Protection of outfall structures

Master Thesis

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Wout Grote

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Delft University of Technology
Faculty of Civil Engineering
Hydraulic and Geotechnical Engineering Division
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Experimenting with models seems to afford a ready means of investigating and determining beforehand the effects of any proposed estuary or harbor works; a means, after what I have seen, I should feel it madness to neglect before entering upon any costly undertaking.

Osborne Reynolds

Preface

This report is written as an assignment for the Technical University of Delft, Faculty of Civil Engineering in order to fulfill the last official requirement for the degree of engineer, ir. (Master of Science).

First I would like to thank and express my gratitude to all the members of my thesis committee:

Prof. ir. K. d'Angremond, ir. G.J. Schiereck, Dr. ir. H.L. Fontijn, ir. C.J. Stam, Dr. ir. J. v.d. Meer and ir. M.H. Lindo for their counselling and advice during this study. A special note of thanks is owed to my day to day counsellor ir. G. J. Schiereck for his inspiring contributions.

Without any doubt I would still be working and experimenting in the large wave flume if there hadn't been a great laboratory supporting staff. I would like to sincerely thank K. de Bruin, J. van Duin, F. Kalkman and J. Groeneveld for their efforts during my stay in the Laboratory of Fluid Mechanics. I also wish to thank ir. P. de Wit for his assistance in the correct usage of the instruments involved.

The model structure could not have been built without the help of B. Grasmeyer who was a student assistent during the construction phase. I like to thank him for teaching me the ins and outs of the 'lange speurwerkgoot'.

Wout Grote
Delft, August 20, 1994

Abstract

Stability of rock on horizontal bottoms and steep slopes subjected to wave attack has been a subject of investigation in the past. But the stability of rock on gentle slopes has not been investigated systematically. The objective of this research is to investigate the relations between the different variables involved. A possible application is the protection of outfall structures.

Due to the lack of information on this subject, relations derived for stability of rock on horizontal bottoms subjected to wave attack were applied. Application of these theories imply a destabilization of the rock by orbital velocities causing shear stresses at the bottom. Orbital velocities were calculated along the profile of the structure with the linear wave theory and substituted in the stability relations for horizontal bottoms according to the theories of Rance & Warren and Jonsson / Sleath, respectively. The results of the calculations were expressed in the stability variable $H/\Delta D_{n50}$ versus the relative water-depth, h/H. This was done for regular as well as for irregular waves. The calculations showed an increase in the stability for increasing values of the wave steepness. Also, the deeper the water the higher the stability values.

Experiments were conducted in the large wave flume of the Laboratory of Fluid Mechanics at the Delft University of Technology. The model consisted of an impermeable 1:25 slope, on which several materials were tested. Regular and irregular waves were applied and for various conditions the wave heights and bottom velocities along the test slope were measured.

The experimental results were compared with the calculations. For regular waves it appeared that for h/H values larger than one the calculations describe the stability of the rock quite well. For h/H values smaller than one the calculations are not adequate to describe the stability of the rock. The location of maximum attack was around h/H = 1. For irregular waves the location of attack was not that clear. The damage was not as concentrated and more spread out. The location of maximum attack was around $h/H_s = 1$. For both regular as irregular waves the general tendency could be described by the calculations but the 'plunging' effect of the more curl-shaped waves with lower values of the wave steepness resulted into a more severe attack on the structure. For irregular waves more experiments have to be conducted for the slope section where waves are not yet broken. This to confirm or reject the theories derived applied to horizontal bottoms for the stability of rock on gentle slopes attacked by irregular waves.

To investigate whether the computer simulation ODIFLOCS, can be used to simulate wave motion on gentle slopes, a comparison was made with the measurements in the experimental model. ODIFLOCS proved not to be suitable for simulation of wave motion on gentle slopes, mainly due to short comings of the numerical scheme used by ODIFLOCS which was developed for 'short' steep slopes.

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Appendix XI **Stability calculation according to Rance & Warren and Jonsson / Sleath with the software package Mathcad**

1 Introduction

1.1 General

When a pipeline crosses a beach, for example in the case of an oil pipeline or a sewage outfall, a protection against erosion and wave attack is needed. This is realized by a filter layer and a protection layer of rock. A schematic representation of the structure is given in figure 1.1. Much research has been done on the stability of rock on horizontal bottoms and steep slopes subjected to wave attack. But the stability of rock on gentle slopes in the breaker zone has not been extensively dealt with as a subject of investigation, until now.

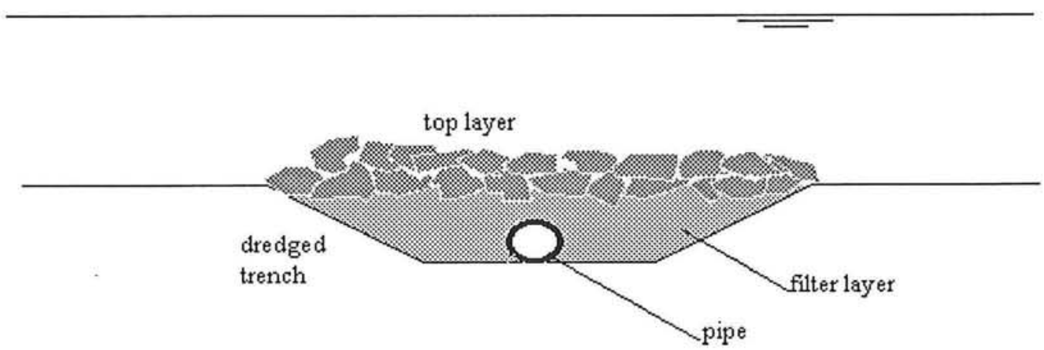


figure 1.1: Construction of a pipe protection

1.2 Background of the research

The research done in this thesis is a continuation of the research conducted by P. Sistermans for his Master thesis, Stabilility of Rock on Beaches (1993). Due to the lack of research dealing with this subject and the gentle slopes involved (nearly horizontal), Sistermans used theories of incipience of motion of rock on horizontal bottoms for the incipience of motion of rock on slopes with breaking waves. In this schematization orbital velocities due to wave motion were substituted. The schematization is based on the presumption that the orbital bottom-velocities at the point of breaking cause the critical forces acting on the rocks. This was not verified after conducting experiments. For regular waves maximum damage occurs directly beyond the point of breaking, which means that the most endangered position is there where most wave energy is dissipated. For irregular waves the tendency in instability proved to be maximum around the run-up region, that is around the still-water level. The conclusion can be drawn that instability on gentle slopes can not only be related to orbital velocities, but should also be related to the forces caused by "plunging" characteristics of the breaking waves and high run-up velocities. When a wave breaks according to a "plunging" breaker type, the wave attack can be seen as a water jet hitting the bottom. See figure 1.2.

figure 1.2: A "plunging" wave attacking the bottom (Fredsøe and Deigaard, 1992)

Sistermans (1993) measured only damage in the region of the slope where the waves break, see figure 1.3. In this region the instability to the stones is not caused by the orbital velocities only and therefore the used stability relations are not correctly applied. But on the slope section where no waves break, approximatily $h \geq 1.25 \cdot H$, (h is the water depth and H is the wave height), the orbital velocities may play a more dominating role, which could result in a stability relation according to the combination of theories as applied by Sistermans. So it might be better to divide the approach of stability of rocks on gentle slopes in two sections: one applied from the deep water region to the outer region (before the wave breaking point), whereas the other covers the outer region and the inner region. See figure 1.3.

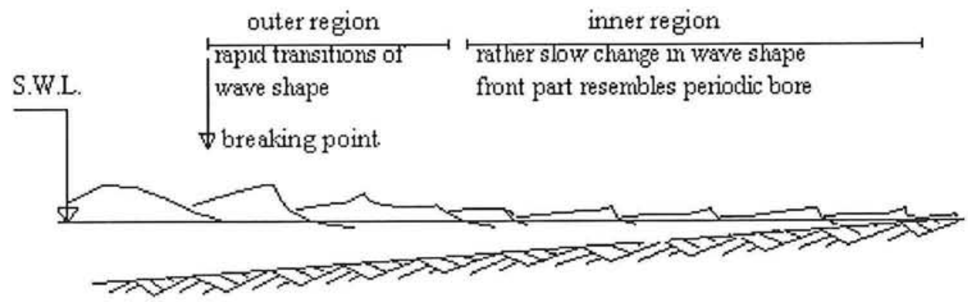


figure 1.3: Wave characteristics in the surf-zone (after Svendsen et al., 1978)

The results of the experimental research by Sistermans (1993) are presented as design formulae with dimensionless variables like $H/\Delta D_{n50}$ and ξ (H = wave height, Δ = relative mass density, D_{n50} = nominal stone diameter and ξ is the breaker index). These dimensionless variables are composed of independent variables, which might have their own influence on the stability of the rock on gentle slopes. However, these variables are not varied in the experiments, with exception of the wave steepness. So the presentation of the experimental results according to Sistermans are actually only valid for the values of the variables they are tested for.

1.3 Objective and scope of the present study

The objective of the present study is to investigate the relation between the different variables involved in the stability of stone on gentle slopes, subjected to wave attack.

This report gives a selection and a description of the variables dealing with stability of rock on gentle slopes, and dimensionless variables are generated.

A new and critical evaluation of the existing theories for stability of rock on horizontal bottoms is made. This despite the disappointing results found by Sistermans (1993), who compared theories for the incipience of motion of rock on horizontal bottoms with the incipience of motion of rock on gentle slopes.

The generated dimensionless variables were varied for various test in a laboratory situation. Both regular and irregular waves were applied: regular waves to get more insight in the processes involved and to compare results with possible theorectical derived stability relations, and irregular waves to represent a natural situation and to gain more information for possible design formulae.

Finally a set of test runs was made with the computer simulation program ODIFLOCS (One Dimensional Flow on and in Coastal Structures), in order to compare and to find out whether this program simulates the motion of waves on gentle slopes correctly.

2 Governing Variables

2.1 Overall view

Till recently in coastal engineering models were widely used. However nowadays scale models are less used because of numerical modelling with the aid of computers. Still physical models are needed in cases where no or at least not enough theoretical insight into the the process is available. Physical models are also used to verify numerical models and to confirm formulae and coefficients of semi-emperical theories used in numerical models.

Stability of coastal structures has mostly been investigated with physical models because the process can not or only partially be described by theory. Also the structures and forces acting upon them are relatively easy to reproduce on a small scale.

The results obtained in model experiments can be translated to prototype results by means of scaling. This should be done according to scale rules, De Vries (1977). If one neglects these scale rules, scale effects might influence the results found. One should consider the limitations and be careful in up scaling results found with a model to a prototype. For scaling and scale effects concerning this reseach see section 6.5.1.

The variables involved effecting coastal structures attacked by waves can be divided into two groups: the environmental variables and the structural variables. The environmental variables describe the water motion acting upon the structure, representing the loads. The structural variables are used to describe the structure itself. They represent the strength of the structure. It is possible for a designer to influence the structural variables, for example the size of the rock, but it is impossible to influence the environmental variables, like the wave period. Combinations of these two types of variables determine the damage on the structure. The variables will be discussed in section 2.4 and 2.5.

2.2 Stability

In breakwater design a division is made between static stability and dynamic stability. According to Van der Meer (1988), statically stable structrures are structures where no or minor damage is allowed under design conditions. Dynamically stable structures are structures where profile development is accepted. Armour units are displaced by wave action until a profile has reached an equilibrium. In the case of an outfall through the breakerzone on a gentle slope only a certain necessary amount of filter and rock layer will be placed. So, no or little damage is permitted to the structure. The profile has to be statically stable.

2.3 Damage

Damage could be defined by the amount of displacement of armour units under design conditions. Various methods of determining damage are used by researchers all over the world. Basically they are summed up by: damage after a test is measured by counting the number of stones displaced, or by comparing slopes before and after the experiment. For a more detailed description see the review of methods by Van der Meer (1988). The method of comparing slopes before and after the experiment is a difficult one for research on stability of rock on gentle slopes. The waves break according to the spilling breaker type and the damage is distributed along the profile. This is the case for regular waves as well as for irregular waves. The breaker zone is so long that it's practically impossible to see the difference in the slope profile before and after the experiment. For breakwaters, e.g. structures with steeper slopes the waves break at more or less the same position, so the damage distribution is not that extended and more concentrated than on gentle slopes.

Because of the mentioned problems for the research of stability of rock on gentle slopes the damage will be determined by counting displaced stones. This raises the problem how to count them. The displaced stones have to be visible to be counted. This can be done by coloring the stones and putting them in strips of different colors along the slope. The number of displaced stones has to be related to the local number of stones available for movement. This can be done by determining the number of stones that can be fitted in an area of D_{n50}^2 in the top layer of the strip. The local damage percentage, $S_{\%}$, can now be defined as:

$$S_{\%} = \frac{n}{A} D_{n50}^2 \tag{2.1}$$

where: n = number of stones displaced
A = area of strip

2.4 Environmental variables

2.4.1 Wave field variables

A regular wave field can be described by several variables such as the wave height and the wave period. For an irregular wave field the description is more complicated. There is not such a thing like 'a wave height' or 'a wave period'. An irregular wave field can be described by means of an energy density spectrum. In an energy density wave spectrum the distribution of the energy of a wave field over the frequencies is given. It is used to simulate a wave field for numerical or physical modelling purposes. In both cases one can simulate an irregular wave field with a given energy density spectrum by adding sinusoidal components, each with it's own amplitude given by the spectrum with an independent phase. Various spectra can be chosen to describe an irregular wave field. An example is the Pierson and Moskowitz spectrum used to describe a full-grown sea in deep water. The spectrum used by Sistermans (1993) was the JONSWAP (Joint North Sea Wave Project) spectrum. It is used to describe an energy density spectrum for a growing swell for a so called ideal wind field at the North Sea. Van der Meer (1988) found that different tested spectra had no significant influence on the stability of the structure. This was of course only tested for steep slopes. In this research only the JONSWAP spectrum will be used.

The wave height, H, can be considered as one of the most important destabilizing variables in the process of causing damage to a structure. Damage is caused when the stabilizing variables are not sufficient to withstand the destabilizing variables.

When investigating the stability of rocks on gentle slopes the wave height is also an important variable in the sense that the location of breaking depends on the ratio of wave height to waterdepth. So, when considering irregular waves this means that the location of breaking waves along the slope is not defined. Higher waves tend to break further offshore then lower waves. This is not the case when investigating stability of rock on breakwaters with steep slopes, the location of wave attack is more defined.

A wave height commonly used for describing an irregular wave field is the significant wave height, H_s, defined by the average of the highest one third part of the waves in a time series. This significant wave height, H_s, is approximately $4\sqrt{m_0}$, where m_0 is the zero-th moment of the wave energy density spectrum.

In this rapport, the wave height in an irregular wave field will be characterized by H_s.

The wave period, T, is a variable of importance, because it determines the breaker type. According to the linear wave theory the wave celerity in deep water can be defined as:

$$c_0 = \frac{gT}{2\pi} \tag{2.2}$$

The wave period also defines the deep-water wave length, L_0, with $L_0 = c_0 \cdot T$ as:

$$L_0 = \frac{gT^2}{2\pi} \tag{2.3}$$

where: g = gravitational acceleration

So far the wave period is easy to define, as regular waves are concerned. For an irregular wave field a wave period can be found from the energy density spectrum. Again several characteristic values are possible; there is not just one wave period. The values depend on the shape of the energy density spectrum. The peak period used in this research is defined by the peak frequency, f_p, as:

$$T_p = \frac{1}{f_p} \tag{2.4}$$

The peak frequency is the frequency in the energy density spectrum where the maximum energy density is located. The wave peak period will also be used in the present thesis to describe the irregular wave field.

2.4.2 Orbital velocities

Conventional breakwater design does not deal with water velocities of breaking waves on the slope of a structure. This is because the damage was always related to the wave height only, which is one of the most important destabilizing variables for structures with steep slopes. In the case of an outfall structure, with a spilling breaker type, Sistermans (1993) expected that the bottom velocity would play an important destabilizing role. This hypothesis, however, was not verified by the experiments conducted. It appeared that the breaker type was also an important variable for the destabilizing process on gentle slopes. This can be concluded for the area attacked in the breaker zone. It is interesting to know, whether the hypothesis is correct for the section of the slope where the waves aren't yet broken.

To get more insight in the bottom velocity distribution over the slope, velocity measurements were done in the present experiments. A comparison will be made with the computer software-package ODIFLOCS (chapter 7) which calculates velocities in and on porous structures attacked by waves.

When using the variable u_0 in this thesis, the velocity amplitude at the bottom is meant.

2.4.3 Water depth

For a structure with a gentle slope the water depth is an important variable. As mentioned before, the point of breaking depends on the ratio of wave height to water depth. The point of breaking is important for the distribution of damage along the slope. If the water depth before the structure varies in time by the influence of a tide, it is obvious that the location of damage will fluctuate in time. The local wave height and with it the orbital bottom velocity varies also with the water-depth.

2.4.4 Storm duration

The storm duration can be described by a length of time or by a number of waves, N. By using the dimensionless number of waves the problem of scaling is by-passed. The number of waves in a model and a prototype is equal.

Sistermans (1993) found for regular waves a rapid development in damage for the first

250 waves when starting with a loosely-packed rock bed, simulating a just constructed slope protection. After that, the damage progressed at a much lower rate, but did not reach an equilibrium after the 750 waves tested for.

For irregular waves the situation is different. The successive wave forces on the structure aren't the same in magnitude and location of attack. This is due to the stochastic nature of irregular waves. The higher the number of waves attacking the structure in a test period, the higher the chance of occurrence of high waves causing damage to the structure. Compared to regular waves it will take longer to get the same maximum damage level. The duration will therefore be of importance.

2.4.5 Remaining environmental variables

The remaining environmental variables are the mass density of the water, ρ_w, the dynamic fluid viscosity, υ, and the acceleration of gravity, g. These variables will not be varied in this thesis. The last variable to describe is the angle of wave attack, ψ. This variable can not be varied with the equipment available; the angle of attack will be perpendicular to the imaginary coastline.

2.5 Structural variables

The environmental variables described in the previous section can be seen as the destabilizing factors of the armor units on the slope of the structure. The structural variables are the stabilizing factors of the armor units.

2.5.1 Block weight and size

The relationship between size and weight of individual stones may be defined in terms of the equivalent-volume cube (side D_n) which , with weight density ρ_a and block mass M, gives the relation:

$$D_n=\left(\frac{M}{\rho_a}\right)^{1/3} \tag{2.5}$$

When the stones are small (less than 20 mm) the statistical values can be derived from sieve analysis. The median sieve size, D_{50}, for example, is the sieve diameter through which 50% of the total weight of the sample can pass.

The conversion factor relating D_{50} to D_{n50} or M_{50} has been determined experimentally by various researchers. The value depends on the shape of the rock. According to Laan (1981): D_{n50}/D_{50} = 0.84 or $\frac{M_{50}}{\rho_a D_{50}^3}=0.60$ for angular rock.

2.5.2 Grading

In a sample of natural stone there will be a range of stone weights. These weights can be measured and presented in a sieve curve. This is a curve where the percentage of weight passing through a certain sieve diameter is presented as a function of this sieve diameter. The ratio of the D_{85} over the D_{15} is called the grading of the sample. The smaller this ratio the steeper the sieve curve. So the ratio defines if a sample is narrow-graded or wide-graded. The values range from approximately 1.25 up to 5.0 for a very wide or 'quarry run' gradation. Van der Meer (1988) concluded that the influence of this variable on the stability of rocks was negligible. Of course this was only tested for steep slopes, ξ-values of 1.5 and larger. Whether variation in grading on the stability of rocks on gentle slopes is also negligible, is questionable. The grading will not be varied in this thesis. The values are approximately 1.4.

2.5.3 Mass density

The mass density of the rock is definitely a very important stabilizing factor. It's defined by mass over volume (kg/m^3). The density varies between different materials. Limestone for example has a mass density of 2300 kg/m^3, but basalt has a density of approximately 3000 kg/m^3. A relative mass density can be formulated by relating the mass density of the rock, ρ_a and the mass density of water ρ_w. It's defined as:

$$\Delta = \frac{\rho_a - \rho_w}{\rho_w} \tag{2.6}$$

2.5.4 Slope angle

The slope angle, α, is one of the factors which determine the breaker type on the structure. The breaker type is important, because it has a direct effect on the stability of the rocks on the slope. Therefore it is interesting to vary this variable in the model to know how it effects the stability. However, the experiments in this thesis were done on a 1:25 slope only.

A variable also be seen in this context is the natural angle of repose, Φ. In this thesis the natural angle of repose will not be varied.

2.6 Dimensional analysis

Dimensional analysis is a valuable tool in reducing the apparent chaos of experimental results involving many variables. A dimensional analysis gives an arrangement of knowledge of the physical processes; it doesn't give knowledge about the physical processes themselves.

If a physical process can be described by n variables p_i and if one works with the commonly used elementary dimensions (m), mass, length, time, then it's possible to arrange the variables according to n-m dimensionless products.

