≈1.5 - ≈2	< 3	> 3
Wave height ratio, R_H $R_H = H_{s\text{-}toe}/H_{so}$	< 70%	70% < R_H < 90%	> 90%
Stability formulae:			
Van der Meer 'deep water' Equation No's 5.146 and 5.147			
Van der Meer-shallow water Equation No's 5.149 and 5.150			

4-2 Validity of armour stability equations

When stability for toe material is divided in three sections according to this principle:

- In deep water, the waves break at the structure slope and not on the fore shore. The toe is built deep enough under the water level and is only attacked by local water velocities. In fact this is the most normal way of wave attack at the toe. The ratio of h/H_s determines if you can still speak of deep water.
- In shallower conditions, the waves shoal far more and wave energy concentrates in the peak of the waves. The waves start feeling the bottom, shoal and start breaking at a certain moment. Wave breaking occurs at fore shore and structure slope. As the space for the toe is limited, it is built closer to the water surface. The wave attack to the toe material, broken or non broken, has a more direct attack.
- In very shallow water, the toe is exposed and lots of breaking or already broken waves hit the toe rock immediately. This wave breaking causes even more damage. As the toe is more exposed, the waves are able to attack the toe more directly.

This last water depth characterization is mainly tested in the experiment. The water depth characterization "Very Shallow" applies for the main part of the performed dataset. In these very shallow water conditions, the toe is mainly attacked by already broken waves (at foreshore) and directly breaking waves at the toe itself.

It must be noticed that the numbers from the figure do not correspond with above mentioned characterization. This water depth characterization is derived for toes while the figure gives a characterization for armour. In this situation the water level in front of the toe (h_m) is used instead of the water level at the toe (h_t). A limit for very shallow water is found at $h_m/H_s<2.0$.

Breaking height for different fore shore slopes

From observations and from data can be concluded that waves shoal to larger wave heights near shore before they start breaking because of a steeper fore shore slope. In the table the wave height off shore and near shore are given for the fixed water level (h_t=0.093m), wave height (H_s=0.10m) and both wave steepness (S_{op}=0.02 & 0.04). The off shore wave height are about the same while the near shore wave height is larger for steeper fore shore slopes:

S_{op}	S_{op}=0.04			S_{op}=0.02		
α_{shore}	$H_{offshore}$ (m)	$H_{nearshore}$ (m)	H_{ns}/H_{os}	$H_{offshore}$ (m)	$H_{nearshore}$ (m)	H_{ns}/H_{os}
1:50	0.105	0.79	0.75	0.105	0.74	0.70
1:20	0.098	0.80	0.82	0.98	0.80	0.82
1:10	0.096	0.88	0.92	0.99	1.00	1.01

This increase in local wave height, due to a steeper fore shore, contributes to a higher damage for steeper slopes. However this is probably not the only reason for damage increase. Different breaker types were observed for the tested fore shores. The breaker type is expected to have influence as well.

4.2.2. Influence of wave steepness on stone stability

An interesting observation is done to the influence of wave steepness to toe stability. The wave steepness, or better said wave period, does have influence on stone stability. In fact, a remarkable difference in damage was observed by variation of the wave steepness between 0.02 and 0.04 near the paddle.

This conclusion is contradicting to the conclusions, made by Gravesen and Sørensen by (1977) and van der Meer (1995). Van der Meer could not find a significant trend indicating an influence of wave steepness while Gravesen and Sørensen claimed the opposite. They concluded that waves with high steepness were causing more damage. This is already mentioned in paragraph 2.1. This paragraph mainly compares the observations from this research with the conclusions by Van der Meer.

Comparison with Van der Meer

The experimental research, done by Gerding and the analysis by Van der Meer, is considered as the most important background literature for this research. Both concluded that wave steepness had no important influence on toe stability.

For both studies wave steepness between 0.02 and 0.04 are considered. However, from these wave steepness, the wave period is not calculated in the same way. This is already explained in paragraph 3.5. Gerding research used the formula for fictitious wave steepness (4-3) and based his test program on this wave steepness near the structure. In this research wave steepness near the paddle is determined, using the equations for transitional water depth. The result is that the wave periods used for this research are larger in relation to wave height from Gerding's research.

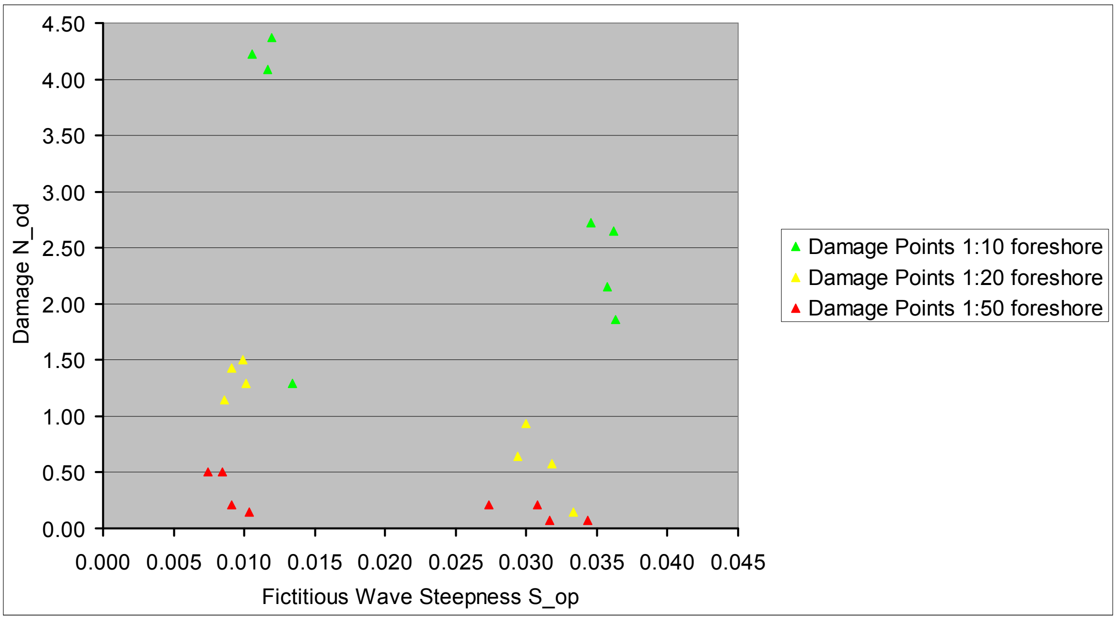
The different approaches can be compared best if the measured wave height and periods from both experiments are analysed in the same way. This is done by using the formula for fictitious wave steepness with near shore significant wave height (H_s) and the off shore peak period (T_p).

$$S_{op} = \frac{2\pi \cdot H_s}{g \cdot T_p^{\ 2}} \qquad \textbf{(4-3)}$$

It is obvious that for Gerding's data, wave steepness between 0.02 and 0.04 are found. For this dataset, analysis leads to fictitious wave steepness between 0.01 and 0,035. This proves that relatively longer waves are used for this research.

The reason for this is found in the different calculation method, formulae for transitional water depth (3-12) against formulae for fictitious wave steepness. Besides that, the shallower water conditions are experiencing more wave breaking. Wave breaking leads to lower fictitious wave steepness as well.

The dataset of this research has a wider range of fictitious wave steepness. In figure 4-3, wave steepness is plotted against damage N_{od}. This plot is made for fixed wave height, water level and stone diameter. It shows an increase in damage for decreasing wave steepness. Gerding made the same plot but created horizontal lines, implying no influence.



4-3 Graph S_{op} against N_{od} for h_t=-0.007, 0.13, 0.033 & 0.053m, D_{n50}=2.15cm and H_s=0.10m

The fictitious wave steepness (S_{op}) is chosen as the parameter to present the steepness. S_{op} is the most common way tot calculate wave steepness and in this sense easy to compare with other studies.

From the given plot can be concluded that wave steepness is influencing damage development. This was already observed and noticed in the experiments. This influence is concluded quite high from analysis.

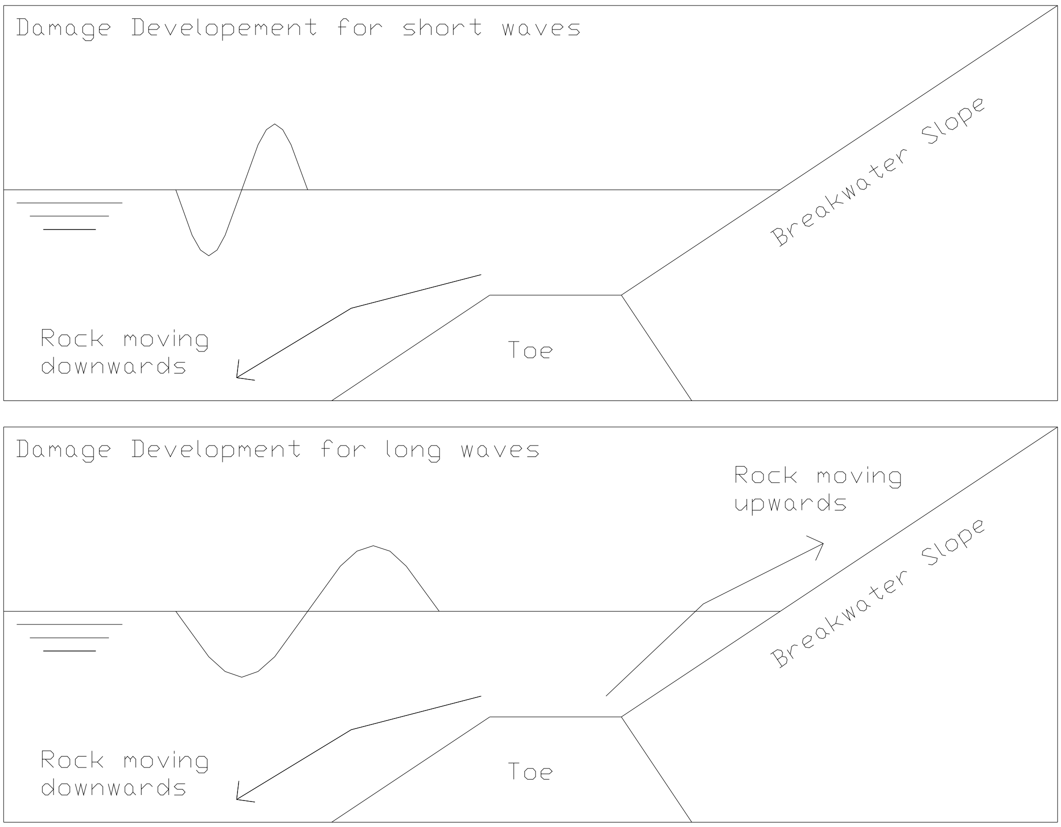
Two remarks are made to figure:

- The water levels given in the subscript are not similar with the proposed water level in the experiment set up. The deviation of 7mm is the result of differences in measuring off shore and near shore. This was noticed during the experiment and this deviation is maintained for the whole test program.
- The second remark is made to the single green data point on the left. This outfield data point is a result of cumulative damage reporting. In the sequence of test series, reshaping of the toe

occurred and stones fell downward or were pushed up. With the test of the concerning data point, the wave field pushed all downward fallen stones back in to the toe profile. A sort of negative damage was reported. This way the extremely low damage was obtained. Because of a different type of failure and history, this point will not be used in further analysis anymore.

Different mechanisms in damage development for short and long waves

For the two situations with different wave steepness, the behaviour of the toe elements was clearly different. Besides the fact that more stones are removed from the toe structure for longer waves, the rock moves also in different directions. Rock falls in downward direction for both two wave steepness. An interesting observation was that stones were also moved in upward direction by the longer waves. This process only occurred for the larger wave heights (10 and 12cm). The accompanying wave periods were 2.4 and 2.8 seconds, far larger than the other tested wave periods (≤ 2.0 seconds). The process is given in the figure below.



4-4 Figure separating different mechanisms for drag of rock

It is a fact that longer waves contain more energy. The transformation of energy for longer waves is apparently different. From observations, it seems that the long waves with a lot of wave energy were able to create a flux of water over the toe. This flux first uplifts the rock and next pushes them in upward direction. The shorter and smaller waves were only able to uplift the rock but not push them in upward direction. The wave is too short and starts to retreat too soon, in this case the rock falls downward of back to the toe profile.

4.2.3. Current test program compared with Van der Meer test program

The observed damage is the result of the sum of tests with different wave height and wave period. The built up in wave load and reshaping of the toe of this test program describes how a toe behaves in prototype. This different approach makes it difficult to compare the result with dataset from Gerding. The test program, executed by Gerding, contained only solitary tests. After each test, damage was determined and the toe profile rebuilt. This way damage is the result of one test, containing 1000 waves. Van der Meer calls this “pure testing”. The test program for this research does not contain rebuilt of the toe after each test. The damage is taken cumulatively and the considered damage is the result of different tests with different wave heights and wave lengths. However, the datasets correspond very well. The dataset of this research shows less stability but this is plausible because of the larger number of waves that attacked the structure.

In paragraph 4.2.2 is described that wave steepness has an influence on damage development. As wave steepness and wave height are changed in sequence, it is difficult to derive the influence of both variables from the performed data. Damage development was influenced by two parameters which were changed in the test program in turn. This makes it difficult to quantify both influences.

Because of the difficult interpretation of the damage development, a set of tests for a 1:20 fore shore slope and a fixed water level have been repeated according to ‘Gerding’ test sequence. The toe has been rebuilt each test. This way the damage from this research can be compared with the dataset from Gerding. The datasets for the original test sequence and the dataset according to pure testing are given in table below.

Tests(α=1:20 h_t/h_m=0.292)				Original data		Data “pure” tests
H_s (m)	S_0 (s)	D_{n50} (m)		$N_{cum, tot}$		N_{tot}
0.06	0.04	0.0215		1		0
0.06	0.02	0.0215		2		6
0.08	0.04	0.0215		4		2
0.08	0.02	0.0215		9		6
0.1	0.04	0.0215		9		7
0.1	0.02	0.0215		21		20
<u>0.12</u>	<u>0.04</u>	<u>0.0215</u>		<u>21</u>		<u>14</u>
0.12	0.02	0.0215		25		20
0.06	0.04	0.0268		0		0
0.06	0.02	0.0268		2		0
0.08	0.04	0.0268		3		0
0.08	0.02	0.0268		4		2
0.10	0.04	0.0268		4		4
0.10	0.02	0.0268		10		8
0.12	0.04	0.0268		9		4
0.12	0.02	0.0268		9		9

Testing according to cumulative damage and pure testing correspond quite well. However, the interference of wave height and wave steepness in the test program is visible in the original dataset. An example of this interference is given in the underlined row. The damage is the result of this test and previous tests. Stones were pushed upwards in long wave tests while this did not happen in short wave tests. A modification is made to the original dataset in which upward fallen stones are excluded from the dataset for short wave tests. This modification is based on the observations explained in previous paragraph 4.2.2. This results in:

Tests(α=1:20 h_t/h_m=0.292)				Data "pure" tests		Modified data
H_s (m)	S_0 (s)	D_{n50} (m)		N_{tot}		$N_{mod, cum, tot}$
0.06	0.04	0.0215		0		1
0.06	0.02	0.0215		6		2
0.08	0.04	0.0215		2		4
0.08	0.02	0.0215		6		9
0.1	0.04	0.0215		7		8
0.1	0.02	0.0215		20		21
0.12	0.04	0.0215		14		14
0.12	0.02	0.0215		20		25
0.06	0.04	0.0268		0		0
0.06	0.02	0.0268		0		2
0.08	0.04	0.0268		0		3
0.08	0.02	0.0268		2		4
0.10	0.04	0.0268		4		4
0.10	0.02	0.0268		8		10
0.12	0.04	0.0268		4		8
0.12	0.02	0.0268		9		9

Two columns with damage are given:

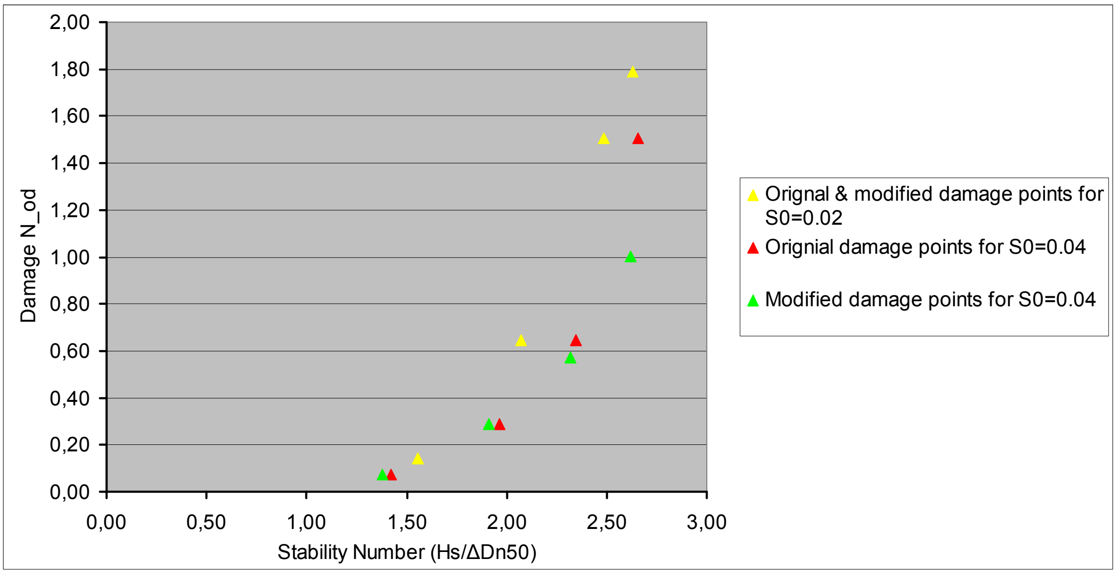
- The first column presents the measured damage for extra tests, executed according to "pure testing". Every test, the toe profile is rebuilt.
- The second column gives the modified damage values. For the long waves, upward moved and downward fallen stones are counted. For the short waves, only downward fallen stones are counted.

This way the interference of increase in wave height and variance in wave steepness is tried to be solved. By this modification, the dataset is more reliable.

It can be concluded that cumulative testing is a good alternative for pure testing. The amounts of damage do correspond quite well. Of course some difference is visible but this is inherent to scale model testing. In general, the results are about similar.

It is not tried to modify the Current dataset to a Gerding dataset. The reason for this modification is the attempt to show a significant difference in stone stability for different wave steepness.

Without this modification this would not be visible in the dataset as it was observed during the experiments. Figure 4-5 shows a plot of stability number against damage.



4-5 Graph with results modification for α_{shore}=1:20, h_t=0.033m and D_{n50}=2.15cm

A graph is made for fixed fore shore slope, water level and stone size. In the graph it self a difference is made in wave steepness. Original and modified data points are plotted. The modification has no influence on the data points for shore wave steepness. These data points are given in yellow. The red points are the original damage points and the green points the modified points. The red points (S_0=0.04) are pulled to the damage curve for S_0=0.02 while the modified points (green) do not show an interaction with the yellow points. This graph represents the damage development as it was observed during the experiments.

4.2.4. Damage behaviour in relation to N_{od} values

For users of the design formula for toe material, the N_{od} is a difficult number to interpret. Papers give acceptable values for the damage number. Unfortunately most of the designers do not have a feeling with this number. In this paragraph it is tried to give an impression of the behaviour and meaning of N_{od}.

The acceptance of N_{od} is depending on the fact whether the toe is still able to fulfil its function. The primary task of the toe is to provide a fundament to the armour layer, Xbloc units in this case. The acceptance of N_{od} in this research is directly related to Xbloc units. As single layer armour units require a more stringent fixation than armour rock does, the acceptable N_{od} values will be more stringent as well.

Most of the tests are done in very shallow water. The impression for the behaviour of N_{od} is made for this area. This behaviour is dominated by breaking waves in an exposed situation.

Design values of N_{od} are given by Van der Meer and by Gerding, which are determined in combination with armour rock. Van der Meer suggests a design value of 0.5 and Gerding 2. N_{od}=0.5 is defined by start of damage. This implies that hardly any damage occurs until a value of 0.5. Gerding gave N_{od}=2.0 as design value. Flattening out of the toe is occurring but is still acceptable. An overview is given in paragraph 3.2.

Mainly two processes of moving rock have occurred. They are explained below.

<u>Reshaping of the toe structure (Dynamically stable)</u>
Small wave attack already leads in first place to rocking of stones. Because of rocking the stones start to settle a little bit. After wave attack grows removal of rock occurs. They are washed out and lie down in front of the toe structure. For larger wave attack, rock also start to be pushed up and lies on the edge of toe and armour layer. Reshaping of the toe profile to a certain extent improves toe stability. A more natural toe slope is created. This process was observed very clear. However, if reshaping gets too large, the toe profile is not able to support the armour layer anymore.

<u>Continuously moving stones (Dynamically unstable)</u>
When wave load increases, the rock becomes dynamically unstable. Damage development cannot be described as reshaping anymore. The rock moves up and down with the waves. A single rock is not moving to a more stable location anymore but is continuously moving with the wave load. From pictures, this process cannot be determined but the result of this process is damage on a large scale.

This process was mainly observed for long waves in shallow water. In this situation the wave can attack the toe as a bore of water rushing over the stones. Because of shallow water the toe is exposed to this attack, the long wave period leads to a large horizontal flux. As the fore shore slope got steeper, this effect was larger as well. The combination of these parameters led in some situations to damage in such extent that the armour layer failed.

Another effect of continuously moving rock is the impact on the above laying concrete armour units which are hit by the rock. These could break easily by the impact of the stones.

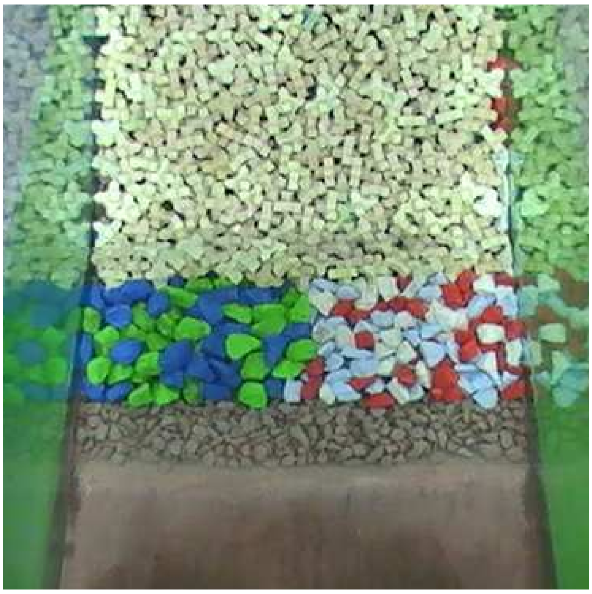
As can be understood the second kind of rock behaviour is not desirable. The first process is acceptable to a certain extent but the second process must be avoided. This can be done by a restriction in N_{od} number. From the experiments follows that dynamic instability of the rock happens quite soon. The main thought is that this behaviour occurs because of the very shallow situations. The toe is forced by the wave energy directly. For deeper water levels, this would not happen very soon because the toe is not exposed to direct wave attack.

Rocking & Shaking of toe profile

When looked at the individual behaviour of stones, the movement is divided in three parts. For some wave load, the stones start rocking, they shake a little bit within their fixed location. After increase of the wave load, some stones are displaced and move to a more stable location. This is described as reshaping of the toe profile. After wave load has increased again, the stones start moving with the wave, described as dynamically unstable movement.

When the behaviour of the toe profile is studied, the behaviour is divided in four parts. First the top layer is rocking. Second, the top layer of stones starts to move to a more stable location. As wave load increases again the top layer is rocking with the waves and starts to move with the wave. As wave load is increased even more, it can lead to shaking of the whole toe profile. This can cause settlements of the above laying armour layer.

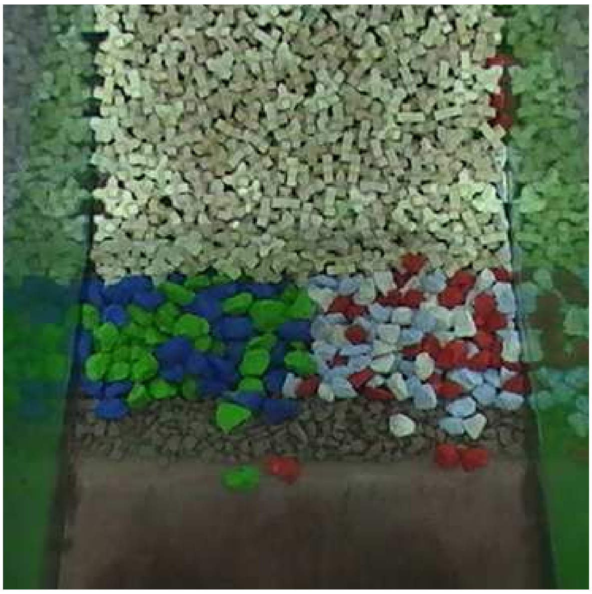
In below figures, examples are given for different N_{od} values. All pictures are taken from tests with a 1:20 fore shore and a water level h_t of 0.033m. The test conditions, N_{od} value, percentage of damage and comments from the experiments are picture.



H_s	-
T_p	-
N_{od}	-
$N_{\%}$	-
Comments wave	-
Comments damage	-

4-6 Picture of zero-situation toe profile

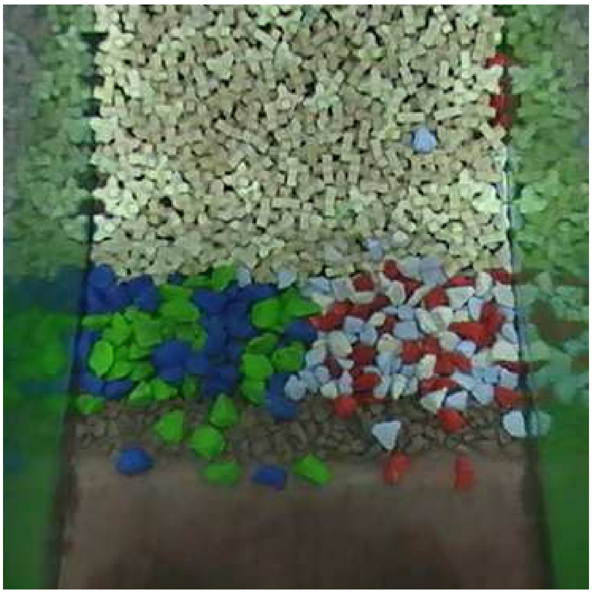
This is the zero situation. No test has been done yet.



H_s	0.08 m
T_p	2.0 sec (0.02)
N_{od} D_{n50}=2.15 cm D_{n50}=2.68 cm	0.65 0.36
$N_{\%}$ D_{n50}=2.15 cm D_{n50}=2.68 cm	4.7 % 3.8 %
Comments wave	waves break on edge toe profile, toe like little berm
Comments damage	already flattening out of toe profile

4-7 Picture toe profile after test with H_s=0.08 & S_0=0.02

This damage level still considered as safe. Reshaping occurs but within margins. Besides that, the rock behaved quite stable during the experiment.



H_s	0.10 m
T_p	2.4 sec (0.02)
N_{od} D_{n50}=2.15 cm D_{n50}=2.68 cm	1.51 0.89
$N_{\%}$ D_{n50}=2.15 cm D_{n50}=2.68 cm	11.0 % 9.5 %
Comments wave	bore of water rushing over toe profile
Comments damage	rocking and shaking of whole profile

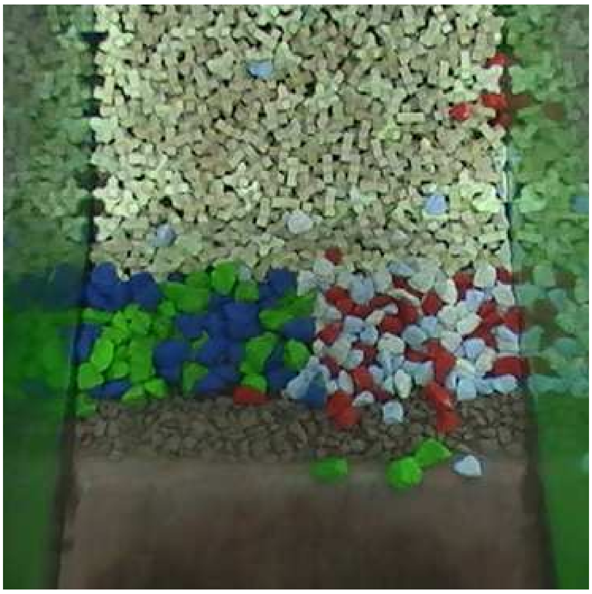
4-8 Picture toe profile after test with Hs=0.10 & S0=0.02

The toe profile is not stable anymore, rocking and shaking occurred during the test. This is not preferable. Some stones were taken along with the waves, especially the lighter stone sizes. The relative long wave length was due to this process.

H_s	0.12 m
T_p	1.5 sec (0.04)
N_{od} D_{n50}=2.15 cm D_{n50}=2.68 cm	1.0 0.71
$N_{\%}$ D_{n50}=2.15 cm D_{n50}=2.68 cm	7.4 % 7.6 %
Comments wave	Some high waves, quite some impact
Comments damage	Visible damage not representative, because of reshaped profile

4-9 Picture toe profile after test with Hs=0.12 & S0=0.04

This test happened immediately after previous test. The damage numbers are smaller because the upward moved stones are not included in the number as described in paragraph 4.2.3. No extra stones are pushed upward. Extra stones have fallen downwards.