The reason of using dimensionless variables can be to apply the results found in a model to a prototype. Another reason to use dimensionless variables, is to compare the results for different tests and to compare results with research previously carried out.

The variables described in the previous section were ordered as environmental and structural variables. Another division which can be made is into variables that will be varied in the model and variables that will not be varied in the model. Only the variables which are important to describe the process will be taken into consideration.
H, T, h, u_0, N, ρ_a, D_{n50}, D_{85}/D_{15} and tanα belong to the group of variables that can be varied in the model.
ρ_w, g and υ belong to the group that will not be changed. This division is useful to get a variable, which will be changed in the model, in every formed dimensionless variable. Other useful dimensionless variables to describe the process can be formed out of these variables (a dimensionless variable divided or multiplied by another dimensionless variable is again dimensionless).

From the variables p_i with i = 1,...,n a dimensionless variable Π can be formed as:

$$\Pi = p_1^{k_1} \cdot p_2^{k_2} \cdots p_n^{k_n} \tag{2.7}$$

When p_i has the dimensions according to:

$$[M^{\alpha_i} L^{\beta_i} T^{\gamma_i}] \tag{2.8}$$

the dimensionless equation yields:

$$[\Pi] = [M^{\alpha_1} L^{\beta_1} T^{\gamma_1}]^{k_1} [M^{\alpha_2} L^{\beta_2} T^{\gamma_2}]^{k_2} \ldots [M^{\alpha_n} L^{\beta_n} T^{\gamma_n}]^{k_n} \tag{2.9}$$

Π will only be dimensionless if:

$$\begin{aligned} \alpha_1 k_1 + \alpha_2 k_2 + \ldots + \alpha_n k_n &= 0 \\ \beta_1 k_1 + \beta_2 k_2 + \ldots + \beta_n k_n &= 0 \\ \gamma_1 k_1 + \gamma_2 k_2 + \ldots + \gamma_n k_n &= 0 \end{aligned} \tag{2.10}$$

The coefficients α_i, β_i and γ_i are known, so the problem is to find the n exponents k_i. According to Langhaar (1957) k_i can be determined systematically. The coefficients α_i, β_i and γ_i can systematically ordered like:

gr.	group 1									group 2		
par.	H	T	h	U_0	N	ρ_a	D_{n50}	grading	tan α	ρ_w	g	υ
M	0	0	0	0	0	1	0	0	0	1	0	0
L	1	0	1	1	0	-3	1	0	0	-3	1	2
T	0	1	0	-1	0	0	0	0	0	0	-2	-1

According to equation 2.10 values for k_n can be expressed into each other. Nine dimensionless variables can be chosen and are displayed in the matrix:

	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}	k_{11}	k_{12}
par	H	T	h	U_0	N	ρ_s	D_{n50}	grading	tan α	ρ_w	g	υ
Π_1	1	0	0	0	0	0	0	0	0	0	1/3	-2/3
Π_2	0	1	0	0	0	0	0	0	0	0	2/3	-1/3
Π_3	0	0	1	0	0	0	0	0	0	0	1/3	-2/3
Π_4	0	0	0	1	0	0	0	0	0	0	-1/3	-1/3
Π_5	0	0	0	0	1	0	0	0	0	0	0	0
Π_6	0	0	0	0	0	1	0	0	0	0	0	0
Π_7	0	0	0	0	0	0	1	0	0	0	1/3	-2/3
Π_8	0	0	0	0	0	0	0	1	0	0	0	0
Π_9	0	0	0	0	0	0	0	0	1	0	0	0

This yields the following dimensionless variables:

$\Pi_1 = H \cdot g^{1/3} \cdot \upsilon^{-2/3}$
$\Pi_2 = T \cdot g^{2/3} \cdot \upsilon^{-1/3}$
$\Pi_3 = h \cdot g^{1/3} \cdot \upsilon^{-2/3}$
$\Pi_4 = U_0 \cdot g^{-1/3} \cdot \upsilon^{-1/3}$
$\Pi_5 = N$
$\Pi_6 = \rho_a/\rho_w$
$\Pi_7 = D_{n50} \cdot g^{1/3} \cdot \upsilon^{-2/3}$
$\Pi_8 = D_{85}/D_{15}$ (grading)
$\Pi_9 = \tan\alpha$

2.7 Dimensionless variables

As said before it is possible to form dimensionless variables out of these nine elementary dimensionless variables. A few, which are useful to describe the processes involved, will be mentioned here.

- The dimensionless waterdepth:

$$\begin{aligned}\Pi_{10} &= \Pi_1^{-1} \cdot \Pi_3 \\ &= H^{-1} \cdot g^{-1/3} \cdot \upsilon^{2/3} \cdot h \cdot g^{1/3} \cdot \upsilon^{-2/3} \\ &= h/H\end{aligned} \tag{2.11}$$

- The dimensionless stability variable $H/\Delta D_{n50}$, to describe the stability of rock under wave attack.

$$\begin{aligned}\Pi_{11} &= \Pi_1 \cdot \Pi_8^{-1} \cdot \Pi_7^{-1} \\ &= H/\Delta D_{n50}\end{aligned} \tag{2.12}$$

The physical meaning is the ratio between the wave height, H or H_s, describing the destabilizing forces, and ΔD_{n50}, describing the stabilizing forces.

- The Reynolds number, which represents the ratio between the inertia forces and the viscous friction forces.

$$\begin{aligned}\Pi_{12} &= \Pi_4 \cdot \Pi_3 \\ &= U_0 \cdot g^{-1/3} \cdot \upsilon^{-1/3} \cdot h \cdot g^{1/3} \cdot \upsilon^{-2/3} \\ &= (U_0 \cdot h)/\upsilon\end{aligned} \tag{2.13}$$

$$\begin{aligned}\Pi_{13} &= (\Pi_1)^{1/2} \cdot \Pi_8 \\ &= (g \cdot H)^{1/2} \cdot D_{n50}/\upsilon\end{aligned} \tag{2.14}$$

- The wave steepness. This is the ratio between the wave height and the deep-water wave length.

$$\begin{aligned}\Pi_{14}(s) &= 2\pi \cdot (\Pi_2)^{-2} \cdot \Pi_1 \\ &= H/L_0\end{aligned} \tag{2.15}$$

- The breaker index according to Iribarren (1950). It represents the ratio between the slope angle, α, and the wave steepness, s. This ratio was found to be important for the determination of the breaker type.

$$\begin{aligned}\Pi_{15}(\xi) &= (2\pi)^{-1/2} \cdot \Pi_9 \cdot ((\Pi_2)^{-2} \cdot \Pi_1)^{-1/2} \\ &= \tan(\alpha)/(H/L)^{1/2}\end{aligned} \tag{2.16}$$

- The relative mass density of rock.

$\Pi_{16}(\Delta)$ = relative version of Π_6 as: $(\rho_a - \rho_w)/\rho_w$ (2.17)

- The Froude number, which represents the ratio between the inertia and the gravity forces.

$$\begin{aligned}\Pi_{17} &= \Pi_4/\Pi_3 \\ &= U_0 \cdot g^{-1/2} \cdot h^{-1/2}\end{aligned} \tag{2.18}$$

3 Calculation of possible stability relations

3.1 Introduction

Sistermans (1993) made an attempt to form stability relations for gentle slopes with the existing theories dealing with the stability of rock on horizontal bottoms. The theories used where those according to Jonsson / Sleath and Rance & Warren. After comparing the theories with the stability relations found in his experimental research, Sistermans (1993) concluded that the used approach was not satisfactory. For higher values of the wave steepness the theoretical stability proved to be less than for lower values of the wave steepness while the experimental results gave the opposite tendency. Sistermans (1993) concluded that the plunging effect of the breaking waves as described in the introduction caused this opposite tendency.

In this thesis a new attempt is made to form stability relations for gentle slopes with the existing theories dealing with the stability of rock on horizontal bottoms. In the next sections a review is given on the existing theories dealing with the stability of rock on horizontal bottoms, and possible stability relations for regular as well as for irregular waves are derived. Also a comparison of the methods of calcultation of the bottom velocities for regular waves in this thesis and Sistermans approach (1993) is made.

3.2 Horizontal bottoms

In this thesis only the stability formulae according to Rance & Warren (1968) and Jonsson / Sleath (1978) are dealt with. This is because according to Sistermans (1993) they seemed to be the most promising to describe the stability of rock on gentle slopes.

3.2.1 Jonsson / Sleath

Sleath (1978) combined the results of different researchers to establish a "modified Shields-curve", see figure 3.1. The "modified Shields curve" is a modification of the original relation established by Shields (1936) for the incipience of motion of particles in a uniform flow. The "modified Shields curve" can be used to calculate the stability of particles in an oscillatory flow.

The critical Shields parameter in turbulent oscillatory flows is given by Sleath (1978) as:

$$\Psi_{cr} = \frac{\tau_b}{(\rho_s - \rho_w) \cdot g \cdot D_{s50}} = 0.056 \tag{3.1}$$

In this equation is τ_b the maximum bottom shear stress, given by:

$$\tau_b = \frac{1}{2} \cdot \rho_w \cdot f_w \cdot u_0^2 \tag{3.2}$$

where: f_w = wave friction factor according to Jonsson
u_0 = max. orbital velocity at boundary layer

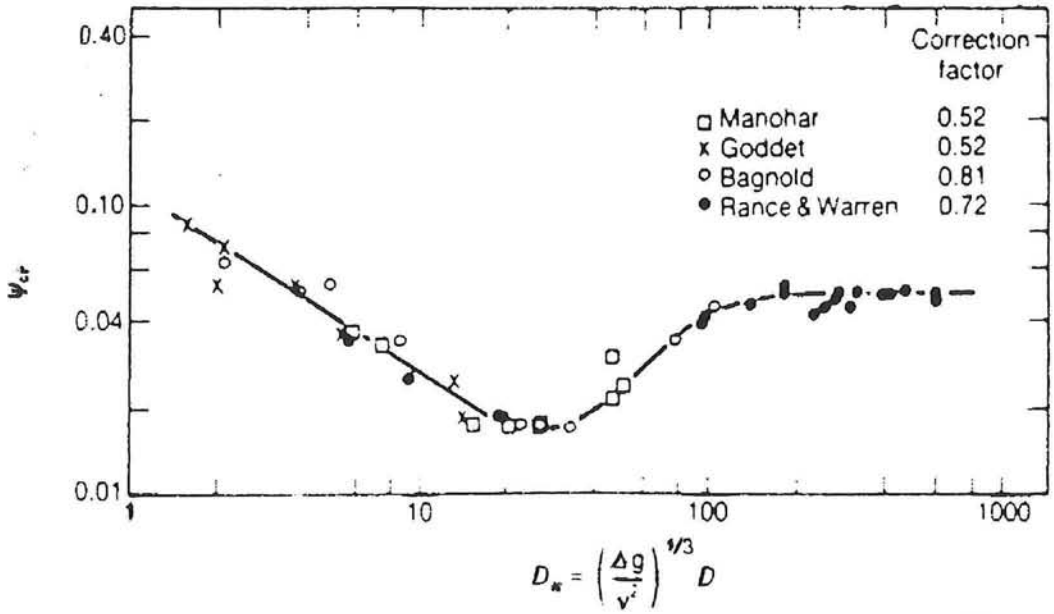


figure 3.1: Modified Shields curve according to Sleath (1978)

The wave friction-factor, f_w, given by Jonsson (1966) is an empirical relationship, applicable when the flow near the bed is fully turbulent. It was rewritten by Swart (1976) into a more practical expression as:

$$f_w = \exp[\,-5.977 + 5.213\ (a_0/k_s)^{-0.194}] \qquad \text{for } a_0/k_s > 1.57$$

$$f_w = 0.30 \qquad \text{for } a_0/k_s < 1.57 \tag{3.3}$$

where: a_0 = displacement of water particle at the bottom = $(u_0 \cdot T)/2\pi$
k_s = Nikuradse roughness length

The Jonsson friction factor, f_w, depends, besides on the relative roughness (a_0/k_s), on the Reynolds number. When the Reynolds number is small, fw is a function of Reynolds. For large values of the Reynolds number (flow near the bed is fully turbulent), the value of f_w appears to depend only on the relative roughness. Since the prototype conditions are turbulent, the Reynolds number dependence is commonly ignored. It plays a role however in assessing the possibility of scale effects.

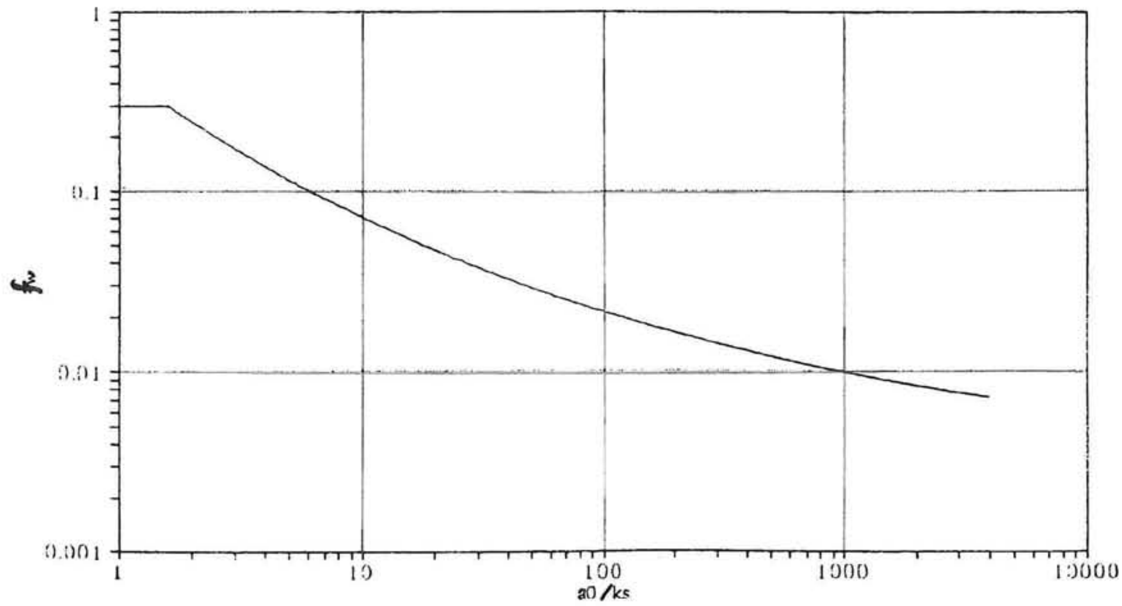


figure 3.2: Jonsson friction factor plotted versus relative roughness length

From figure 3.2 it can be seen that when the relative roughness has relatively low values, the friction factor increases, which results in a higher bottom shear stress.

The Nikuradse roughness length parameter, k_s, is related to the diameter of the largest grains on the surface of the bed. There are quite some different values recommended by various researchers. In this thesis the value of the sphere diameter, D_{s50} will be used.

$k_s = D_{s50}$ Sleath (1978)

D_{s50} is related to the D_{n50} by: $D_{s50} = 1.24 \cdot D_{n50}$

The phenomenon in figure 3.2 can be explained by the development of the boundary layer.

This is schematically shown by an infinitely thin plate placed in a uniform flow.

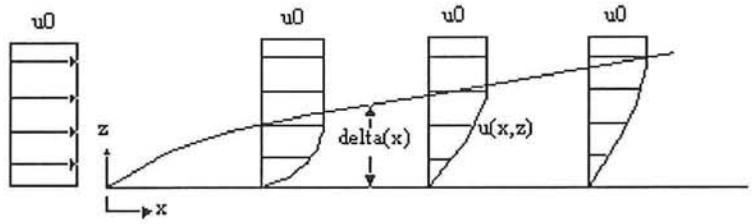


figure 3.3: Developement of boundary layer

At the start, delta(x)=0, leading to a theoretically infinite shear stress. The boundary layer grows because of the exchange of momentum, smoothing the velocity differences. The limit at the downstream end is reached when the whole water-depth is boundary layer.

In case of short wind waves as discussed here the boundary layer is relatively thin. Every wave period has to start a new and the situation is similar to that of the start of a flow along the plate in figure 3.3. For a large displacement of the water particles at the bottom there is a possibility of growth of the boundary layer which will result in a low value of the friction factor. For a small amplitude of the particle motion the value of the friction factor will be relatively high.

3.2.2 Rance & Warren

Rance & Warren (1968) performed a series of tests in an oscillating water-tunnel to analyze the stability of particles in oscillatory water motion. They plotted their results in a diagram, in which an acceleration number, $a_0/(T^2 \cdot \Delta \cdot g)$ was plotted as a function of the relative horizontal displacement of a water particle, a_0/D_s. See figure 3.3.

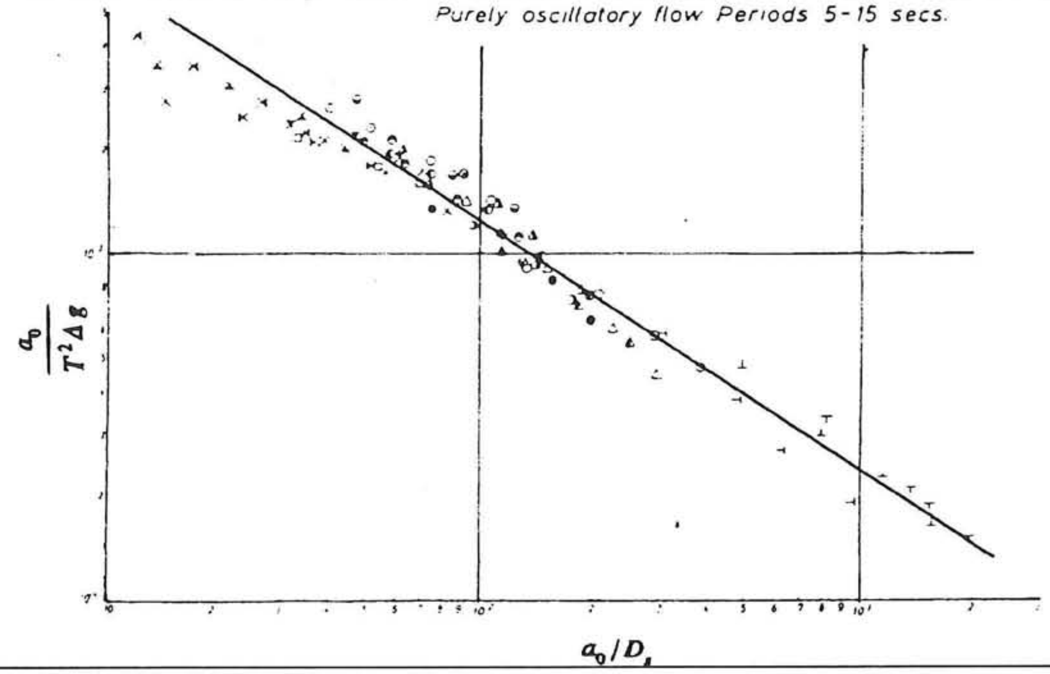


figure 3.3: Test results of Rance & Warren (1968)

Rance & Warren (1968) only used this diagram to present their results. Therefore Sistermans (1993) "curve fitted" their results by a visual best-fit. This resulted in the description:

$$\frac{a_0}{T^2 \Delta g} = 0.025 [\frac{a_o}{D_s}]^{-\frac{2}{3}} \tag{3.4}$$

It is to be mentioned that the constants 0.025 and -2/3 depend on the correctness of the curve fit and are therefore rather subjective. Equation 3.4 can be substituted with $a_0 = U_0 \cdot T/2 \cdot \pi$ and $D_s = D_{50}$. This yields:

$$D_{50} = 2.56 \frac{u_0^{\frac{5}{2}}}{T^{\frac{1}{2}} (\Delta \cdot 9.81)^{\frac{3}{2}}} \tag{3.5}$$

3.3 Regular waves on gentle slopes

To be able to use the stability formulae from the previous section, information about the orbital bottom velocities is needed. For regular waves on gentle slopes the derivation is given in section 3.3.1. In section 3.3.2 a comparison is given between the method of calculation of bottom velocities in this thesis and that by Sistermans (1993). Finally a comparison between the results of both stability formulae used is given in section 3.3.3.

3.3.1 Derivation

When trying to describe the stability of rock on gentle slopes with stability relations which originate from relations derived for horizontal bottoms, the assumption is made that the orbital bottom velocities cause instability of the rock. Sistermans (1993) assumed that as the ratio of the water depth and the wave height reaches the breaking criterium, h/H = 1.25, the maximum orbital velocity would occur and therefore the maximum damage would be located at that particular point on the slope. This proved not to be true, because of more dominant involved destabilizing factors, like turbulent fluctuations causing instability after breaking. Interesting is the investigation of how the stability of the rock behaves before the breaking point. One should expect that the orbital bottom velocities are playing a more dominant role on this section of the slope. To get a clear view of the stability of the rock along the slope a relation of the orbital bottom velocity combined with a stability relation should be used. Then the rock dimensions can be calculated for every location along the slope for a combination of wave height, wave period and water depth. The complete linear wave theory will be used to calculate the orbital velocities. The amplitude of the orbital bottom velocities is given as:

$$\hat{u}_0 = \frac{\omega H}{2} \frac{1}{\sinh kh} \qquad (3.6)$$

where: $\omega = 2 \cdot \pi / T$
$k = 2 \cdot \pi / L_0$

According to Le Méhauté (1968) the use of the linear wave theory to describe the orbital bottom velocity is a good approximation.

Sinusoidal waves approaching coastlines do transform into non sinusoidal waves at the surface but the bottom velocities can be well described with the linear wave theory. Le Méhauté compared several velocity measurements with existing theories. See figure 3.4.

Figure 3.5 shows that the wave motion at the water surface of a wave approaching the shore, in this case a 1:40 fore-shore, cannot be described by the existing wave theories.

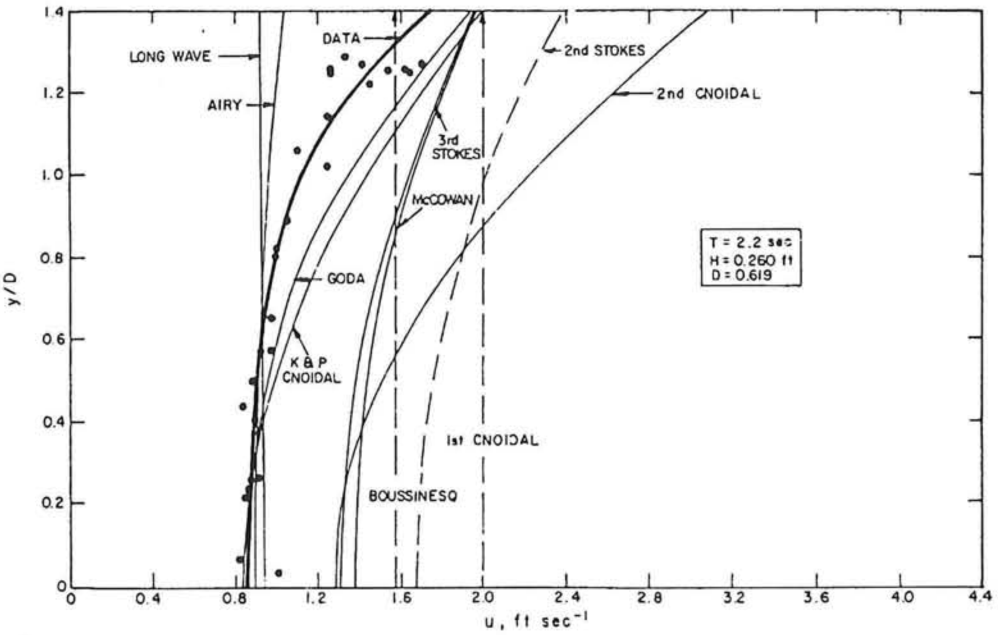


figure 3.4: Arbitrary example of velocity distributions compared for various theories and a data serie

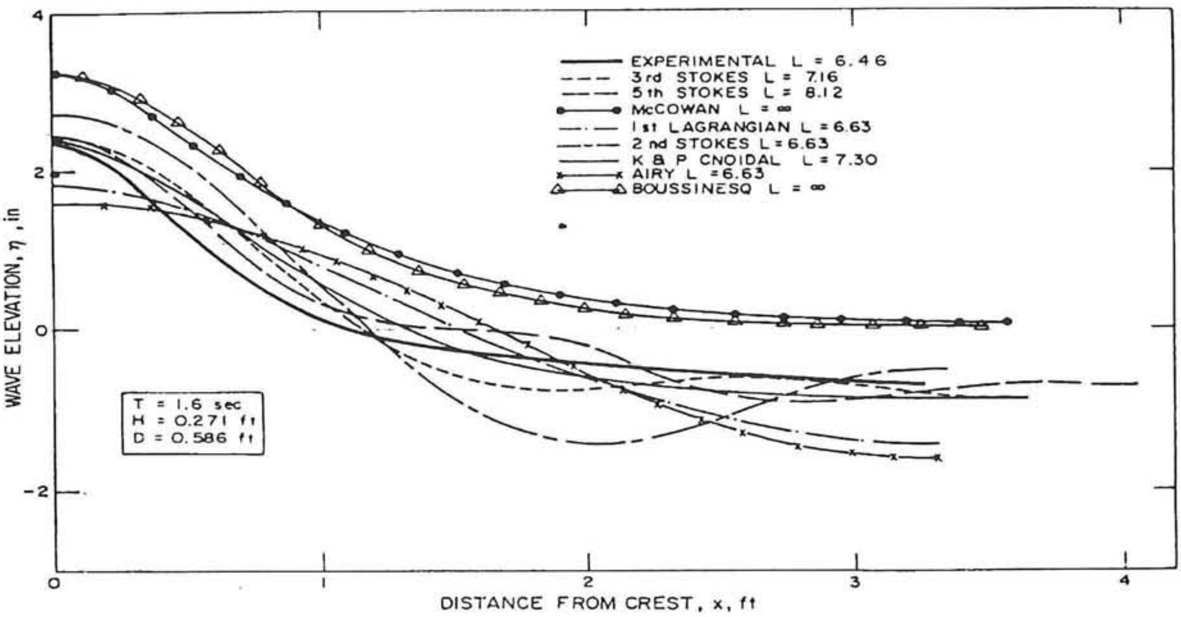


figure 3.5: Arbitrary example of wave elevations versus distance wave crest compared for various theories and a data serie

To be able to calculate the orbital velocities at every position along the slope the appropriate wave length should be calculated. The complete formula according to the linear wave theory yields:

$$L \approx \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi}{L} h\right) \tag{3.7}$$

The wave length can now be found through an iterative substitution.

When using formula 3.6 the local wave height should be known. This local wave height is not the same as the deep water wave height and depends on the shoaling coefficient, K_{sh}. For the phenomenon of shoaling see Battjes (1991). The local wave height, H, can be found by multiplying the deep water wave height, H_0, with the shoaling factor, K_{sh} as: $H = K_{sh} \cdot H_0$.

The shoaling factor is defined by:

$$K_{sh} = \frac{1}{\sqrt{\tanh kh \left[1 + 2\frac{kh}{\sinh 2kh}\right]}} \tag{3.8}$$

The orbital bottom velocity can now be calculated along the profile. The just mentioned formulae are assumed to be valid till the point of breaking. When knowing the orbital velocities the needed rock dimensions can be determined with the available stability formulae (section 3.2).

The just described formulae in combination with the stability formulae were solved for several ranges of involved variables with the software package MathCad. See appendix XII. The calculations can be summarized by presenting the calculated values for $H/\Delta D_{n50}$ as a function of the relative water-depth for different values of the wave steepness. See figure 3.6. The wave height, H_0, is defined in 'deep' water ($L_0 \leq 2 \cdot h$).

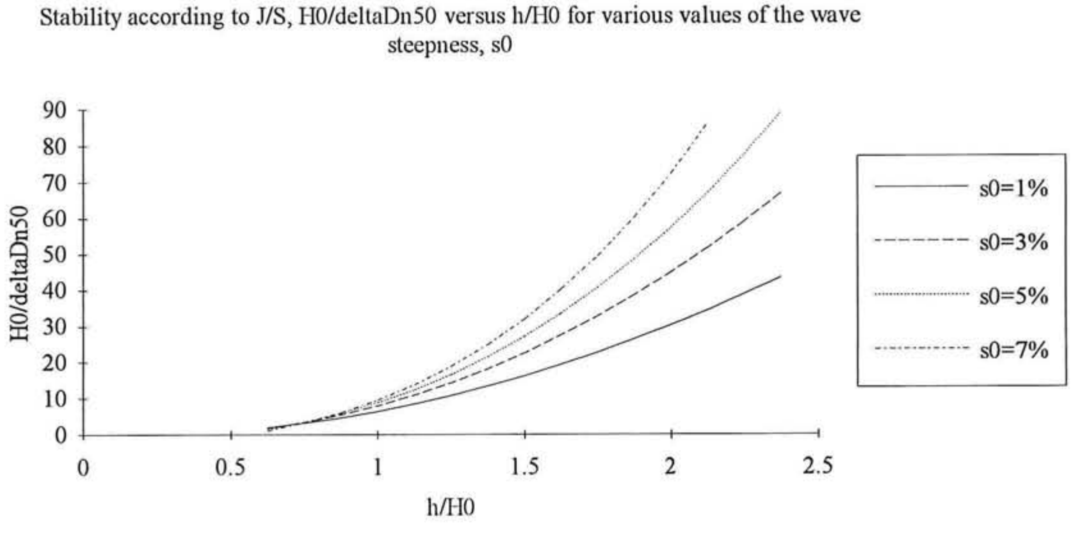


figure 3.6: Stability according to Jonsson/Sleath

The general tendency in figure 3.6 is, higher stability values, $H_0/\Delta D_{n50}$, for larger relative water-depths, h/H_0. It can also be seen that for increasing values of the wave steepness, s_0, the stability increases.

The previous calculation was also performed for the stability formulae according to Rance & Warren. The results are plotted in figure 3.7. The wave height, H_0, is defined in 'deep' water ($L_0 \leq 2 \cdot h$).

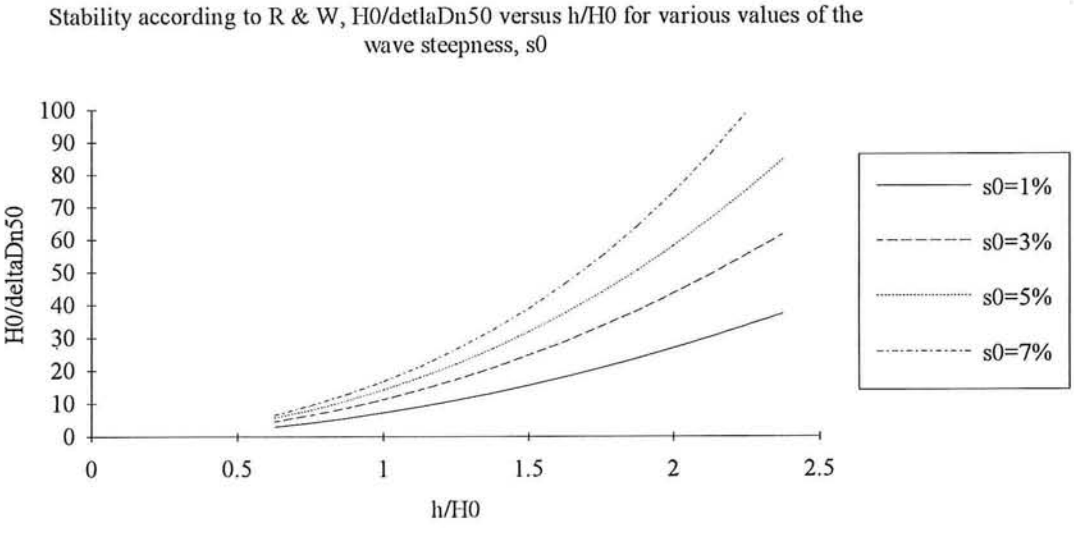


figure 3.7: Stability according to Rance & Warren

The general tendency in figure 3.7 is, higher stability values, $H_0/\Delta D_{n50}$, for larger relative water-depths, h/H_0. It can also be seen that for increasing values of the wave steepness, s_0, the stability increases. So in general the Rance & Warren theory has the same tendency as that of Jonsson & Sleath.

3.3.2 Comparison with Sistermans (1993)

When comparing the above results with results found by Sistermans (1993) it is obvious that the tendency is completely different. Figure 3.8 shows the stability parameter, $H/\Delta D_{n50}$ versus the wave steepness. The values of $H/\Delta D_{n50}$ were calculated for $h/H = 1.25$ (breaking point).

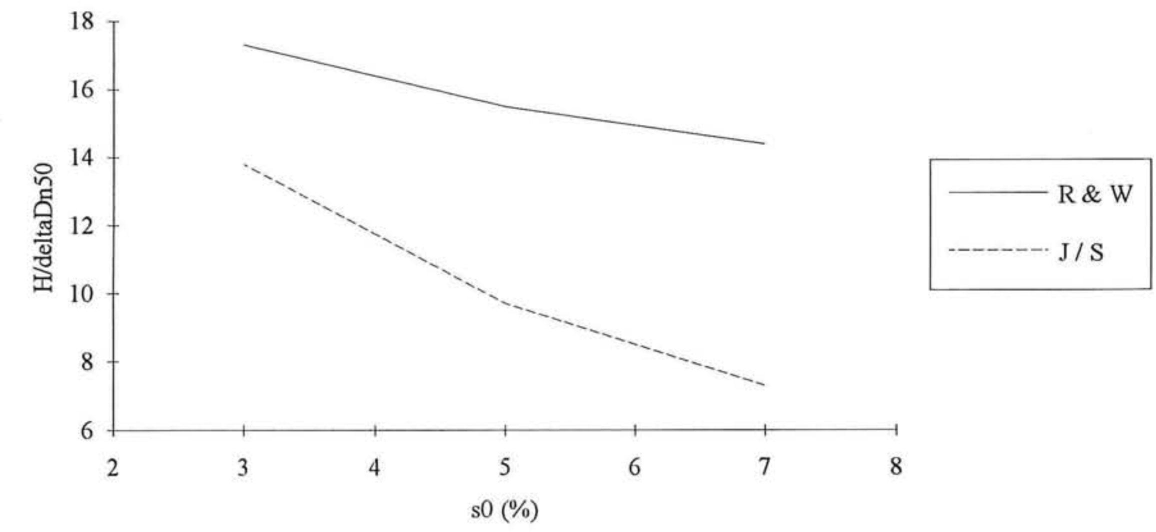


figure 3.8: Stability according to R & W and J / S calculated by Sistermans (1993)

Sistermans (1993) concluded that for an increasing wave steepness the stability decreases. The difference between the results found in this chapter and the results found by Sistermans (1993) can be explained by the difference in calculation method of the orbital bottom velocity. Sistermans used the long-wave theory to calculate the bottom velocities by assuming an shallow water situation, e.g. $L/h > 0.5$.

By using the long-wave theory the assumption is made of a velocity profile which is equally distributed over the water-depth. See figure 3.9.

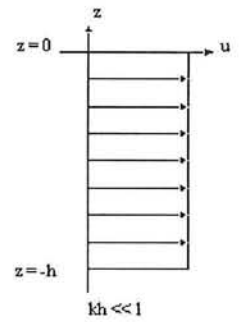


figure 3.9: Schematized velocity profile

The velocities at the bottom, for example at the wave breaking point, can then be calculated by:

$$u_0 = \frac{\gamma_{br}}{2}\sqrt{gh} \tag{3.9}$$

where: $\gamma_{br} = H_{br}/h_{br}$

The difference between the long-wave theory and the linear wave theory can clearly be seen in figure 3.10, where the stability parameter, H_0/deltaD_{n50} is plotted versus the wave steepness, s_0.

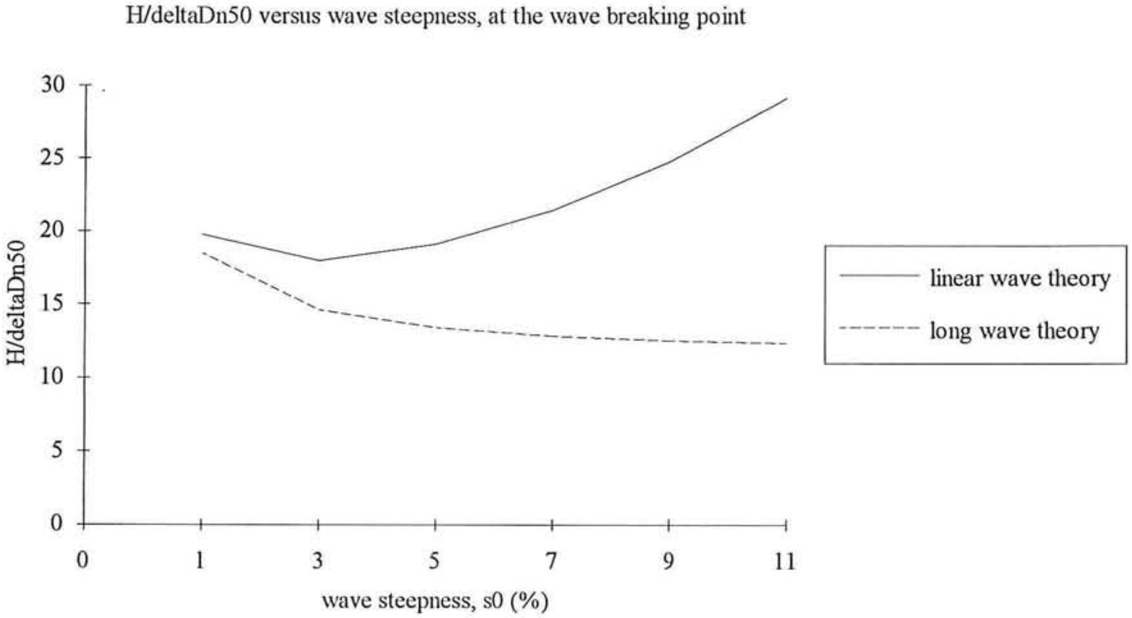


figure 3.10: Stability according to Rance & Warren versus the wave steepness

For small values of the wave steepness (relativaly long wave length) the tendency in the stability is the same, but for higher values of the wave steepness the linear wave theory gives deviating stability values. This can be explained by the not equally developed velocity distribution over the water-depth. Higher values of the wave steepness yield, for the same wave height, lower values of the wave period. With lower values of the wave period the velocity profile cannot equally develope over the water-depth. Using the long wave theory to calculate the bottom velocities will therefore lead to incorrect results.

3.3.3 Evaluation

The values of $H_0/deltaD_{n50}$, for regular waves, found with the different calculation methods (Rance & Warren versus Jonsson / Sleath), can now be compared. The results for regular waves are plotted in figure 3.11. Both methods give approximately the same values.

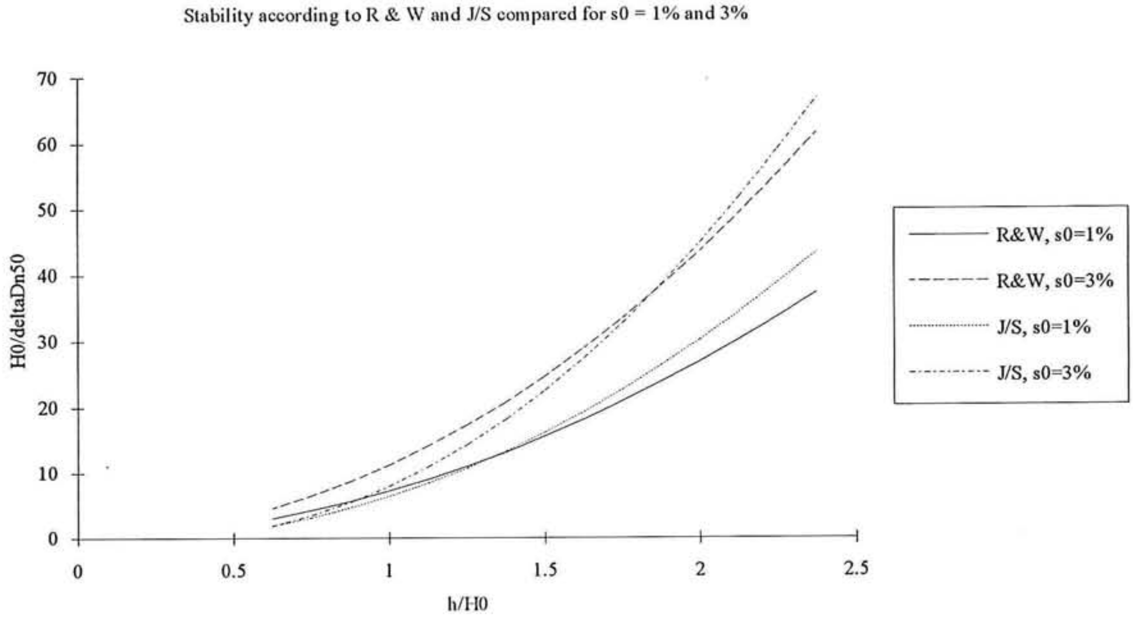


figure 3.11

Which method is most promising has to be verified by the experimental results which will be discussed in chapter 6.

Two phenomena are of importance when evaluating figure 3.11.

At the right side of the figure, with relatively large water-depths, the difference in stability for various values of the wave steepness is caused by the amount of development of the velocity profile over the water-depth. For higher values of the wave steepness the velocity profile over the water-depth cannot or not completely develop till the bottom. For lower values of the wave steepness the velocity profile will develop more. The result is movement of water particles over the bottom which results into lower stability values.

Going to the left side of the figure the difference in stability between the different values of the wave steepness is becoming less. For all the different wave steepnesses there is water movement at the bottom. The phenomenon of the development of a boundary layer is now of importance. For higher values of the wave steepness the friction factor according to Jonsson is high. Because of the small values of the displacement of water particles at the bottom there is no developement of the boundary layer which results into a significant value of the shear stress. For lower values of the wave steepness the friction factor according to Jonsson is relatively low. Because of the relatively large displacements of the water particles at the bottom there is a possibility of forming a boundary layer. This results into lower values of the shear stress.