H_s	0.12 m
T_p	2.8 sec (0.02)
N_{od} D_{n50}=2.15 cm D_{n50}=2.68 cm	1.79 0.80
$N_{\%}$ D_{n50}=2.15 cm D_{n50}=2.68 cm	13.0 % 8.5 %
Comments wave	bore of water, lots of impact
Comments damage	huge impact waves because of wave length

4-10 Picture toe profile after test with Hs=0.12 & S0=0.02

The profile looks cleaner than the previous picture. The rock is pushed back into the profile and upwards to the Xbloc units. A number of stones are lying on the Xbloc units. The cause for this is the long wave period. The toe profile is not stable anymore, during the experiment lots of stones were taken along with the wave and were hitting the structure slope.

Safe Design level

A safe design level for N_{od} in shallow water is determined at 0.5. This damage number corresponds with $N_{\%}$ until 5% in this set of experiments. This design value tolerates some reshaping of the toe structure but doesn't allow the toe to be totally reshaped.

As this conclusion follows from experiments with rather low wave steepness (S_{op}=$^{+}/_{-}$0.01 representing swell waves), this low steepness is included in the design value. As large difference in damage was found for the two tested wave steepness, a larger design value can be considered for waves with only high wave steepness because no upward moving stones are considered (S_{op}=$^{+}/_{-}$0.035 representing wind waves). A safe design level for this situation is considered N_{od}=1.0. N_{od}=1.0 corresponded in this test with 10%.

Damage expressed in N_{od} versus percentage

In paragraph 3.2 a formula is given for calculating the percentage of damage out the number of fallen stones. When dimensions of the toe profile and the porosity of the toe profile are known, the percentage can be calculated. The properties per alternative are given.

Properties N_{od} value	Properties percentage of damage $N_{\%}$
No extra parameters are needed to calculate damage according to N_{od}.	For determination, different conditions must be known like porosity and dimensions toe. Porosity depends on packing density of toe.
Thus, easy to calculate from scale tests	More difficult to determine from scale tests
Stone size has a big influence on the behaviour of the N_{od} number. Damage numbers for different stone sizes do not represent same amount of visible damage.	Damage expressed in percentage gives a better description of the visible damage. It expresses the physical damage.
Designer has no feeling with this number, non transparent number	Designer has feeling with this number, able to interpret physically
Design value depend on toe size, larger toe accepts a larger damage level.	Design value depends on toe size. Larger toe accepts a larger damage level

From the table can be interpreted that the percentage of damage seems a better number to describe damage with. The biggest advantage is that the percentage of damage describes damage development for different stone sizes better. The use of damage in percentages in data analysis reduces the amount of spread due to differences in stone size. This makes it a better parameter to describe damage than the damage number N_{od}.

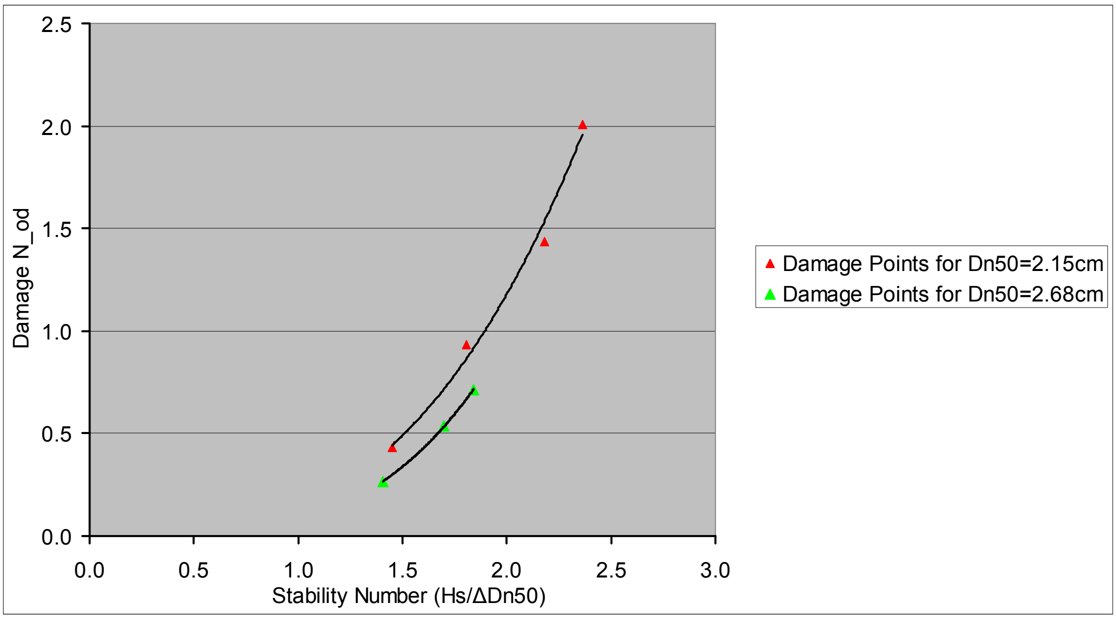
4.2.5. Consequence of the use of Stability Number $H_s/(\Delta D_{n50})$

The stability number is the ratio of wave height to the multiplication of relative density and diameter of the material. This stability number was empirically found by Hudson in the 1950's. It is nowadays known as the Hudson-type stability number:

$$\frac{H_s}{\Delta D_{n50}} \tag{4-4}$$

Equation (4-4) is the formulation as it is used in practice, significant wave height H_s and nominal diameter D_{n50} are used as input. The stability number is assumed to be a correct ratio between wave height and diameter to scale the different stone sizes and is used in the experiment.

If the stability number is a correct relation, the damage development should be the same for different stone sizes as long as they are related to each other in terms of $H_s/\Delta D_{n50}$. This means that if stability number is plotted against damage, using different stone sizes, the data points follows the same line. This scenario is checked in the plot below.



4-11 Graph for reliability of stability number for α_{shore}=1:20, h_t=0.013m, S_0=0.02 & Hs=all

Figure 4-11 is a representative graph for the behaviour of the stability number and damage found for many configurations of fore shore, water level, wave steepness and wave height. Two trend lines are visible, one for each stone size. The data points for both stone sizes show a similar trend but the rate of damage development is not similar for different stone sizes. This means that the use of the stability number is not fully correct in this dataset. This is confirmed in other figures from the dataset, which can be found in appendix B. The shape and angularity of the different stone sizes were about the same. So, this cannot explain the differences found.

There is no better approach known. Therefore, this stability number is used in this research. However, the mathematical analysis is done for only one stone size. In order to decrease variation due to the use of the stability number, the analysis of this research is done for one stone size.

Besides damage curve for stability number with N_{od}, also damage curves for stability number with the percentage of damage ($N_{\%}$) are attached in the appendix. The curves for N_{od} show a better correlation between stone sizes than $N_{\%}$.

4.2.6. Transition from observations to mathematical analysis

Because hydro dynamical processes differ in shallow waters, it is difficult to link damage to parameters of influence in a correct way.

The best way of relating these parameters is describing the hydrodynamical processes in a mathematical way. As they are not understood at this moment, turbulent wave attack is complex and relations between the parameters are studied using common sense.

The following general representation is used to display the stability relations, explained in paragraph 3.2:

$$Damage = f\left(\frac{WaveLoad}{Strength}, Geometry\right) \tag{4-5}$$

All parameters of influence are given as a function of damage. Damage is developing because of three interacting matters, wave load and strength of toe material and geometrical features of the neighbourhood. All three matters consist of different parameters which relate to each other.

A relation between wave load and strength is already given in the stability number. This stability number is often used in stability relations and the reliability of this number is checked in paragraph 4.2.5. Wave period is not included in the stability number, only wave height, so it is necessary to expand this stability number. Equation (4-6) gives the different parameters which define the wave load, strength and geometry. The geometrical features, which are studied in this research are the slope, the water level above toe and in front of toe. Other geometrical features are kept constant.

$$N_{od} = f\left(\frac{(H,T)}{(\Delta, D_{n50})}, (\alpha_{foreshore}, h_t, h_m)\right) \tag{4-6}$$

For making mathematical relations between damage and wave load, strength and geometry, it is necessary to have some understanding of the physical processes. In shallow water, this is quite complex because of different kinds of wave attacks. The different wave attacks have influence on damage development. The different kinds of wave attacks can be described by mainly wave height, wave length, water level, fore shore slope and structure slope. As the structure slope is not varied, this is a fixed value as well.

For high water levels in comparison with wave height, the waves do not break and attack the wave by surging and collapsing waves at the structure slope. This wave attack is quite predictable and in other studies some attempts are already made to link damage to the local velocities. As the water level decreases but the physical processes stay the same, damage development is larger. This is caused by the more exposed situation of the toe. In this scenario wave height in comparison to water level determines if the wave will break or will not break. The amount of damage is influenced by fore shore slope and wave length as well. This is observed and follows from the Iribarren number.

Main problem for relating the wave attack to damage, is the difference in location of wave breaking. For deep water (H_s/h_t>2.0), the waves break at the slope of the structure while for shallow water the waves break on the foreshore. This difference in physical behaviour is the main reason for a separation in analysis of the data.

This difference is also made by van Gent and Van der Meer as they gave different formulas for armour stability. Van der Meer and Van Gent use the Iribarren number to define breakwater slope and wave steepness in the stability condition. It seems in their studies that the square root of this number describes the influence of these two parameters. This has been a curve fitting analysis. In these formulas the slope of the structure is used, not the slope of the fore shore.

According to figure 4-2, the hydrodynamical system can be divided in three systems, deep, shallow and very shallow. The data from this research belong to shallow and very shallow water. Most tests from the experiment are done in very shallow water where wave breaking occurs at the fore shore slope and on the toe.

First analysis

The data is implemented in the Van der Meer graph. As described before, there are quite some differences in the experimental set up for both datasets. For this analysis, only the data with similar fore shore slope is used.

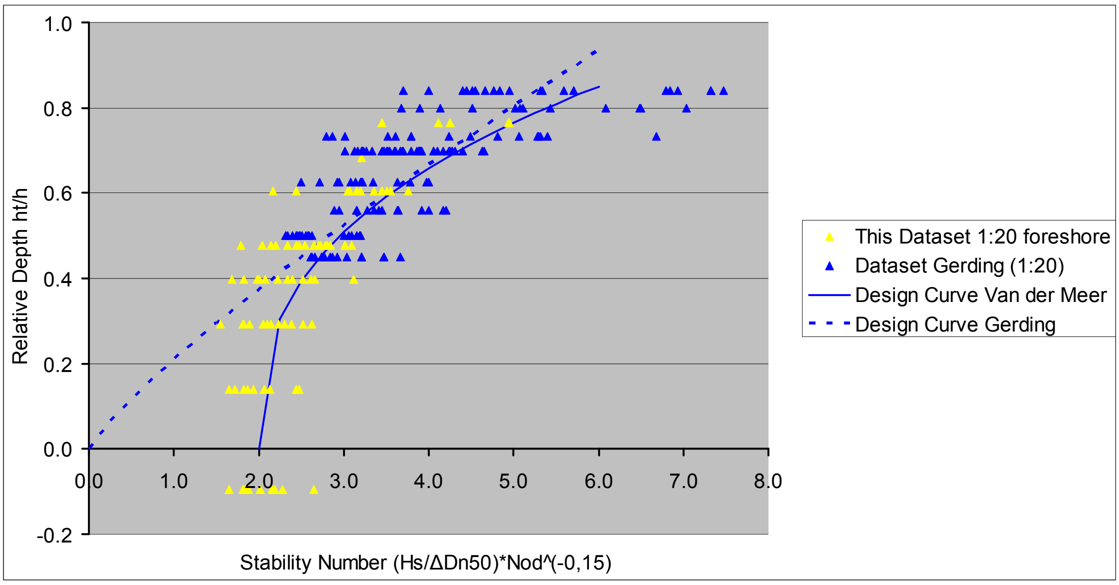
Second analysis

A complete new analysis is done for the data in very shallow water. This area represents mainly the situation where a toe is in fact part of the armour layer. The influence of fore shore slope is included and a study is done to derive a reliability equation for this domain.

4.3. Research Question "Extension Van der Meer Curve"

The Extension of the Van der Meer design curve for toe stability is the primary research question for this study. With the help of new scale tests the blind spot in the design graph is filled in.

Figure 4-12 shows the original Van der Meer design curve for N_{od}=0.5 and the accompanying data points. The yellow dots are the new data points from this research for a 1:20 fore shore slope. The modified damage numbers are used, as explained in paragraph 4.2.3.



4-12 Graph toe stability according to Van der Meer with new data points

The horizontal axis gives a multiplication of the stability number with an inverse power function of damage according to Van der Meer. The vertical axis gives the dimensionless water level above the toe.

At first sight they seem to fit nice, although there are some differences between both datasets:

- The armour layer varies. Gerding used double layered rock for the armour layer. For this research single layer Xbloc units are used. Xbloc units create more energy dissipation because of the high percentage of pores in between. Wave reflection is lower for Xbloc units in this sense.
- The relative depth is obtained in different ways. Gerding lowered water level but also

raised the toe height. For this research only the water level is decreased. See paragraph 3.4.4 for details.

- The executed test program varied. Gerding rebuilt the toe profile each test while cumulative testing was done for this research. There is also variation in tested wave heights, Gerding tested 15-25 cm in comparison with 6-12 cm for this research. In spite of the difference in wave height, wave periods did not vary ($^{+}/_{-}$1-3 s).

Looking closely to the new data points, they show less stability (they are located more to the left). From the differences in test set up, it was expected that this research would give less stable test results according to the cumulative character of testing. The damage number is the result of a sequence of cumulative tests and larger damage is expected.

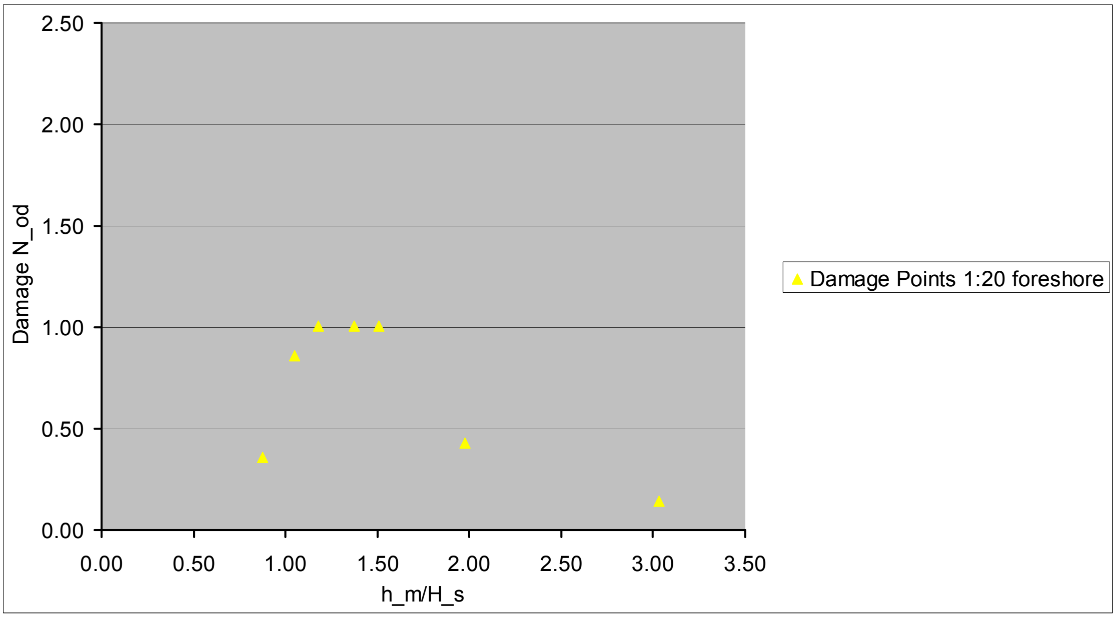
Based on the new tests, it is concluded that the Van der Meer design equation describes the toe stability in the right way. The trend line from both datasets matches. The trendline from combined dataset can be given by the Van der Meer equation. Rather small stone sizes are given for deep water and stone sizes, in the order of armour stone are given in very shallow water.

The trend lines correspond with each other but there are some remarks to be made.

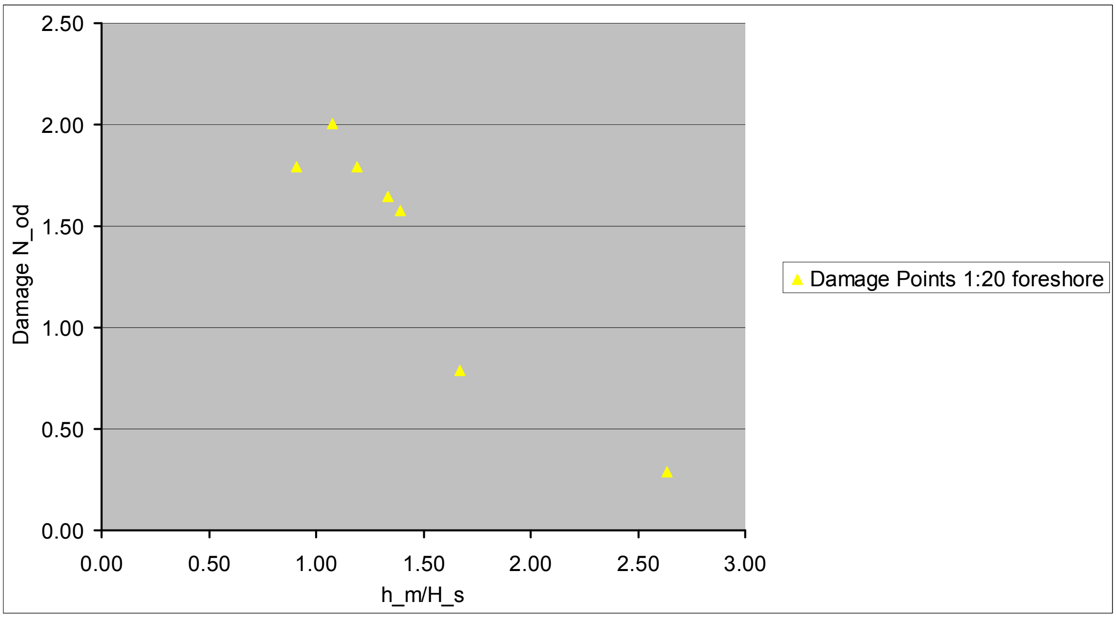
Relation between ratio h_m/H_s and Damage

The pattern of the yellow dots gives a lot of information about the behaviour of the wave attack. As the relative depth gets smaller (implying lower water levels) the toe gets more exposed and the waves could attack the toe more directly. At a certain moment the water is lowered so much that the wave load has reduced enough that the results indicate smaller damage. This is seen in the data points for h_t/h_m=-0.007. At this point the stability of the toe material is increasing again. The interaction between exposedness to waves and reduced wave attack is visible.

This interaction is made more clearly in figure 4-13 and 4-14. The ratio between the water level before the toe and the local wave height is plotted against damage. This is done for a 1:20 fore shore because most data is available for this fore shore slope. This plot gives the relation between the decrease in wave height and the exposedness of the toe.



4-13 Graph for ratio near shore wave height / waterlevel above toe and damage. (D_{n50}=2.15cm, H_s=0.12, α_{shore}=1:20 & S_{op}=0.04)

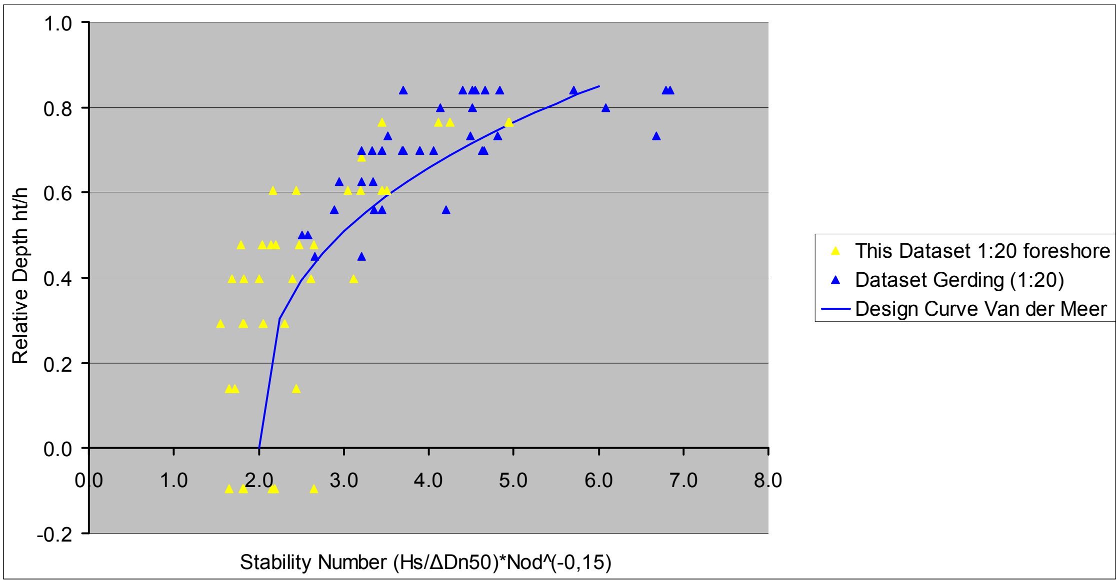


4-14 Graph for ratio near shore wave height / waterlevel above toe and damage. (D_{n50}=2.15cm, H_s=0.12, α_{shore}=1:20 & S_{op}=0.02)

First, damage development increased strongly, as the water level is lowered. At a certain moment, wave load is reduced and damage development stagnates. The results might indicate a small reduction in damage development. The dataset varies a lot at these low water levels. Therefore, this observation is difficult to display in a formula, Van der Meer didn't include it either.

Given design line for N_{od} value

Van der Meer gave N_{od}=0.5 for safe design. Figure 4-15 gives the data points for N_{od}<0.5. The variation is significant. Safe design in this content would require an envelope on the left side of the data cloud. The design line by Van der Meer is a trend line of the data points. This still implies uncertainty for design.

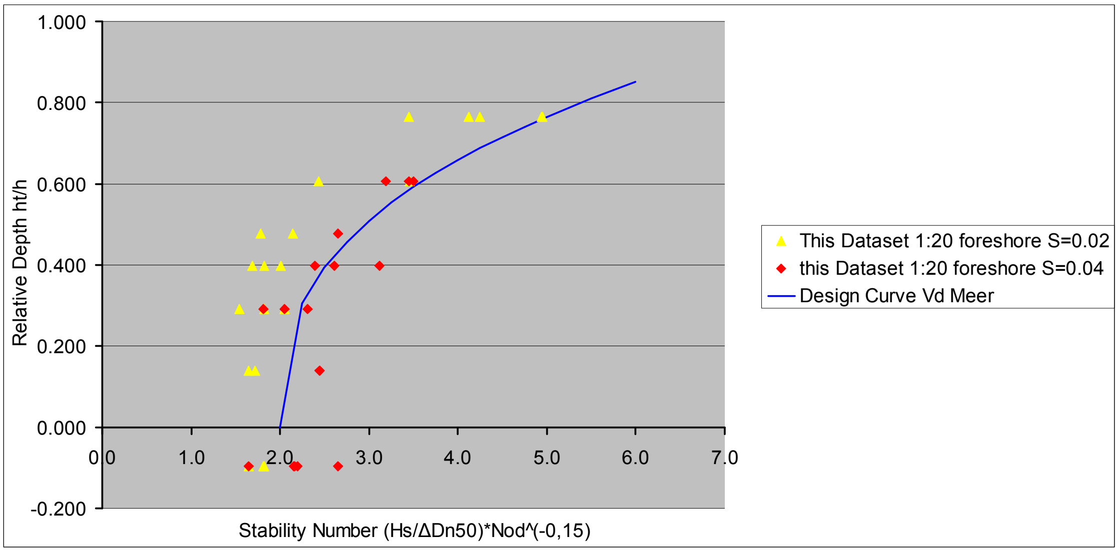


4-15 Graph toe stability according to Van der Meer with new data points N_{od}≤0.5

An envelope of the data for N_{od}<0.5 requires a more conservative design line. This uncertainty can be intercepted by choosing a more safe N_{od} value. Whether Van der Meer already included this uncertainty in his advised design value is not known.

Influence wave steepness

The test program contained two wave steepness. The variation in wave period was significant. The steep waves represented wind waves while the small steepness represented swell waves. It was concluded previously that steepness influences damage development of the toe. Figure 4-16 presents the data points for both wave steepness in different colours. It shows that waves with high steepness (shore waves) result in higher stability (less damage).

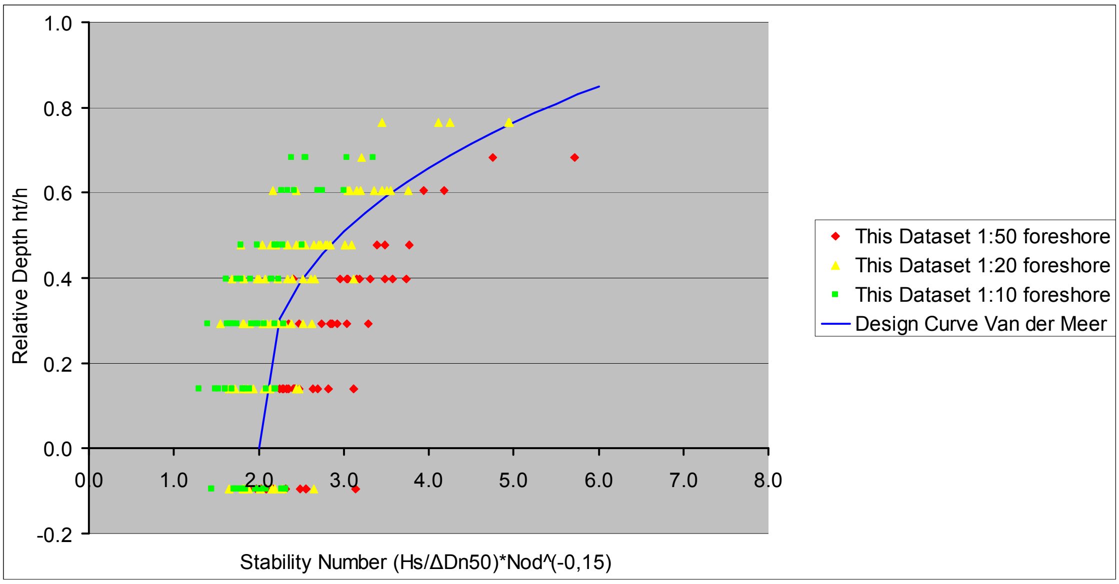


4-16 Graph toe stability according to Van der Meer with variations in wave steepness S_0

A correction for wave steepness seems preferable. The remarks made in this paragraph are considered in the continuation of this chapter. In paragraph 4.4 a entire analysis is done to toe stability very shallow water.

4.4. Research Question "Influence of fore shore slope to damage"

The second research question is answered in this paragraph. This is done by fully analyzing the obtained dataset. First start is made by plotting all data in the configuration as Van der Meer was used to. See figure 4-17.



4-17 Graph toe stability according to Van der Meer including different fore shore slopes α_{shore}

A clear difference is visible between the three fore shore slopes. The 1:50 slope caused smallest damage. Damage development increased for steeper slopes and was highest for a 1:10 slope. This plot confirms the expectation that fore shore slope influences toe stability.

The comparison with the Van der Meer analysis stops here and a analysis from a different point of view is done on the new dataset.

The main tests from the experiment are done in depth limited conditions, $h_t/h_m<0.4$. The water depth characterization "very shallow water", explained in paragraph 4.2.1, is valid for the tested conditions. The general limitation for very shallow water is $h_m/H_s \leq 2.0$. In this condition wave breaking appears at the fore shore and on the toe. This is the physical process behind this dataset. The conclusions that are derived from this analysis are valid for this hydrodynamical situation.

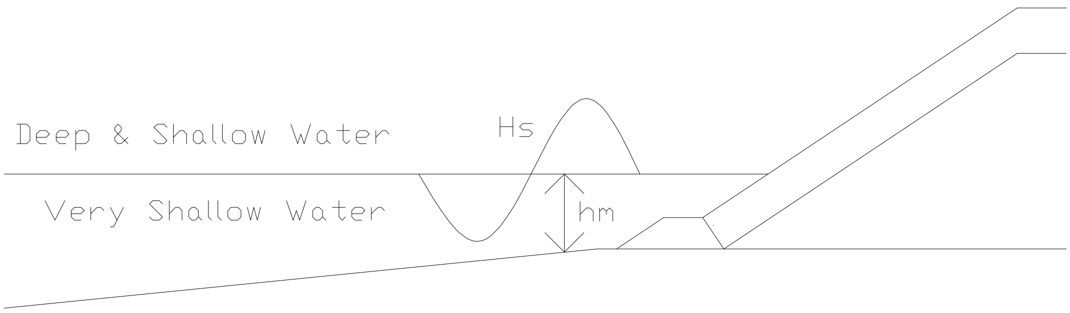
4.4.1. Data Analysis in very shallow water

The dataset is analyzed according to the general representation of damage development:

$$Damage = f\left(\frac{WaveLoad}{Strength}, Geometry\right) \qquad \textbf{(4-7)}$$

This representation is the basic thought for the analysis. The Hudson stability number is used to configure the wave load / strength relation, although this relation could not be fully confirmed in paragraph 4.2.5. Because of this, the strength is fixed in the analysis (D_{n50}=2.15 cm). The other parameters that are implemented are wave steepness, water level and fore shore slope.

This damage description is valid for $h_m/H_s<2.0$. This range of validity represents the area where wave breaking mainly takes place at fore shore and toe. The wave attack is characterized by breaking or already broken waves at the toe. The ratio is calculated with water depth before the toe and the significant wave height before the toe.