3.4 Irregular waves on gentle slopes

3.4.1 Derivation

The graphs presented in section 3.3 might be appropriate to describe the stability of stones subjected to regular waves, but for irregular waves it is not that simple. Possible stability relations for irregular waves are needed to be able to predict stone dimensions for a more natural situation. When trying to describe the stability of stones for irregular waves one has to realize that only the highest waves of an irregular wave field cause instability. Substitution of the significant wave height, H_s, in the formulae representing the theories mentioned in section 3.2 will result in stability relations which are too optimistic, implying a $H_s/\Delta D_{n50}$ value which is generally too high. The use of the formulae described in section 3.2 for irregular waves will only be possible when substituting a wave height which describes the highest waves in an irregular wave field. In this chapter the hypothesis will be made that the damage occuring to a structure is caused by the highest 1% of the waves in a wave field. Whether this $H_{1\%}$ can be used in the described stability formulae in calculating the stone dimensions of the involved structure is questionable. Laboratory tests will have to verify or reject the use of this $H_{1\%}$ wave height. In this section the $H_{1\%}$ will be used in the derivation of possible stability relations for irregular waves.

In a deep water situation, $L_0 \leq 3 \cdot h$, the wave heights of an irregular wave field can be described via a theoretical distribution model: the Rayleigh distribution. This distribution is completely characterized by a single variable. The significant wave height, H_s, for example is sufficient to characterize the distribution. The Rayleigh distribution reads:

$$P(H) = e^{-2\left(\frac{H}{H_s}\right)^2} \tag{3.10}$$

where: $P(H)$ = the probability of exceedance of wave height H
H_s = the significant wave height of the record

Unfortunately, the Rayleigh distribution is not valid for shallow water situations, $L \geq 3 \cdot h$.

This is caused by breaking of the highest waves. The wave heights are subsequently no longer Rayleigh distributed, see figure 3.12.

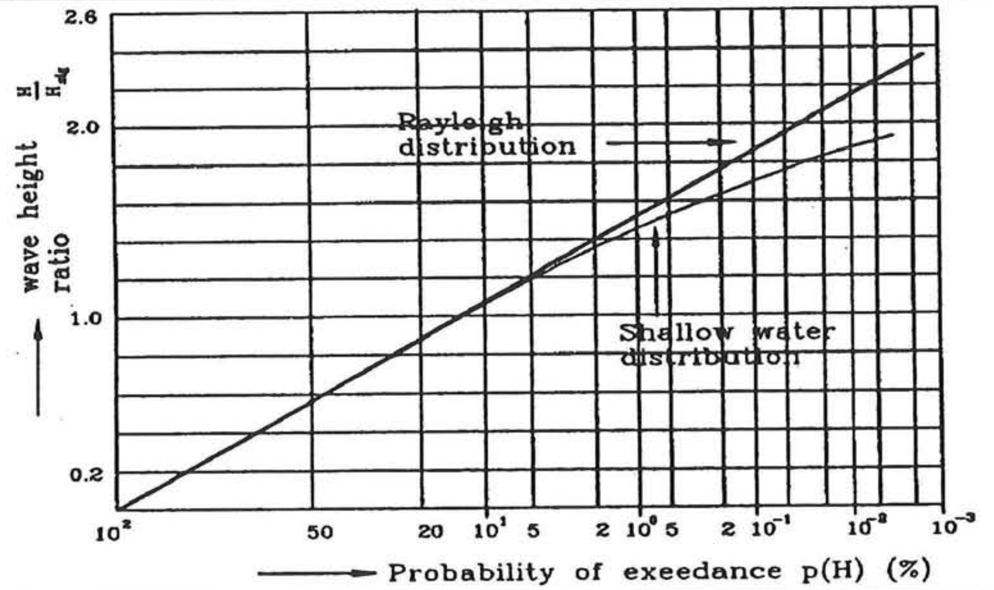


figure 3.12: Wave-height distribution in shallow water, CUR/CIRIA, 1991

But one could 'correct' the values calculated with the Rayleigh distribution. According to Stive (1984) is $H_{1\%}$, $1/(1+H_s/h)^{1/3}$ times smaller than would follow from the Rayleigh distribution, see also CUR/CIRIA, 1991.

With this correction it is possible to predict the $H_{1\%}$ value as a function of the water-depth. As done in the previous section it is possible to calculate the wave heights along the slope profile at various positions. This can be done for the significant wave height, H_s. With the Rayleigh distribution the $H_{1\%}$ can be calculated, which has to be corrected for the 'shallow' water situation. The corrected value of the $H_{1\%}$ can now be used for substitution in the stability relations according to Rance & Warren and Jonsson / Sleath. The final stability relations of $H_s/\Delta D_{n50}$ versus h/H_s were calculated as done in section 3.3 with the software package MathCad.

For the stability according to Jonsson / Sleath, see figure 3.13. The significant wave height, H_s, is defined in 'deep' water, $L_0 \leq 2 \cdot h$.

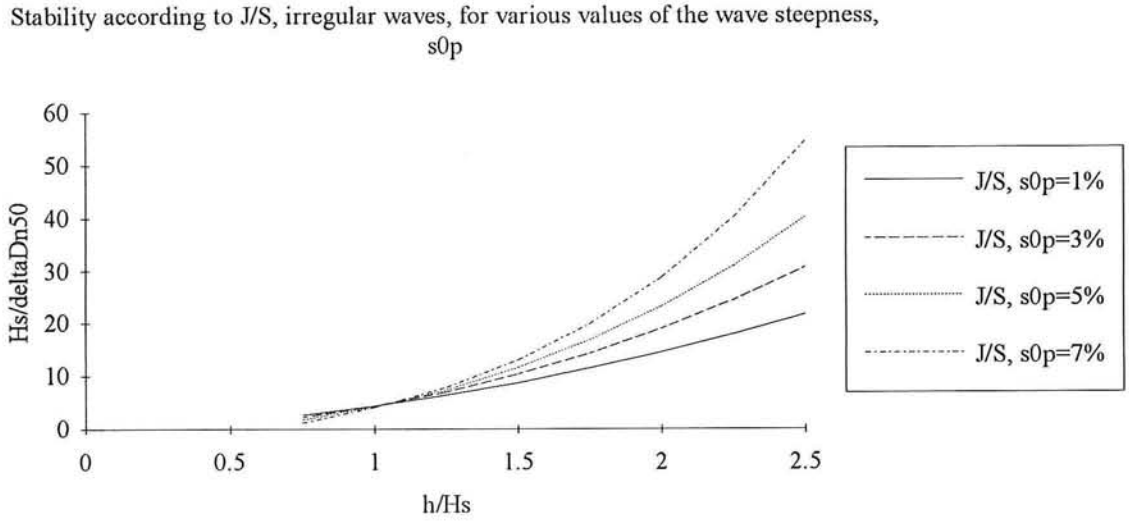


figure 3.13

The general tendencies are the same as described in section 3.3, for deeper relative water-depth's, h/H_s higher stability values, $H_s/\Delta D_{n50}$ can be expected. Also increasing values of the wave steepness, s_{0p}, will result in higher stability values. See also regular waves, section 3.3.

These same general tendencies can be concluded for the stability according to Rance & Warren. See figure 3.14. The significant wave height is again defined in 'deep' water.

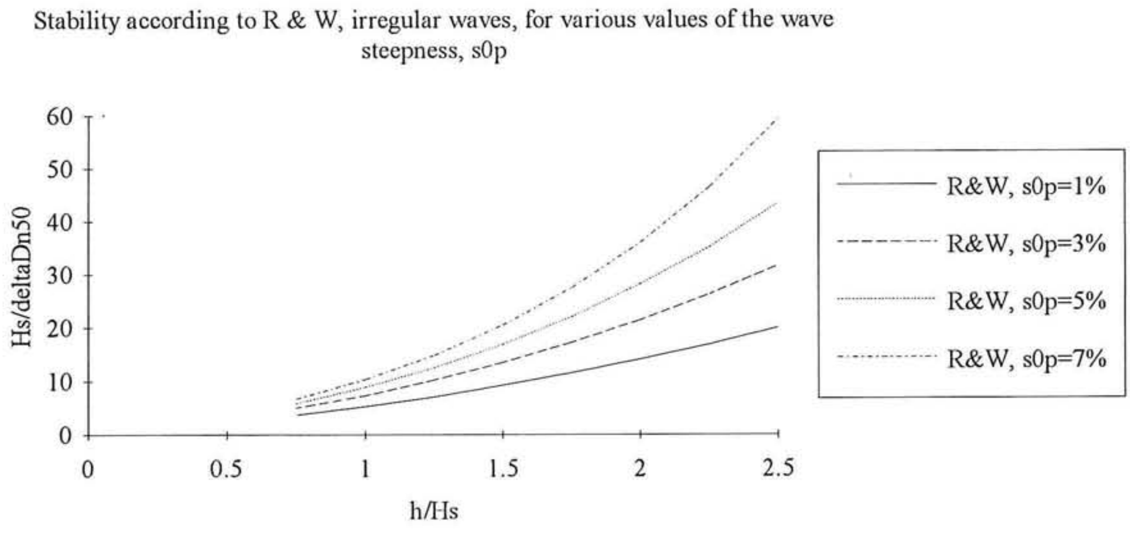


figure 3.14

3.4.2 Evaluation

As done for regular waves it is possible for irregular waves to compare the derived stability relations. See figure 3.15.

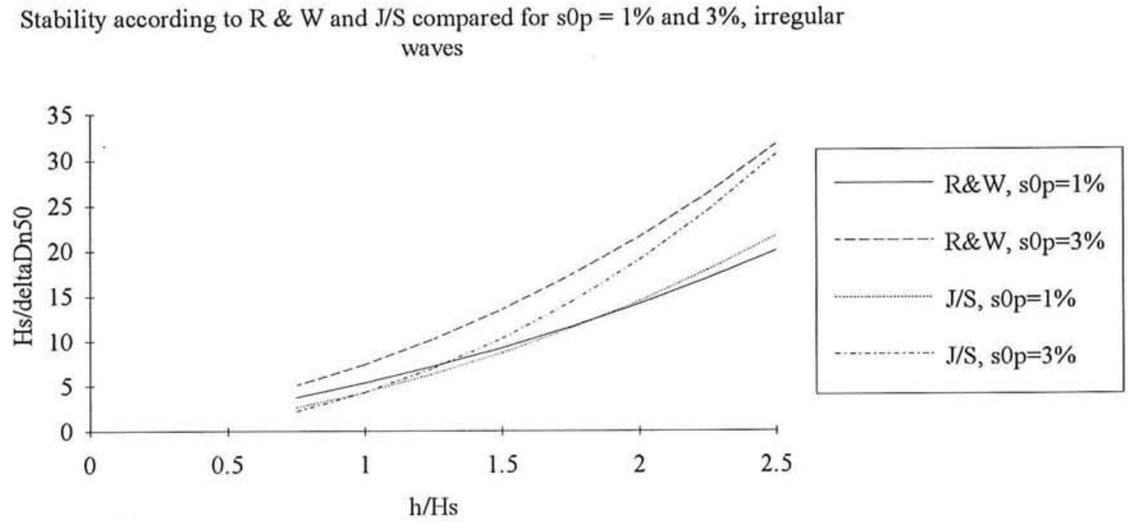


figure 3.15

The methods compared for s_{0p} = 1% do give approximately the same stability values. However, for a wave steepness, s_{0p}, of 3% the methods are not equal. Which of the methods is most promising has to be verified by the experimental results which will be discussed in chapter 6.

3.5 Comparison of regular waves and irregular waves

Finally a comparison can be made between the stability relations for regular and irregular waves. See figure 3.16.

The stability values, $H_s/\Delta D_{n50}$ for irregular waves are smaller then the stability values, $H_0/\Delta D_{n50}$ for regular waves, when compared for the same wave steepness. The local $H_{1\%}$ wave heights used in the calculations for irregular waves are much higher than the local wave heights used in the calculations for regular waves and will therefore result in lower stability values.

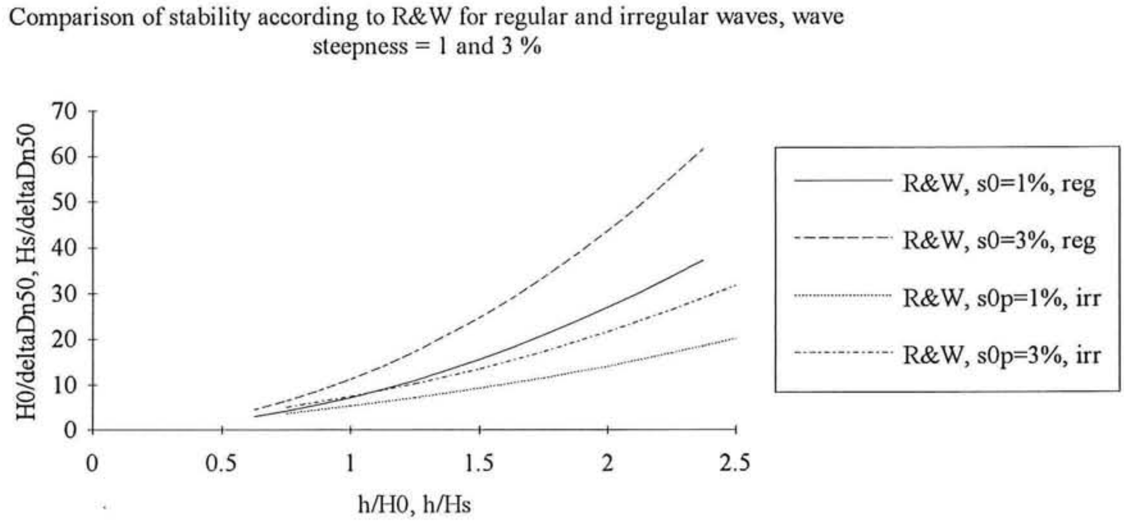


figure 3.16

The calculations performed in this chapter might give a good approximation for the stability of stones on gentle slopes. Model experiments with regular waves as well as with irregular waves will be needed for comparison.

4 Model tests

The set-up of the model tests was constructed in such a way that the generated dimensionless variables could be varied in the tests, to confirm or reject the possible stability relations presented in chapter 3.

4.1 Test facility

All test were carried out in the large wave flume of the Laboratory of Fluid Mechanics of the Faculty of Civil Engineering of the Delft University of Technology. The total length of the flume is 40 m, the width 0.8 m and the height 1.0 m. The wave generator is able to produce regular as well as irregular waves. The wave board can only make translational movements and is provided with a compensating device for reflected long waves. Standing waves in the wave flume will be avoided by this device.

4.2 Test configuration

A "gentle", 1:25 slope was built in the wave flume (figure 4.1). The structure was constructed out of a body of sand and an impermeable layer of cement, with a thickness of ablout 4 cm.

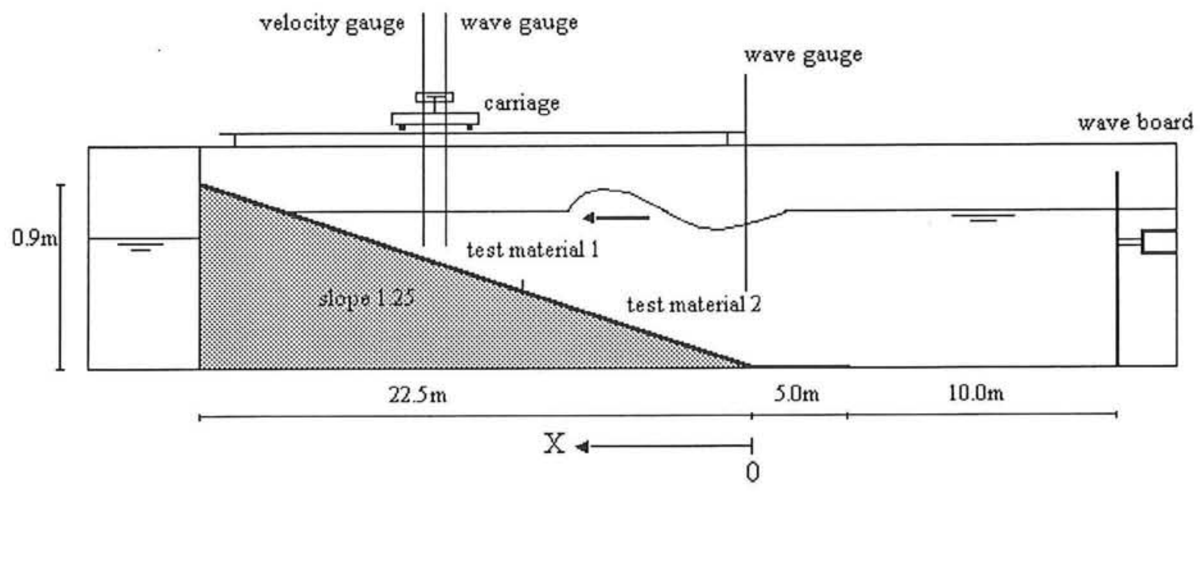


figure 4.1: model structure (scale distorted)

The test material used was laid upon the cement layer. This was done in strips of 25 cm over the width of the flume and the length of the slope. Different types of rock were tested. Per test two materials were laid down on the slope. The reason for this was to be able to gain as much information as possible over the slope region per test session. Figure 4.1 shows test material 1 laid down, till a water depth of approximately $1.25 \cdot H$. Test material 2 covered the remaining part of the test section, till the toe of the slope. In front of the slope a section of 5 m was covered with rock to simulate a certain roughness. The thickness of the layer was approximately $3 \cdot D_{n50}$.

As just mentioned two types of material were used per test. In total four different types of stones were used.

$D_{n50} = 0.84 \cdot D_{50}$, where 0.84 is a conversion factor according to Laan (1981). The use of this conversion factor is justified when the stones are small, less then 20 mm.

Test material 1 consisted of stones with the following characteristics:

- $D_{n50} = 14.7$ mm (see sieve curve in figure 4.2), and $\Delta = D_{85}/D_{15} = 1.4$.
- $D_{n50} = 9.6$ mm with a grading, Δ, of 1.4. (for sieve curve see appendix I).

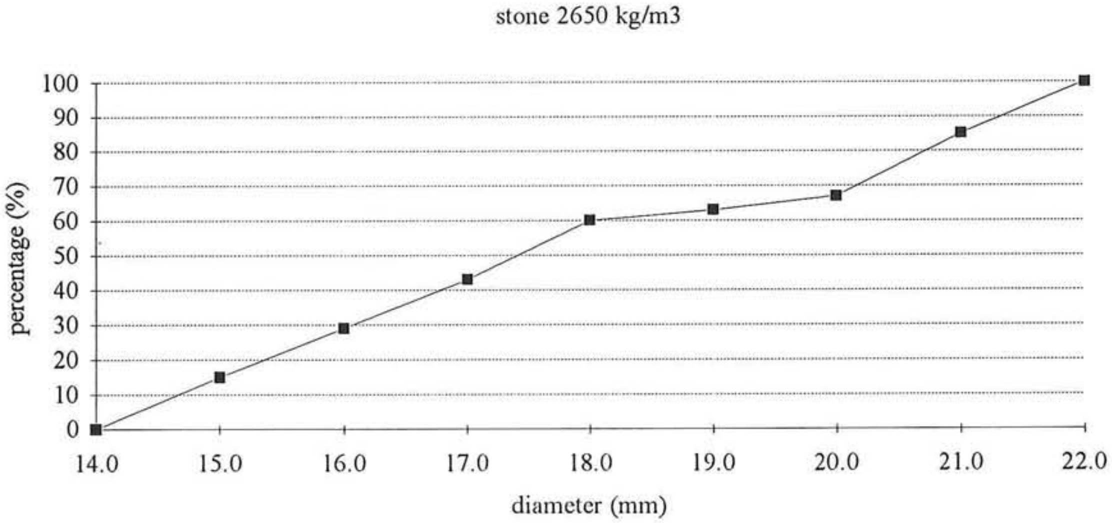


figure 4.2: Sieve curve stone $D_{50} = 17.5$ mm, with a mass density of 2650 kg/m^3

Test material 2 consisted of stones with the following characteristics:

- $D_{n50} = 6.1$ mm with a grading, Δ, of 1.48 (for sieve curve see figure 4.3)
- $D_{n50} = 6.3$ mm with a grading, Δ, of 1.4 (for sieve curve see appendix I).