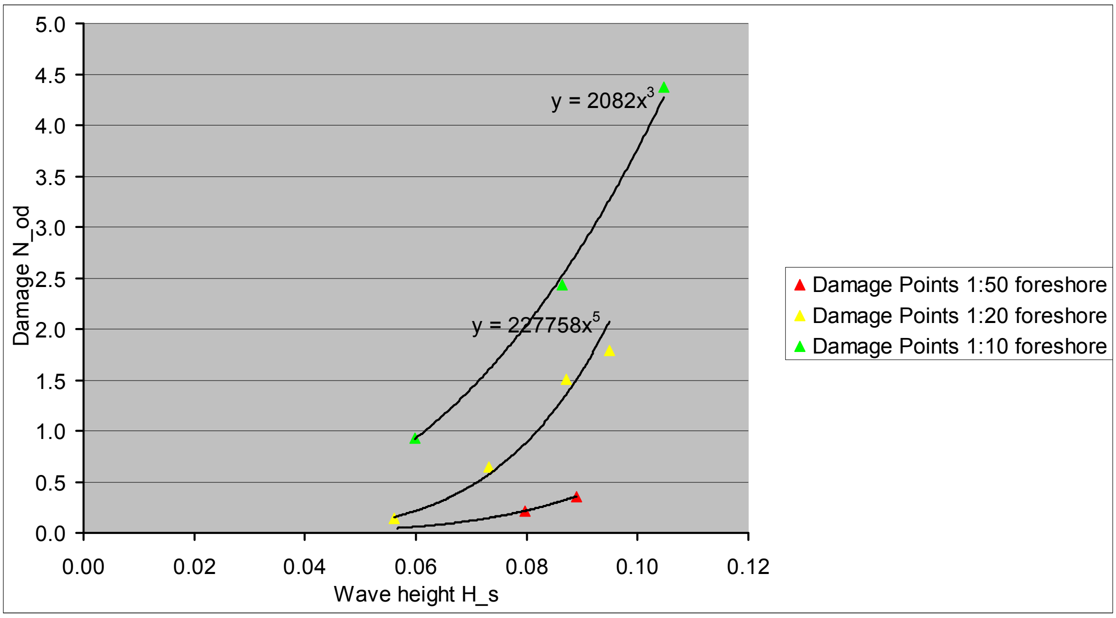


4-18 Water depth characterization for h_m/H_s for validity of stability formula

The figure shows a deviation between deep & shallow water and very shallow water. The first characterization is based on wave breaking at the breakwater slope. In this case, the slope of the breakwater is the significant slope parameter. The characterization of very shallow water is based on wave breaking at fore shore slope and toe. The slope of the fore shore is the significant parameter in wave breaking. In the rest of this report, the given slope is the fore shore slope and not the breakwater slope.

Wave height

When the stone size (2.15cm) is fixed, the wave height H_s is the only variable in the stability number $H_s/\Delta D_{n50}$ that influences damage N_{od}. This relation is expected to be power. Different configurations are compared and a representative figure is given below. The stone size, the water level above toe and the wave steepness are fixed.



4-19 Trend line for wave height to damage for S_0=0.02, D_{n50}=2.15cm & h_t=0.033m

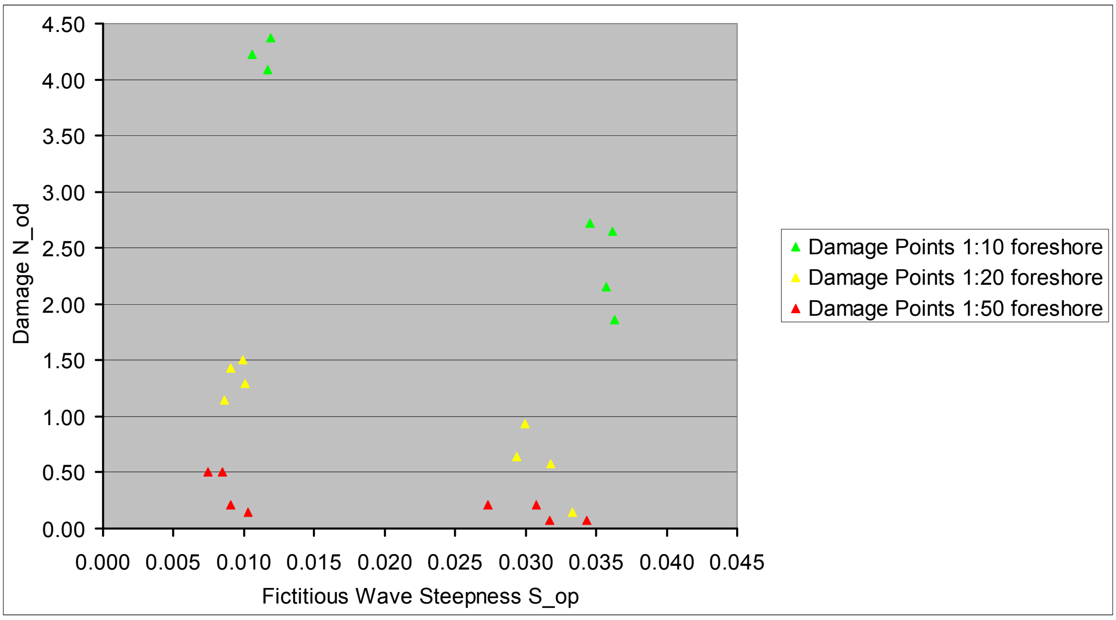
Three different lines are given, dividing the different fore shores. A power function is displaying the behaviour of wave height to damage in the best way. Damage growth is concluded to be more than linear. The curve should start at a certain value of H_s. It is expected that a certain wave height is needed to cause initial damage. On the other side of the curve, damage is not endless. There is a certain range of validity for H_s. This range is a ratio of wave height and strength of the toe material.

A remark is made to the damage development of rock for a 1:10 fore shore. Damage developed for a 1:10 fore shore was highest in comparison with other fore shores and reached its maximum. Therefore, damage development stagnated for large H_s as the toe profile was already reshaped. Damage for the 1:50 fore shore was smaller and therefore the damage development behaves different as well.

The power functions for different configurations have quite some variance between power 2 and power 5. $N_{od} = B * H_s^{\ 4}$ is on average the best fit. This power is an approach for the behaviour of H_s to N_{od}. The Hudson formula for stone stability uses a power 3 while Van der Meer uses a power 5 for his armour stability equation and a power 6.5 for toe stability equation.

Wave period (wave steepness)

The influence of the wave period is given in terms of wave steepness. Wave steepness is dimensionless and therefore easy to use. The influence of wave steepness is confirmed in paragraph 4.2.2. This influence was larger than expected beforehand. Only two different wave steepness are tested and therefore it is difficult to reveal the behaviour of wave steepness in relation to damage. Figure 4-20 shows the correlation between wave steepness S_{op} and damage N_{od}. In this case the water level is not fixed but wave height is fixed.



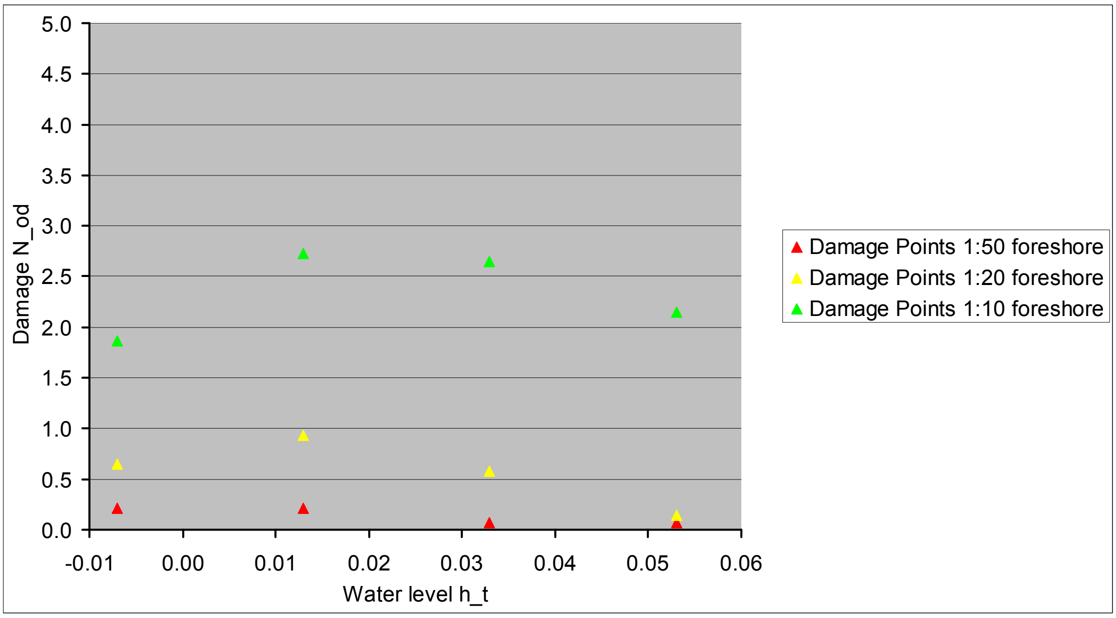
4-20 Graph for wave steepness to damage for ht=-0.007-0.053m, D_{n50}=2.15cm and Hs=0.10m

The concentrated four points present each a different water level. The concentration of 4 points shows that the water level is not really influencing the damage development in relation to wave steepness. The wave period is a parameter to be considered in stability formula. The relation has a negative derivative but how the relation develops can not be seen from limited variations in wave steepness. It can be linear but could be an inverse function or an inverse power function as well.

The armour stability formulas from Van der Meer and Van Gent consider wave steepness in their formulas and present wave steepness as an inverse power function.

Water level

The water level is a geometrical parameter. In formulation, the water level is made dimensionless as dimensionless parameters are needed in a regression analysis. Figure 4-20 from previous paragraph already proves that in very shallow water, water level is not of much influence to damage development. Each one of the four concentrated points stands for a different water level. Unless this difference, they have similar damage.



4-21 Relation water level and damage for S_0=0.04, D_{n50}=2.15cm & H_s=0.10m

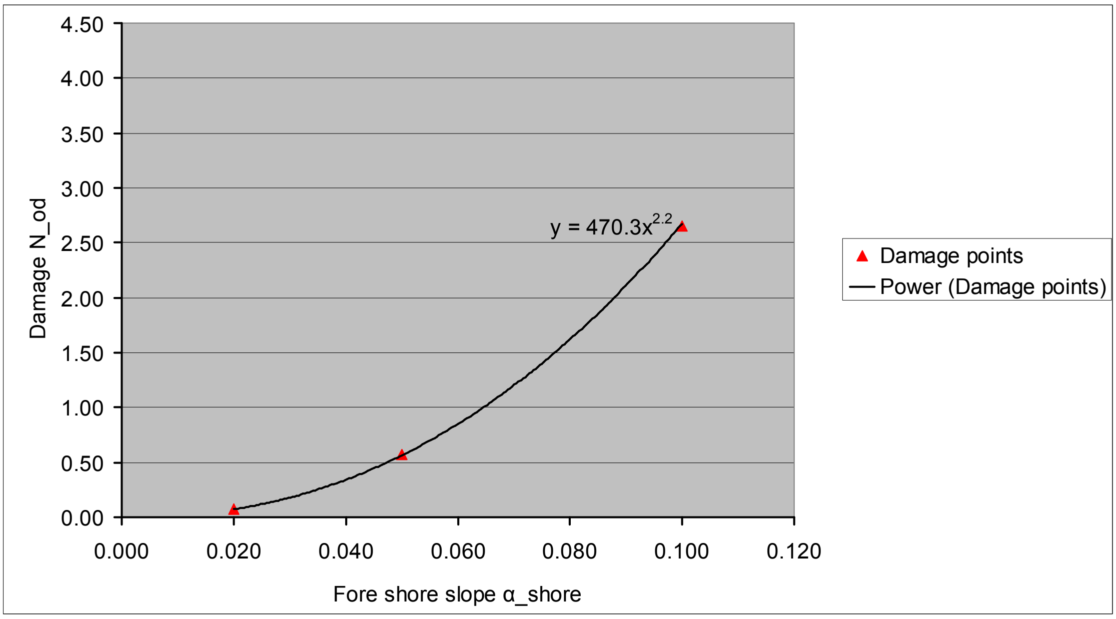
Figure 4-21 shows this even more clear. The differences can be explained as well. As the water level decreases, damage increases as the toe gets more exposed. At a certain water level, the wave has already most of its energy when it reaches the toe, so damage decreases. This effect is relatively small in comparison with the other parameters and is ignored in formulation. Note that this is only valid for very shallow water, $h_t/h_m<0.4$ or expressed differently $h_m/H_s<2.0$.

Fore shore slope

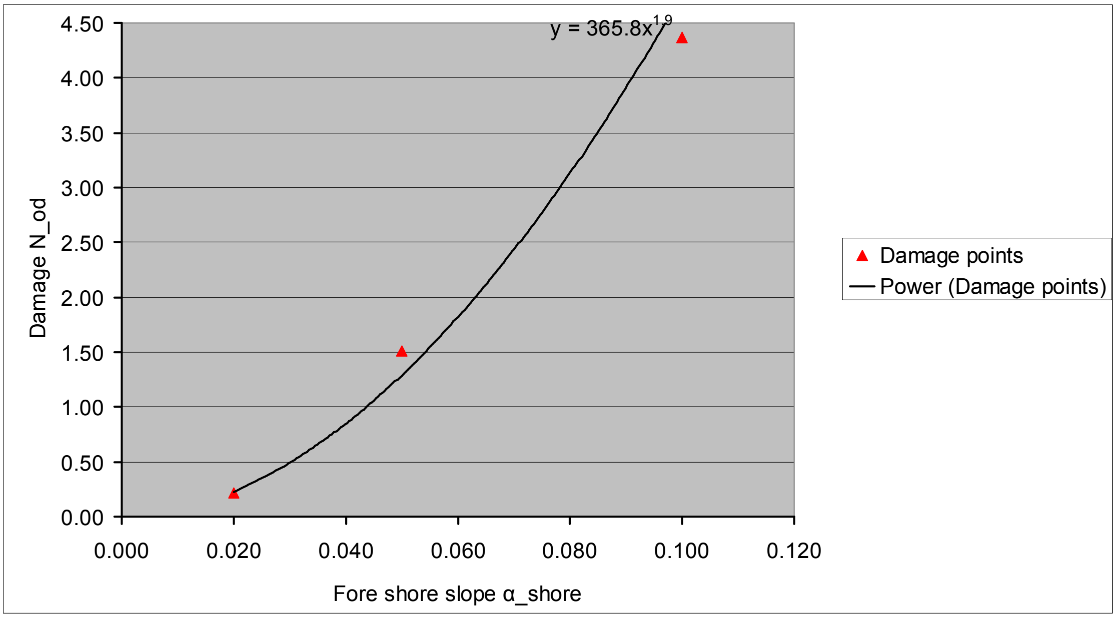
The effect on toe stability by a change in fore shore slope was not known before the experiment. There is a difference in damage development for three fore shore slopes. Damage for the 1:50 slope was very small even though the smallest two stone sizes were used. The damage for the 1:20 slope was much bigger even though the largest two stone sizes were used. Damage for the 1:10 turned so large that the test program could not be completely finished.

The deviation in damage did not only happen for shallow water conditions. The calibration tests, done in deep water, show a significant difference because of fore shore variations as well. Figure 4-22 and 4-23 give the development of damage by fore shore slope α_{shore} for short and long waves. The wave steepness, stone diameter, wave height and water level are fixed to be able to display the relation between slope and damage.

It is expected that still some damage will occur when the fore shore slope is zero. In this scenario, the damage curve starts at the vertical axis. When very steep fore shores are considered, similar to the breakwater slope, the damage should go to two. This is the N_{od} value for h_t/h_m=0 in the toe stability equation from Van der Meer. Below figures give an power trend for damage development. This trend has a range of validity.



4-22 Relation between slope and damage for S_0= 0.04, D_{n50}=2.15cm, H_s=0.10m & h_t=0.033m

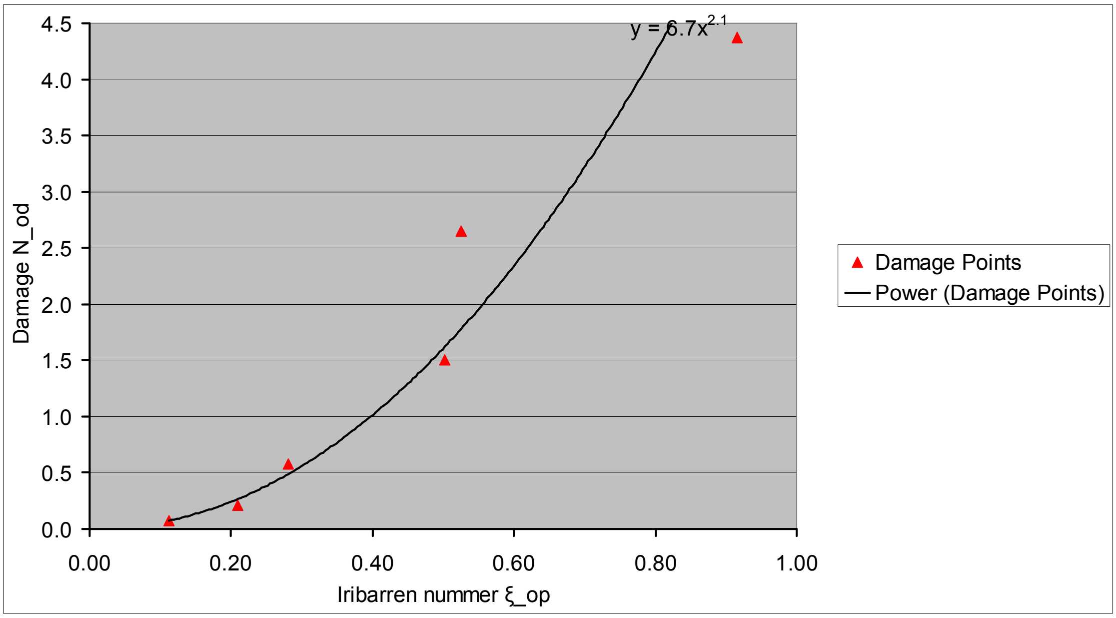


4-23 Relation between slope and damage for S_0= 0.02, D_{n50}=2.15cm, H_s=0.10m & h_t=0.033m

The damage grows as a power for steeper slopes. A power function 2 corresponds with the trend from the figures. This is derived from different configurations for S_o, H_s and h_t. A square of the foreshore is a general approach for the behaviour of damage.

4.4.2. Proposed toe stability equation

Because the behaviour of wave steepness to damage can not be determined, this relation is given by the Iribarren number: $\xi_{op} = \tan\alpha / \sqrt{H/L_0}$. Wave steepness is related to fore shore slope with an inverse square root. Figure 4-24 shows the Iribarren number against damage for the same data points used in figure 4-22 and 4-23.



4-24 Graph between Iribarren number and damage for D_{n50}=2.15cm, H_s=0.10m & h_t=0.033m

This figure gives a rather good display of relating fore shore slope and wave steepness to damage. The figure has the same range of validity as figure 4-22 and 4-23. It is surprising that the Iribarren number is capable of relating fore shore slope and wave steepness in a correct way to damage.

Iribarren is used to characterize different breaker types but in this case it seems that is also relates damage in a correct way. The Iribarren parameter helps to define damage in an area where different kinds of wave attack occurred at the toe. Breaking waves appeared as spilling, plunging and collapsing. Already broken waves appeared as turbulent propagating water mass. In exposed situation, these waves did not look like a wave anymore but more like a volume of water rushing over the stones. Unless these differences in wave attack, the Iribarren number can be used properly to predict damage.

The stability number and the Iribarren number are combined to describe damage. When these two parameters a used in stability formula, all necessary parameters are included in the design equation. The mathematical relations found are:

$$N_{od} = B \cdot \left(H_s / \Delta D_{n50}\right)^4 \quad \textbf{(4-8)}$$

$$N_{od} = B \cdot \alpha_{shore}{}^2 \quad \textbf{(4-9)}$$

$$N_{od} = B \cdot \left(\frac{\alpha_{shore}}{\sqrt{S_{op}}} \right)^2 = B \cdot \xi_{op}^{\ 2} \qquad \textbf{(4-10)}$$

It is determined that steepness has influence and relates to damage according to the Iribarren number. Below, some mathematical steps are presented. They go step by step from general formulation to a formulation, in which every thing is brought between brackets. This is done to plot the equation in an orderly way.

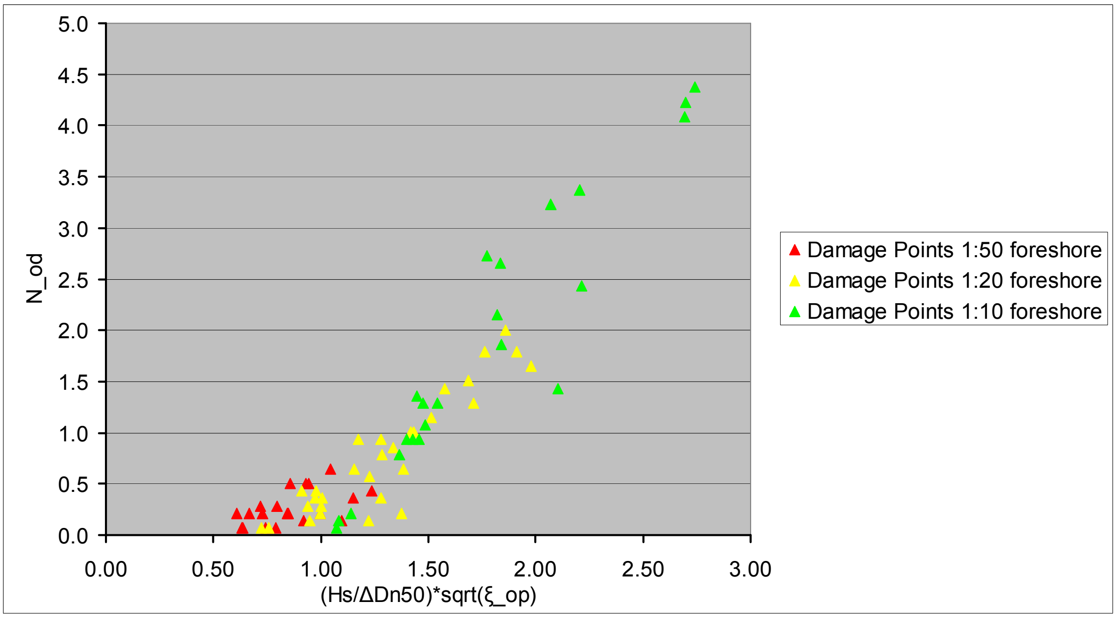
$$Damage = f\left(\frac{WaveLoad}{Strength}, (Geometry) \right) \qquad \textbf{(4-11)}$$

$$N_{od} = C_{bw} \cdot \left(\frac{H_s}{\Delta D_{n50}} \right)^4 \cdot \left(\frac{\alpha_{shore}}{\sqrt{S_{op}}} \right)^2 \qquad \textbf{(4-12)}$$

$$N_{od} = C_{bw} \cdot \left(\frac{H_s}{\Delta D_{n50}} \right)^4 \cdot \xi_{op}^{\ 2} \qquad \textbf{(4-13)}$$

$$N_{od} = C_{bw} \cdot \left(\frac{H_s}{\Delta D_{n50}} \cdot \sqrt{\xi_{op}} \right)^4 \qquad \textbf{(4-14)}$$

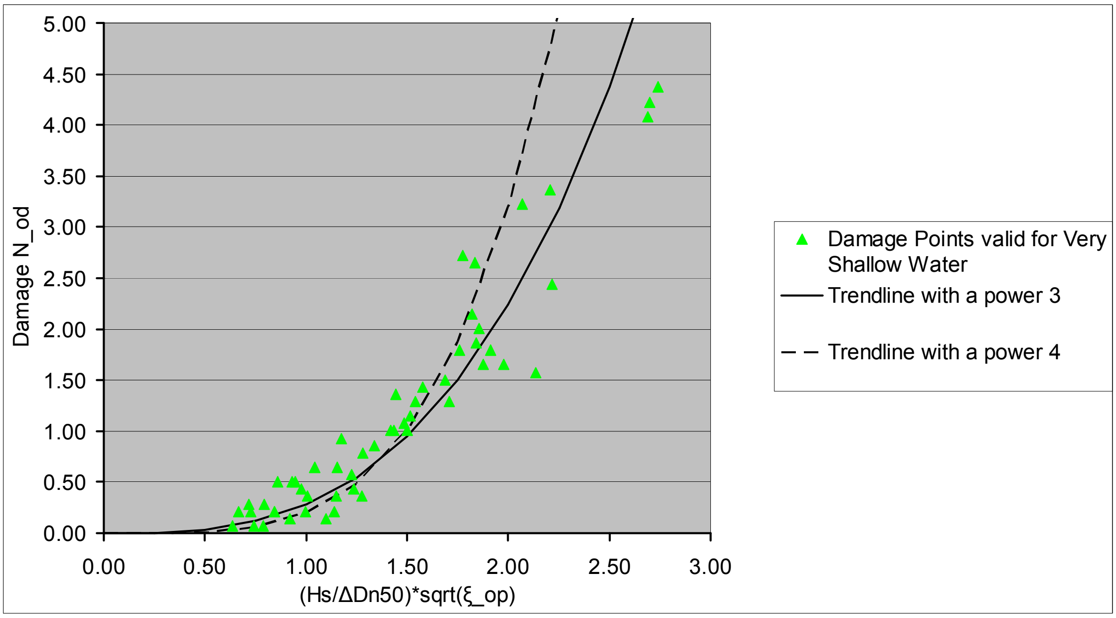
Equation 4-14 is the total solution. This equation is the result of the relation between H_s & S_{op}, α_{shore} and result N_{od}. Strength parameters D_{n50} and Δ are included but are not proved.



4-25 Relation design formula to damage for D_{n50}=2.15cm & h_t/h_m<0.4

It is concluded that the design curve has to start in the origin of the graph. When $\frac{H_s}{\Delta D_{n50}}\sqrt{\xi_{op}}$ is smaller than 0.5, no data points are found. This is the case because no tests with real small wave heights are done. The design curve should give values for D_{n50} for small values of H_s as well.

Figure 4-25 is the final solution for toe stability in very shallow water for given restrictions. A separation in data points is still made for different fore shore slopes. The three data clouds are overlapping but still separated from each other. From this is seen that the different ranges of N_{od} are found for the three fore shores. It is expected that the data cloud behaves as a power function 4 as is derived from the individual influences. This power function is tried to be found in figure 4-26.



4-26 Relation design equation to damage with trend line for D_{n50}=2.15cm & h_t/h_m<0.4

The trend line derived from the data cloud (continuous) gives a power 3:

$$N_{od} = B * \left(\frac{H_s}{\Delta D_{n50}} \sqrt{\xi_{op}} \right)^3 \qquad \textbf{(4-15)}$$

The line with a power 4 (dashed) is also given. This line gives more conservative stone size for large damage values while the stone size for small damage values is less conservative in comparison with the trend line.

The data cloud still contains some variation. Especially in the lower parts (N_{od}<0.5), the plot gives quite some variation. In this region, the design curve should give a correct display as the design value for N_{od}. The trend line with power 3 gives a good trend from visual point of view. The acceptable uncertainty can be decreased by changing constant B.

The largest outfield data points are plotted on the right side. These points have a rather high stability number but relatively lower damage. The data on the left side of the cloud have a smooth curving character.

Another way of presenting the design curve is by giving an envelope of the data. When a design wave height and wave period is considered which stands for a particular design storm, the chance of probability is enclosed in these parameters. The design curve for toe material should be a 100%

sure design line in this case. This can lead to too conservative design.

Influence ΔD_{n50} in design equation as a result of N_{od} and $N_{\%}$

The relation of ΔD_{n50} in the stability number is not confirmed in paragraph 4.2.5. The different damage classification, in terms of $N_{\%}$ can partly solve this spread. A comparison is made between N_{od} and $N_{\%}$.. For completeness both calculation methods are given again:

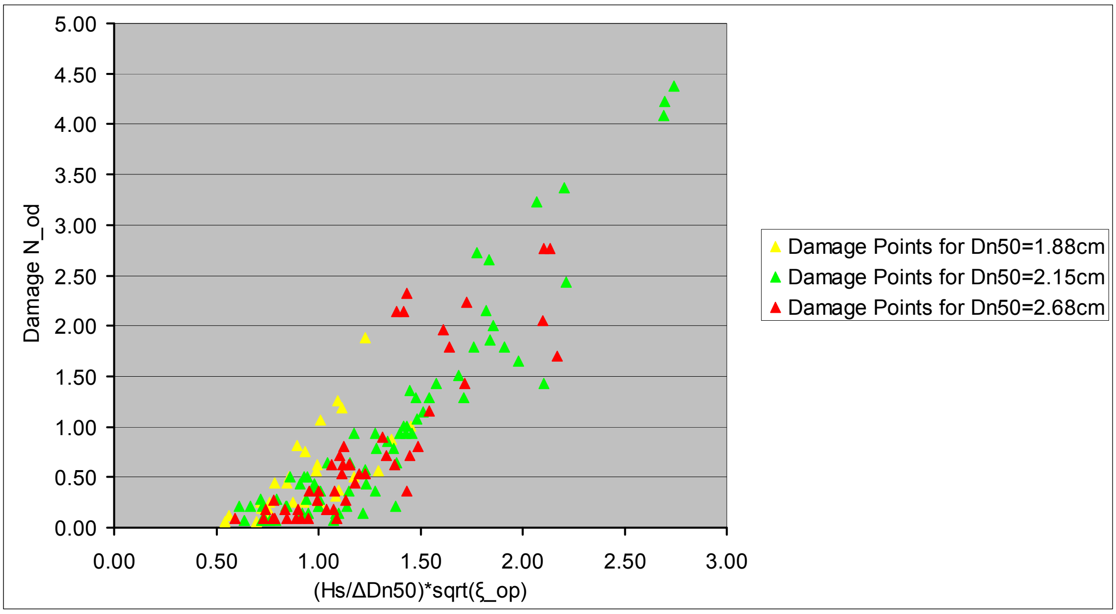
$$N_{od} = \frac{N}{B/D_{n50}} \qquad \textbf{(4-16)}$$

$$N_{\%} = 100 \cdot N \cdot \frac{(D_{n50})^3}{(1-n)V_{tot}} \qquad \textbf{(4-17)}$$

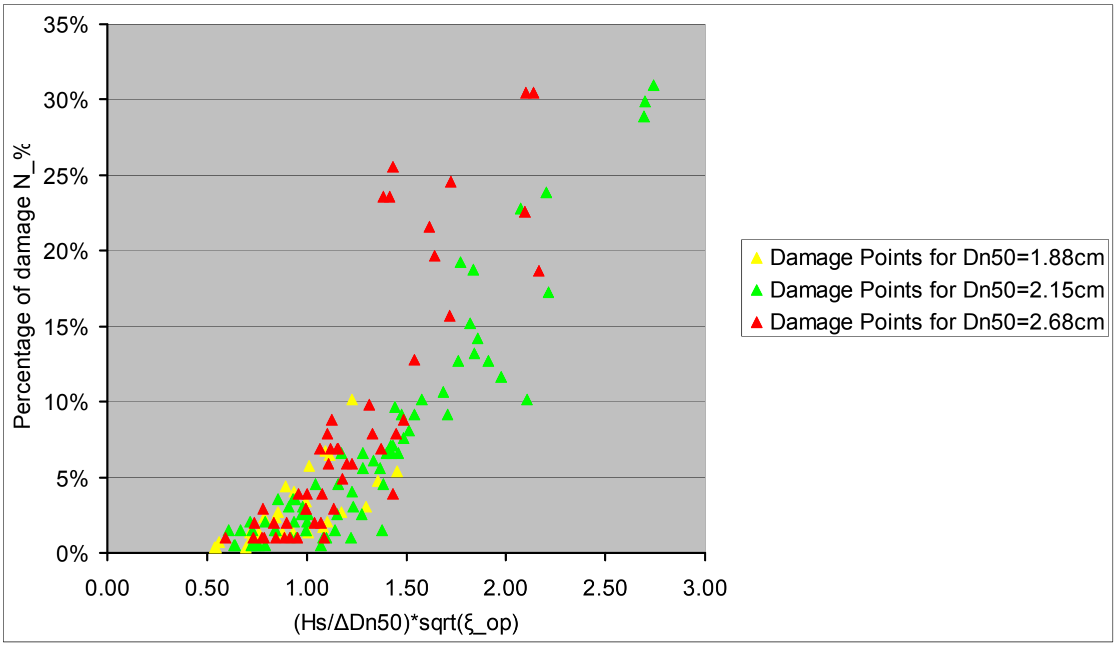
The analysis, presented in previous paragraph, is done for a description of damage in N_{od}. This analysis is also valid for damage classification in percentages as the stone diameter is fixed and both classifications behave similar for fixed stone diameter. Thus, similar trends are found.

In paragraph 4.2.4 is already concluded that the percentage of damage shows a better relation with observed damage than N_{od}. This is the main reason to use $N_{\%}$ instead of N_{od}. Both damage classifications are compared for the stability equation in very shallow water.

Both damage classifications are given in following figures. All stone sizes, used in the experiments, are given. A distinction in colour is made for each stone size.



4-27 Relation design equation to damage N_{od} for all stone sizes for h_t/h_m<0.4

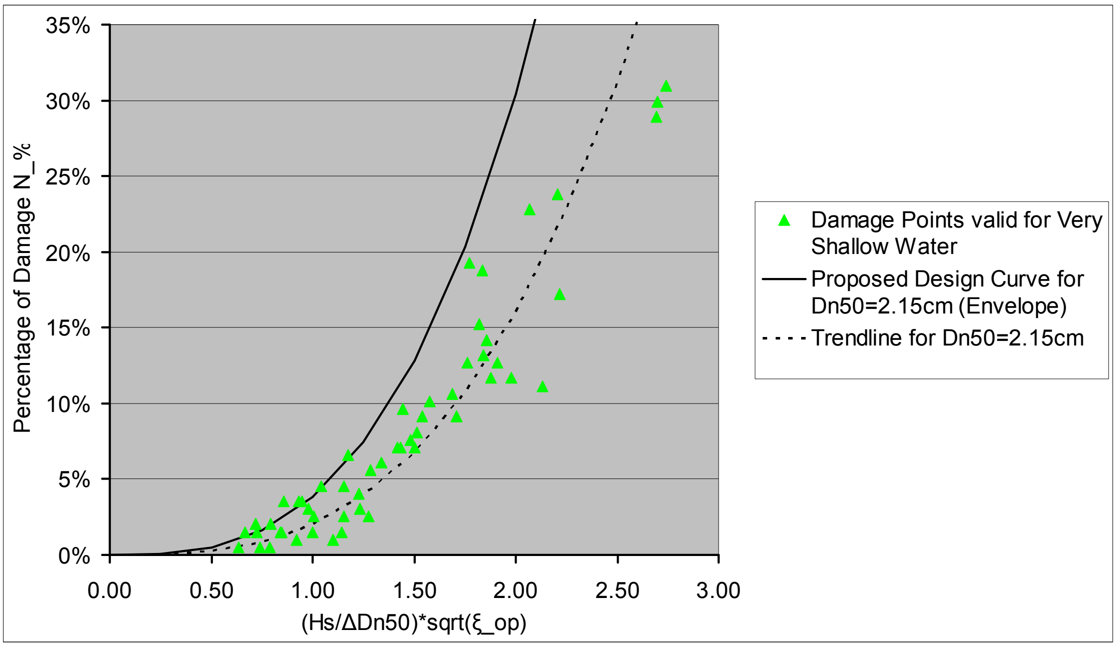


4-28 Relation design equation to damage $N_{\%}$ for all stone sizes for h_t/h_m<0.4

Figure 4-27 is expressed in N_{od}. This plot shows variation over the whole length of the curve. In Figure 4-28, a similar profile is found, it shows most of its variation in the area for large damage. In this zone, the data for D_{n50}=2.15 & 2.68cm do not fit nice anymore. The different stone sizes follow the same curve in the area for $N_{\%}$ < 10%.

Formulation of design equation

The final formulation is for toe stability in very shallow water. It is based on the data for D_{n50}=0.0215m and is derived as a function for the percentage of damage. Figure 4-29 shows the final presentation of the dataset. The dashed line through the middle of the data points is the trend line of the data points. This trend line is already given in figure 4-26. The long continuous line is the envelope of the data cloud that represents 100% safe design for data points with D_{n50}=2.15cm.



4-29 Design curve for toe stability in very shallow water for D_{n50}=2.15cm for h_t/h_m<0.4

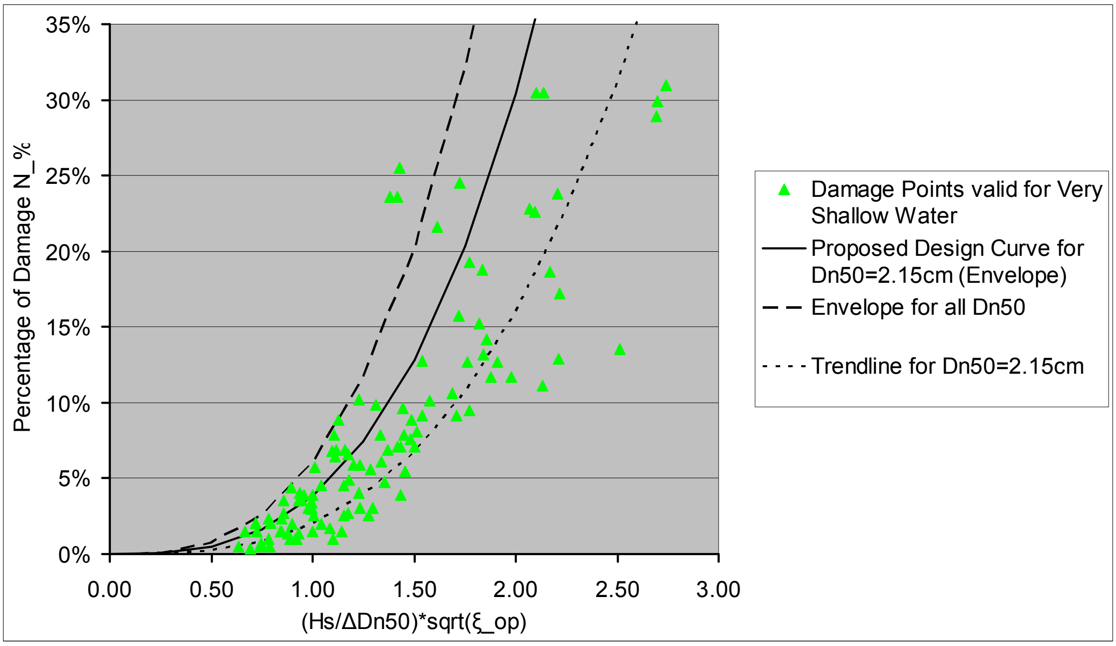
The trend line is (4-18) and the envelope is function (4-19):

$$N_{\%} = 0.02 * \left(\frac{H_s}{\Delta D_{n50}} \sqrt{\xi_{op}} \right)^3 \qquad \textbf{(4-18)}$$

$$N_{\%} = 0.038 * \left(\frac{H_s}{\Delta D_{n50}} \sqrt{\xi_{op}} \right)^3 \qquad \textbf{(4-19)}$$

The power is derived from the trend line and is from visual point of view a correct display. The dashed line on the left is a 100% design curve and is the envelope of the data cloud.

When the data for all stone sizes are implemented, more variation is visible.



4-30 Design curve for toe stability in very shallow water for all stone sizes for $h_t/h_m<0.4$

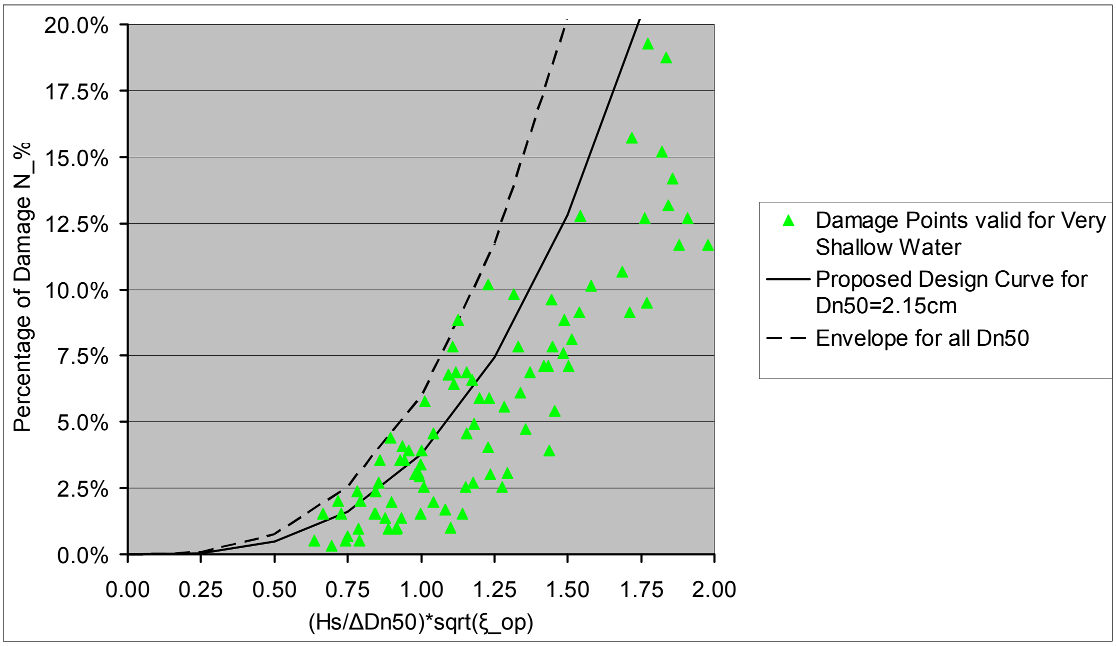
The continuous line, following from figure 4-29, gives a curve with some uncertainty. A new envelope is given for all data points. This is the 100% safe design curve for the data until $N_{\%}$ =10%. This conservative design equation is $N_{\%} = 0.06 * \left(\frac{H_s}{\Delta D_{n50}} \sqrt{\xi_{op}} \right)^3$.

However this envelope is considered too conservative. Some uncertainty is accepted. An estimate of the uncertainty is made by counting the number of data points on each side of the design curve and taking the distance from each data point into account as well. A design curve is tried to be found with 10% uncertainty on the risky side of the curve. The continuous line has 10% of its uncertainty on the risky side and is proposed as design curve for this dataset.

Equation (4-20) is the rewritten version of the proposed design equation (4-19) for toe stability in very shallow water. The Iribarren number is calculated with near shore significant wave height and deep water wave length:

$$\frac{H_s}{\Delta D_{n50}} = 3.0 \cdot \frac{N_{\%}^{1/3}}{\sqrt{\xi_{op}}} \qquad \textbf{(4-20)}$$

The accompanying design graph is given in figure 4-31.



4-31 Proposed design equation for toe stability in very shallow water for h_m/H_s<2.0

Design values for very shallow water are given for $N_{\%}$ in paragraph 4.2.4. For long waves $N_{\%}$=5% and for short waves $N_{\%}$=10% is advised. The figure, for $N_{\%}$, gives a denser data cloud in the lower area, which makes it reliable for design. The main argument to use the percentage of damage is the improved physical character of the damage classification. The percentage of damage is used for the final formulation of the design equation. A range of validity is given for the design equation. The table below gives the range of parameters for which the experiments are executed. The design equation is validated for this range.

Parameter:	Symbol:	Range:
Damage level	$N_{\%}$	< 0.3
Fore shore angle	$\tan(\alpha_{shore})$	1:50 - 1:10
Fictitious wave steepness	S_{op}	0.008 - 0.04
Iribarren number using T_p	ξ_{op}	0.3 - 0.9
Relative water depth in front of toe	$H_m/H_{s\text{-}m}$	< 2.0
Stability number	$H_s/\Delta D_{n50}$	1.5 - 3.5
Toe material gradation	D_{85}/D_{15}	< 2.0

5. Conclusions & Recommendations

5.1. Conclusions

Theory:

- The Van der Meer equation for toe stability (1998) is correct for h_t/h_m<0.4 as it is validated with new scale model tests. There was difference in the experimental settings, but both data clouds for a 1:20 shore show the trend in the Van der Meer configuration.

- A difference in hydrodynamics is observed for very shallow water. The difference is characterized by wave breaking on fore shore slope instead of breaking on the breakwater slope.

- Wave breaking, observed on the fore shore slope, behaved according to the Iribarren number. Therefore ξ_{op} turned out to be a good measure of describing the breaker types.

- From this experiment, scaling of different stone sizes according to the stability number ($H_s/\Delta D_{n50}$) is confirmed. The correlation is not exactly right but fulfils within its range.

Toe Stability:

- Fore shore slope has influence on toe stability. This influence is significant and should be included in stability formulation. This influence is noticed in both very shallow water but in deep water as well.

- Wave steepness is influencing damage development of the toe. The behaviour is noticed for very shallow water. This influence seemed smaller in deeper water, but not enough tests are executed to make conclusions.

- The influence of water level variations on damage development is an interaction of exposedness of the toe, breaking of waves and a reduced wave height due to breaking. This interaction leads to a situation where maximum damage occurs. Exposed situations made the toe vulnerable to damage. In very shallow water, the water level is concluded to be of minor influence to toe stability formulation. .

Wave Behaviour:

- Long waves, representing swell waves, cause different damage of toe rock than short waves do. Both waves cause downward moving rock but long waves also pushed the stones in upward direction.

- Long waves in very shallow water behaved like a bore of water in shallow water. As the water retreats from the breakwater structure, the new wave approaches the exposed toe and hits the toe structure with a volume of water. This hydro dynamical system was able to take toe rock with the wave and smash it on the armour layer.

- In very shallow water, the hydrodynamics change from wave breaking at the armour slope to breaking at the fore shore slope or toe. This shift of wave breaking from armour slope to fore shore slope occurs for ($h_m/H_s<2.0$). There is some variation due to the irregular wave pattern.

General:

- The percentage of damage $N_{\%}$ leads to be a better way of describing damage than damage N_{od}. The percentage of damage has physical background and therefore better understood by designers. Besides that, $N_{\%}$ gives smaller scatter in the proposed stability equation than N_{od} gives.

- Cumulative damage in scale model testing is concluded a good way of damage recording. The test program shows more resemblance with damage in prototype. A remark is made that only one parameter a time should be varied for a sequence tests with cumulative damage.

- Describing damage of toe rock due to breaking waves in terms of wave energy dissipation helps to explain the increase in damage development in a breaking wave climate.

Design Equation:

- A design equation for toe material in very shallow water is proposed:

$$\frac{H_s}{\Delta D_{n50}} = 3.0 \cdot \frac{N_{\%}^{1/3}}{\sqrt{\xi_{op}}}$$

The equation can be used for $h_m/H_s<2.0$.

Proposed design values are given for toe design for interlocking armour units:

$N_{\%}$= 5% for swell waves (S_{op}=0.01)

$N_{\%}$= 10% for wind waves (S_{op}=0.035)

Design conditions for swell waves are stricter because of upward moving rock.

5.2. Recommendations

The stability number $H_s/\Delta D_{n50}$ was not capable of relating the different stone sizes. Differences were found in the data analysis. More research is advised to relate wave load to strength in a correct way:

- Strength of the rock is not given correctly in this number. Smaller stones develop more damage for the same increase in wave height. The diameter is probably not the only parameter that describes strength. The shape of the rock is an important parameter as well.
- Besides researching the strength part, it should help to implement wave period in the wave load. Wave period is concluded just as important in damage development as wave height in this research.

The influence of wave steepness is noticed in toe stability. The test program did not contain enough variability in wave steepness to investigate its behaviour. Therefore it is related to fore shore steepness with the help of the Iribarren number. Extra study is necessary to investigate the behaviour of wave steepness.

The influence of fore shore slope and wave steepness is noticed in shallow and deep water. Both parameters are included in the formula for very shallow water. They are advised to be implemented in toe stability equations for shallow and deep water as well. The proposed stability equation is not valid for these regions.

Reflection is expected to have influence on toe stability. The amount of reflection is highly influenced by the amount of permeability of the breakwater structure. Extra research to this influence is advised as well.

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Appendix A Specifications Toe Material

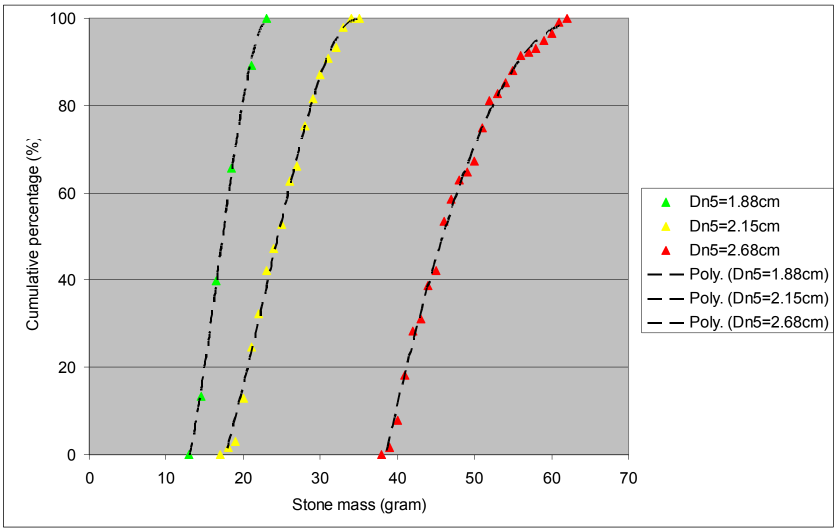
Three different stone sizes of toe material are used. The qualifications of the rock determine in a high rate the behaviour of the rock. Therefore the qualifications are given in this appendix.

The rock size resembles 70%, 80% and 100% of the design stone size for a 10cm wave height, according to the Van der Meer (1998) design approach. The table gives the quantifications per stone size. All available information about the specifications of the rock is given in this table. The accompanying pictures and tables are given below.

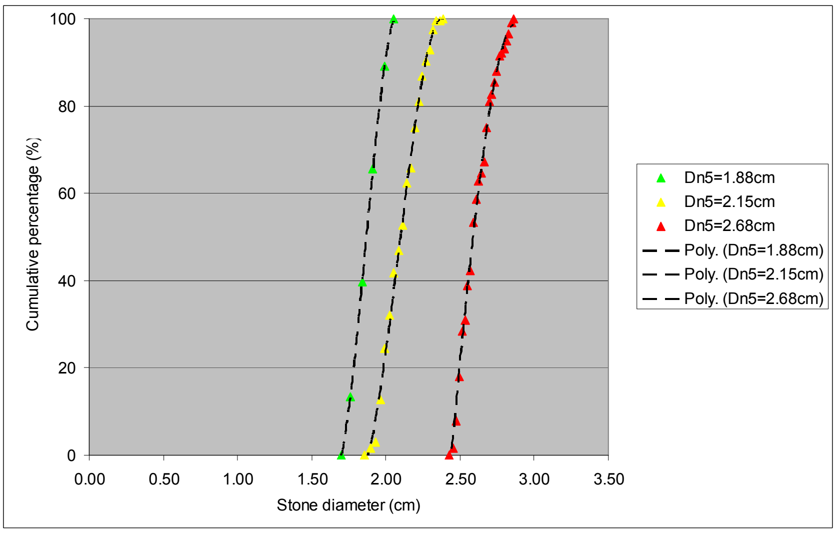
D_{n50} (nominal rock density)	(m)	0.0188	0.0215	0.0268
ρ (density of rock)	(kg/m^3)	2650	2700	2750
Blc (Blockiness)	(-)	50%	55%	60%
D_{85}/D_{15} (grade)	(-)	1.5	1.5	1.5
n (rock porosity)	(-)	0.36	0.33	0.32
ρ_{rock} (packing density)	(-)	0.64	0.67	0.68
N_o (Number of stones in toe)	(-)	300	190	105
N (layer thickness)	(-)	$^{+}/_{-}$ 4	$^{+}/_{-}$ 3	$^{+}/_{-}$ 2

A 1 Impression of toe from left side

A 2 Impression of toe from right side

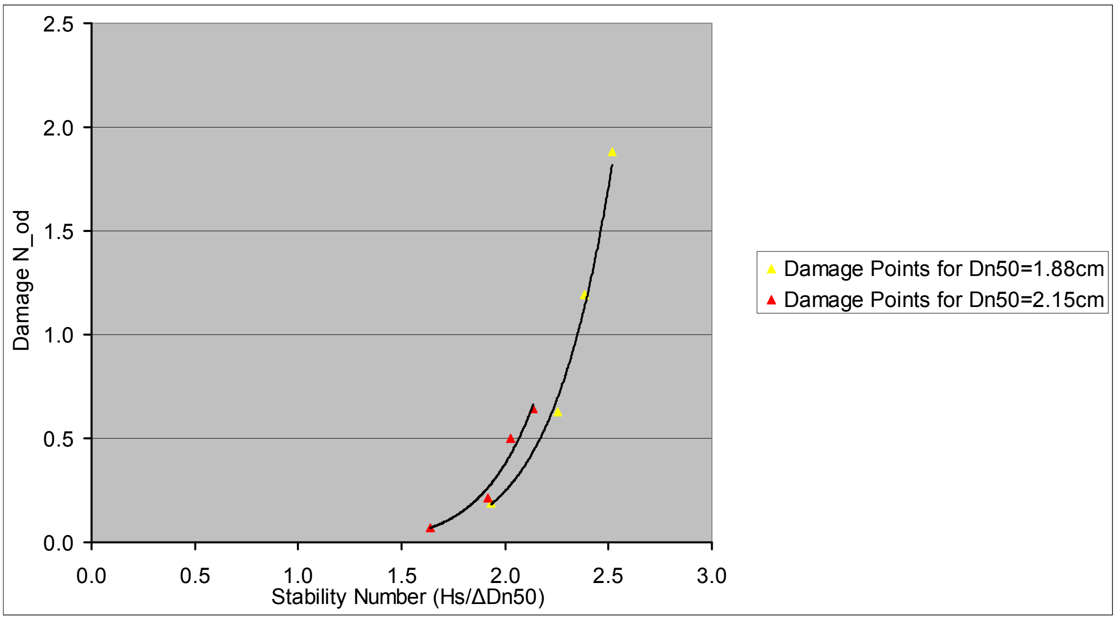


A 3 Sieve curves of three stone fractions, mass on horizontal axis

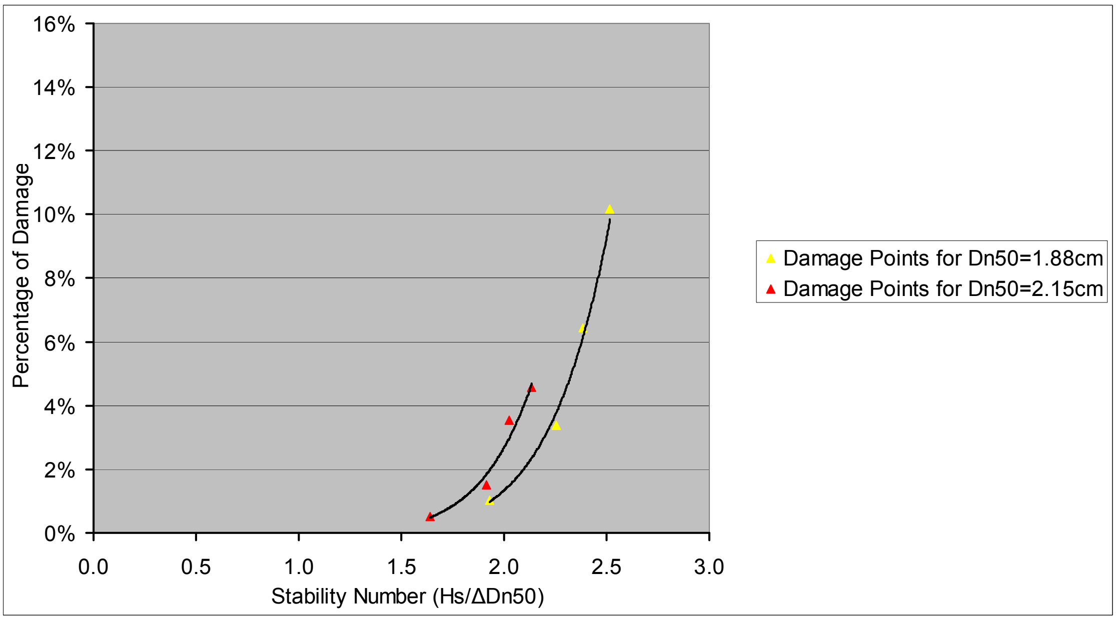


A 4 Sieve curves of three stone fractions, nominal diameter on horizontal axis

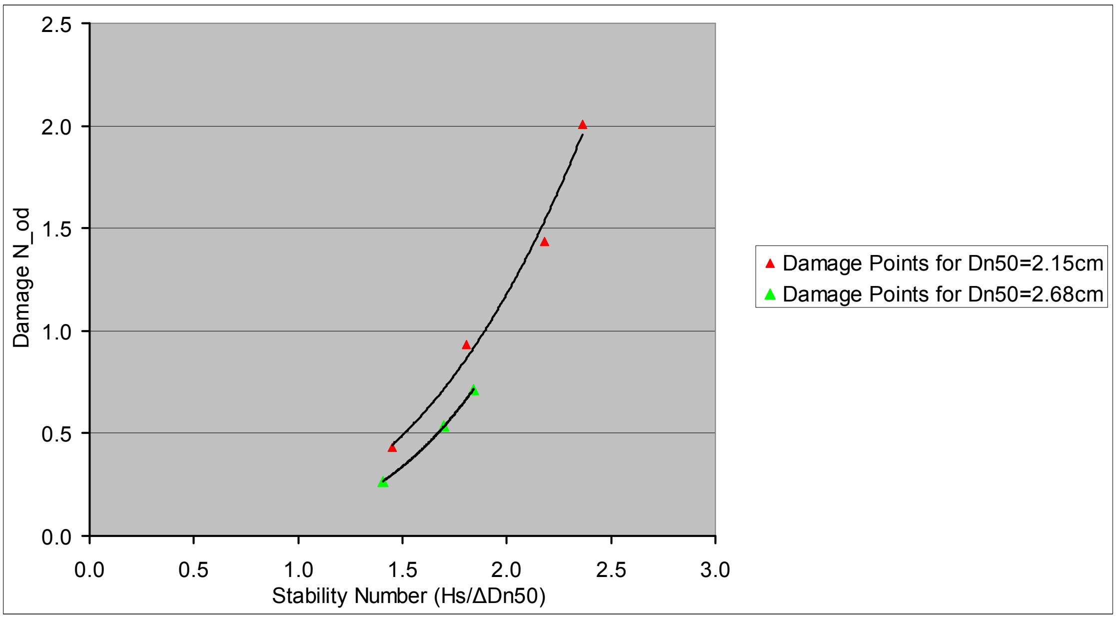
Appendix B Attached figures paragraph 4.2.5