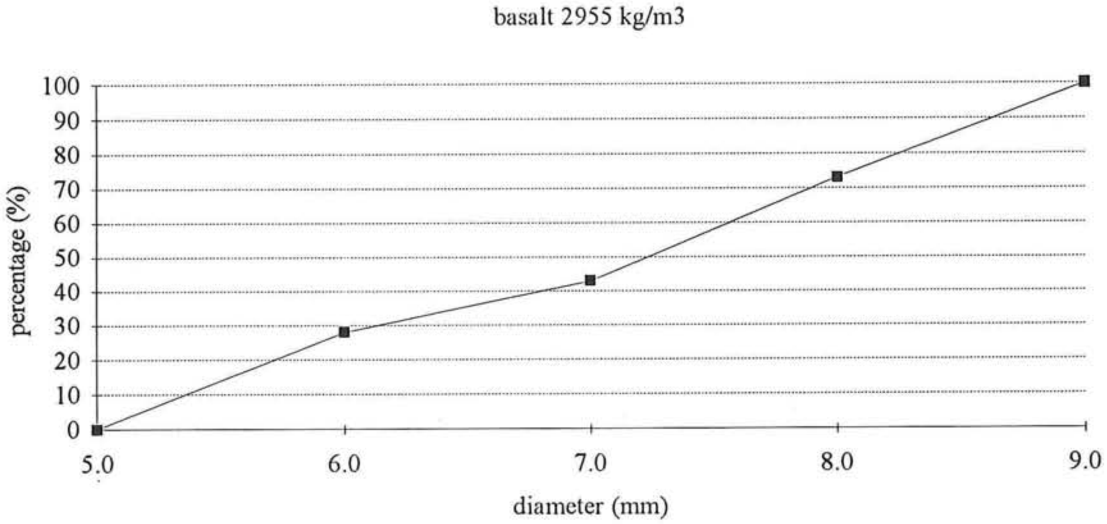


figure 4.3: Sieve curve of stone D_{50} = 7.3 mm, with a mass density of 2955 kg/m^3

The stones were painted in different colors to be able to visually recognize any displacement. In total 6 colors were used. These were all laid down in strips of 25 cm width.

4.3 Wave conditions and duration

The tests were conducted with regular as well as with irregular waves. Both types of waves were generated with the Delft Hydraulics software, AUKE/pc. For regular waves equal sinusoidal components were generated. For irregular waves sinusoidal components according to a defined spectral shape were generated. In all irregular wave experiments the JONSWAP spectrum was used. An example of both input files of AUKE/pc is given in appendix II. The required wave field, measured in the wave flume, did not correspond to the input. Therefore the wanted wave field had to be iterativaly determined before each experiment to be executed.

Sistermans (1993) generated 750 regular waves to "attack" his model structure. When investigating the development in damage after 250, 500 and 750 waves, respectively, he concluded that most of the damage was caused by the first 250, waves but that there was no equilibrium reached after 750 waves. The stability formulae developed by Sistermans (1993) for regular waves were based on 750 waves causing damage. In order to be able to compare results, the amount of 750 waves causing damage will also be used in this thesis.

The regular wave tests were performed with wave steepnesses of 3 % and 5 %. The 7 % wave steepness as generated in the research of Sistermans (1993) was not repeated, because it exerted too much mechanical stress on the wave board. A wave steepness of 1 % was tried but could not be generated by the wave board as a regular wave. Also a test series was conducted with a constant wave period and increasing wave heights.

In the case of irregular waves, 2000 waves were generated. A realistic design storm of approximately six hours and a peak period of 10 seconds contains about 2000 waves. Another reason for choosing 2000 irregular waves in the experiments is the possibility to compare test results with results found by Sistermans (1993). For comparison of irregular waves with regular waves see chapter 6.

The fictive wave steepness, s_{0p}, for irregular waves was chosen as the ratio of the significant wave height, H_s, over the deep water wave length, L_0. The deep water wave length for irregular waves is defined by the peak period of the energy density spectrum as:

$$L_0 = \frac{g T_p^2}{2\pi} \tag{4.1}$$

where: T_p = peak period of the energy density spectrum

4.4 Measurements and data processing

4.4.1 Instruments

Conductivity-type wave gauges were used to measure surface elevations in the wave flume. The gauges consist of two metal rods which measure the conductivity of the water body between them. Complete information about the conductivity-type wave gauges are given in the instrument manual of De Wit (1992). Two wave gauges were used to acquire the wave data. One at the toe of the slope to continuously measure the incoming wave. This is initially the wave height that will be used to derive the stability relations. The second one is positioned on a carriage to be able to get wave height information along the slope till the wave breaking point.

Velocity measurements were obtained with an electromagnetic velocity meter (EMS). The meter was also positioned on the carriage to acquire velocity information along the slope. After the breaking point too much air enclosure in the water made it impossible to measure velocities with the EMS.

Both the wave gauges and the velocity meter were connected to a computer. The analog signals from the meters were converted by an A/D converter, after which the data acquisition system, DACON, collected and stored the data in files.

For regular waves it proved to be useful to monitor the measured wave height with a pen recorder during the test.

The computer which was used to generate the wave field was also used to translate the input data to the wave board.

4.4.2 Calibration

Unfortunately, every wave gauge and electromagnetic velocity meter is subjected to instability of output voltage. Measurements have to be corrected for this fault. At the beginning of each test a calibration procedure had to be followed.

For the wave gauges this meant a calibration in still water. This was done by giving the gauges five different immersion depths. For each immersion depth a measurement was done. The measurements combined were used to calibrate the wave gauges by using the least-squares method. The slope and the offset found with this calibration were used to elaborate the data afterwards.

An example of the results of a wave gauge calibration is given in figure 4.4.

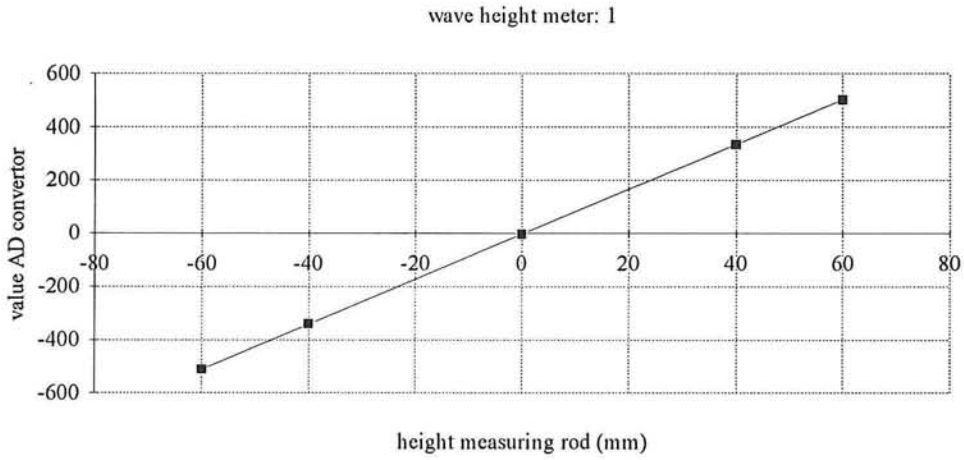


figure 4.5: Calibration of wave gauges

The electromagnetic velocity meter was calibrated by conducting a measurement before and after the tests in still water. By means of these measured files a correction 'drift' factor was calculated. The 'drift' factor is the drift of voltage per unit time. By multiplying the data with this factor the 'correct' data were obtained.

More specific information on calibrating data files is given by De Wit (1992).

4.5 Measurements and data elaboration

Surface elevations and velocities at 7 positions along the slope were measured for regular waves. An example of a regular wave height measurement is given in figure 4.6. Measurements were taken at each position with a measureing time of 60 seconds, except for the position at the toe of the slope, where the measurements were taken continuously. In this period of 60 seconds, the number of waves varied between 30 and 50, depending upon the wave period. This proved to be sufficient to get a good impression of the local wave height and the local bottom velocity. An example of a regular velocity measurement is given in figure 4.7. For a distribution of the velocity profile over the water-depth see appendix III. It proved to be that measurements at approximately 2 cm above the mean average bed were correct to measure the orbital bottom velocity.

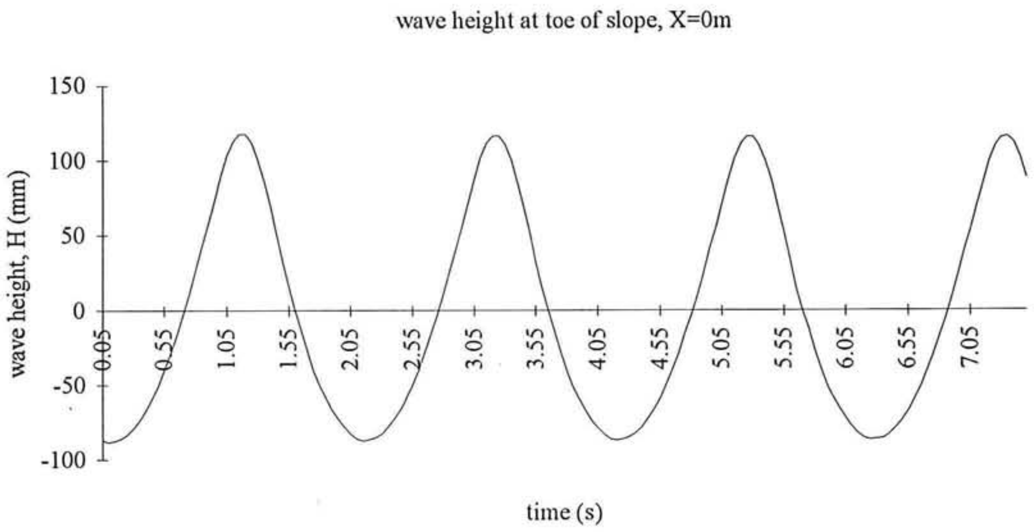


figure 4.6: Example of a wave height measurement for regular waves at the toe of the slope, exp. H20s3

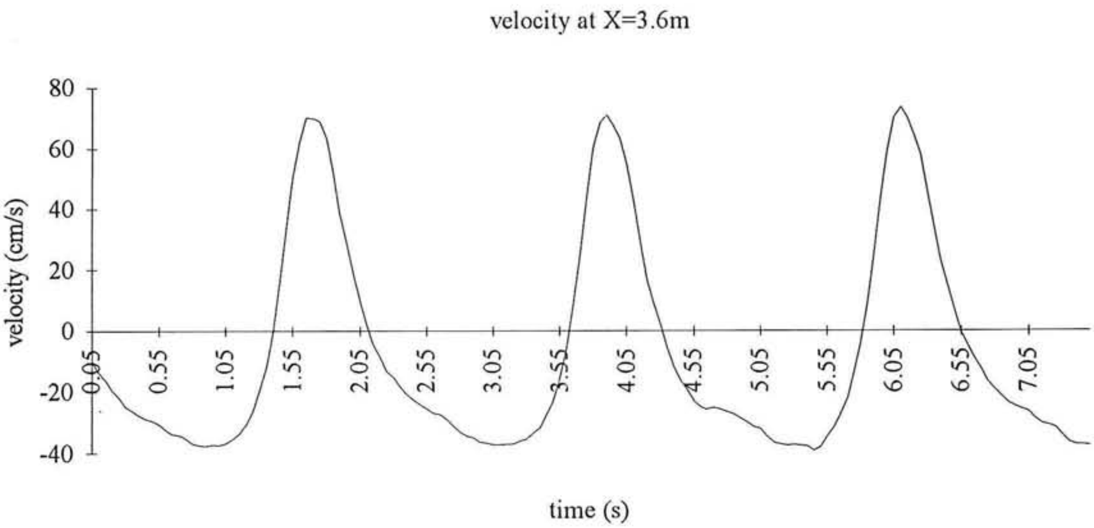


figure 4.7: Example of a velocity measurement for regular waves, experiment H24s3

Irregular waves and velocities were measured along the profile at only 3 different positions along the slope. This was because information of the whole spectrum (duration of about 15 min.) had to be measured. Therefore the total test period was only sufficient to do 3 measurements. Examples of measurements are given in figure 4.8 and 4.9.

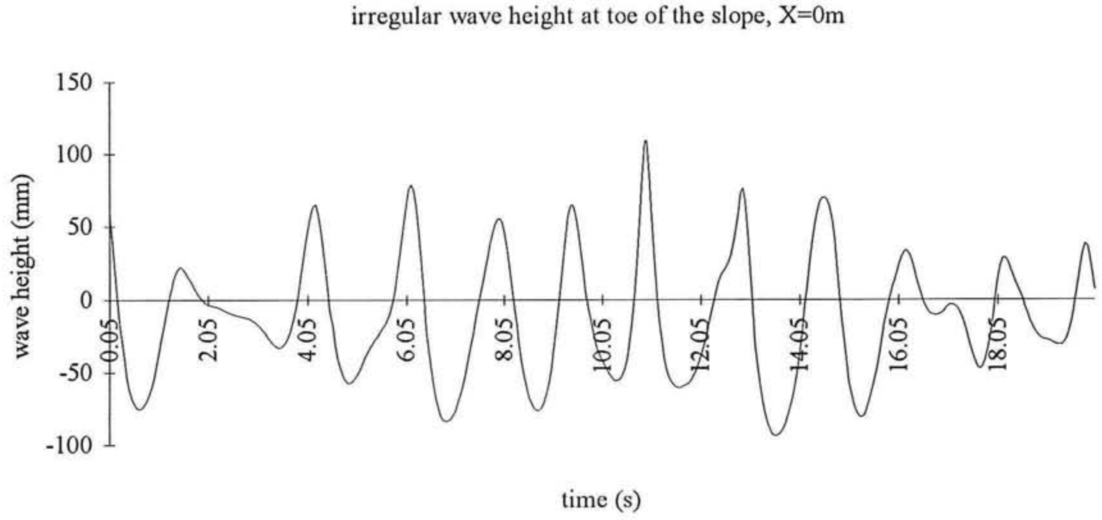


figure 4.8: Example of a wave height measurement for irregular waves at X=0m, experiment Hs14s3

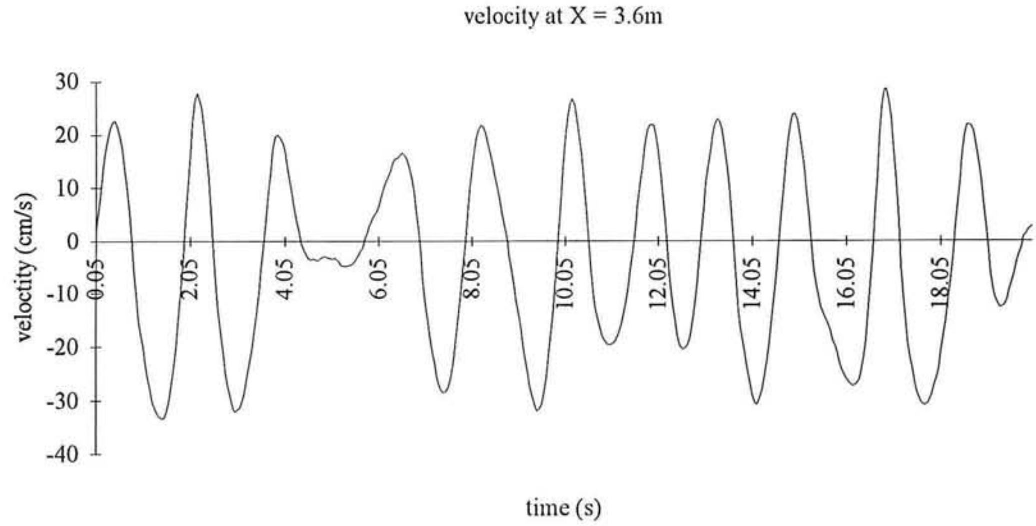


figure 4.9: Example of a velocity measurement for irregular waves at X=3.6m, experiment Hs14s3

For irregular waves the significant wave height and the peak period, had to be checked after every measurement with the software package AUKE/pc. The spectrum used was measured with the wave height gauge at the toe of the slope. The shape had to be approximately the same as the shape of the input spectrum, which was, for all irregular wave tests, the JONSWAP wave spectrum. An example of a measured energy density spectrum is given in figure 4.10.

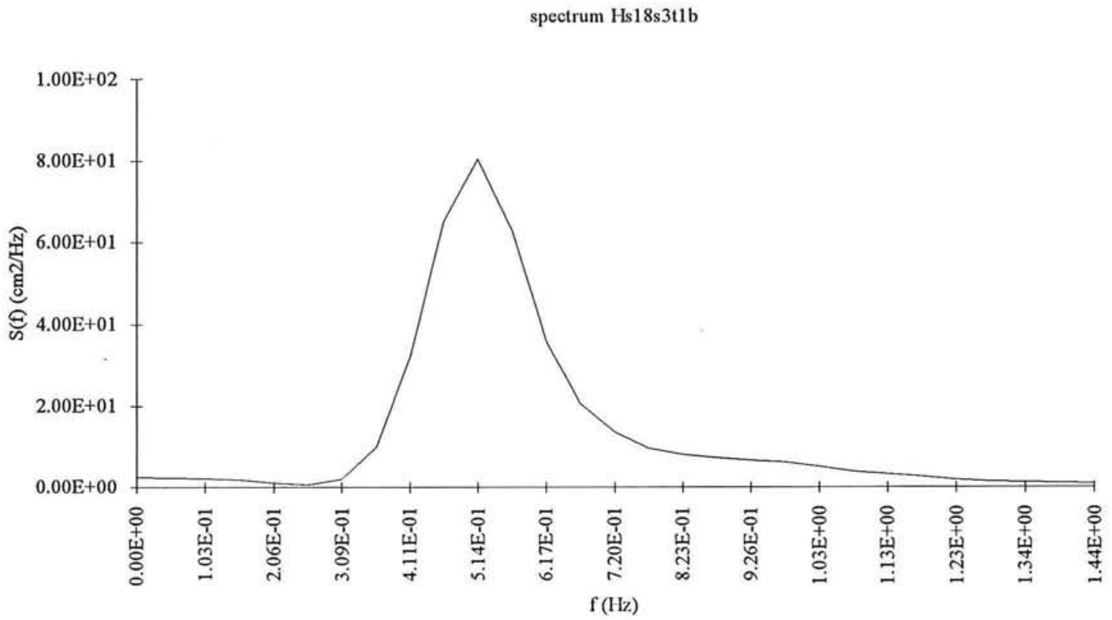


figure 4.10: Energy density spectrum for experiment H_s18s3, f_p = =0.51 Hz, H_s = 0.18m

Damage measurements were conducted by means of counting stones which were displaced from one strip to another. Difference was made between up and down slope displacements. The distance of displacement was not measured.

To represent the situation of stones being freshly dumped, the layer of rock was loosened by hand before each test. During a test the stones tend to settle into a more stable position. By loosening the top layer after each test, the begin situation was more or less equal.

A point gauge was used to measure the water-depths for each test.

4.6 Test procedures

The followed test procedure is shortly described in this paragraph. For a more detailed test procedure the reader is referred to appendix IV.

Procedure for both regular and irregular wave tests:

1. Put the stones in their corresponding colored strips and be sure that the top layer is 'loosely' packed as described in paragraph 4.5.

2. Fill the wave flume till the required depth is reached. (70 cm for regular waves and 60 cm for irregular waves)

3. Run the data acquisition set for the determination of the 'drift' factor of the EMS in still water.

4. Run the control file in AUKE/pc for the wave-board controller.

5. Calibrate the wave height gauges.

6. Change the calibration factors in AUKE/pc.

7. Turn on the wave-board controller.

8. Run the data-acquisition set at the required positions.

9. Stop the tests after 750 waves (regular waves) or 2000 waves (irregular waves).

10. Run the data-acquisition set for the determination of the 'drift' factor of the EMS in still water.

11. Let the water out of the flume

12. Determine the damage.

5 Experimental results

This chapter summarizes the results of the experiments performed. Results are given in damage distribution curves and in damage curves per strip. The complete experimental results are given in appendix V.

5.1 Regular waves

5.1.1 Performed experiments

The regular wave tests were performed for various wave conditions. The first two test series were conducted with a constant wave steepness and an increasing wave height.

s_0, req.	T, req.	experiments	H_0, req.	H_0, meas.	T, meas.	s_0, meas.	test material 1	test material 2
3		H12s3t2	12	11.8	1.6	2.95	D_{n50}= 15mm	D_{n50}= 6.3mm
		H16s3t1	16	16.8	1.84	3.18	D_{n50}= 15mm	D_{n50}= 6.3mm
		H20s3t1	20	20.3	2.08	3.0	D_{n50}= 15mm	D_{n50}= 6.3mm
		H24s3t2	24	22.6	2.24	2.89	D_{n50}= 15mm	D_{n50}= 6.3mm
		H24s3t3	24	23.5	2.24	3.0	D_{n50}= 15mm	D_{n50}= 6.3mm
		H26s3t1	26	27.3	2.36	3.13	D_{n50}= 15mm	D_{n50}= 6.3mm
3		H16s3t1b	16	15.9	1.81	3.1		D_{n50}= 6.1mm
		H20s3t1b	20	21.4	2.08	3.17		D_{n50}= 6.1mm
		H24s3t1b	24	25.1	2.24	3.2		D_{n50}= 6.1mm
	2	H5T2b	5	5	2		D_{n50}= 6.1mm	D_{n50}= 6.1mm
		H10T2b	10	9.86	2		D_{n50}= 6.1mm	D_{n50}= 6.1mm
		H15T2b	15	14.8	2		D_{n50}= 6.1mm	D_{n50}= 6.1mm
		H20T2b	20	19.3	2		D_{n50}= 6.1mm	D_{n50}= 6.1mm
		H25T2b	25	25.0	2		D_{n50}= 6.1mm	D_{n50}= 6.1mm
		H30T2b	30	31.7	2		D_{n50}= 6.1mm	D_{n50}= 6.1mm

table 5.1: Performed experiments, regular waves

Later on a test serie was performed with a constant wave period and an increasing wave height. The total number of waves 'attacking' the structure was 750. No damage development in time was measured.