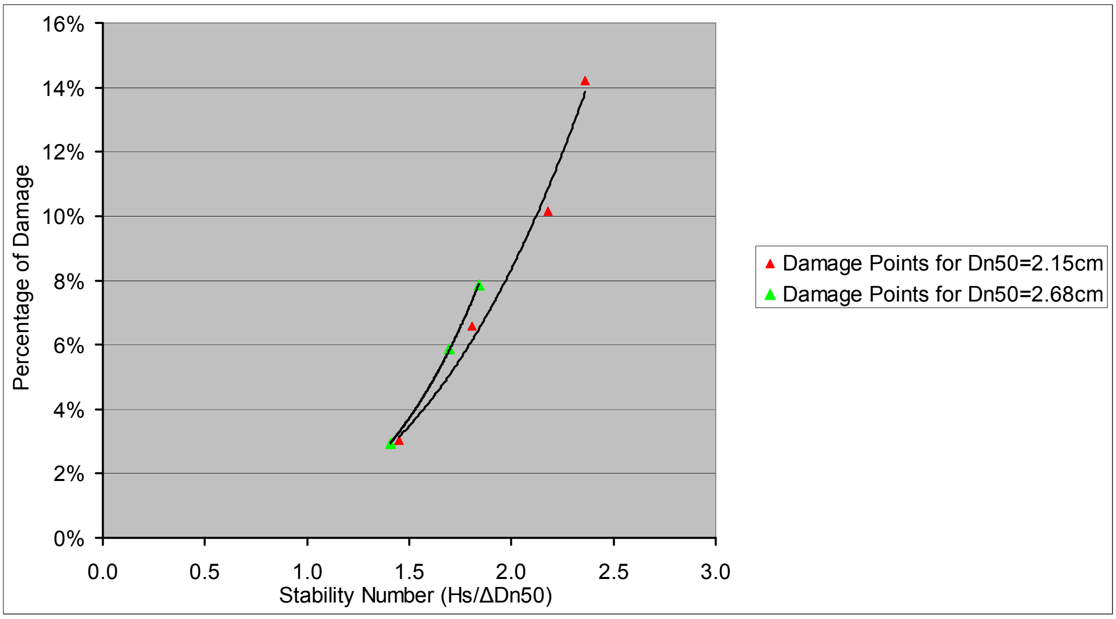
B 1 Stability number to damage N_{od} for a_{shore}=1:50, h_t=0.013m & S_0=0.02



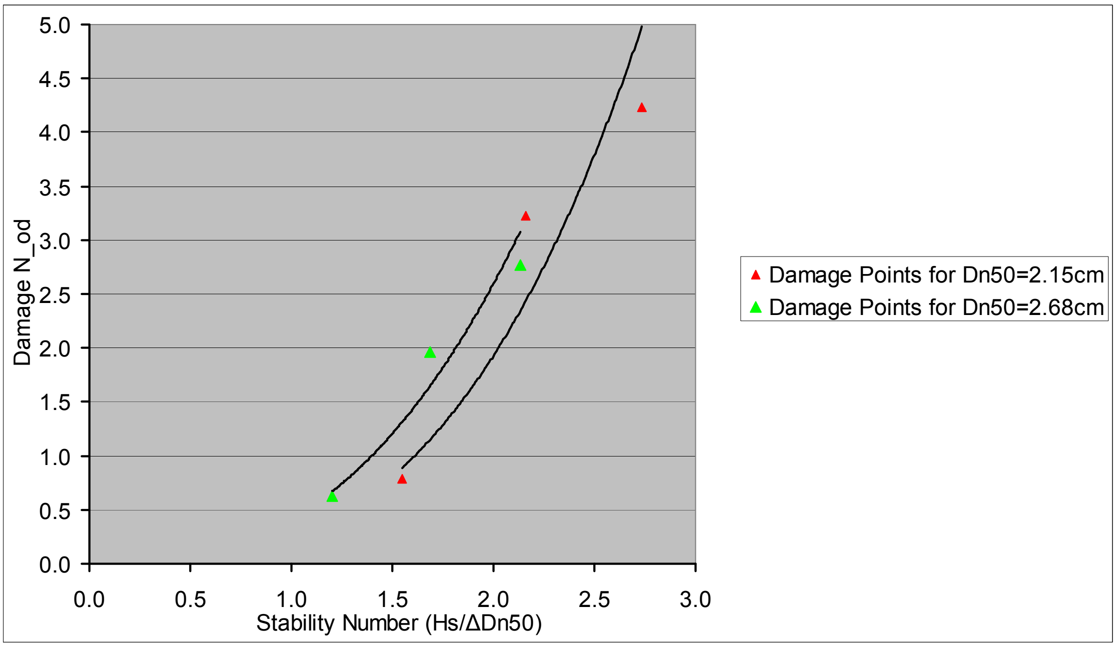
B 2 Stability number to percentage damage for, a_{shore}=1:50, h_t=0.013m & S_0=0.02



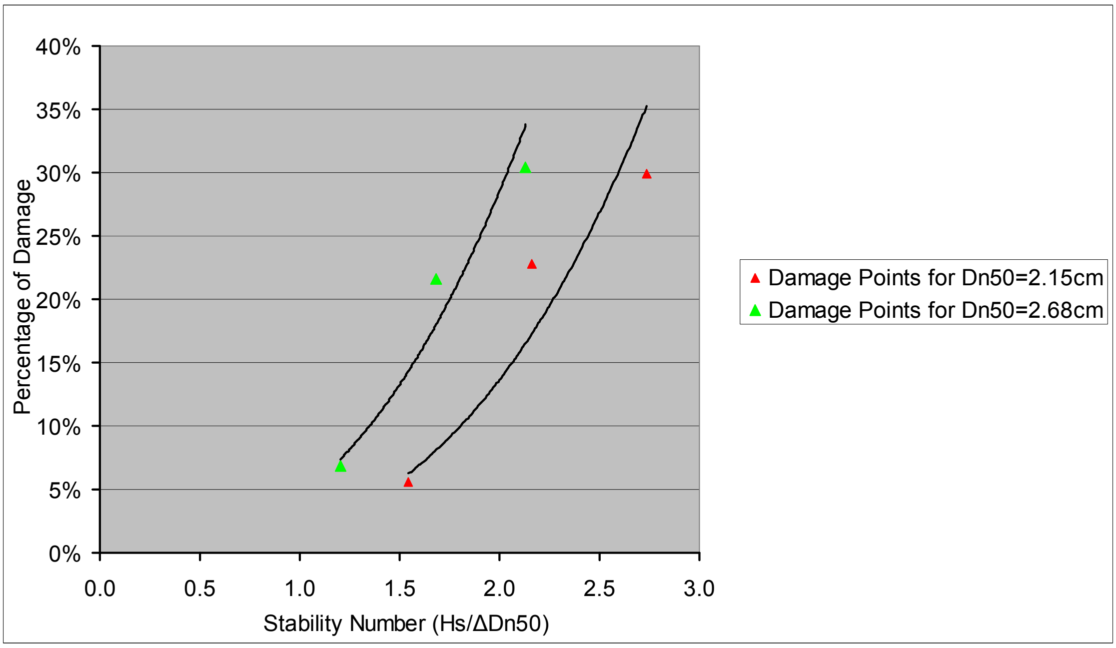
B 3 Stability number to damage N_{od} for a_{shore}=1:20, h_t=0.013m & S_0=0.02



B 4 Stability number to percentage damage for a_{shore}=1:20, h_t=0.013m & S_0=0.02

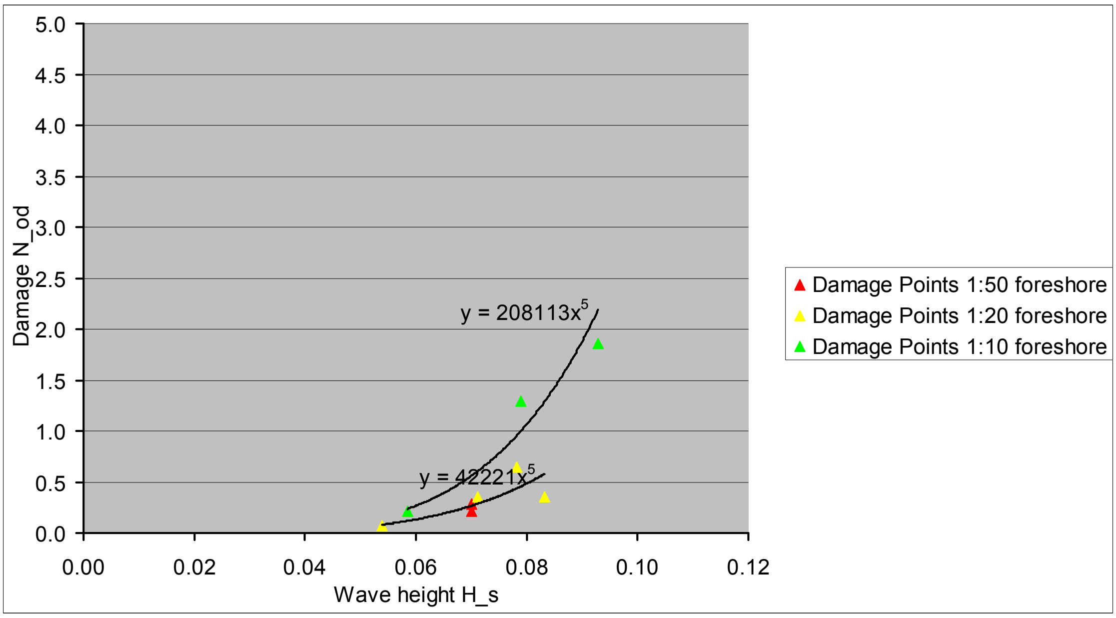


B 5 Stability number to damage N_{od} for a_{shore}=1:10, h_t=0.013m & S_0=0.02

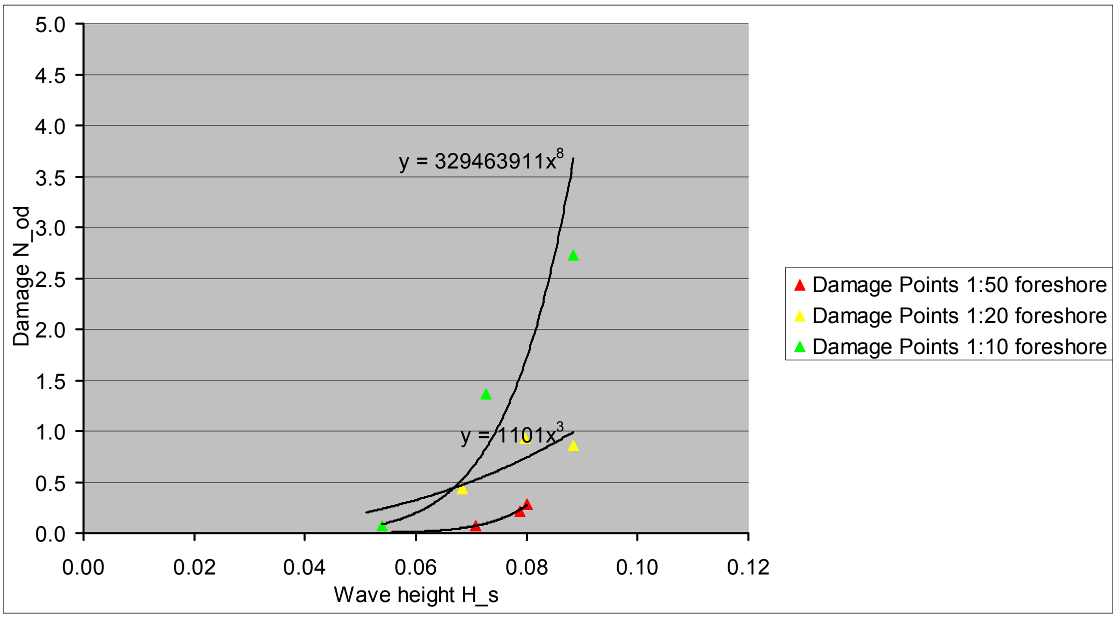


B 6 Stability number to percentage damage for a_{shore}=1:10, h_t=0.013m & S_0=0.02

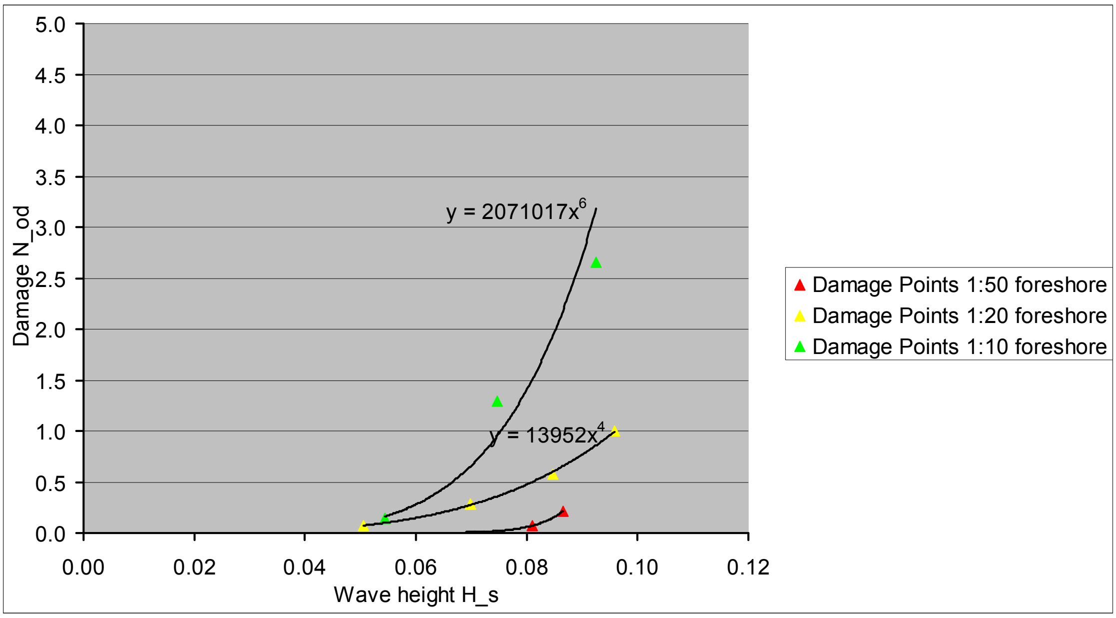
Appendix C Attached figures paragraph 4.4.1



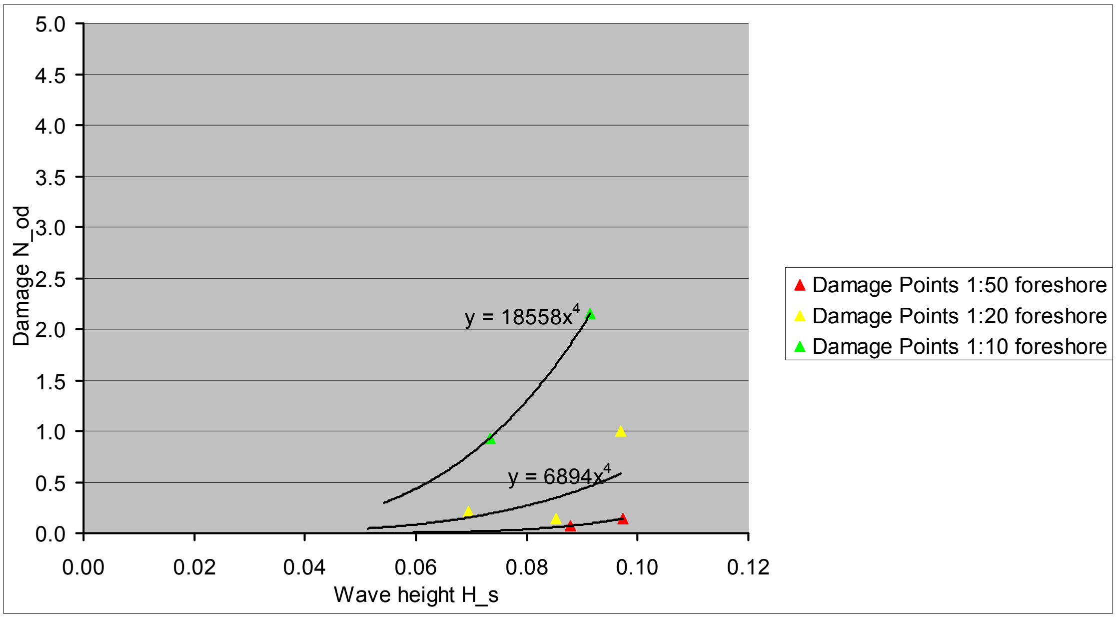
C 1Wave height to damage for D_{n50}=2,15cm, a_{shore}=1:20, h_t=-0.007m & S_0=0.04



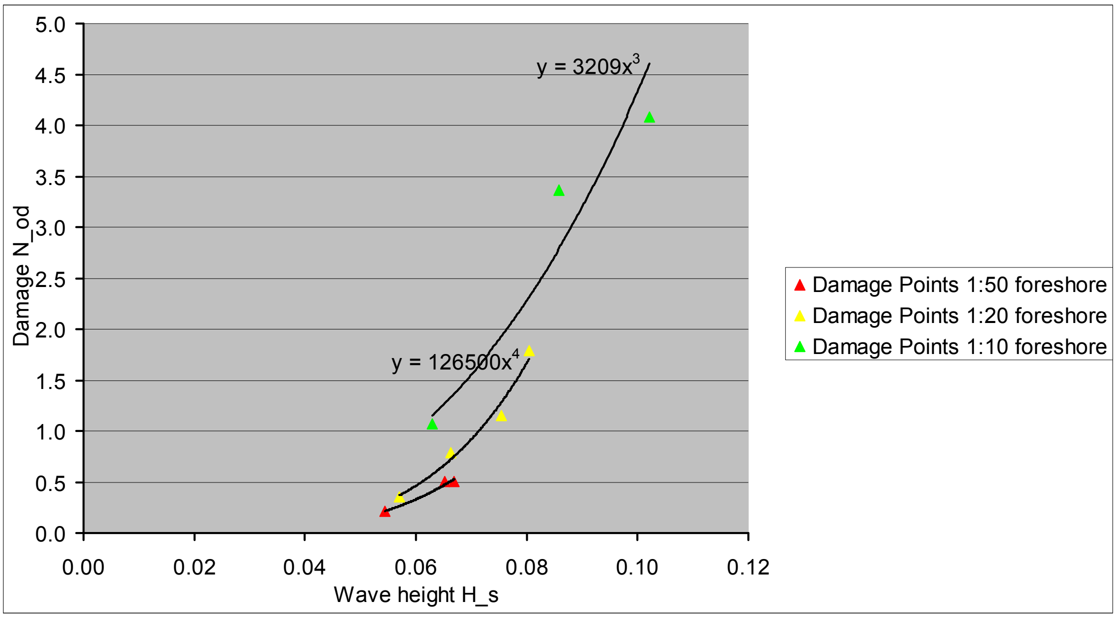
C 2 Wave height to damage for D_{n50}=2,15cm, a_{shore}=1:20, h_t=0.013m & S_0=0.04



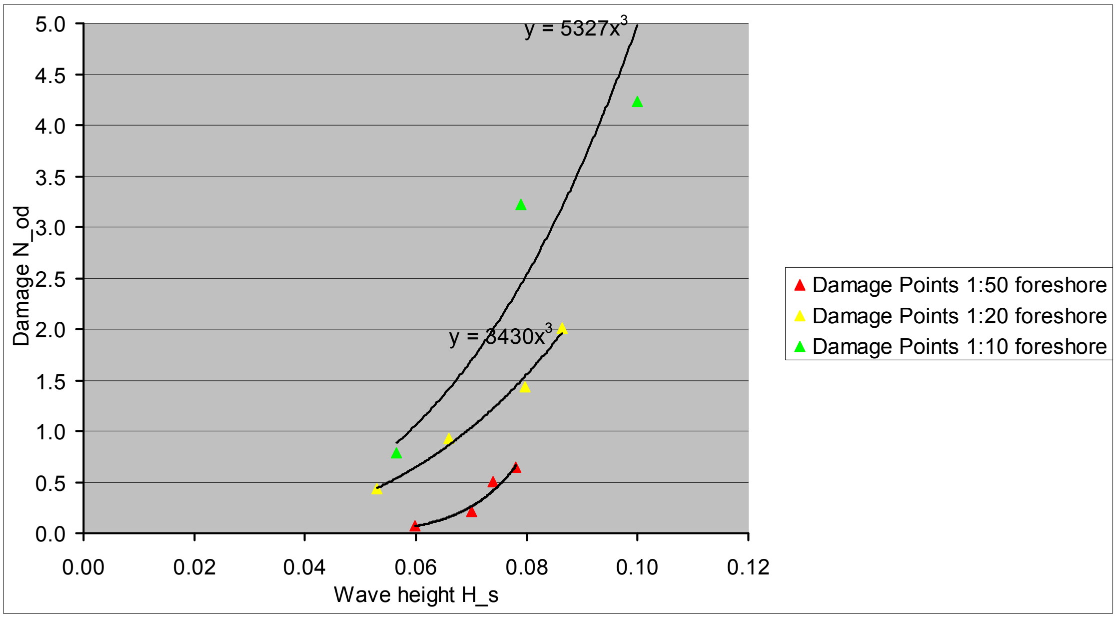
C 3 Wave height to damage for D_{n50}=2,15cm, a_{shore}=1:20, h_t=0.033m & S_0=0.04



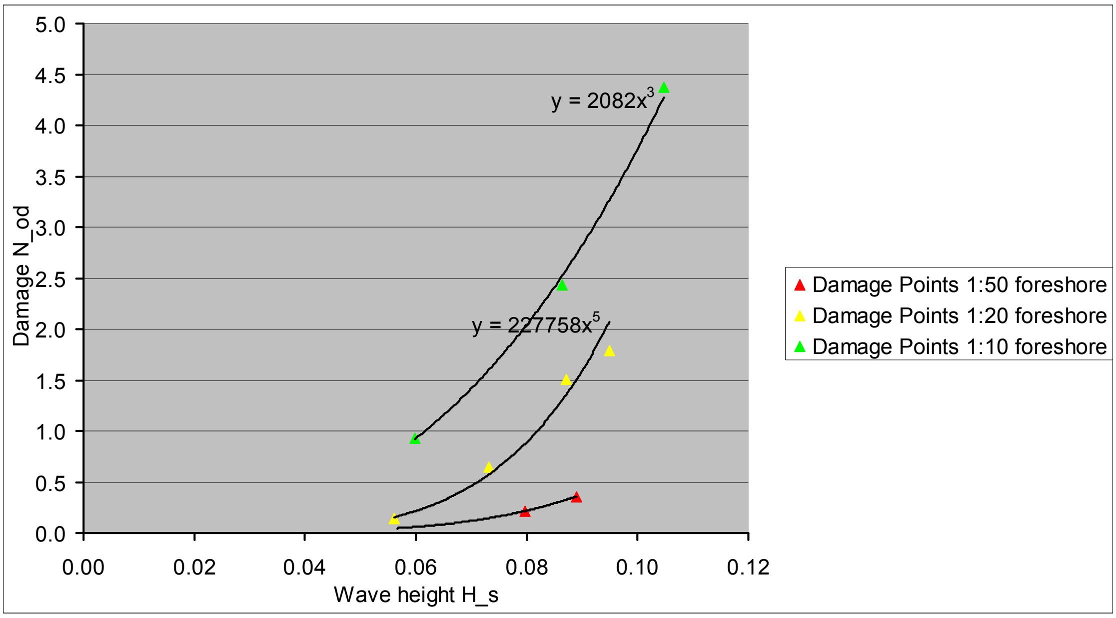
C 4 Wave height to damage for D_{n50}=2,15cm, a_{shore}=1:20, h_t=0.053m & S_0=0.04



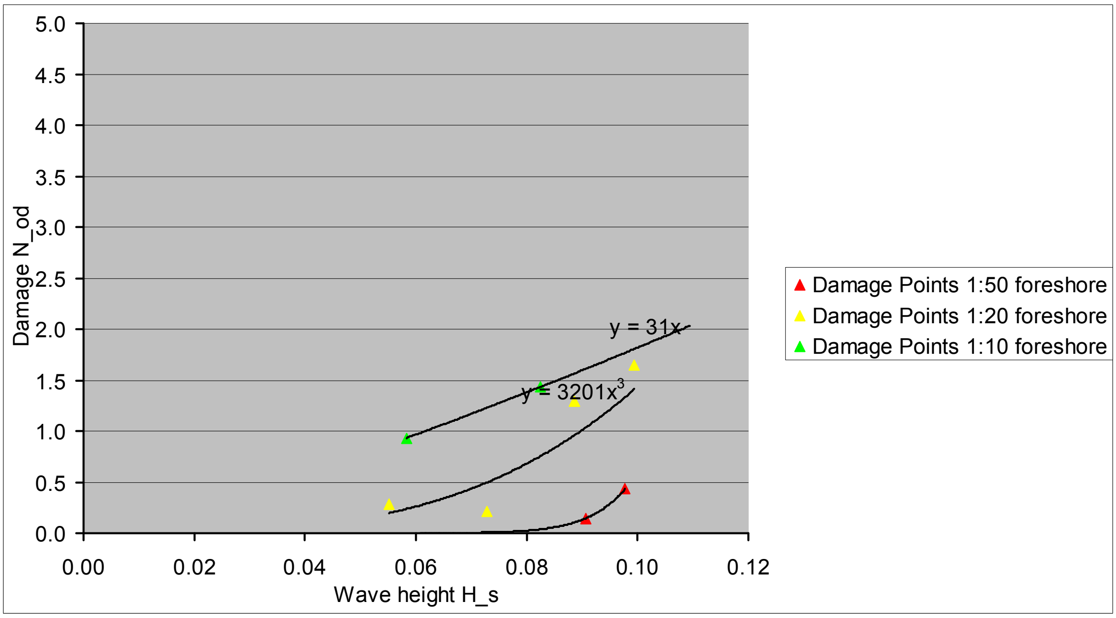
C 5 Wave height to damage for D_{n50}=2,15cm, a_{shore}=1:20, h_t=-0.007m & S_0=0.02



C 6 Wave height to damage for D_{n50}=2,15cm, a_{shore}=1:20, h_t=0.013m & S_0=0.02

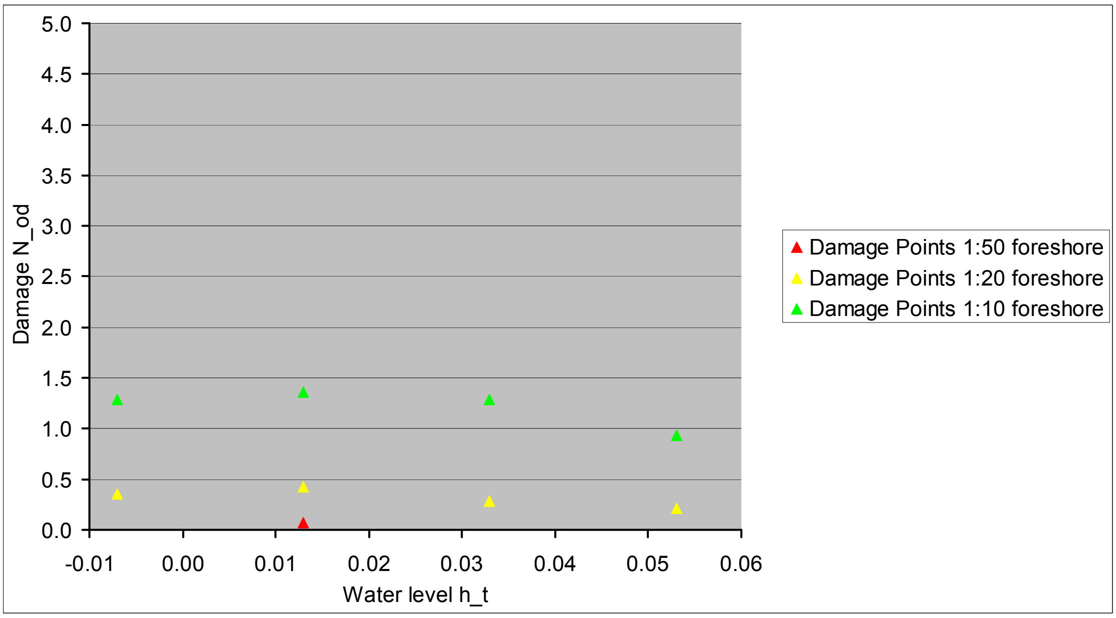


C 7 Wave height to damage for D_{n50}=2,15cm, a_{shore}=1:20, h_t=0.033m & S_0=0.02

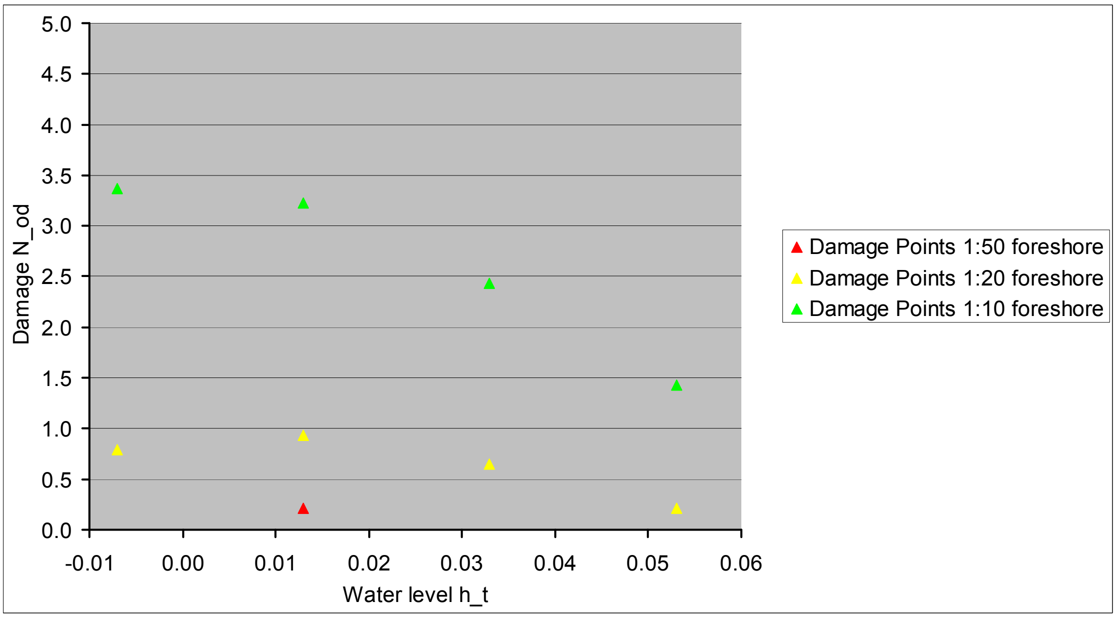


C 8 Wave height to damage for D_{n50}=2,15cm, a_{shore}=1:20, h_t=0.053m & S_0=0.02

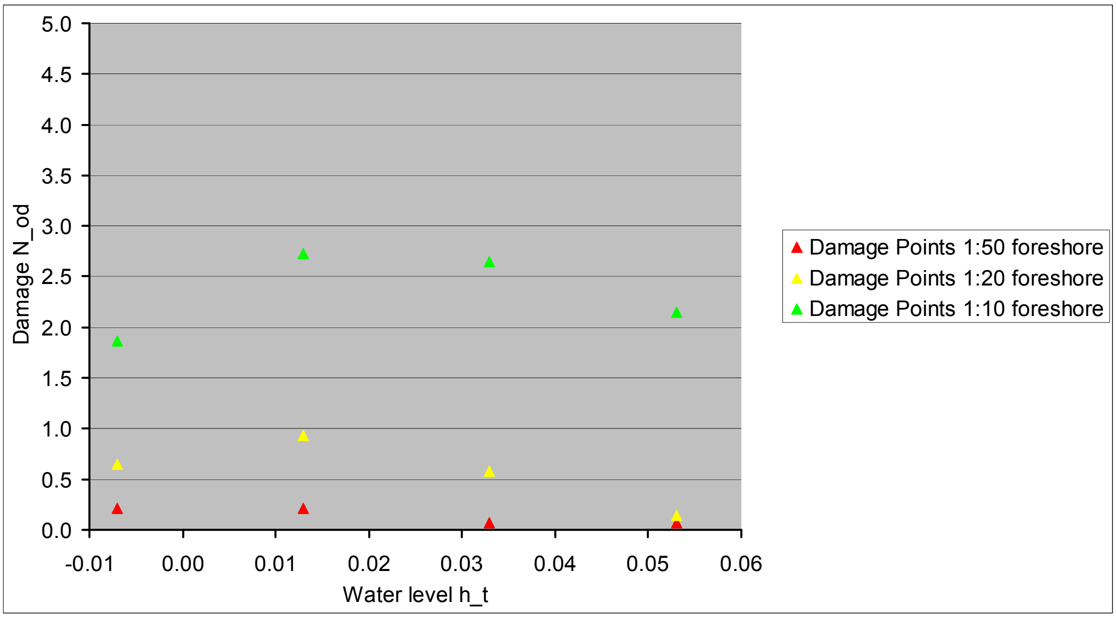
Appendix D Attached figures paragraph 4.4.1



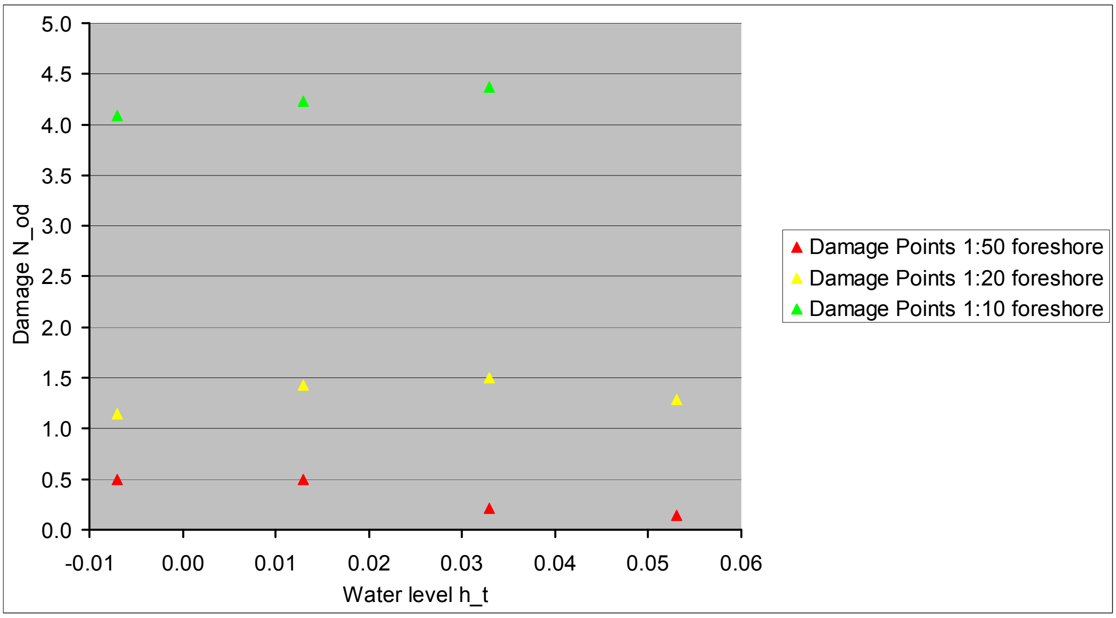
D 1 Water level to damage for D_{n50}=2,15cm, a_{shore}=1:20, S_0=0.04 & H_s=0.08m



D 2 Water level to damage for D_{n50}=2,15cm, a_{shore}=1:20, S_0=0.02 & H_s=0.08m

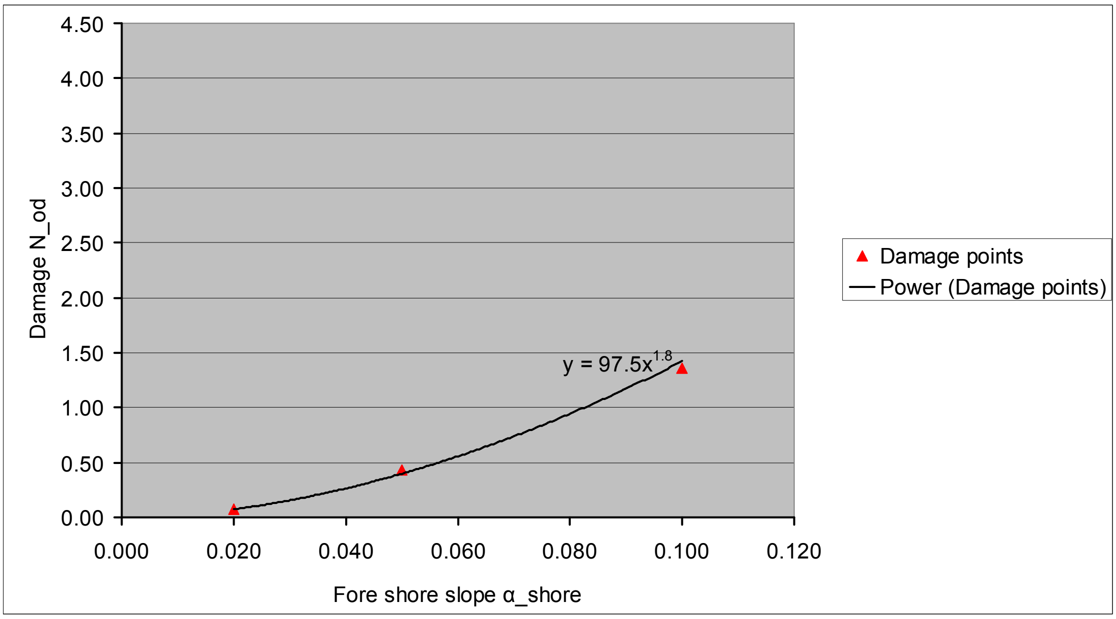


D 3 Water level to damage for D_{n50}=2,15cm, a_{shore}=1:20, S_0=0.04 & H_s=0.10m

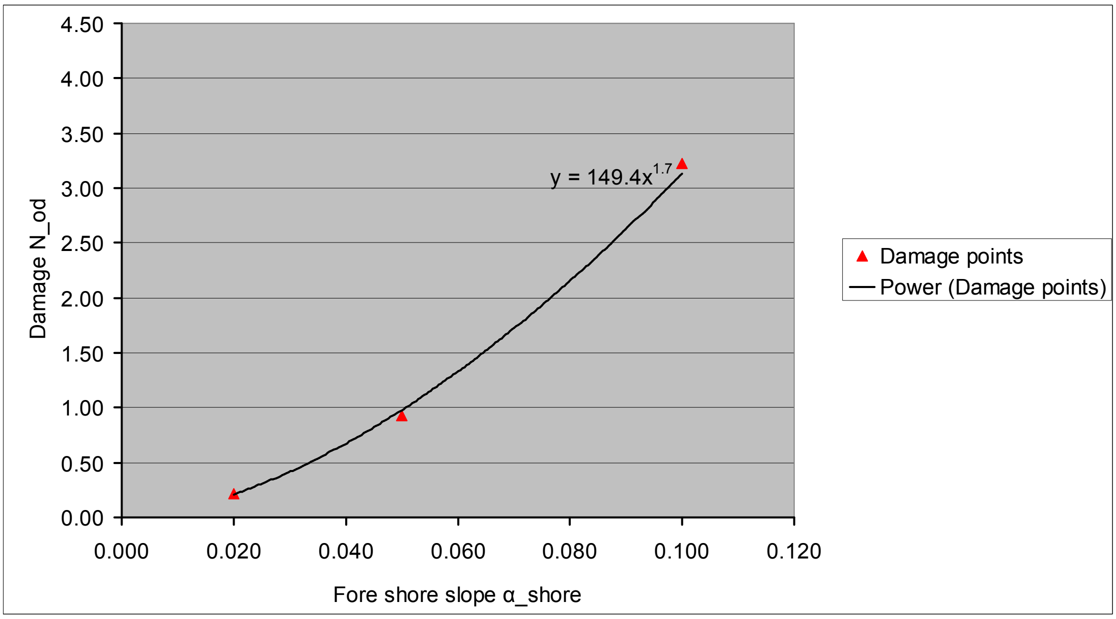


D 4 Water level to damage for D_{n50}=2,15cm, a_{shore}=1:20, S_0=0.02 & H_s=0.10m

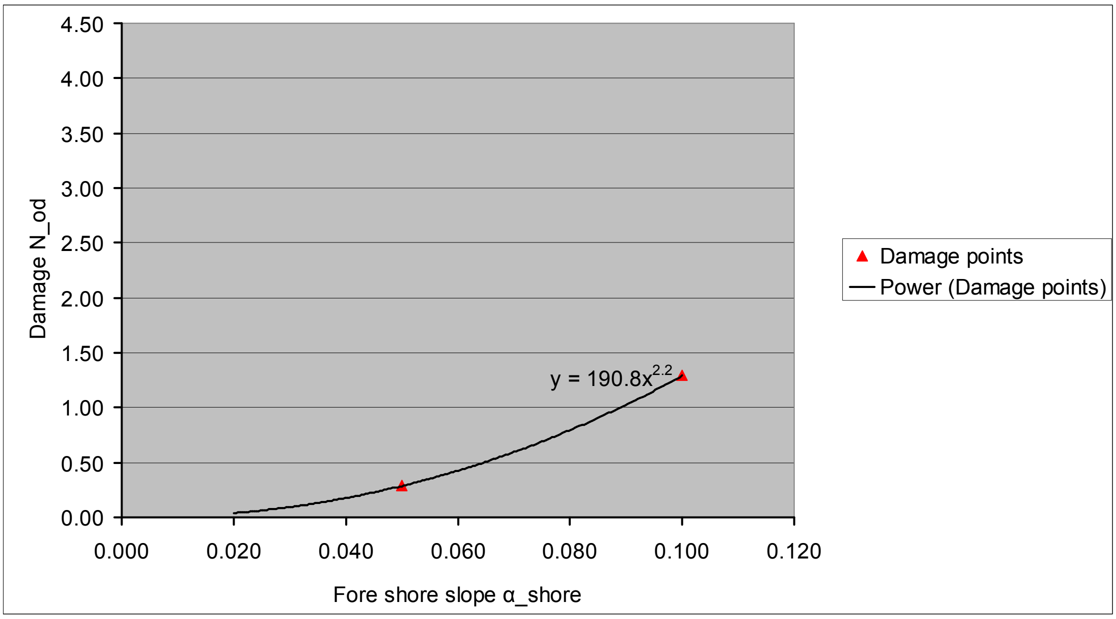
Appendix E Attached figures paragraph 4.4.1



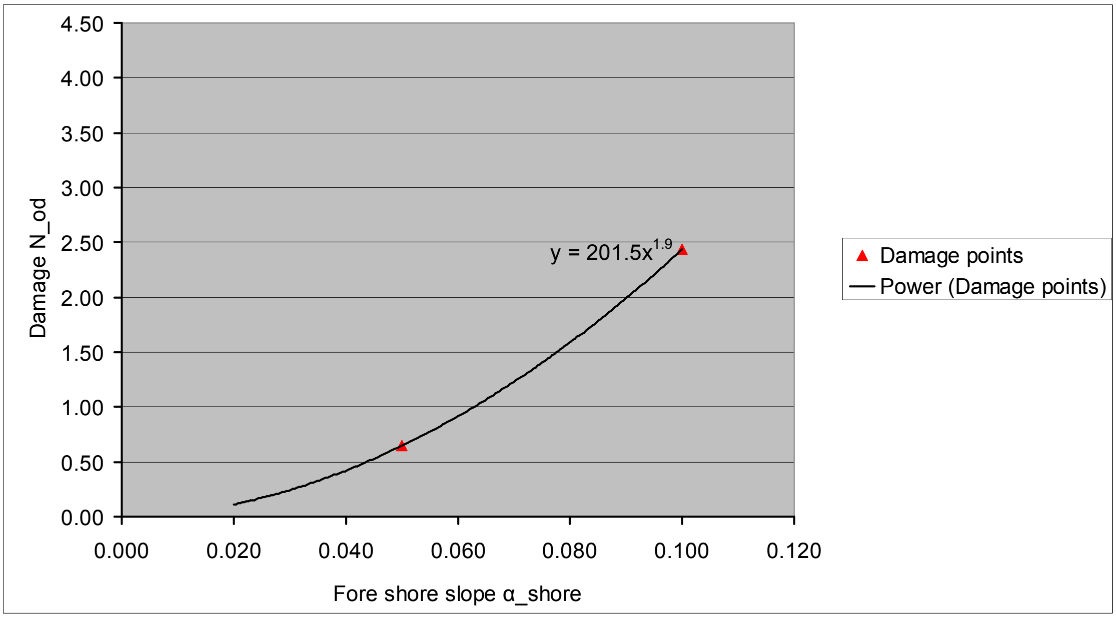
E 1 Fore shore slope to damage for D_{n50}=2,15cm, h_t=0.013m S_0=0.04 & H_s=0.08m



E 2 Fore shore slope to damage for D_{n50}=2,15cm, h_t=0.013m S_0=0.02 & H_s=0.08m

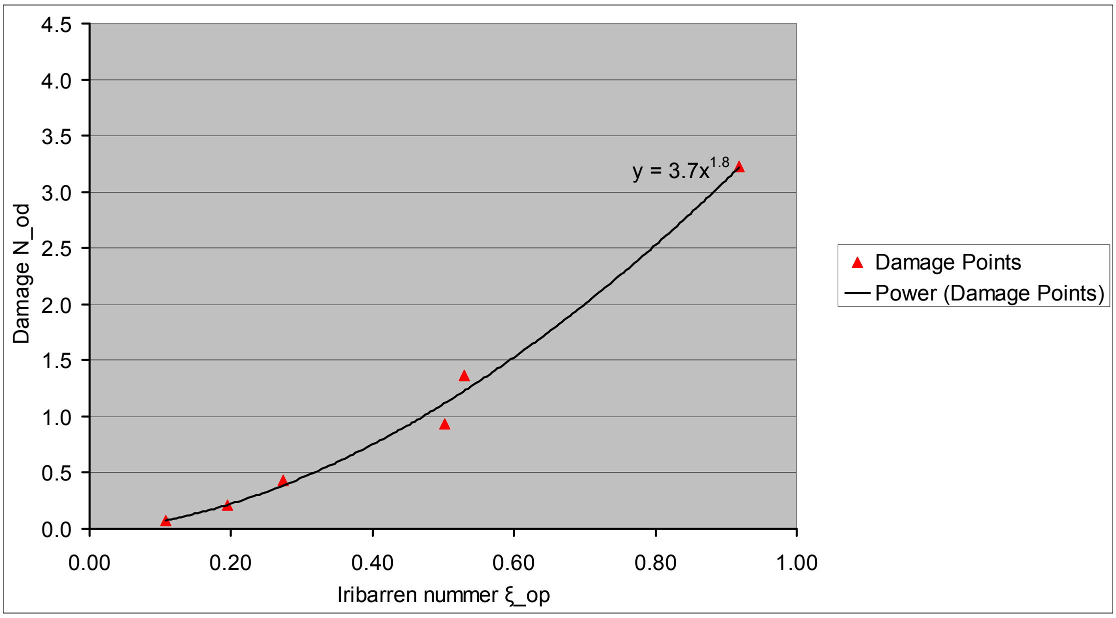


E 3 Fore shore slope to damage for D_{n50}=2,15cm, h_t=0.033m S_0=0.04 & H_s=0.08m

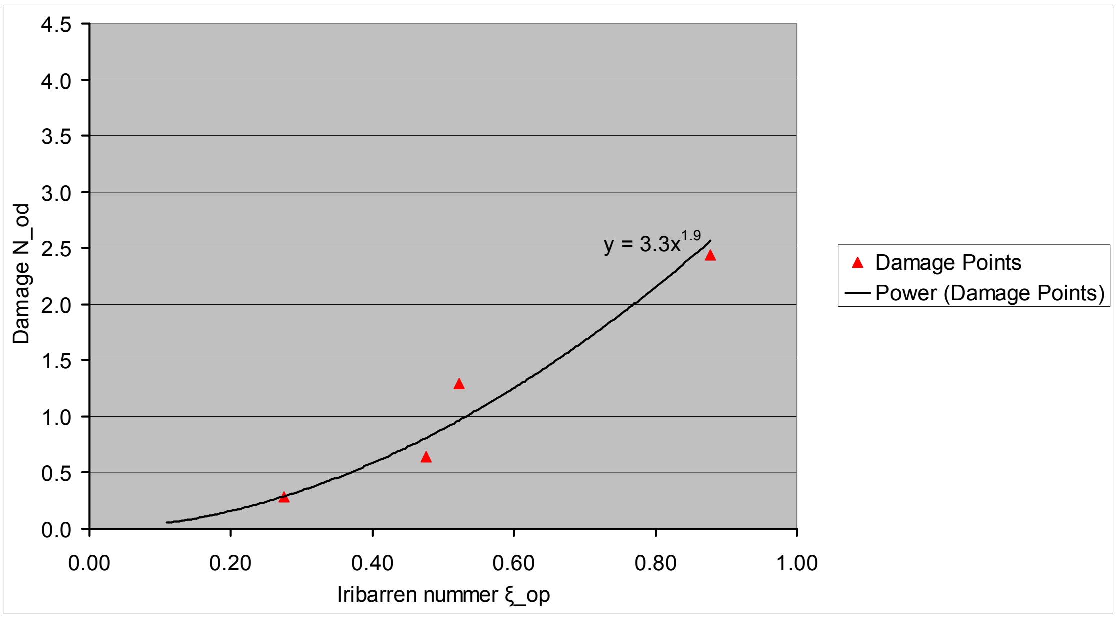


E 4 Fore shore slope to damage for D_{n50}=2,15cm, h_t=0.033m S_0=0.02 & H_s=0.08m

Appendix F Attached figures paragraph 4.4.1



F 1 Iribarren to damage for D_{n50}=2,15cm, h_t=0.013m & H_s=0.08m



F 2 Iribarren to damage for D_{n50}=2,15cm, h_t=0.033m & H_s=0.08m

Appendix G Example from reflection analysis

Reflection Analysis

Input Parameters

Generel

Data file:	*F:\...\Wave Gauge Output\Test A32.t*		
Sample frequency:	*32 Hz*		
Water depth:	*0.434 m*		
Length scale (Prototype/Model):	*1*		
Distance between gauge 1 and 2:	*0.2 m*		
Distance between gauge 1 and 3:	*0.65 m*		
	Gauge 1	*Gauge 2*	*Gauge 3*
Channel number:	*9*	*10*	*11*
Calibration function:	*1.0*X*	*1.0*X*	*1.0*X*
Skipped lines	*Header: 5*	*Start: 0*	*End: 0*

Bandpass filtering

Freq. lower bound:	*0.161 Hz*
Freq. upper bound:	*1.453 Hz*

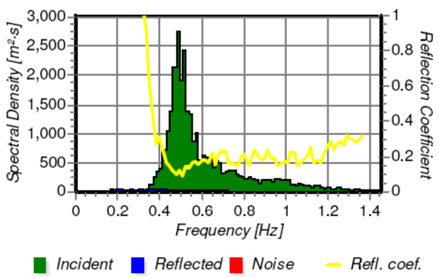
Freq. Domain Analysis (MF)

Overlap of subseries:	*20%*
Cosine taper width:	*20%*
Data No. in FFT block:	*2048*
Number of FFT blocks:	*37*

Time Domain Analysis (MF+InvFFT)

Min. points between downcrossings:	*13*
Hilbert filter length:	*1024*
X-Coord for results:	*0 m*

Frequency Domain Analysis (Mansard & Funke)

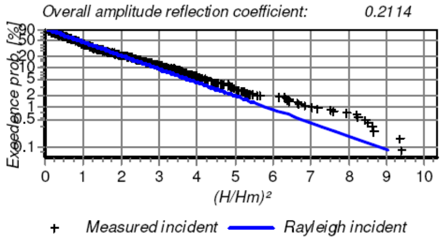


Overall amplitude reflection coefficient: *0.213*

	Incident	**Reflected**
Sig. wave height H_{m0} (m):	*85.06*	*18.12*
Peak wave period T_P (s):	*2.065*	*3.2*
Mean wave period $T_{-1,0}$ (s):	*1.78*	*2.545*
Mean wave period $T_{0,1}$ (s):	*1.633*	*1.94*
Mean wave period $T_{0,2}$ (s):	*1.548*	*1.7*
Spectral Width (Broadness):	*0.6113*	*0.757*
Spectral Width (Narrowness):	*0.3359*	*0.5506*

Time Domain Analysis (MF+InvFFT)

Overall amplitude reflection coefficient: *0.2114*



Wave height (m) / *Wave period (s)*

			2	3	4			
				11	4			
			11	34	12			
			22	71	27			
		4	35	67	56	5		
		29	90	121	89	22	1	
	19	115	118	39	35	6		
	89	52	15	9	1			

	Incident	**Reflected**
Number of waves:	1218	1122
Mean wave height H_m (m):	*50.64*	*10.45*
Mean wave period T_m (s):	*1.562*	*1.694*
Sig. wave height H_s (m):	*83.9*	*16.07*
$T_{H_{1/3}}$ (s):	*1.835*	*2.236*
$T_{1/3}$ (s):	*2.103*	*2.558*
H_{max} (m):	*155.2*	*30.06*
T_{Hmax} (s):	*2.044*	*4.138*
$H_{1/10}$ (m):	*109.9*	*20.36*
$H_{1/50}$ (m):	*137.2*	*24.87*
$H_{1/100}$ (m)	*145.8*	*26.29*
$H_{1/250}$ (m):	*151.1*	*28.05*
$H_{0.1\%}$ (m):	*155.1*	*29.86*
$H_{1\%}$ (m):	*135.4*	*24.15*
$H_{2\%}$ (m):	*120.2*	*22.72*
$H_{10\%}$ (m)	*92*	*16.95*
Groupiness factor GF:	*1.164*	*0.9999*
Skewness b1:	*0.3343*	*0.02115*
Kurtosis b2:	*3.51*	*3.018*

WaveLab 3

Delta Marine Consultants

Project title	
Drawn by	
Date	*24. Sep 2008*
Remarks	
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Reflection Analysis

Input Parameters

Generel

Data file:	*F:\...\Wave Gauge Output\Test A32.t*
Sample frequency:	*32 Hz*
Water depth:	*0.13 m*
Length scale (Prototype/Model):	*1*
Distance between gauge 1 and 2:	*0.16 m*
Distance between gauge 1 and 3:	*0.4 m*

	Gauge 1	*Gauge 2*	*Gauge 3*
Channel number:	*13*	*14*	*15*
Calibration function:	*1.0*X*	*1.0*X*	*1.0*X*
Skipped lines	*Header: 5*	*Start: 0*	*End: 0*

Bandpass filtering

Freq. lower bound:	*0.141 Hz*
Freq. upper bound:	*1.266 Hz*

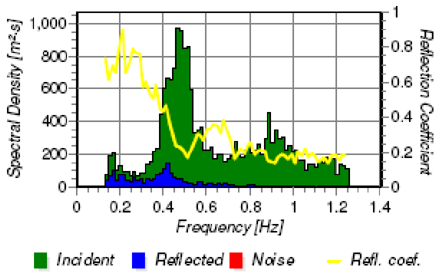
Freq. Domain Analysis (MF)

Overlap of subseries:	*20%*
Cosine taper width:	*20%*
Data No. in FFT block:	*2048*
Number of FFT blocks:	*37*

Time Domain Analysis (MF+InvFFT)

Min. points between downcrossings:	*15*
Hilbert filter length:	*1024*
X-Coord for results:	*0 m*

Frequency Domain Analysis (Mansard & Funke)

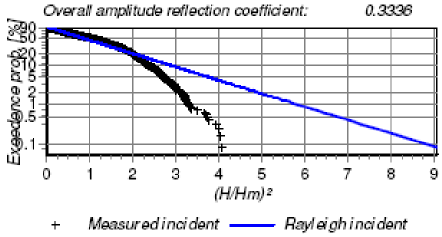


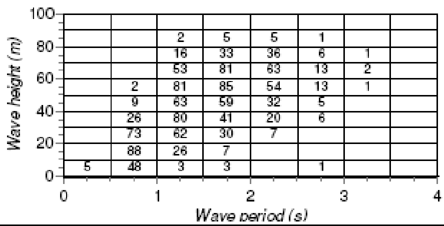
Overall amplitude reflection coefficient: *0.3313*

	Incident	**Reflected**
Sig. wave height H_{m0} (m):	*69.55*	*23.04*
Peak wave period T_P (s):	*2.133*	*2.37*
Mean wave period $T_{-1,0}$ (s):	*1.897*	*2.954*
Mean wave period $T_{0,1}$ (s):	*1.545*	*2.275*
Mean wave period $T_{0,2}$ (s):	*1.426*	*2.014*
Spectral Width (Broadness):	*0.6195*	*0.7459*
Spectral Width (Narrowness):	*0.4157*	*0.5257*

Time Domain Analysis (MF+InvFFT)

Overall amplitude reflection coefficient: *0.3336*





	Incident	**Reflected**
Number of waves:	1247	898
Mean wave height H_m (m):	*44.07*	*13.98*
Mean wave period T_m (s):	*1.523*	*2.114*
Sig. wave height H_s (m):	*65.52*	*21.39*
$T_{H_{1/3}}$ (s):	*1.888*	*2.611*
$T_{1/3}$ (s):	*2.168*	*2.958*
H_{max} (m):	*88.74*	*35.77*
T_{Hmax} (s):	*1.394*	*3.264*
$H_{1/10}$ (m):	*74.16*	*26.48*
$H_{1/50}$ (m):	*81.67*	*31.96*
$H_{1/100}$ (m)	*84.71*	*33.6*
$H_{1/250}$ (m):	*87.65*	*34.94*
$H_{0.1\%}$ (m):	*88.68*	*Not enough data*
$H_{1\%}$ (m):	*80.18*	*31.6*
$H_{2\%}$ (m):	*78.05*	*29.9*
$H_{10\%}$ (m)	*68.15*	*22.33*
Groupiness factor GF:	*0.88*	*1.004*
Skewness b1:	*0.5058*	*0.2979*
Kurtosis b2:	*2.663*	*2.989*

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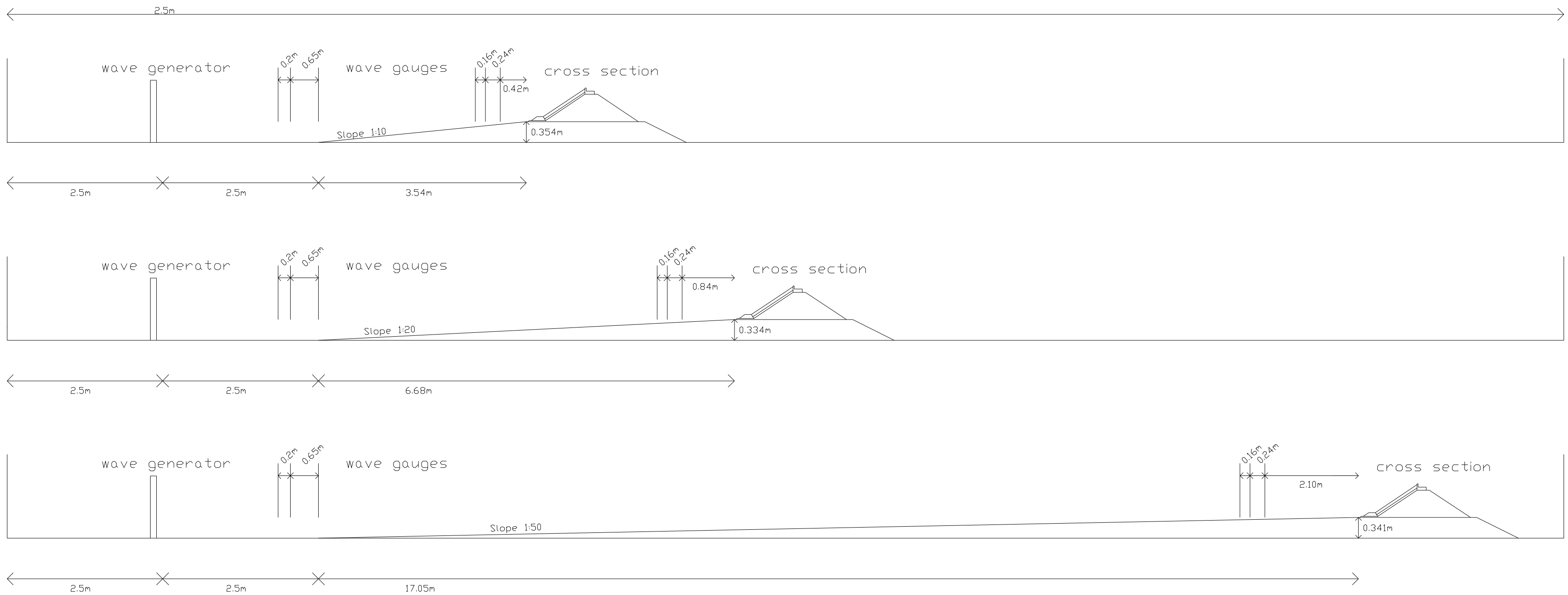
Appendix H Overview Flume Lay out