For both test series the wave height was the main variable involved. In total 4 damage measurements with increasing wave heights were needed to be able to format a reasonable damage curve per strip. Since the output wave height was never equal to the input wave height it is possible that the wave conditions wanted deviate from the measurements. For the results see table 5.1. The first two columns in table 5.1 show the wanted wave steepness and wave period. The third column is used to number the test. H12s3t2, for example, means that a wave height of 12 cm is wanted with a wave steepness of 3%. The addition t2 represents the number of tests which where performed to get the final wanted output. Columns four and five give the wanted and measured wave height. Columns 6 and 7 show the measured wave period and the measured wave steepness. The last two columns give the materials used along the slope of the test section. In general the input wave period was almost equal to the measured wave period.

5.1.2 Distribution of damage

When discussing the distribution of damage along the slope, the total displacement of stones is used. With total displacement is meant: stones displaced in either down-ward or up-ward direction. Stones that move cause damage and can therefore endanger the local stability, so the direction of the displacement is not relevant. In general, stones were moving in up-ward direction, that is towards the shore-line.

The distibution of damage over the slope is given for test example H24s3t3. The damage in number of displaced stones after 750 waves is plotted versus the water-depth. The arrow in figure 5.1 represents the approximate point of breaking.

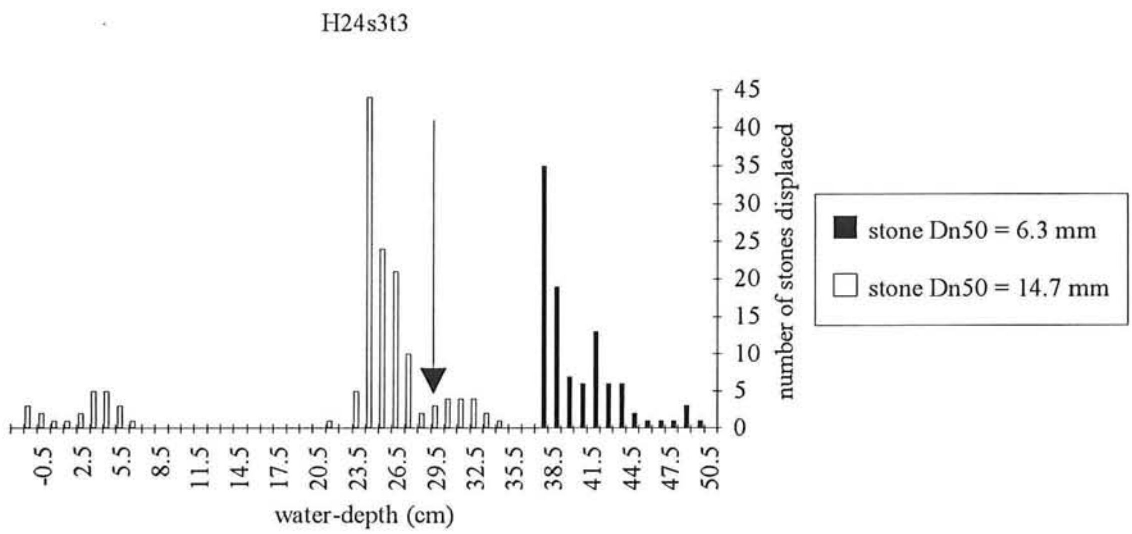


figure 5.1: Damage distribution for regular waves, experiment H24s3t3

It shows that the most endangered position along the slope occurs beyond the point of breaking. This is also what Sistermans (1993) found. What was not found by Sistermans (1993) was damage occuring around the still water level. This is damage caused by run-up and run-down velocities. Damage distribution graphs of other experiments with regular waves are given in appendix VI.

Sistermans (1993) related the maximum damage to the total damage along the slope and plotted this 'relative damage' versus the relative water-depth, h/H_0. Since the total damage was not completely found (there were no test strips around the still water level), one should be careful to interpret the results. In the present study one can not define a relative damage since the total damage of just one material along the slope is not known. This is obviously the concequence of using two test materials on the same slope.

To be able to get an idea of the damage distribution along the slope for various wave heights and with a different steepness one can plot the damage versus the relative water-depth, h/H_0. The absolute value of the number of displaced stones is not that interesting, but the relative position of the most severe attacked location will be obvious. See figure 5.2. The test material used in graph 5.2 is basalt, D_{n50} = 6.1 mm, ρ = 2950 kg/m^3.

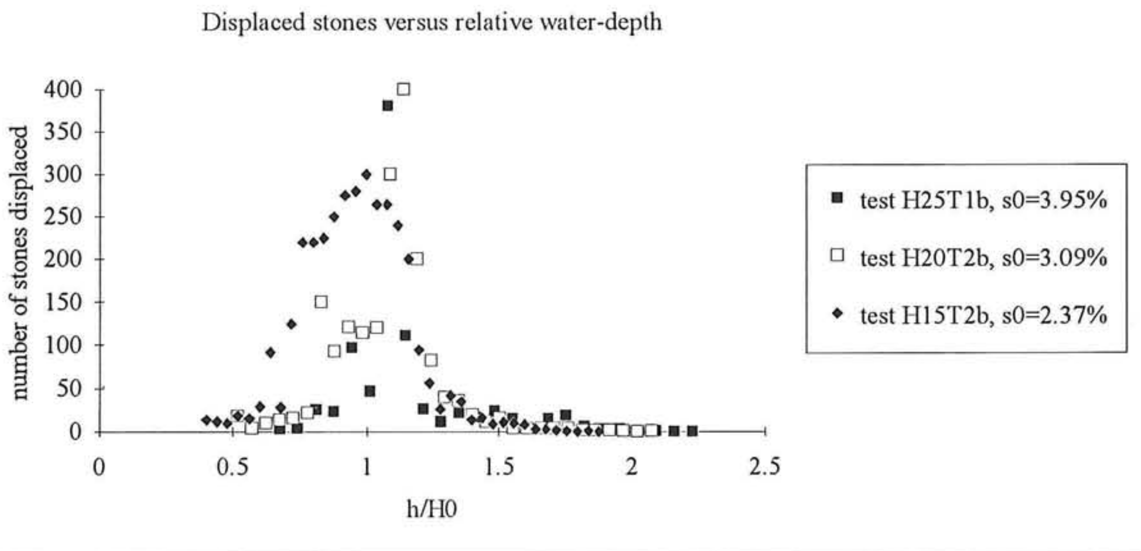


figure 5.2: Number of displaced stones versus h/H_0 for 3 wave heights with a wave period of 2 sec.

All three plotted tests have their maximum location of attack at approximately $h/H_0 = 1$. This is beyond the point of breaking which occurred in the laboratory wave flume at around $h/H_0 = 1.25$. What also can be concluded from figure 5.2 is that with an increasing wave height the damage in number of displaced stones is not nessecerily higher. This has to do with the 'plunging' effect of the breaking wave. For lower values of the wave steepness the 'plunging' effect is more severe than for higher values of the wave steepness.

5.1.3 Damage curves

The damage distribution figures as presented in the previous section and in appendix VI have to be analyzed for different wave heights. This is nessecary to find the wave height which causes the stones to start moving. Since information along the slope is wanted, it is needed to plot the development in damage versus the increasing wave height for several water-depths (damage meaning damage in one strip). See figure 5.3. As example an experiment with the test material with stone dimensions D_{n50} = 6.3mm and Δ = 1.65 is chosen. The plotted points are linearly connected to clearly show the damage development at a particular water-depth. It can be seen in figure 5.3 that generally for larger water-depths a higher wave height is needed to cause the same amount of damage.

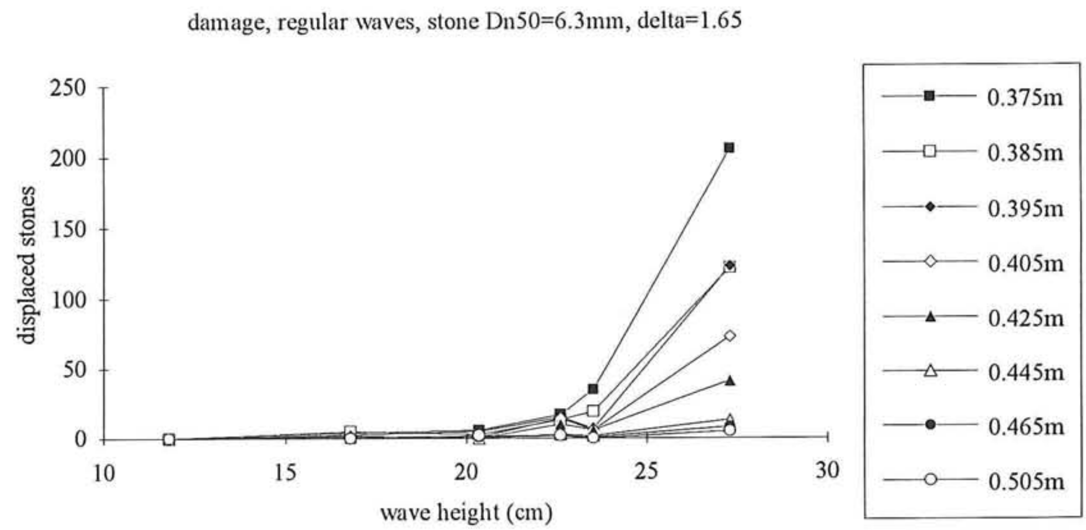


figure 5.3: Displaced stones versus the wave height, for various water-depths, wave steepness = 3%

Because Sistermans (1993) only plotted damage curves for the total damage and the maximum damage, a re-evaluation of his results has been made to get appropriate damage information alonge the slope for regular wave tests performed with a stone dimension of D_{n50} = 9.6 mm and Δ = 1.65.

5.2 Irregular waves

5.2.1 Performed experiments

The irregular wave tests were performed for various wave conditions. For each chosen wave steepness, a number of experiments was carried out. For each test serie the significant wave height, H_s, was the main variable involved. In total 4 damage measurements with increasing significant wave heights were needed to be able to format a reasonable damage curve per strip. As with regular waves the output wave height was never equal to the input wave height. Therefore it is possible that the wave conditions wanted deviate from the measurements. For the results see table 5.2. In general the input wave period, T_p, was almost equal to the measured wave period.

The total number of waves 'attacking' the structure per experiment was 2000, which is approximately 2000 times the peak period, T_p, of the spectrum. No damage development in time was measured.

s_0, req.	experiment	H_s, req.	H_s, meas.	T_m	T_p	s_{0p}, meas.	material 1	material 2
1	Hs10s1t1	10	10.67	2.07	2.43	1.15	D_{n50}=14.7mm	D_{n50}=6.3mm
	Hs12s1t2	12	12.54	2.21	2.78	1.04	D_{n50}=14.7mm	D_{n50}=6.3mm
	Hs14s1t1	14	13.95	2.36	2.78	1.15	D_{n50}=14.7mm	D_{n50}=6.3mm
	Hs15s1t2	15	14.6	2.38	2.78	1.21	D_{n50}=14.7mm	D_{n50}=6.3mm
3	Hs10s3t1	10	10	1.19	1.49	2.9	D_{n50}=14.7mm	D_{n50}=6.3mm
	Hs14s3t1	14	14.63	1.47	1.77	3.0	D_{n50}=14.7mm	D_{n50}=6.3mm
	Hs18s3t1	18	18.24	1.65	1.95	3.09	D_{n50}=14.7mm	D_{n50}=6.3mm
	Hs20s3t2	20	19.4	1.77	2.16	2.66	D_{n50}=14.7mm	D_{n50}=6.3mm
5	Hs16s5t1	16	16.19	1.33	1.4	5.3	D_{n50}=14.7mm	D_{n50}=6.3mm
	Hs18s5t1	18	17.9	1.40	2.36	5.0	D_{n50}=14.7mm	D_{n50}=6.3mm
	Hs23s5t1	23	20.13	1.41	1.62	5.0	D_{n50}=14.7mm	D_{n50}=6.3mm
1	Hs9s1t1b	9	9.84	2.07	2.43	1.07	D_{n50}=9.6mm	D_{n50}=6.1mm
	Hs10s1t1b	10	10.52	2.05	2.43	1.14	D_{n50}=9.6mm	D_{n50}=6.1mm
	Hs14s1t1b	14	12.72	2.38	2.78	1.05	D_{n50}=9.6mm	D_{n50}=6.1mm
	Hs15s1t1b	15	13.29	2.37	2.78	1.10	D_{n50}=9.6mm	D_{n50}=6.1mm
3	Hs10s3t1b	10	9.9	1.20	1.5	2.81	D_{n50}=9.6mm	D_{n50}=6.1mm
	Hs14s3t1b	14	13.79	1.51	1.77	2.81	D_{n50}=9.6mm	D_{n50}=6.1mm
	Hs18s3t1b	18	17.97	1.63	1.95	3.04	D_{n50}=9.6mm	D_{n50}=6.1mm
	Hs20s3t1b	20	18.83	1.73	2.16	2.6	D_{n50}=9.6mm	D_{n50}=6.1mm

table 5.2: Performed experiments, irregular waves

5.2.2 Distribution of damage

The damage distribution for irregular wave experiments is slightly different compared to experiments with regular waves. As an example of the damage distribution for irregular waves see figure 5.4. This is a typical damage distribution for an experiment with a wave steepness of 1 %. The difference with regular waves is the increase of damage around the still water level. The damage in this region is caused by high run-up velocities due to the irregularity of the waves. High run up velocities can occur when a high wave breaks after a few small waves. The water level then is low and the run-up velocities are high.

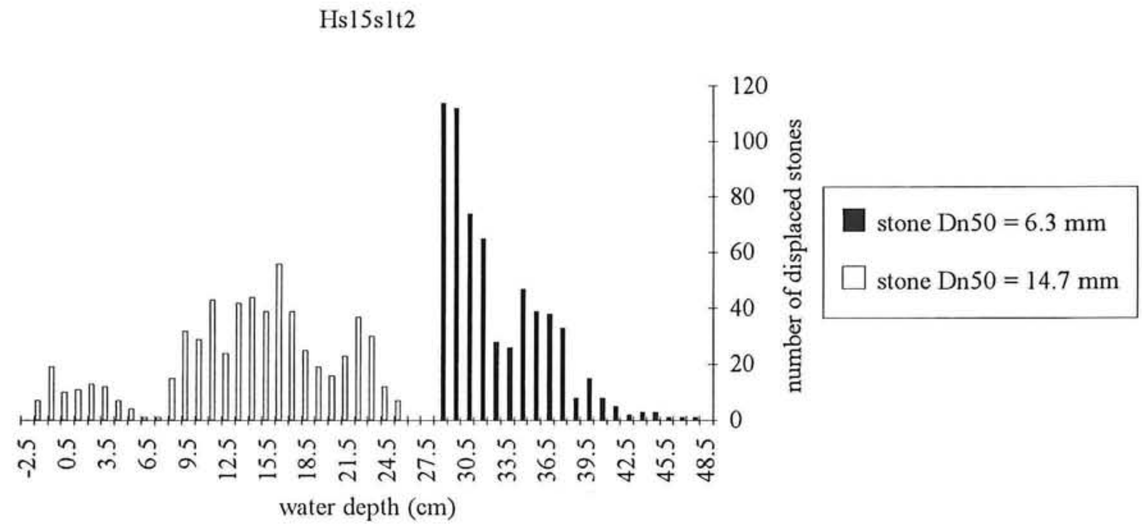


figure 5.4: Distribution of displaced stones over the slope for an irregular wave experiment, $s_0 = 1\%$

Plotting and comparing the experiments for different values of the wave steepness is again very interesting. Since there is no information on the total damage a relative damage cannot be defined. But the general tendency can be seen when showing a damage distribution of an experiment with a higher wave steepness as in figure 5.5. The 'plunging' effect at $h/H_s \approx 1$, (for figure 5.4 this is at a water-depth of approximately 15 cm and for figure 5.5 at a water-depth of approximately 20 cm) is far less severe than in figure 5.4. The damage around the still water level remains of course.

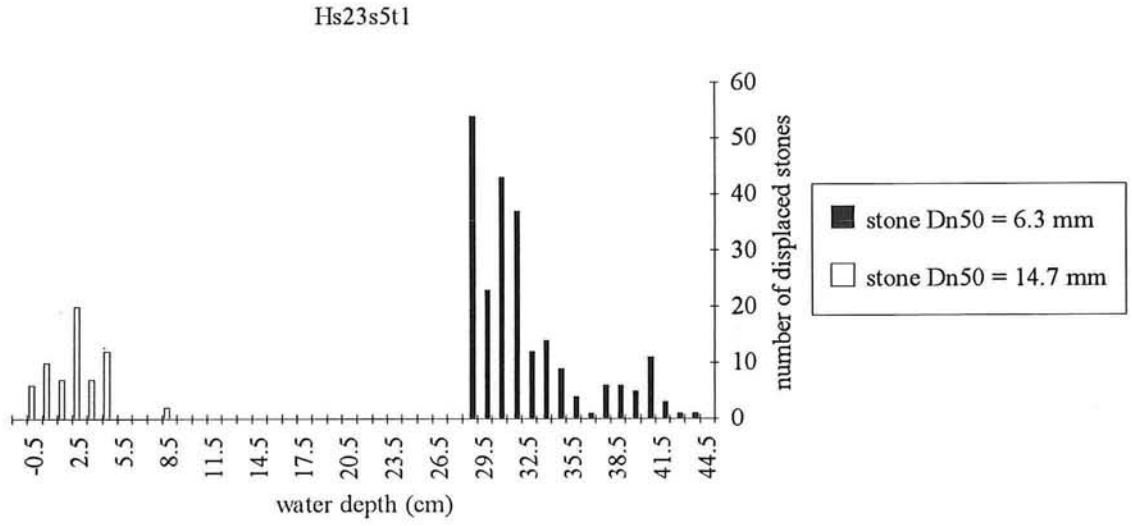


figure 5.5: Damage distribution over the slope for an irregular wave experiment, for s_0 = 5%

More damage distribution graphs as figure 5.4 and 5.5 are presented in appendix VI.

5.2.3 Damage curves

As for regular waves the damage development as a function of the wave height is nessecary to be able to find the wave height which causes the stones to start moving. Since information along the slope is wanted, it is needed to plot the development in damage versus the increasing wave height for several water-depths (damage meaning damage in one strip).

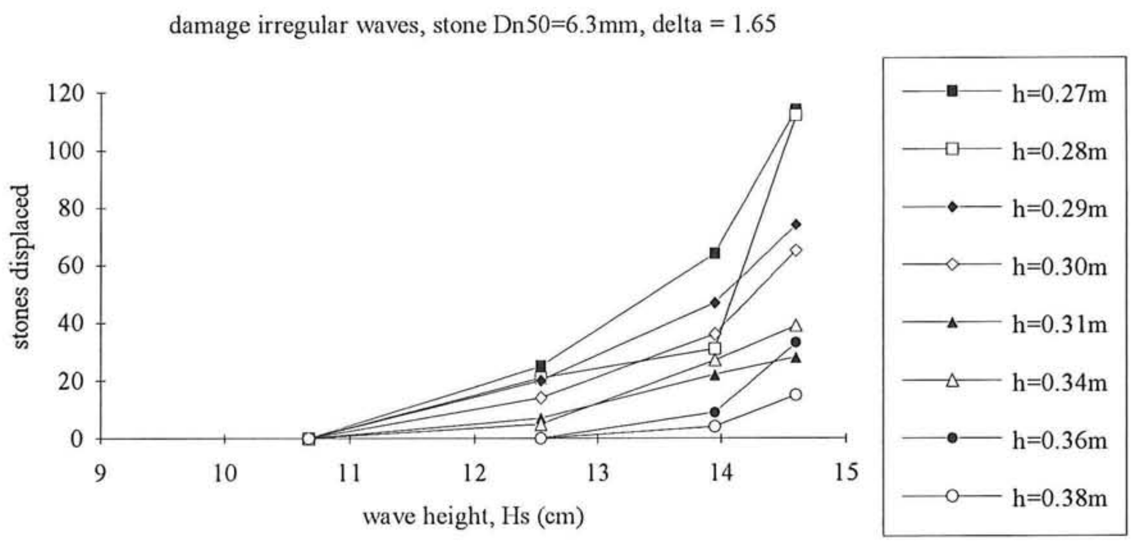


figure 5.6: Displaced stones versus the wave height, Hs, for various water-depthts, wave steepness = 1%

As example an experiment with the test material with stone dimensions D_{n50} = 6.3mm and Δ = 1.65 is chosen. See figure 5.6. The plotted points are linearly connected to show the damage development at a particular water-depth. It can be seen in figure 5.6 that generally for deeper water a higher wave height is needed to cause the same amount of damage.