H 1 Overview of wave flume set up for three fore shore slopes, 1st 1:10, 2nd 1:20 & 3rd 1:50

Appendix I Dataset from Experiment

Test Conditions				Paddle Spectrum Analysis			Structure Spectrum Analysis				Time Domain Analysis				Damage						
N_0	α_{shore}	H_s	S_0	H_{m0}	T_p	h	H_{m0}	T_p	$T_{m-1,0}$	r.c.	$H_{1/3}$	$H_{2\%}$	h_m	h_t	D_{dn50}	Δ	N_{down}	N_{up}	N_{mcum}	N_{od}	Damage
(-)	(m/m)	(m)	(m/m)	(m)	(s)	(m)	(m)	(s)	(s)	(-)	(m)	(m)	(m)	(m)	(m)	(-)	(-)	(-)	(-)	(-)	(%)
1	1:50	0.06	0.03	0.061	1.14	0.594	0.053	1.16	1.08	0.306	0.052	0.074	0.253	0.173	0.0188	1.65	0	0	0		
2	1:50	0.08	0.03	0.085	1.28	0.594	0.077	1.31	1.21	0.336	0.074	0.108	0.253	0.173	0.0188	1.65	0	0	0		
3	1:50	0.10	0.03	0.115	1.49	0.594	0.106	1.56	1.39	0.380	0.103	0.142	0.253	0.173	0.0188	1.65	0	0	0		
4	1:50	0.12	0.03	0.125	1.64	0.594	0.117	1.73	1.55	0.419	0.112	0.149	0.253	0.173	0.0188	1.65	1	0	1	0.06	0.34%
5	1:50	0.06	0.03	0.063	1.14	0.544	0.055	1.16	1.09	0.324	0.054	0.074	0.203	0.123	0.0188	1.65	0	0	0		
6	1:50	0.08	0.03	0.085	1.28	0.544	0.077	1.31	1.23	0.338	0.074	0.103	0.203	0.123	0.0188	1.65	0	0	0		
7	1:50	0.10	0.03	0.106	1.49	0.544	0.097	1.56	1.40	0.371	0.095	0.129	0.203	0.123	0.0188	1.65	0	0	0		
8	1:50	0.12	0.03	0.129	1.64	0.544	0.114	1.73	1.59	0.394	0.110	0.139	0.203	0.123	0.0188	1.65	0	0	0		
9	1:50	0.06	0.03	0.058	1.14	0.494	0.052	1.16	1.09	0.293	0.050	0.068	0.153	0.073	0.0188	1.65	0	0	0		
10	1:50	0.08	0.03	0.076	1.28	0.494	0.070	1.33	1.21	0.299	0.069	0.097	0.153	0.073	0.0188	1.65	0	0	0		
11	1:50	0.10	0.03	0.094	1.49	0.494	0.086	1.56	1.39	0.336	0.085	0.110	0.153	0.073	0.0188	1.65	2	0	2	0.13	0.68%
12	1:50	0.12	0.03	0.113	1.64	0.494	0.098	1.73	1.51	0.349	0.096	0.117	0.153	0.073	0.0188	1.65	0	0	2		
13	1:50	0.06	0.04	0.060	0.98	0.474	0.051	1.07	0.96	0.248	0.049	0.068	0.133	0.053	0.0188	1.65	0	0	0		
14	1:50	0.06	0.02	0.063	1.49	0.474	0.061	1.56	1.37	0.308	0.060	0.086	0.133	0.053	0.0188	1.65	3	1	4	0.25	1.36%
15	1:50	0.08	0.04	0.082	1.14	0.474	0.071	1.21	1.10	0.243	0.069	0.090	0.133	0.053	0.0188	1.65	0	0	3	0.19	1.02%
16	1:50	0.08	0.02	0.086	2.00	0.474	0.082	2.13	1.82	0.380	0.081	0.105	0.133	0.053	0.0188	1.65	1	1	6	0.38	2.03%
17	1:50	0.10	0.04	0.103	1.28	0.474	0.088	1.46	1.22	0.254	0.086	0.104	0.133	0.053	0.0188	1.65	0	1	4	0.25	1.36%

18	1:50	0.10	0.02	0.106	2.37	0.474	0.091	2.56	2.12	0.418	0.089	0.110	0.133	0.053	0.0188	1.65	1	1	9	0.56	3.05%
19	1:50	0.12	0.04	0.126	1.49	0.474	0.097	1.73	1.39	0.297	0.092	0.106	0.133	0.053	0.0188	1.65	0	0	5	0.31	1.69%
20	1:50	0.12	0.02	0.126	2.67	0.474	0.098	3.05	2.24	0.438	0.096	0.114	0.133	0.053	0.0188	1.65	1	6	16	1.00	5.42%
21	1:50	0.06	0.04	0.058	0.98	0.454	0.051	1.07	0.96	0.205	0.050	0.069	0.113	0.033	0.0188	1.65	1	0	1	0.06	0.34%
22	1:50	0.06	0.02	0.058	1.49	0.454	0.057	1.49	1.39	0.270	0.055	0.077	0.113	0.033	0.0188	1.65	2	0	3	0.19	1.02%
23	1:50	0.08	0.04	0.078	1.14	0.454	0.069	1.21	1.09	0.213	0.067	0.087	0.113	0.033	0.0188	1.65	0	0	3	0.19	1.02%
24	1:50	0.08	0.02	0.077	2.00	0.454	0.072	2.07	1.84	0.352	0.071	0.089	0.113	0.033	0.0188	1.65	1	0	4	0.25	1.36%
25	1:50	0.10	0.04	0.097	1.28	0.454	0.081	1.36	1.22	0.237	0.078	0.092	0.113	0.033	0.0188	1.65	0	0	4	0.25	1.36%
26	1:50	0.10	0.02	0.099	2.37	0.454	0.080	2.56	2.19	0.412	0.077	0.094	0.113	0.033	0.0188	1.65	2	2	8	0.50	2.71%
27	1:50	0.12	0.04	0.117	1.49	0.454	0.087	1.73	1.42	0.274	0.080	0.093	0.113	0.033	0.0188	1.65	3	0	9	0.56	3.05%
28	1:50	0.12	0.02	0.117	2.67	0.454	0.089	3.05					0.113	0.033	0.0188	1.65	-1	4	14	0.88	4.75%
29	1:50	0.06	0.04	0.061	0.98	0.434	0.053	1.07	0.98	0.152	0.052	0.070	0.093	0.013	0.0188	1.65	2	0	2	0.13	0.68%
30	1:50	0.06	0.02	0.064	1.49	0.434	0.060	1.73	1.39	0.247	0.059	0.076	0.093	0.013	0.0188	1.65	0	1	3	0.19	1.02%
31	1:50	0.08	0.04	0.085	1.14	0.434	0.071	1.21	1.09	0.195	0.068	0.081	0.093	0.013	0.0188	1.65	0	0	2	0.13	0.68%
32	1:50	0.08	0.02	0.084	2.07	0.434	0.070	2.07	1.90	0.332	0.066	0.078	0.093	0.013	0.0188	1.65	5	2	10	0.63	3.39%
33	1:50	0.10	0.04	0.105	1.28	0.434	0.079	1.36	1.21	0.216	0.074	0.085	0.093	0.013	0.0188	1.65	1	0	8	0.50	2.71%
34	1:50	0.10	0.02	0.105	2.37	0.434	0.074	2.56	2.25	0.388	0.069	0.083	0.093	0.013	0.0188	1.65	3	5	19	1.19	6.44%
35	1:50	0.12	0.04	0.126	1.49	0.434	0.080	1.88	1.47	0.280	0.073	0.085	0.093	0.013	0.0188	1.65	1	0	12	0.75	4.07%
36	1:50	0.12	0.02	0.127	2.67	0.434	0.078	3.05	2.60	0.437	0.072	0.087	0.093	0.013	0.0188	1.65	2	8	30	1.88	10.17%
37	1:50	0.06	0.04	0.059	0.98	0.414	0.051	1.07	0.97	0.191	0.051	0.065	0.073	-0.007	0.0188	1.65	1	0	1	0.06	0.34%
38	1:50	0.06	0.02	0.058	1.56	0.414	0.055	1.73	1.38	0.247	0.054	0.067	0.073	-0.007	0.0188	1.65	0	3	4	0.25	1.36%
39	1:50	0.08	0.04	0.078	1.14	0.414	0.064	1.26	1.09	0.210	0.061	0.071	0.073	-0.007	0.0188	1.65	0	1	1	0.06	0.34%
40	1:50	0.08	0.02	0.078	2.07	0.414	0.061	2.29	1.99	0.336	0.055	0.066	0.073	-0.007	0.0188	1.65	6	2	13	0.81	4.41%
41	1:50	0.10	0.04	0.098	1.28	0.414	0.070	1.46	1.23	0.225	0.065	0.076	0.073	-0.007	0.0188	1.65	0	0	7	0.44	2.37%

42	1:50	0.10	0.02	0.097	2.37	0.414	0.065	2.56	2.27	0.377	0.061	0.073	0.073	-0.007	0.0188	1.65	0	4	17	1.07	5.76%
43	1:50	0.12	0.04	0.118	1.49	0.414	0.070	1.73					0.073	-0.007	0.0188	1.65	0	0	7	0.44	2.37%
44	1:50	0.12	0.02	0.118	2.67	0.414	0.067	3.05	2.70	0.424	0.062	0.077	0.073	-0.007	0.0188	1.65	0	3	20	1.25	6.78%
45	1:50	0.06	0.03	0.061	1.14	0.594	0.053	1.16	1.08	0.306	0.052	0.074	0.253	0.173	0.0215	1.70	0	0	0		
46	1:50	0.08	0.03	0.085	1.28	0.594	0.077	1.31	1.21	0.336	0.074	0.108	0.253	0.173	0.0215	1.70	0	0	0		
47	1:50	0.10	0.03	0.115	1.49	0.594	0.106	1.56	1.39	0.380	0.103	0.142	0.253	0.173	0.0215	1.70	0	0	0		
48	1:50	0.12	0.03	0.125	1.64	0.594	0.117	1.73	1.55	0.419	0.112	0.149	0.253	0.173	0.0215	1.70	1	0	1	0.07	0.51%
49	1:50	0.06	0.03	0.063	1.14	0.544	0.055	1.16	1.09	0.324	0.054	0.074	0.203	0.123	0.0215	1.70	0	0	0		
50	1:50	0.08	0.03	0.085	1.28	0.544	0.077	1.31	1.23	0.338	0.074	0.103	0.203	0.123	0.0215	1.70	0	0	0		
51	1:50	0.10	0.03	0.106	1.49	0.544	0.097	1.56	1.40	0.371	0.095	0.129	0.203	0.123	0.0215	1.70	0	1	1	0.07	0.51%
52	1:50	0.12	0.03	0.129	1.64	0.544	0.114	1.73	1.59	0.394	0.110	0.139	0.203	0.123	0.0215	1.70	0	1	2	0.14	1.01%
53	1:50	0.06	0.03	0.058	1.14	0.494	0.052	1.16	1.09	0.293	0.050	0.068	0.153	0.073	0.0215	1.70	0	0	0		
54	1:50	0.08	0.03	0.076	1.28	0.494	0.070	1.33	1.21	0.299	0.069	0.097	0.153	0.073	0.0215	1.70	0	0	0		
55	1:50	0.10	0.03	0.094	1.49	0.494	0.086	1.56	1.39	0.336	0.085	0.110	0.153	0.073	0.0215	1.70	0	1	1	0.07	0.51%
56	1:50	0.12	0.03	0.113	1.64	0.494	0.098	1.73	1.51	0.349	0.096	0.117	0.153	0.073	0.0215	1.70	1	1	3	0.22	1.52%
57	1:50	0.06	0.04	0.060	0.98	0.474	0.051	1.07	0.96	0.248	0.049	0.068	0.133	0.053	0.0215	1.70	0	0	0		
58	1:50	0.06	0.02	0.063	1.49	0.474	0.061	1.56	1.37	0.308	0.060	0.086	0.133	0.053	0.0215	1.70	0	0	0		
59	1:50	0.08	0.04	0.082	1.14	0.474	0.071	1.21	1.10	0.243	0.069	0.090	0.133	0.053	0.0215	1.70	0	0	0		
60	1:50	0.08	0.02	0.086	2.00	0.474	0.082	2.13	1.82	0.380	0.081	0.105	0.133	0.053	0.0215	1.70	0	0	0		
61	1:50	0.10	0.04	0.103	1.28	0.474	0.088	1.46	1.22	0.254	0.086	0.104	0.133	0.053	0.0215	1.70	1	0	1	0.07	0.51%
62	1:50	0.10	0.02	0.106	2.37	0.474	0.091	2.56	2.12	0.418	0.089	0.110	0.133	0.053	0.0215	1.70	1	0	2	0.14	1.01%
63	1:50	0.12	0.04	0.126	1.49	0.474	0.097	1.73	1.39	0.297	0.092	0.106	0.133	0.053	0.0215	1.70	0	0	2	0.14	1.01%
64	1:50	0.12	0.02	0.126	2.67	0.474	0.098	3.05	2.24	0.438	0.096	0.114	0.133	0.053	0.0215	1.70	2	2	6	0.43	3.04%
65	1:50	0.06	0.04	0.058	0.98	0.454	0.051	1.07	0.96	0.205	0.050	0.069	0.113	0.033	0.0215	1.70	0	0	0		

66	1:50	0.06	0.02	0.058	1.49	0.454	0.057	1.49	1.39	0.270	0.055	0.077	0.113	0.033	0.0215	1.70	0	0	0		
67	1:50	0.08	0.04	0.078	1.14	0.454	0.069	1.21	1.09	0.213	0.067	0.087	0.113	0.033	0.0215	1.70	0	0	0		
68	1:50	0.08	0.02	0.077	2.00	0.454	0.072	2.07	1.84	0.352	0.071	0.089	0.113	0.033	0.0215	1.70	0	0	0		
69	1:50	0.10	0.04	0.097	1.28	0.454	0.081	1.36	1.22	0.237	0.078	0.092	0.113	0.033	0.0215	1.70	1	0	1	0.07	0.51%
70	1:50	0.10	0.02	0.099	2.37	0.454	0.080	2.56	2.19	0.412	0.077	0.094	0.113	0.033	0.0215	1.70	2	0	3	0.22	1.52%
71	1:50	0.12	0.04	0.117	1.49	0.454	0.087	1.73	1.42	0.274	0.080	0.093	0.113	0.033	0.0215	1.70	0	0	3	0.22	1.52%
72	1:50	0.12	0.02	0.117	2.67	0.454	0.089	3.05					0.113	0.033	0.0215	1.70	2	0	5	0.36	2.54%
73	1:50	0.06	0.04	0.061	0.98	0.434	0.053	1.07	0.98	0.152	0.052	0.070	0.093	0.013	0.0215	1.70	0	0	0		
74	1:50	0.06	0.02	0.064	1.49	0.434	0.060	1.73	1.39	0.247	0.059	0.076	0.093	0.013	0.0215	1.70	1	0	1	0.07	0.51%
75	1:50	0.08	0.04	0.085	1.14	0.434	0.071	1.21	1.09	0.195	0.068	0.081	0.093	0.013	0.0215	1.70	0	0	1	0.07	0.51%
76	1:50	0.08	0.02	0.084	2.07	0.434	0.070	2.07	1.90	0.332	0.066	0.078	0.093	0.013	0.0215	1.70	2	0	3	0.22	1.52%
77	1:50	0.10	0.04	0.105	1.28	0.434	0.079	1.36	1.21	0.216	0.074	0.085	0.093	0.013	0.0215	1.70	0	0	3	0.22	1.52%
78	1:50	0.10	0.02	0.105	2.37	0.434	0.074	2.56	2.25	0.388	0.069	0.083	0.093	0.013	0.0215	1.70	1	3	7	0.50	3.55%
79	1:50	0.12	0.04	0.126	1.49	0.434	0.080	1.88	1.47	0.280	0.073	0.085	0.093	0.013	0.0215	1.70	0	0	4	0.29	2.03%
80	1:50	0.12	0.02	0.127	2.67	0.434	0.078	3.05	2.60	0.437	0.072	0.087	0.093	0.013	0.0215	1.70	1	1	9	0.65	4.56%
81	1:50	0.06	0.04	0.059	0.98	0.414	0.051	1.07	0.97	0.191	0.051	0.065	0.073	-0.007	0.0215	1.70	0	0	0		
82	1:50	0.06	0.02	0.058	1.56	0.414	0.055	1.73	1.38	0.247	0.054	0.067	0.073	-0.007	0.0215	1.70	3	0	3	0.22	1.52%
83	1:50	0.08	0.04	0.078	1.14	0.414	0.064	1.26	1.09	0.210	0.061	0.071	0.073	-0.007	0.0215	1.70	0	0	3		
84	1:50	0.08	0.02	0.078	2.07	0.414	0.061	2.29	1.99	0.336	0.055	0.066	0.073	-0.007	0.0215	1.70	0	0	3		
85	1:50	0.10	0.04	0.098	1.28	0.414	0.070	1.46	1.23	0.225	0.065	0.076	0.073	-0.007	0.0215	1.70	0	0	3	0.22	1.52%
86	1:50	0.10	0.02	0.097	2.37	0.414	0.065	2.56	2.27	0.377	0.061	0.073	0.073	-0.007	0.0215	1.70	1	3	7	0.50	3.55%
87	1:50	0.12	0.04	0.118	1.49	0.414	0.070	1.73					0.073	-0.007	0.0215	1.70	0	0	4	0.29	2.03%
88	1:50	0.12	0.02	0.118	2.67	0.414	0.067	3.05	2.70	0.424	0.062	0.077	0.073	-0.007	0.0215	1.70	0	0	7	0.50	3.55%
89	1:20	0.06	0.04	0.062	0.98	0.698	0.056	0.98	0.94	0.212	0.055	0.076	0.339	0.259	0.0188	1.65	0	0	0		

90	1:20	0.06	0.02	0.060	1.49	0.698	0.056	1.56	1.35	0.318	0.054	0.078	0.339	0.259	0.0188	1.65	0	0	0		
91	1:20	0.08	0.04	0.080	1.14	0.698	0.073	1.21	1.06	0.231	0.071	0.096	0.339	0.259	0.0188	1.65	0	0	0		
92	1:20	0.08	0.02	0.088	2.00	0.698	0.085	2.07	1.81	0.438	0.081	0.113	0.339	0.259	0.0188	1.65	0	0	0		
93	1:20	0.10	0.04	0.101	1.28	0.698	0.094	1.28	1.19	0.260	0.090	0.121	0.339	0.259	0.0188	1.65	0	0	0		
94	1:20	0.10	0.02	0.114	2.29	0.698	0.113	2.37	2.16	0.497	0.107	0.153	0.339	0.259	0.0188	1.65	2	0	2	0.13	0.68%
95	1:20	0.12	0.04	0.122	1.49	0.698	0.112	1.46	1.35	0.317	0.108	0.151	0.339	0.259	0.0188	1.65	0	3	2	0.13	0.68%
96	1:20	0.12	0.02	0.129	2.91	0.698	0.129	2.91	2.47	0.591	0.127	0.157	0.339	0.259	0.0188	1.65	0	0	5	0.31	1.69%
97	1:20	0.06	0.04	0.061	0.98	0.562	0.054	0.98	0.94	0.262	0.052	0.073	0.203	0.123	0.0188	1.65	0	0	0		
98	1:20	0.06	0.02	0.059	1.49	0.562	0.054	1.56	1.35	0.338	0.052	0.078	0.203	0.123	0.0188	1.65	0	0	0		
99	1:20	0.08	0.04	0.079	1.14	0.562	0.071	1.14	1.06	0.271	0.068	0.091	0.203	0.123	0.0188	1.65	1	0	1	0.06	0.34%
100	1:20	0.08	0.02	0.084	2.07	0.562	0.079	2.07	1.79	0.427	0.077	0.113	0.203	0.123	0.0188	1.65	1	0	2	0.13	0.68%
101	1:20	0.10	0.04	0.098	1.33	0.562	0.088	1.31	1.19	0.286	0.085	0.114	0.203	0.123	0.0188	1.65	2	1	4	0.25	1.36%
102	1:20	0.10	0.02	0.109	2.46	0.562	0.103	2.46	2.10	0.466	0.105	0.145	0.203	0.123	0.0188	1.65	5	5	15	0.94	5.08%
103	1:20	0.12	0.04	0.117	1.56	0.562	0.103	1.56	1.37	0.324	0.101	0.142	0.203	0.123	0.0188	1.65	1	0	10	0.63	3.39%
104	1:20	0.12	0.02	0.129	2.67	0.562	0.122	2.91	2.34	0.484	0.127	0.162	0.203	0.123	0.0188	1.65	0	5	21	1.32	7.12%
105	1:20	0.06	0.04	0.060	1.05	0.512	0.053	0.98	0.96	0.257	0.052	0.072	0.153	0.073	0.0188	1.65	0	0	0		
106	1:20	0.06	0.02	0.059	1.49	0.512	0.054	1.46	1.36	0.302	0.054	0.081	0.153	0.073	0.0188	1.65	4	0	4	0.25	1.36%
107	1:20	0.08	0.04	0.079	1.14	0.512	0.071	1.14	1.07	0.239	0.068	0.091	0.153	0.073	0.0188	1.65	2	1	6	0.38	2.03%
108	1:20	0.08	0.02	0.089	2.00	0.512	0.080	2.07	1.77	0.363	0.081	0.116	0.153	0.073	0.0188	1.65	3	1	11	0.69	3.73%
109	1:20	0.10	0.04	0.100	1.28	0.512	0.089	1.28	1.19	0.246	0.087	0.115	0.153	0.073	0.0188	1.65	3	2	12	0.75	4.07%
110	1:20	0.10	0.02	0.112	2.37	0.512	0.100	2.37	2.08	0.436	0.102	0.135	0.153	0.073	0.0188	1.65	14	8	38	2.38	12.88%
111	1:20	0.12	0.04	0.117	1.49	0.512	0.102	1.56	1.36	0.300	0.101	0.137	0.153	0.073	0.0188	1.65	2	-3	28	1.75	9.49%
112	1:20	0.12	0.02	0.121	2.67	0.512	0.110	2.91	2.36	0.465	0.113	0.137	0.153	0.073	0.0188	1.65	-6	9	40	2.51	13.56%
113	1:20	0.06	0.04	0.062	0.98	0.698	0.056	0.98	1.06	0.212	0.051	0.070	0.339	0.259	0.0215	1.70	0	0	0		

114	1:20	0.06	0.02	0.060	1.49	0.698	0.056	1.56	1.19	0.318	0.070	0.096	0.339	0.259	0.0215	1.70	0	0	0		
115	1:20	0.08	0.04	0.080	1.14	0.698	0.073	1.21	1.36	0.231	0.091	0.135	0.339	0.259	0.0215	1.70	0	0	0		
116	1:20	0.08	0.02	0.088	2.00	0.698	0.085	2.07	1.50	0.438	0.103	0.142	0.339	0.259	0.0215	1.70	1	0	1	0.07	0.51%
117	1:20	0.10	0.04	0.101	1.28	0.698	0.094	1.28	1.06	0.260	0.052	0.073	0.339	0.259	0.0215	1.70	0	0	1	0.07	0.51%
118	1:20	0.10	0.02	0.114	2.29	0.698	0.113	2.37	1.18	0.497	0.069	0.095	0.339	0.259	0.0215	1.70	1	0	2	0.14	1.01%
119	1:20	0.12	0.04	0.122	1.49	0.698	0.112	1.46	1.35	0.317	0.086	0.121	0.339	0.259	0.0215	1.70	0	2	2	0.14	1.01%
120	1:20	0.12	0.02	0.129	2.91	0.698	0.129	2.91	1.46	0.591	0.106	0.146	0.339	0.259	0.0215	1.70	0	0	4	0.29	2.03%
121	1:20	0.06	0.04	0.061	0.98	0.562	0.054	0.98	1.07	0.262	0.049	0.067	0.203	0.123	0.0215	1.70	0	0	0		
122	1:20	0.06	0.02	0.059	1.49	0.562	0.054	1.56	1.19	0.338	0.066	0.090	0.203	0.123	0.0215	1.70	0	0	0		
123	1:20	0.08	0.04	0.079	1.14	0.562	0.071	1.14	1.34	0.271	0.083	0.116	0.203	0.123	0.0215	1.70	0	0	0		
124	1:20	0.08	0.02	0.084	2.07	0.562	0.079	2.07	1.44	0.427	0.096	0.126	0.203	0.123	0.0215	1.70	5	1	6	0.43	3.04%
125	1:20	0.10	0.04	0.098	1.33	0.562	0.088	1.31	0.96	0.286	0.050	0.069	0.203	0.123	0.0215	1.70	1	0	6	0.43	3.04%
126	1:20	0.10	0.02	0.109	2.46	0.562	0.103	2.46	1.34	0.466	0.055	0.082	0.203	0.123	0.0215	1.70	1	0	8	0.57	4.06%
127	1:20	0.12	0.04	0.117	1.56	0.562	0.103	1.56	1.07	0.324	0.068	0.091	0.203	0.123	0.0215	1.70	-1	0	6	0.43	3.04%
128	1:20	0.12	0.02	0.129	2.67	0.562	0.122	2.91	1.72	0.484	0.077	0.109	0.203	0.123	0.0215	1.70	1	3	11	0.79	5.58%
129	1:20	0.06	0.04	0.060	1.05	0.512	0.053	0.98	1.19	0.257	0.083	0.109	0.153	0.073	0.0215	1.70	0	0	0		
130	1:20	0.06	0.02	0.059	1.49	0.512	0.054	1.46	2.04	0.302	0.096	0.129	0.153	0.073	0.0215	1.70	4	0	4	0.29	2.03%
131	1:20	0.08	0.04	0.079	1.14	0.512	0.071	1.14	1.34	0.239	0.097	0.123	0.153	0.073	0.0215	1.70	0	0	4	0.29	2.03%
132	1:20	0.08	0.02	0.089	2.00	0.512	0.080	2.07	2.35	0.363	0.103	0.126	0.153	0.073	0.0215	1.70	3	2	9	0.65	4.56%
133	1:20	0.10	0.04	0.100	1.28	0.512	0.089	1.28	0.96	0.246	0.049	0.066	0.153	0.073	0.0215	1.70	2	0	9	0.65	4.56%
134	1:20	0.10	0.02	0.112	2.37	0.512	0.100	2.37	1.34	0.436	0.056	0.084	0.153	0.073	0.0215	1.70	6	6	23	1.65	11.66%
135	1:20	0.12	0.04	0.117	1.49	0.512	0.102	1.56	1.06	0.300	0.069	0.089	0.153	0.073	0.0215	1.70	-1	-1	14	1.00	7.10%
136	1:20	0.12	0.02	0.121	2.67	0.512	0.110	2.91	1.70	0.465	0.077	0.105	0.153	0.073	0.0215	1.70	2	-1	22	1.58	11.15%
137	1:20	0.06	0.03	0.059	1.14	0.612	0.052	1.16	1.18	0.271	0.084	0.105	0.253	0.173	0.0215	1.70	0	0	0		