6 Analysis of experimental results

Chapter 6 presents the analysis of the experimental results. The results obtained for regular and irregular waves are discussed in separate sections. For both wave types a comparison is made with the theoretical approach as described in chapter 3. Also a comparison between the results for regular and irregular waves is made. The last section is used to discuss the validity of the results.

6.1 Damage definition

The damage measured in the experiments is the number of stones moved out of a strip in the wave flume. To express the number of stones displaced into a percentage of damage per strip, a definition of the local damage percentage, $S_{\%}$, was introduced in chapter 2 as:

$$S_{\%} = \frac{n}{A} D_{n50}^{2} \tag{6.1}$$

where: n = number of stones displaced
A = area of strip

All tests were performed with a constant strip width of 25 cm and a strip length of 80 cm (flume width). See figure 6.1 for definition sketch.

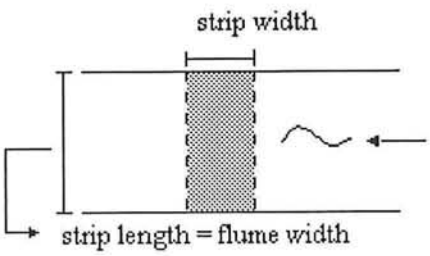


figure 6.1: definition sketch of the strip

Determining damage by using strips introduces two problems.

The first problem when measuring damage by using strips is the width of the strip itself. The question is what the ideal strip width is. Obviously, when using a strip which has a relatively large width, the damage percentage, $S_{\%}$, will not be as large when using a strip with a smaller width. The number of stones which will move within the strip cannot be measured; what will be measured are the stones on the edges of the strip. When using a strip with only one stone diameter, D_{n50}, width, the problem of stone transport within the strip is avoided. But conducting experiments with such a small strip is almost impossible.

So the use of a strip width of 25 cm is an arbitrary one and will introduce an error. The influence of the strip width on the damage level, which is directly related to the number of stones in a strip, will be discussed in section 6.5 (validity of results).

By relating the visible number of stones displaced to the total number of stones with an area D_{n50}^2 that can be fitted into the total area of a strip, introduces the second problem. For every tested stone diameter only a certain number of stones fit in a strip. For comparison of tests with different stone diameters the total amount of stones in a strip should be the same. The dependency on the total number of stones in a strip is discussed in section 6.5.

6.2 Regular waves

This section presents the damage percentage curves which where used to determine the wave heights causing the incipience of motion of the stone. Stability relations with these wave heights are plotted versus the water-depth. Also a comparison with the theoretically derived relations of chapter 3 is made.

6.2.1 Damage percentage curves

To derive stability relations from the performed experiments it is nessecary to know for which wave height the stone starts moving and at what water-depth this takes place. Therefore tests were performed for increasing wave heights, to be able to form damage curves. These were presented in chapter 5. In this chapter the curves are rewritten to plot the damage percentage versus the wave height for various water-depths. An example with stone diameter, D_{n50} = 6.3 mm and Δ = 1.65 is plotted in figure 6.2. This kind of graph is made for all performed experiments. See appendix VII for other curves.

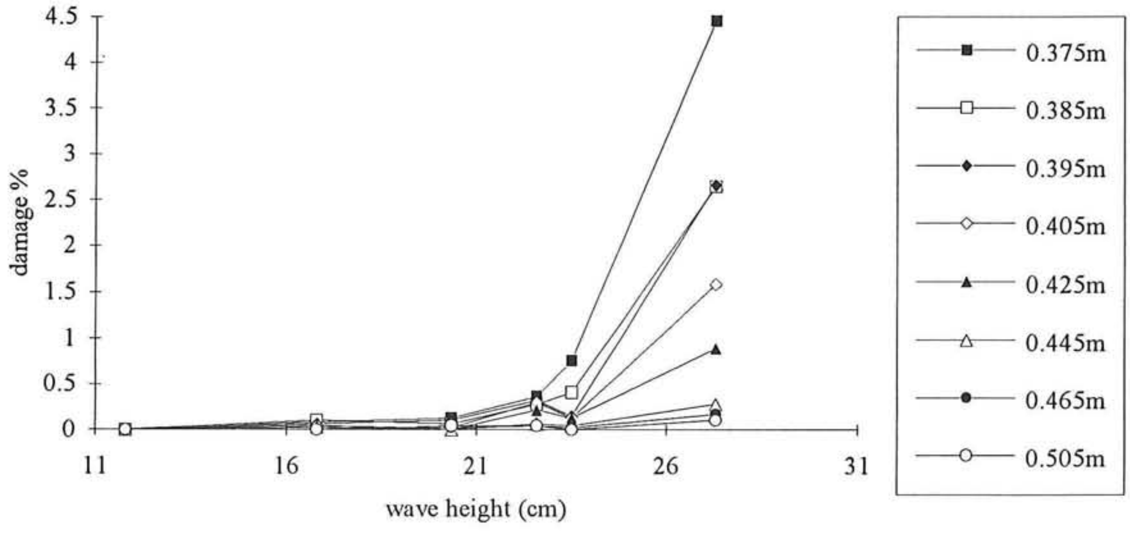


figure 6.2: Damage percentage, S%, versus wave height for various water-depths, wave steepness = 3%

The incipience of motion can now be determined. Theoretically this would be at zero %. In practice it is not clear to define. The method of determining damage is quite subjective. The displacement of one stone can or cannot be seen as damage. One will never know wether the stone was displaced by water motion during the test run or during the filling procedure of the wave flume, even when the filling is done carefully. For design purposes the exact incipience of motion under design conditions is not that interesting. It is interesting to know a local damage percentage which will not be exceeded. Therefore the damage percentage curves will be horizontally intersected for a certain damage percentage level higher than zero. To do this accurately one should 'curve-fit' all the plotted points in figure 6.2 and describe these by a function. For this research it would be practically impossible to curve-fit all the results. Therefore the plotted points of all measurements are linearly connected. By doing this the wave height values which are obtained when intersecting a damage percentage curve horizontally, would lead in general to lower, more conservative values.

The results from the performed intersection in figure 6.2 are grouped together in table 6.1. Two damage percentage levels, 0.5% and 1% are elaborated.

water-depth (cm)	0.5 % damage	1.0 % damage
	wave height (cm)	wave height (cm)
37.5	22.8	23.8
38.5	23.6	24.5
39.5	24	24.8
40.5	24.5	25.7
42.5	25.2	27.7

table 6.1

By choosing a higher damage percentage level it is clear that the wave height which is allowed at a certain water-depth is higher.

6.2.2 Comparison with theory

The results obtained in the previous section can now be compared with the theoretically derived stability relations for regular waves. Before a comparison can be made, a modification of the theoretical stability relations has to be made. The wave heights which are mentioned in table 6.1 are wave heights defined for the laboratory situation, which means, related to the toe of the slope. The wave height values of the theoretically derived stability relations are related to 'deep' water, $L_0 \leq 2 \cdot h$. The situation at the toe of the slope in the laboratory flume is not alway's a 'deep' water situation, which means that theoretically the wave would already have been influenced by shoaling and is therefore not the same as the deep water wave height. It is important to define for every stability graph to which wave height is referred. Which wave height is chosen is not that important, it can also be the local wave height. In general it would be useful to relate to the 'deep' water wave height, since most wave height measurements are executed in water with $L_0 \leq 2 \cdot h$.

The calculations give a value for the local wave height which is nessecary to cause a certain percentage of damage to the structure. This local wave hiehgt has to be transformed to the value of the wave height at the toe of the slope. The wave height at the toe of the slope is determined by the deep water wave height times the shoaling coefficient at the toe of the slope, $H_{toe} = H_{deep} \cdot K_{sh,toe}$. The local wave height is determined by the deep water wave height times the local shoaling coefficient, $H_{local} = H_{deep} \cdot K_{sh,local}$. By combining these two wave heights and eliminating the deep water wave height, the wave height at the toe of the slope can be calculated as a function of the local wave height.

$$H_{toe} = \frac{K_{sh,\,toe}}{K_{sh,\,local}} H_{local} \tag{6.1}$$

A comparison with the experimental results can now be made.

The choice is made to plot a basic graph which shows the wave height needed to cause damage to a stone with certain dimensions versus the water-depth. For an example see figure 6.3 where the theorectically derived stability relations and the elaborated values of table 6.1 are plotted. The wave height is defined at the toe of the slope.

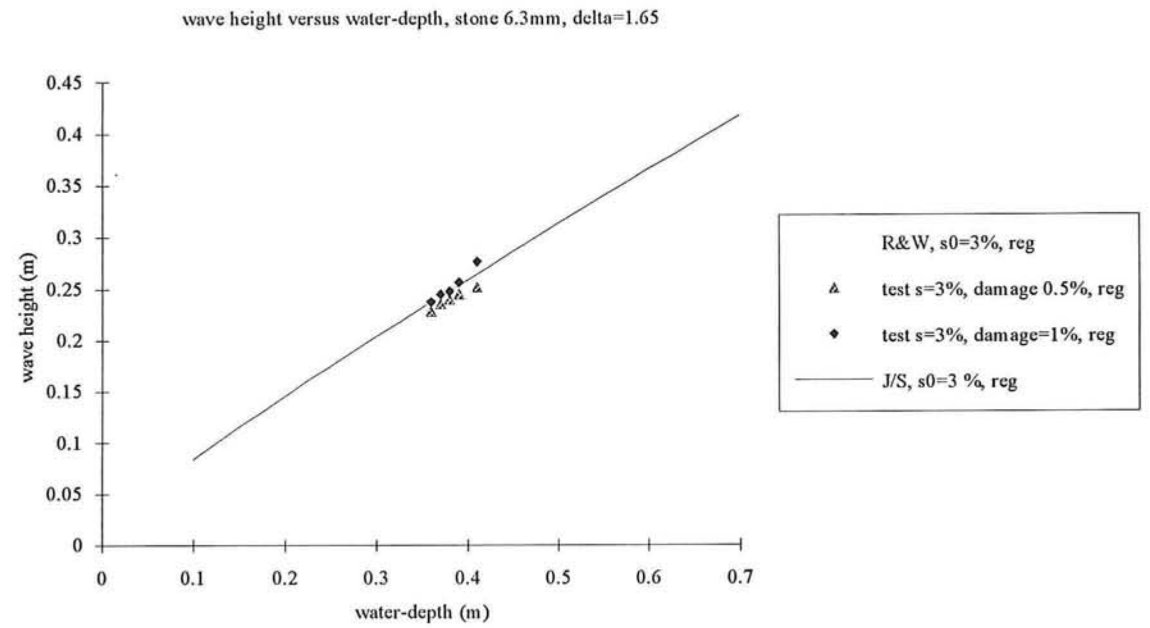


figure 6.3

It can be seen that the theorectical values calculated by Rance & Warren and Jonsson / Sleath match the plotted points obtained from the laboratory experiments very well. Unfortunately the damage measured from the experiments for a 'material 2' stone in 'deeper' water is only for a few strips visible. Damage around the still water line is measured with the 'material 1' stones. For an example see figure 6.4. The wave height is defined at the toe of the slope.

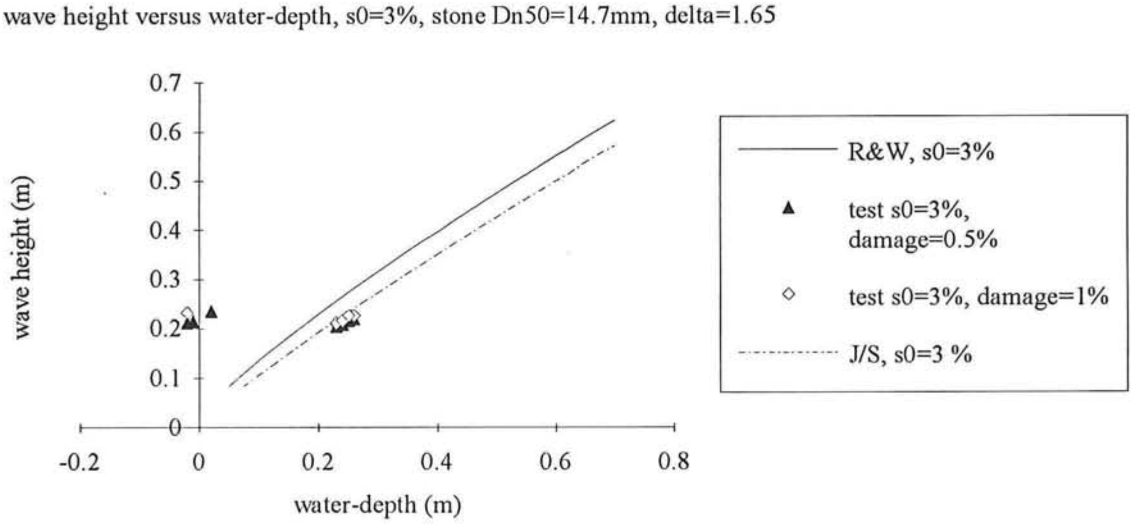


figure 6.4

Again the theoretically derived relations match with the plotted points obtained from the experiments till the wave breaking point. The breaking point appeared to be, for the regular waves at $h/H \approx 1.25$. Around the still water level it can clearly be seen that the nessecary wave height to cause damage deviates from the calculated values (the theoretical wave height at the still water level is zero). The damage around the still water level is caused by the run-up and run-down velocities. The theoretical approach will therefore not be suitable to calculate stability values around the still water level.

For other graphs as figure 6.3 and 6.4, with different stone dimensions the reader is referred to appendix VIII. In appendix VIII also graphs are presented which confirm the same tendencies just described for other values of the wave steepness.

To show the damage over more than 4 or 5 strips an experiment was performed with a 'material 2' stone, with dimensions, D_{n50} = 6.1mm and Δ = 1.95 over almost the whole slope section. Instead of experimenting with a constant wave steepness the wave period was kept constant. For the result see figure 6.5.

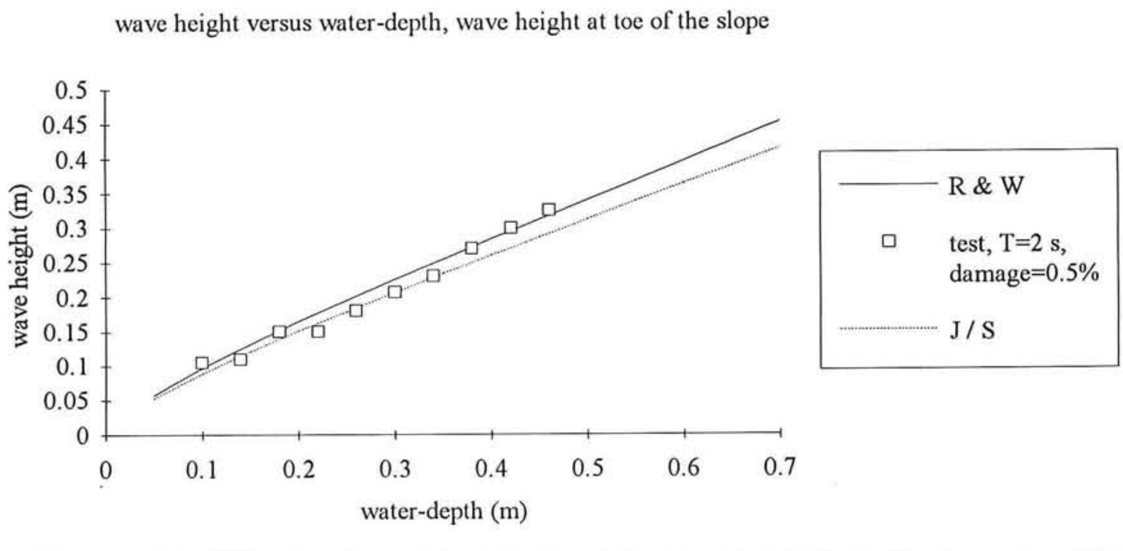


figure 6.5

The theoretically calculated relations according to Rance & Warren and Jonsson / Sleath both do match well with the experimental results. Even for a combination of wave height over water-depth, h/H = 1, beyond the wave breaking point.

Concluding for regular waves with values $h/H > 1$ the experiments match well with the theoretically derived stability relations. For values $h/H < 1$ the theoretical approach is not succesful.

6.3 Irregular waves

This section presents the damage percentage curves for irregular waves. With the obtained results from these damage percentage curves a comparison is made with the derived stability relations; see chapter 3, for irregular waves.

6.3.1 Damage percentages curves

Also for irregular waves it is nessecary to know for which wave heights, H_s, there is incipience of motion and at what water-depth, h, this takes place. Basically the same procedure is followed as in section 6.2.1. The damage curves of chapter 5 were rewritten into curves which show the damage percentage of displaced stones, $S_{\%}$, versus the wave height, H_s. This is done for various water-depths. An example with stone diameter, D_{n50} = 6.3 mm and $\Delta = 1.65$ is shown in figure 6.6.

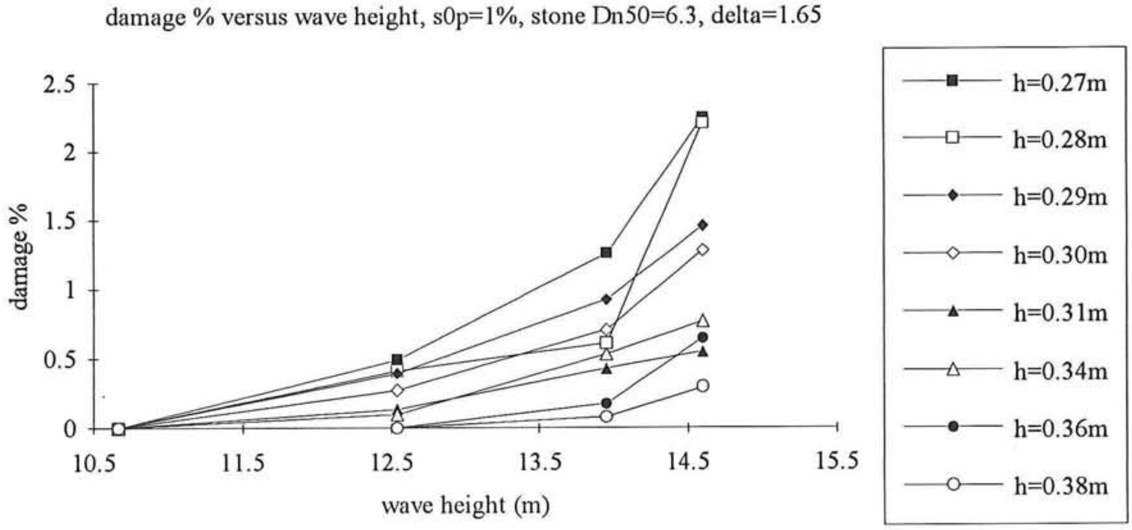


figure 6.6

This is done for all performed experiments. See appendix VII.

Again a local damage percentage, $S_{\%}$, can be chosen, which for design purposes may not be exceeded. In this case a damage percentage 0.5 % will be chosen as an example. For the final results for figure 6.6 see table 6.2.

damage percentage = 0.5%							
water-depth (cm)	27	28	29	30	31	34	36
wave height	12.5	13	12.75	13.2	14.2	13.55	14.35

table 6.2

6.3.2 Comparison with theory

The results calculated in the previous section can now be compared with the theorectically derived stability relations for irregular waves. First a modification had to be made for correcting the 'deep' water significant wave height to the significant wave height at the toe of the slope. The procedure is the same as followed for regular waves.

The results are plotted in the wave height versus water-depth graphs. The wave height is defined by the significant wave height at the toe of the slope which is needed to cause damage at the considered location. For an example see figure 6.7 where the theoretically derived stability relations and the elaborated values of table 6.2 are plotted. This is not only done for a wave steepness, s_{0p}, 3% but also for s_{0p} = 1% and s_{0p} = 5%. To keep the graphs surveyable it is chosen to plot only the theoretical calculated values of Rance & Warren. The two theories compared show not much difference, see appendix IX. So the presentation of only the results according to Rance & Warren is sufficient. The significant wave height, H_s, is defined at the toe of the slope.