138	1:20	0.08	0.03	0.083	1.28	0.612	0.072	1.33	2.03	0.297	0.094	0.121	0.253	0.173	0.0215	1.70	0	0	0		
139	1:20	0.10	0.03	0.107	1.46	0.612	0.093	1.49	1.33	0.339	0.093	0.115	0.253	0.173	0.0215	1.70	3	0	3	0.22	1.52%
140	1:20	0.12	0.03	0.122	1.73	0.612	0.106	1.64	2.36	0.389	0.096	0.117	0.253	0.173	0.0215	1.70	0	0	3	0.22	1.52%
141	1:20	0.06	0.03	0.059	1.16	0.562	0.053	1.16	0.95	0.299	0.050	0.068	0.203	0.123	0.0215	1.70	1	0	1	0.07	0.51%
142	1:20	0.08	0.03	0.078	1.31	0.562	0.070	1.33	1.32	0.307	0.053	0.079	0.203	0.123	0.0215	1.70	0	0	1	0.07	0.51%
143	1:20	0.10	0.03	0.098	1.46	0.562	0.088	1.49	1.05	0.336	0.067	0.086	0.203	0.123	0.0215	1.70	2	0	3	0.22	1.52%
144	1:20	0.12	0.03	0.120	1.73	0.562	0.106	1.73	1.70	0.363	0.070	0.094	0.203	0.123	0.0215	1.70	5	0	8	0.57	4.06%
145	1:20	0.06	0.03	0.058	1.14	0.512	0.050	1.16	1.19	0.268	0.077	0.098	0.153	0.073	0.0215	1.70	0	0	0		
146	1:20	0.08	0.03	0.076	1.28	0.512	0.067	1.26	2.08	0.269	0.083	0.103	0.153	0.073	0.0215	1.70	3	1	4	0.29	2.03%
147	1:20	0.10	0.03	0.095	1.46	0.512	0.082	1.46	1.35	0.296	0.085	0.104	0.153	0.073	0.0215	1.70	3	1	8	0.57	4.06%
148	1:20	0.12	0.03	0.114	1.73	0.512	0.095	1.73	2.35	0.316	0.086	0.107	0.153	0.073	0.0215	1.70	2	1	11	0.79	5.58%
149	1:20	0.06	0.04	0.058	0.98	0.492	0.051	1.02	0.95	0.232	0.053	0.068	0.133	0.053	0.0215	1.70	0	0	0		
150	1:20	0.06	0.02	0.060	1.46	0.492	0.055	1.49	1.32	0.286	0.058	0.078	0.133	0.053	0.0215	1.70	3	1	4	0.29	2.03%
151	1:20	0.08	0.04	0.078	1.16	0.492	0.069	1.16	1.04	0.222	0.070	0.084	0.133	0.053	0.0215	1.70	0	0	3	0.22	1.52%
152	1:20	0.08	0.02	0.080	2.07	0.492	0.073	2.07	1.71	0.365	0.068	0.082	0.133	0.053	0.0215	1.70	-1	0	3	0.22	1.52%
153	1:20	0.10	0.04	0.099	1.28	0.492	0.085	1.28	1.18	0.235	0.074	0.087	0.133	0.053	0.0215	1.70	0	0	2	0.14	1.01%
154	1:20	0.10	0.02	0.100	2.37	0.492	0.089	2.37	2.10	0.432	0.076	0.096	0.133	0.053	0.0215	1.70	9	6	18	1.29	9.13%
155	1:20	0.12	0.04	0.119	1.46	0.492	0.097	1.46	1.36	0.284	0.079	0.095	0.133	0.053	0.0215	1.70	3	0	14	1.00	7.10%
156	1:20	0.12	0.02	0.118	2.67	0.492	0.099	2.91	2.42	0.483	0.078	0.096	0.133	0.053	0.0215	1.70	-1	3	23	1.65	11.66%
157	1:20	0.06	0.04	0.058	0.98	0.472	0.050	1.02	0.94	0.180	0.055	0.076	0.113	0.033	0.0215	1.70	1	0	1	0.07	0.51%
158	1:20	0.06	0.02	0.062	1.46	0.472	0.056	1.49	1.35	0.247	0.054	0.078	0.113	0.033	0.0215	1.70	1	0	2	0.14	1.01%
159	1:20	0.08	0.04	0.080	1.16	0.472	0.070	1.16	1.06	0.187	0.071	0.096	0.113	0.033	0.0215	1.70	2	0	4	0.29	2.03%
160	1:20	0.08	0.02	0.085	2.07	0.472	0.073	2.07	1.81	0.345	0.081	0.113	0.113	0.033	0.0215	1.70	4	1	9	0.65	4.56%
161	1:20	0.10	0.04	0.102	1.31	0.472	0.085	1.33	1.19	0.222	0.090	0.121	0.113	0.033	0.0215	1.70	0	0	8	0.57	4.06%

162	1:20	0.10	0.02	0.105	2.37	0.472	0.087	2.37	2.16	0.427	0.107	0.153	0.113	0.033	0.0215	1.70	4	8	21	1.51	10.65%
163	1:20	0.12	0.04	0.124	1.46	0.472	0.096	1.46	1.35	0.272	0.108	0.151	0.113	0.033	0.0215	1.70	2	-2	14	1.00	7.10%
164	1:20	0.12	0.02	0.123	2.67	0.472	0.095	2.91	2.47	0.496	0.127	0.157	0.113	0.033	0.0215	1.70	-2	6	25	1.79	12.68%
165	1:20	0.06	0.04	0.058	0.98	0.452	0.051	1.02	0.94	0.141	0.052	0.073	0.093	0.013	0.0215	1.70	0	0	0		
166	1:20	0.06	0.02	0.058	1.46	0.452	0.053	1.49	1.35	0.241	0.052	0.078	0.093	0.013	0.0215	1.70	6	0	6	0.43	3.04%
167	1:20	0.08	0.04	0.079	1.14	0.452	0.068	1.16	1.06	0.185	0.068	0.091	0.093	0.013	0.0215	1.70	0	0	6	0.43	3.04%
168	1:20	0.08	0.02	0.077	2.07	0.452	0.066	2.00	1.79	0.323	0.077	0.113	0.093	0.013	0.0215	1.70	3	4	13	0.93	6.59%
169	1:20	0.10	0.04	0.098	1.31	0.452	0.080	1.33	1.19	0.219	0.085	0.114	0.093	0.013	0.0215	1.70	4	-1	13	0.93	6.59%
170	1:20	0.10	0.02	0.098	2.37	0.452	0.080	2.37	2.10	0.420	0.105	0.145	0.093	0.013	0.0215	1.70	-1	5	20	1.43	10.14%
171	1:20	0.12	0.04	0.118	1.46	0.452	0.088	1.52	1.37	0.271	0.101	0.142	0.093	0.013	0.0215	1.70	0	1	12	0.86	6.08%
172	1:20	0.12	0.02	0.116	2.91	0.452	0.086	2.91	2.34	0.498	0.127	0.162	0.093	0.013	0.0215	1.70	-4	11	28	2.01	14.20%
173	1:20	0.06	0.04	0.062	0.98	0.432	0.054	1.07	0.96	0.208	0.052	0.072	0.073	-0.007	0.0215	1.70	1	0	1	0.07	0.51%
174	1:20	0.06	0.02	0.065	1.49	0.432	0.057	1.49	1.36	0.262	0.054	0.081	0.073	-0.007	0.0215	1.70	4	0	5	0.36	2.54%
175	1:20	0.08	0.04	0.086	1.14	0.432	0.071	1.19	1.07	0.234	0.068	0.091	0.073	-0.007	0.0215	1.70	0	0	5	0.36	2.54%
176	1:20	0.08	0.02	0.086	2.07	0.432	0.066	2.00	1.77	0.318	0.081	0.116	0.073	-0.007	0.0215	1.70	4	2	11	0.79	5.58%
177	1:20	0.10	0.04	0.106	1.31	0.432	0.078	1.33	1.19	0.238	0.087	0.115	0.073	-0.007	0.0215	1.70	0	0	9	0.65	4.56%
178	1:20	0.10	0.02	0.105	2.37	0.432	0.075	2.56	2.08	0.413	0.102	0.135	0.073	-0.007	0.0215	1.70	-7	12	16	1.15	8.11%
179	1:20	0.12	0.04	0.126	1.46	0.432	0.083	1.73	1.36	0.280	0.101	0.137	0.073	-0.007	0.0215	1.70	3	0	5	0.36	2.54%
180	1:20	0.12	0.02	0.127	2.91	0.432	0.080	2.91	2.36	0.498	0.113	0.137	0.073	-0.007	0.0215	1.70	-5	11	25	1.79	12.68%
181	1:20	0.06	0.03	0.059	1.14	0.612	0.052	1.16	1.06	0.271	0.051	0.070	0.253	0.173	0.0268	1.75	0	0	0		
182	1:20	0.08	0.03	0.083	1.28	0.612	0.072	1.33	1.19	0.297	0.070	0.096	0.253	0.173	0.0268	1.75	0	0	0		
183	1:20	0.10	0.03	0.107	1.46	0.612	0.093	1.49	1.36	0.339	0.091	0.135	0.253	0.173	0.0268	1.75	0	0	0		
184	1:20	0.12	0.03	0.122	1.73	0.612	0.106	1.64	1.50	0.389	0.103	0.142	0.253	0.173	0.0268	1.75	0	0	0		
185	1:20	0.06	0.03	0.059	1.16	0.562	0.053	1.16	1.06	0.299	0.052	0.073	0.203	0.123	0.0268	1.75	0	0	0		

186	1:20	0.08	0.03	0.078	1.31	0.562	0.070	1.33	1.18	0.307	0.069	0.095	0.203	0.123	0.0268	1.75	0	0	0		
187	1:20	0.10	0.03	0.098	1.46	0.562	0.088	1.49	1.35	0.336	0.086	0.121	0.203	0.123	0.0268	1.75	0	0	0		
188	1:20	0.12	0.03	0.120	1.73	0.562	0.106	1.73	1.46	0.363	0.106	0.146	0.203	0.123	0.0268	1.75	0	0	0		
189	1:20	0.06	0.03	0.058	1.14	0.512	0.050	1.16	1.07	0.268	0.049	0.067	0.153	0.073	0.0268	1.75	0	0	0		
190	1:20	0.08	0.03	0.076	1.28	0.512	0.067	1.26	1.19	0.269	0.066	0.090	0.153	0.073	0.0268	1.75	1	0	1	0.09	0.98%
191	1:20	0.10	0.03	0.095	1.46	0.512	0.082	1.46	1.34	0.296	0.083	0.116	0.153	0.073	0.0268	1.75	0	0	1	0.09	0.98%
192	1:20	0.12	0.03	0.114	1.73	0.512	0.095	1.73	1.44	0.316	0.096	0.126	0.153	0.073	0.0268	1.75	2	0	3	0.27	2.95%
193	1:20	0.06	0.04	0.058	0.98	0.492	0.051	1.02	0.96	0.232	0.050	0.069	0.133	0.053	0.0268	1.75	0	0	0		
194	1:20	0.06	0.02	0.060	1.46	0.492	0.055	1.49	1.34	0.286	0.055	0.082	0.133	0.053	0.0268	1.75	1	0	1	0.09	0.98%
195	1:20	0.08	0.04	0.078	1.16	0.492	0.069	1.16	1.07	0.222	0.068	0.091	0.133	0.053	0.0268	1.75	0	0	1	0.09	0.98%
196	1:20	0.08	0.02	0.080	2.07	0.492	0.073	2.07	1.72	0.365	0.077	0.109	0.133	0.053	0.0268	1.75	0	1	2	0.18	1.96%
197	1:20	0.10	0.04	0.099	1.28	0.492	0.085	1.28	1.19	0.235	0.083	0.109	0.133	0.053	0.0268	1.75	0	0	1	0.09	0.98%
198	1:20	0.10	0.02	0.100	2.37	0.492	0.089	2.37	2.04	0.432	0.096	0.129	0.133	0.053	0.0268	1.75	5	1	8	0.71	7.86%
199	1:20	0.12	0.04	0.119	1.46	0.492	0.097	1.46	1.34	0.284	0.097	0.123	0.133	0.053	0.0268	1.75	1	0	7	0.63	6.87%
200	1:20	0.12	0.02	0.118	2.67	0.492	0.099	2.91	2.35	0.483	0.103	0.126	0.133	0.053	0.0268	1.75	3	1	13	1.16	12.77%
201	1:20	0.06	0.04	0.058	0.98	0.472	0.050	1.02	0.96	0.180	0.049	0.066	0.113	0.033	0.0268	1.75	0	0	0		
202	1:20	0.06	0.02	0.062	1.46	0.472	0.056	1.49	1.34	0.247	0.056	0.084	0.113	0.033	0.0268	1.75	2	0	2	0.18	1.96%
203	1:20	0.08	0.04	0.080	1.16	0.472	0.070	1.16	1.06	0.187	0.069	0.089	0.113	0.033	0.0268	1.75	1	0	3	0.27	2.95%
204	1:20	0.08	0.02	0.085	2.07	0.472	0.073	2.07	1.70	0.345	0.077	0.105	0.113	0.033	0.0268	1.75	1	0	4	0.36	3.93%
205	1:20	0.10	0.04	0.102	1.31	0.472	0.085	1.33	1.18	0.222	0.084	0.105	0.113	0.033	0.0268	1.75	0	0	4	0.36	3.93%
206	1:20	0.10	0.02	0.105	2.37	0.472	0.087	2.37	2.03	0.427	0.094	0.121	0.113	0.033	0.0268	1.75	4	2	10	0.89	9.82%
207	1:20	0.12	0.04	0.124	1.46	0.472	0.096	1.46	1.33	0.272	0.093	0.115	0.113	0.033	0.0268	1.75	0	-1	8	0.71	7.86%
208	1:20	0.12	0.02	0.123	2.67	0.472	0.095	2.91	2.36	0.496	0.096	0.117	0.113	0.033	0.0268	1.75	-2	2	9	0.80	8.84%
209	1:20	0.06	0.04	0.058	0.98	0.452	0.051	1.02	0.95	0.141	0.050	0.068	0.093	0.013	0.0268	1.75	0	0	0		

210	1:20	0.06	0.02	0.058	1.46	0.452	0.053	1.49	1.32	0.241	0.053	0.079	0.093	0.013	0.0268	1.75	0	0	0		
211	1:20	0.08	0.04	0.079	1.14	0.452	0.068	1.16	1.05	0.185	0.067	0.086	0.093	0.013	0.0268	1.75	0	0	0		
212	1:20	0.08	0.02	0.077	2.07	0.452	0.066	2.00	1.70	0.323	0.070	0.094	0.093	0.013	0.0268	1.75	1	2	3	0.27	2.95%
213	1:20	0.10	0.04	0.098	1.31	0.452	0.080	1.33	1.19	0.219	0.077	0.098	0.093	0.013	0.0268	1.75	0	0	1	0.09	0.98%
214	1:20	0.10	0.02	0.098	2.37	0.452	0.080	2.37	2.08	0.420	0.083	0.103	0.093	0.013	0.0268	1.75	1	2	6	0.54	5.89%
215	1:20	0.12	0.04	0.118	1.46	0.452	0.088	1.52	1.35	0.271	0.085	0.104	0.093	0.013	0.0268	1.75	0	0	2	0.18	1.96%
216	1:20	0.12	0.02	0.116	2.91	0.452	0.086	2.91	2.35	0.498	0.086	0.107	0.093	0.013	0.0268	1.75	2	0	8	0.71	7.86%
217	1:20	0.06	0.04	0.062	0.98	0.432	0.054	1.07	0.95	0.208	0.053	0.068	0.073	-0.007	0.0268	1.75	1	0	1	0.09	0.98%
218	1:20	0.06	0.02	0.065	1.49	0.432	0.057	1.49	1.32	0.262	0.058	0.078	0.073	-0.007	0.0268	1.75	0	0	1		
219	1:20	0.08	0.04	0.086	1.14	0.432	0.071	1.19	1.04	0.234	0.070	0.084	0.073	-0.007	0.0268	1.75	0	0	1	0.09	0.98%
220	1:20	0.08	0.02	0.086	2.07	0.432	0.066	2.00	1.71	0.318	0.068	0.082	0.073	-0.007	0.0268	1.75	1	2	4	0.36	3.93%
221	1:20	0.10	0.04	0.106	1.31	0.432	0.078	1.33	1.18	0.238	0.074	0.087	0.073	-0.007	0.0268	1.75	0	0	2	0.18	1.96%
222	1:20	0.10	0.02	0.105	2.37	0.432	0.075	2.56	2.10	0.413	0.076	0.096	0.073	-0.007	0.0268	1.75	0	1	5	0.45	4.91%
223	1:20	0.12	0.04	0.126	1.46	0.432	0.083	1.73	1.36	0.280	0.079	0.095	0.073	-0.007	0.0268	1.75	1	0	3	0.27	2.95%
224	1:20	0.12	0.02	0.127	2.91	0.432	0.080	2.91	2.42	0.498	0.078	0.096	0.073	-0.007	0.0268	1.75	-2	3	7	0.63	6.87%
225	1:10	0.06	0.03	0.061	1.14	0.607	0.056	1.14	1.07	0.280	0.054	0.074	0.253	0.173	0.0215	1.70	0	0	0		
226	1:10	0.08	0.03	0.085	1.28	0.607	0.078	1.28	1.19	0.307	0.075	0.102	0.253	0.173	0.0215	1.70	0	0	0		
227	1:10	0.10	0.03	0.110	1.46	0.607	0.102	1.46	1.36	0.342	0.101	0.151	0.253	0.173	0.0215	1.70	7	1	8	0.57	4.06%
228	1:10	0.12	0.03	0.126	1.64	0.607	0.120	1.64	1.49	0.367	0.119	0.179	0.253	0.173	0.0215	1.70	2	2	12	0.86	6.08%
229	1:10	0.06	0.03	0.060	1.14	0.557	0.056	1.14	1.05	0.284	0.054	0.071	0.203	0.123	0.0215	1.70	0	1	1	0.07	0.51%
230	1:10	0.08	0.03	0.079	1.28	0.557	0.074	1.31	1.18	0.301	0.071	0.098	0.203	0.123	0.0215	1.70	1	0	2	0.14	1.01%
231	1:10	0.10	0.03	0.099	1.49	0.557	0.094	1.46	1.35	0.326	0.093	0.143	0.203	0.123	0.0215	1.70	7	0	9	0.65	4.56%
232	1:10	0.12	0.03	0.121	1.64	0.557	0.116	1.64	1.49	0.355	0.116	0.176	0.203	0.123	0.0215	1.70	10	1	20	1.43	10.14%
233	1:10	0.06	0.03	0.058	1.14	0.507	0.054	1.14	1.07	0.256	0.052	0.070	0.153	0.073	0.0215	1.70	1	0	1	0.07	0.51%

234	1:10	0.08	0.03	0.076	1.28	0.507	0.071	1.28	1.19	0.253	0.070	0.094	0.153	0.073	0.0215	1.70	5	0	6	0.43	3.04%
235	1:10	0.10	0.03	0.095	1.49	0.507	0.090	1.49	1.36	0.293	0.090	0.134	0.153	0.073	0.0215	1.70	13	4	23	1.65	11.66%
236	1:10	0.12	0.03	0.112	1.64	0.507	0.108	1.73	1.49	0.329	0.110	0.164	0.153	0.073	0.0215	1.70	23	-4	42	3.01	21.29%
237	1:10	0.06	0.04	0.059	0.98	0.487	0.054	0.98	0.95	0.212	0.052	0.069	0.133	0.053	0.0215	1.70	0	0	0		
238	1:10	0.06	0.02	0.061	1.49	0.487	0.058	1.49	1.36	0.255	0.058	0.089	0.133	0.053	0.0215	1.70	12	1	13	0.93	6.59%
239	1:10	0.08	0.04	0.080	1.14	0.487	0.073	1.14	1.06	0.194	0.071	0.095	0.133	0.053	0.0215	1.70	1	0	13	0.93	6.59%
240	1:10	0.08	0.02	0.081	2.00	0.487	0.083	2.07	1.82	0.380	0.084	0.124	0.133	0.053	0.0215	1.70	7	-1	20	1.43	10.14%
241	1:10	0.10	0.04	0.099	1.28	0.487	0.091	1.28	1.18	0.225	0.090	0.122	0.133	0.053	0.0215	1.70	10	-4	30	2.15	15.21%
242	1:10	0.10	0.02	0.107	2.29	0.487	0.109	2.29	2.14	0.448	0.112	0.172	0.133	0.053	0.0215	1.70	-10	2	18	1.29	9.13%
243	1:10	0.06	0.04	0.059	0.98	0.467	0.055	0.98	0.95	0.150	0.052	0.072	0.113	0.033	0.0215	1.70	2	0	2	0.14	1.01%
244	1:10	0.06	0.02	0.061	1.49	0.467	0.060	1.49	1.36	0.240	0.060	0.092	0.113	0.033	0.0215	1.70	11	0	13	0.93	6.59%
245	1:10	0.08	0.04	0.080	1.14	0.467	0.075	1.14	1.06	0.175	0.073	0.096	0.113	0.033	0.0215	1.70	5	0	18	1.29	9.13%
246	1:10	0.08	0.02	0.085	2.07	0.467	0.086	2.07	1.82	0.386	0.088	0.126	0.113	0.033	0.0215	1.70	6	10	34	2.44	17.24%
247	1:10	0.10	0.04	0.101	1.28	0.467	0.093	1.28	1.18	0.225	0.092	0.122	0.113	0.033	0.0215	1.70	13	-5	37	2.65	18.76%
248	1:10	0.10	0.02	0.103	2.37	0.467	0.105	2.37	2.14	0.461	0.109	0.148	0.113	0.033	0.0215	1.70	2	17	61	4.37	30.93%
249	1:10	0.06	0.04	0.058	0.98	0.447	0.054	0.98	0.95	0.124	0.052	0.071	0.093	0.013	0.0215	1.70	1	0	1	0.07	0.51%
250	1:10	0.06	0.02	0.058	1.49	0.447	0.056	1.56	1.36	0.251	0.056	0.087	0.093	0.013	0.0215	1.70	10	0	11	0.79	5.58%
251	1:10	0.08	0.04	0.077	1.14	0.447	0.073	1.14	1.05	0.169	0.071	0.095	0.093	0.013	0.0215	1.70	8	2	19	1.36	9.63%
252	1:10	0.08	0.02	0.077	2.07	0.447	0.079	2.07	1.83	0.383	0.081	0.116	0.093	0.013	0.0215	1.70	9	15	45	3.23	22.82%
253	1:10	0.10	0.04	0.096	1.28	0.447	0.088	1.28	1.17	0.231	0.088	0.116	0.093	0.013	0.0215	1.70	10	0	38	2.72	19.27%
254	1:10	0.10	0.02	0.099	2.46	0.447	0.100	2.56	2.15	0.457	0.105	0.151	0.093	0.013	0.0215	1.70	-2	6	59	4.23	29.91%
255	1:10	0.06	0.04	0.062	0.98	0.427	0.058	0.98	0.95	0.229	0.056	0.074	0.073	-0.007	0.0215	1.70	3	0	3	0.22	1.52%
256	1:10	0.06	0.02	0.064	1.49	0.427	0.063	1.56	1.35	0.296	0.064	0.092	0.073	-0.007	0.0215	1.70	9	3	15	1.08	7.61%
257	1:10	0.08	0.04	0.084	1.14	0.427	0.079	1.14	1.05	0.238	0.079	0.102	0.073	-0.007	0.0215	1.70	6	0	18	1.29	9.13%

258	1:10	0.08	0.02	0.085	2.07	0.427	0.086	2.07	1.86	0.414	0.088	0.122	0.073	-0.007	0.0215	1.70	8	18	47	3.37	23.83%
259	1:10	0.10	0.04	0.107	1.28	0.427	0.093	1.28	1.17	0.285	0.093	0.116	0.073	-0.007	0.0215	1.70	0	-2	26	1.86	13.18%
260	1:10	0.10	0.02	0.107	2.37	0.427	0.102	2.37	2.16	0.467	0.106	0.137	0.073	-0.007	0.0215	1.70	-2	14	57	4.09	28.90%
261	1:10	0.06	0.03	0.061	1.14	0.607	0.056	1.14	1.07	0.280	0.054	0.074	0.253	0.173	0.0268	1.75	0	0	0		
262	1:10	0.08	0.03	0.085	1.28	0.607	0.078	1.28	1.19	0.307	0.075	0.102	0.253	0.173	0.0268	1.75	1	0	1	0.09	0.98%
263	1:10	0.10	0.03	0.110	1.46	0.607	0.102	1.46	1.36	0.342	0.101	0.151	0.253	0.173	0.0268	1.75	2	1	4	0.36	3.93%
264	1:10	0.12	0.03	0.126	1.64	0.607	0.120	1.64	1.49	0.367	0.119	0.179	0.253	0.173	0.0268	1.75	5	2	11	0.98	10.80%
265	1:10	0.06	0.03	0.060	1.14	0.557	0.056	1.14	1.05	0.284	0.054	0.071	0.203	0.123	0.0268	1.75	0	0	0		
266	1:10	0.08	0.03	0.079	1.28	0.557	0.074	1.31	1.18	0.301	0.071	0.098	0.203	0.123	0.0268	1.75	0	0	0		
267	1:10	0.10	0.03	0.099	1.49	0.557	0.094	1.46	1.35	0.326	0.093	0.143	0.203	0.123	0.0268	1.75	4	0	4	0.36	3.93%
268	1:10	0.12	0.03	0.121	1.64	0.557	0.116	1.64	1.49	0.355	0.116	0.176	0.203	0.123	0.0268	1.75	8	1	13	1.16	12.77%
269	1:10	0.06	0.03	0.058	1.14	0.507	0.054	1.14	1.07	0.256	0.052	0.070	0.153	0.073	0.0268	1.75	0	0	0		
270	1:10	0.08	0.03	0.076	1.28	0.507	0.071	1.28	1.19	0.253	0.070	0.094	0.153	0.073	0.0268	1.75	0	0	0		
271	1:10	0.10	0.03	0.095	1.49	0.507	0.090	1.49	1.36	0.293	0.090	0.134	0.153	0.073	0.0268	1.75	17	1	18	1.61	17.68%
272	1:10	0.12	0.03	0.112	1.64	0.507	0.108	1.73	1.49	0.329	0.110	0.164	0.153	0.073	0.0268	1.75	12	1	31	2.77	30.44%
273	1:10	0.06	0.04	0.059	0.98	0.487	0.054	0.98	0.95	0.212	0.052	0.069	0.133	0.053	0.0268	1.75	0	0	0		
274	1:10	0.06	0.02	0.061	1.49	0.487	0.058	1.49	1.36	0.255	0.058	0.089	0.133	0.053	0.0268	1.75	1	0	1	0.09	0.98%
275	1:10	0.08	0.04	0.080	1.14	0.487	0.073	1.14	1.06	0.194	0.071	0.095	0.133	0.053	0.0268	1.75	2	0	3	0.27	2.95%
276	1:10	0.08	0.02	0.081	2.00	0.487	0.083	2.07	1.82	0.380	0.084	0.124	0.133	0.053	0.0268	1.75	14	3	20	1.79	19.64%
277	1:10	0.10	0.04	0.099	1.28	0.487	0.091	1.28	1.18	0.225	0.090	0.122	0.133	0.053	0.0268	1.75	7	-4	24	2.14	23.57%
278	1:10	0.10	0.02	0.107	2.29	0.487	0.109	2.29	2.14	0.448	0.112	0.172	0.133	0.053	0.0268	1.75	-5	1	19	1.70	18.66%
279	1:10	0.06	0.04	0.059	0.98	0.467	0.055	0.98	0.95	0.150	0.052	0.072	0.113	0.033	0.0268	1.75	1	0	1	0.09	0.98%
280	1:10	0.06	0.02	0.061	1.49	0.467	0.060	1.49	1.36	0.240	0.060	0.092	0.113	0.033	0.0268	1.75	5	0	6	0.54	5.89%
281	1:10	0.08	0.04	0.080	1.14	0.467	0.075	1.14	1.06	0.175	0.073	0.096	0.113	0.033	0.0268	1.75	1	1	7	0.63	6.87%

282	1:10	0.08	0.02	0.085	2.07	0.467	0.086	2.07	1.82	0.386	0.088	0.126	0.113	0.033	0.0268	1.75	12	5	25	2.23	24.55%
283	1:10	0.10	0.04	0.101	1.28	0.467	0.093	1.28	1.18	0.225	0.092	0.122	0.113	0.033	0.0268	1.75	7	-3	26	2.32	25.53%
284	1:10	0.10	0.02	0.103	2.37	0.467	0.105	2.37	2.14	0.461	0.109	0.148	0.113	0.033	0.0268	1.75	-7	9	31	2.77	30.44%
285	1:10	0.06	0.04	0.058	0.98	0.447	0.054	0.98	0.95	0.124	0.052	0.071	0.093	0.013	0.0268	1.75	2	0	2	0.18	1.96%
286	1:10	0.06	0.02	0.058	1.49	0.447	0.056	1.56	1.36	0.251	0.056	0.087	0.093	0.013	0.0268	1.75	5	0	7	0.63	6.87%
287	1:10	0.08	0.04	0.077	1.14	0.447	0.073	1.14	1.05	0.169	0.071	0.095	0.093	0.013	0.0268	1.75	2	1	9	0.80	8.84%
288	1:10	0.08	0.02	0.077	2.07	0.447	0.079	2.07	1.83	0.383	0.081	0.116	0.093	0.013	0.0268	1.75	4	8	22	1.97	21.60%
289	1:10	0.10	0.04	0.096	1.28	0.447	0.088	1.28	1.17	0.231	0.088	0.116	0.093	0.013	0.0268	1.75	11	-2	24	2.14	23.57%
290	1:10	0.10	0.02	0.099	2.46	0.447	0.100	2.56	2.15	0.457	0.105	0.151	0.093	0.013	0.0268	1.75	-6	6	31	2.77	30.44%
291	1:10	0.06	0.04	0.062	0.98	0.427	0.058	0.98	0.95	0.229	0.056	0.074	0.073	-0.007	0.0268	1.75	1	0	1	0.09	0.98%
292	1:10	0.06	0.02	0.064	1.49	0.427	0.063	1.56	1.35	0.296	0.064	0.092	0.073	-0.007	0.0268	1.75	2	4	7	0.63	6.87%
293	1:10	0.08	0.04	0.084	1.14	0.427	0.079	1.14	1.05	0.238	0.079	0.102	0.073	-0.007	0.0268	1.75	3	0	6	0.54	5.89%
294	1:10	0.08	0.02	0.085	2.07	0.427	0.086	2.07	1.86	0.414	0.088	0.122	0.073	-0.007	0.0268	1.75	-2	8	16	1.43	15.71%
295	1:10	0.10	0.04	0.107	1.28	0.427	0.093	1.28	1.17	0.285	0.093	0.116	0.073	-0.007	0.0268	1.75	0	0	4	0.36	3.93%
296	1:10	0.10	0.02	0.107	2.37	0.427	0.102	2.37	2.16	0.467	0.106	0.137	0.073	-0.007	0.0268	1.75	-1	8	23	2.05	22.59%