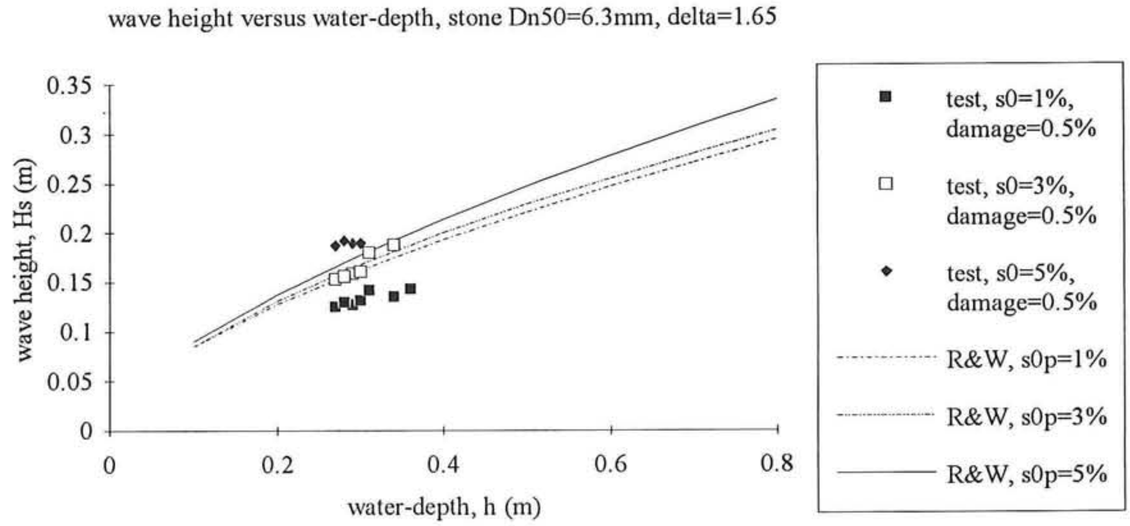


figure 6.7

It can be seen that for a wave steepness 3% the values of the theory do approximate the experimental results. For a wave steepness 1% the theoretically derived relations are too optimistic. As already mentioned in chapter 5 this can probably be explained by the 'plunging' effect of the breaking waves for lower values of the wave steepness. For the deeper water region it is expected that this 'plunging' effect will disappear: the waves will not yet break. And therefore the experiments will probably approximate the theoretically derived relations more in that area of the graph. For regular waves this 'plunging' phenomenon is also noticeable but for irregular waves it is more visible cause the effect can be seen over a larger section of the test slope (the waves break all along the slope).

Another remark on figure 6.7 is that the experimental results for a wave steepness 5% are more stable than the theorectically derived relations. For a wave steepness 5% the effect of plunging is not that severe. This might suggest that the assumption made in chapter 3, namely the highest 1% waves cause damage, is probably a bit high and therefore too negative to use for derivation of stability relations.

The damage measurements around the still water level were conducted with a 'material 1' stone. For an example see figure 6.8. The significant wave height, H_s, is defined at the toe of the slope.

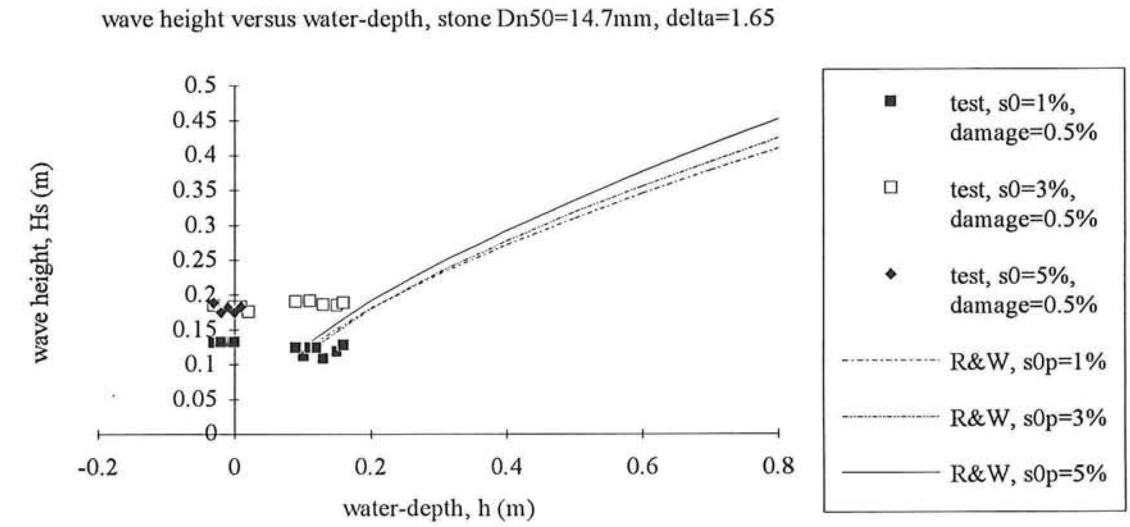


figure 6.8

The figure shows experimental results deviating from the theoretically derived relations, from h/H_s values of approximately 1. This is quite reasonable to understand. The linear wave theory which was used to calculate the orbital bottom velocities does not take into account the breaking of the waves. The calculated values will therefore probably deviate from the measurements.

Around the still water line the damage is caused by the run-up and run-down velocities as described allready for regular waves. The needed wave height which causes damage is in general equal to the wave height around a relative water-depth of $h/H_s = 1$.

Other graphs for different stone dimensions as presented in this section are shown in appendix VIII.

Concluding for the analysis of irregular waves, it seems that the experimentally obtained results do match the theoretically derived stability relations. This holds for the deeper water region where no waves are broken yet. More experimental research has to be conducted to confirm or to reject this assumption. The 'plunging' effect caused by breaking of the waves results into a deviation of the theoretically derived stability relations. This applies especially to waves with lower values of the wave steepness. For values $h/H_s < 1$ the experimentally obtained results can no longer be described by the theoretically derived stability relations.

6.4 Comparison of regular waves and irregular waves

A comparison of regular waves and irregular waves can be made for various different stone dimensions. The best possible graph for comparison would be that where $H_s/\Delta D_{n50}$ is presented versus the relative water-depth, h/H_s. All test results would be presented in one graph. But since the wave heights are defined at the toe of the slope this proved not to be possible. There was no unique presentation of the dimensionless variables obtained. Apparently this is only possible when defining the wave height in 'deep' water, where shoaling has not yet influenced the wave height. A dimensionless presentation of the experimental test results is only possible when 'correcting' all the wave heights to the 'deep' water situation. This would ofcourse be possible, but it should imply a change in wave steepness, which was carefully kept constant during the tests. A comparison for constant wave steepnesses would therefore not be possible.

To get a good impression of a regular wave test compared to an irregular wave test anyway, graph 6.9 is presented. This is only a comparison for one stone diameter but it shows the general tendencies quite well. The wave heights, H_s and H are defined at the toe of the slope.

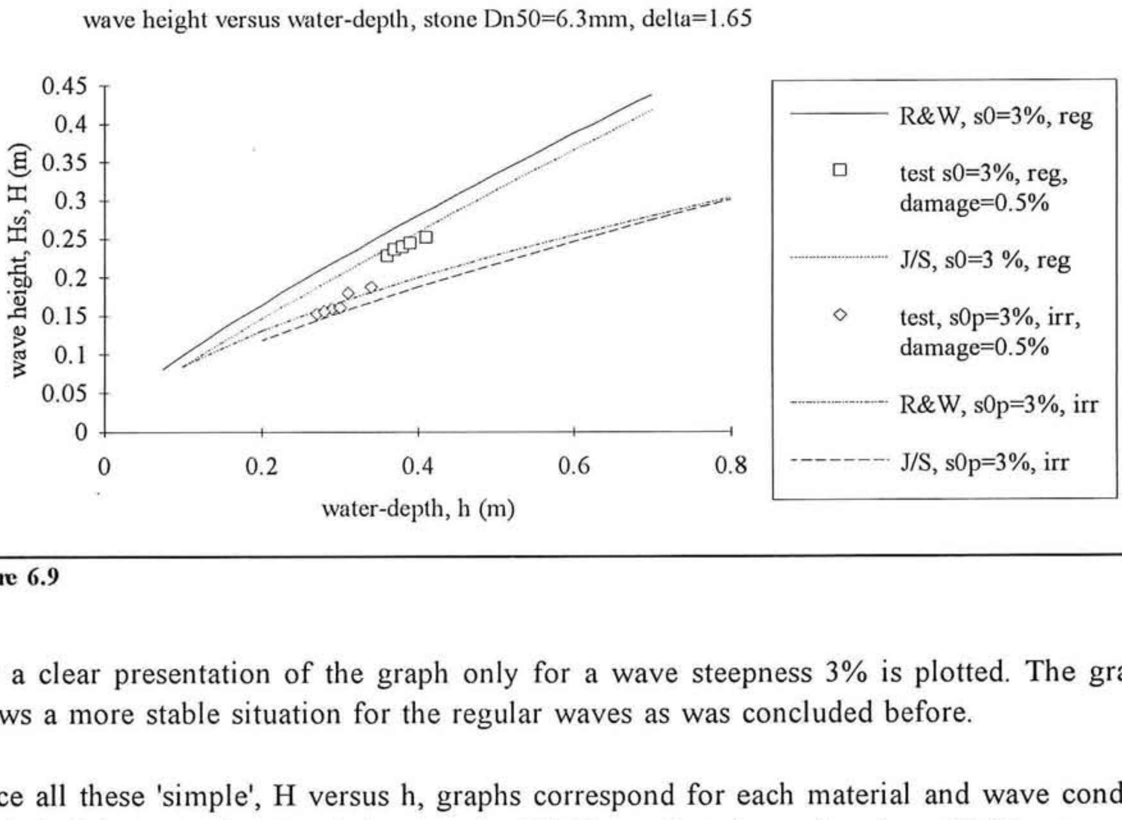


figure 6.9

For a clear presentation of the graph only for a wave steepness 3% is plotted. The graph shows a more stable situation for the regular waves as was concluded before.

Since all these 'simple', H versus h, graphs correspond for each material and wave conditions it is fair to say that the design graphs, $H/\Delta D_{n50}$ plotted as a function of h/H, presented in chapter 3 can possibly be used for design purposes. That is considering the mentioned limitations.

6.5 Validity of the results

6.5.1 Introduction

The results presented in this chapter are derived from experiments performed under laboratory conditions. Various presumptions have been accepted during the analysis of the experiments. If the obtained results, are used to verify existing theories, as done in this chapter, it is nessecary to place some question marks.

One of the question marks is the possible introduction of scale effects. Sistermans (1993) allready investigated this and therefore the reader is referred to his thesis. Sistermans concluded that for the experiments performed in this particular situation no scale effects were introduced.

Another question is the validity of the results for slope angles different from the 1:25 slope used in this research. For horizontal bottoms uptill 1:25 slopes the validity of the mentioned results seem allright. The theories are derived for horizontal bottoms and are verified for 1:25 slopes. For slopes steeper than 1:25 the validity of the used relations is questionable. An answer to this question can probably only be given when conducting more experimental research.

A few problems concerning the validity of the results have been investigated more thouroughly.

- The possibility of spurious correlation when plotting the obtained results in dimensionless graphs.
- The influence of the strip dimensions on the damage level.
- And the usage of the factor $(1+H_s/h)^{-1/3}$, Stive 1984, for correcting the $H_{1\%}$ values of the Rayleight wave height distribution for shallow water.

6.5.2 Spurious correlation

Reed (1921) defined spurious correlation as:

> "Though no correlation exists between any two of a set of variables there will still exist correlation between any two functions of these variables whenever these functions have any of the variables in common. The correlation existing under these conditions will be called <u>spurious correlation</u>."

As an extreme example to explain spurious correlation, two sets of random variables, x_1 and x_2, can be considered that are entirely uncorrelated. Any parameter, x_3, entirely uncorrelated with x_1 or x_2 then be selected. Two sets of ratios, x_1/x_3 and x_2/x_3, are formed and correlated with each other. If the variability of each variable, expressed by the respective coefficients of variation, C_1, C_2, and C_3, is small and equal in value, the coefficients of correlation between the two ratios will be found to be 0.50 (the coefficient of variation is the standard deviation of the parameter divided by its mean value). If the coefficient of variation, C_3, of the common element x_3 is twice that of the other two, a coefficient of 0.8 will result, and if C_3 is equal to 3 times C_1 or C_2, a coefficient of 0.90 will be found. These correlation coefficients, 0.50, 0.80, or 0.90, are referred to as spurious because they appear to indicate correlations where none exists between the original variables.

If the ratios of the example cited are plotted against one another on graph paper, they will appear to define a line or curve of relation. If the graph is now entered with a value of x_2/x_3, a value of x_1/x_3 and therefore a value of x_1 can be determined from the average relation line. As a consequence of the procedure, it is apparently possible to predict a value of x_1 from x_2, although it is known that, because x_1 and x_2 are uncorrelated, this is not reasonable.

In the scope of this study it appeared useful to use certain combinations of variables which also could be spuriously correlated. To investigate the possible spurious correlations, it is necessary to know the coefficients of variation of the variables involved.

The first combination used is: $H_s/\Delta D_{n50}$ as a function of h/H_s
The second combination used is: $H_s/\Delta D_{n50}$ as a function of ξ, with $\xi = \tan\alpha/(H_s/L_0)^{1/2}$

This second combination is not directly used in this thesis to plot results, but since it is commonly used in the existing literature on stability of stones, it will be taken into investigation also. For the result see appendix X.

To get the coefficients of variation it's necessary to know the probability distribution of errors made when determining the values of the variables. The assumption made in this thesis will be that the probability distribution of errors is Gaussian or normal distributed. See figure 5.4.1. The figure shows an area marked by ± 1 times the s.d. (= standard deviation) of the mean value of the variable which represents 68 % of the distribution. The area marked with ± 2 times the standard deviation of the mean value of the variable which represents 95 % of the distribution, can also be used. By stating that the accuracy measured with is represented by one of these two area's, the standard deviation is known.

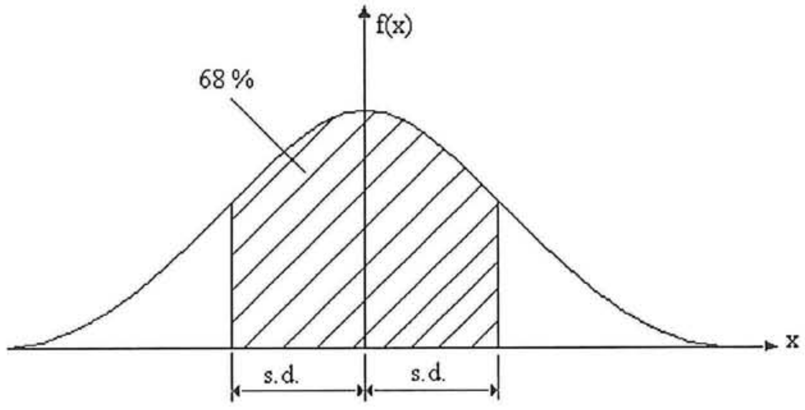


figure 6.10: The Gaussic probability distribution

When for example determining the coefficient of variation of the water-depth, h, the accuracy of the point gauge is needed. The accuracy is ±1 mm and the mean value of the water-depth is 65 cm. It will be assumed that 68 % of the values measured will be between the mean value and ±1 mm. The coefficient of variation in this case is 0.15 %.

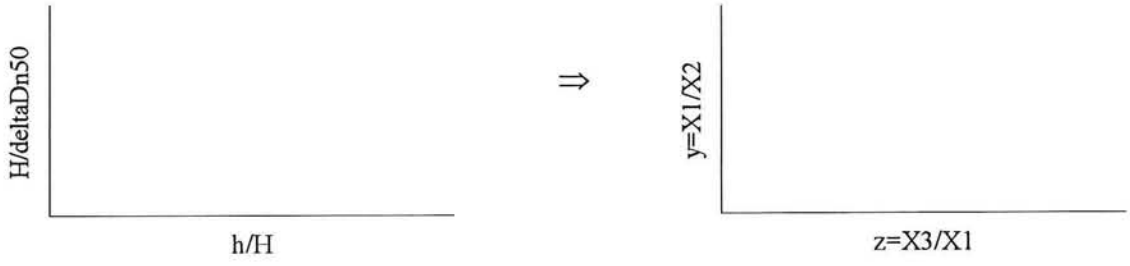
The same approach can be used for the other variables involved. The accuracy of the measurement in every variable is equal to the standard deviation. The chance of occurrence in that interval is 68 %.

- The accuracy of the variable H_s depends on the wave height meter. The coefficient of variation is, $C_H \approx 0.5$ %.
- The accuracy of the wave length in deep water (L_0) depends on the value of T_p with:

$$L_0 = \frac{gT_p^2}{2\pi} \tag{6.2}$$

  T_p is determined with AUKE/pc from the energy density spectrum. So the accuracy of T_p depends on the sample time used during the experiments. With a sample time 50 ms, the coefficient of variation, $C_p \approx 0.2$ %. This gives according to the x-square law of multiplication of errors a coefficient of variation, $C_{L0} \approx 0.4$ %.
- The accuracy of the tangent of the slope anlge, α, depends on the construction itself. This is estimated as approximately, $C_\alpha \approx 0.5$ %.
- The accuracy of the diameter, D_{n50}, depends, with $D_{n50} = \beta \cdot D_{50}$, on the accuracy of the D_{50} in the sieve curve and the shape factor, β. The coefficient of variation is, $C_{Dn50} \approx 1.6$ %.
- The accuracy of the relative density, Δ, depends on the determination of the weight of the rock. The coefficient of variation is, $C_\Delta \approx 0.1$ %.

The first combination can schematically be represented as:



with $X_1 = H$, $X_2 = \Delta D_{n50}$ and $X_3 = h$. Since Δ and D_{n50} are not correlated, $C_{x2}^2 \approx C_\Delta^2 + C_{Dn50}^2$, according to De Vries (1976). $C_{x2} \approx 1.6$ %, which means that the coefficient of variation is determined by the standard deviation of the stones.

According to Benson (1965), the correlation between y and z is defined by:

$$r_{yz} \approx \frac{r_{13}C_1C_3 - r_{11}C_1^2 - r_{23}C_2C_3 + r_{21}C_2C_1}{(C_1^2 + C_2^2 - 2r_{12}C_1C_2)^{\frac{1}{2}}(C_3^2 + C_1^2 - 2r_{31}C_3C_1)^{\frac{1}{2}}} \tag{6.3}$$

With: $r_{11} = 1$
$r_{13} = 0$
$r_{23} = 0$
$r_{21} = 0$
$r_{12} = 0$
$r_{31} = 0$

this yields,

$$r_{yz} \approx \frac{-C_1^2}{(C_1^2 + C_2^2)^{\frac{1}{2}}(C_3^2 + C_1^2)^{\frac{1}{2}}} \tag{6.4}$$

Substitution of the coefficients of variation gives: $r_{yz} \approx -0.29$.

It would be easy to say that when for example permitting a correlation coefficient $|r_{yz}| \leq 0.5$, there is no spurious correlation in the previously mentioned example. The coefficients of variation of the variables are estimated values and are likely to change. So it is more interesting to be able to prevent spurious correlation by investigating how the involved variables influence r_{yz}. Then one could adjust the accuracies of the possible coefficients of variation which cause spurious correlation.

- The coefficient of correlation, C_1, depends on the accuracy of the wave height meter. This is set at 0.5 % which is of course a theoretical value given by the manufacturer of the wave height meter. One could imagine that when the environmental conditions like the temperature are not constant, the accuracy would decrease to for example 1.0 %.

- The coefficient of correlation, C_2, depends mainly on the accuracy of the determination of the diameter, D_{n50}. In the previous example the coefficient was determined by: the error made in the conversion factor for transforming D_{50} to D_{n50} with a 'shape-factor', β = 0.84, and the error made in the sieve curve determining the value D_{50}. One could avoid the error in the shape factor by weighing the stones and making a curve which plots the percentage of stones with a certain weight versus the nominal diameter. The coefficient of variation of the diameter, D_{n50}, decreases from 1.6 % to approximately 1.0 %.
- The coefficient of variation of the water-depth, C_3, will not decrease or increase dramatically. The accuracy of the point gauge is more or less constant.

Combinations of C_1, C_2 and C_3 resulting in different values of r_{yz} are given in table 5.4a.

first combination	1	2	3	4
C_1	0.5 %	1 %	0.5 %	1 %
C_2	1.6 %	1.6 %	1.1 %	1.1 %
C_3	0.15 %	0.15 %	0.15 %	0.15 %
r_{yz}	-0.29	-0.52	-0.40	-0.66

table 6.3

It is obvious, when decreasing the accuracy of the wave height meter, the spurious correlation increases. This is especially the case with an increasing accuracy of the stone diameter. One should pay attention to the accuracy of the wave height meter when wanting to avoid spurious correlation.

With the used variables in combination with their standard deviations in mind it's possible to give judgement of the confidence interval of the values found in the graph of the first combination. As just mentioned 68 % of the measured values is found within ±1 times the standard deviation. So 32 % is the chance of a value found outside the interval of the standard deviation. In situation 1 this yields according to De Vries (1976):

- for the y -axis, (chance of a value outside the interval of ± s.d. for y)^2 = (32 % for H_s)^2 + (32 % for Δ)^2 + (32 % for D_{n50})^2
  chance of a value outside the interval of ± s.d. = 55 %
- for the z -axis, (chance of a value outside the interval of ± s.d. for z)^2 = (32 % for h)^2 + (32 % for H_s)^2
  chance of a value outside the interval of ± s.d. = 45 %

In the graph of combination 1 the total chance of finding a value inside the interval of ± the standard deviation is, (1-0.55)·(1-0.45) = 0.25, or 25 %.

But when stating that the accuracy measured is ±2 times the standard deviation, the marked area under the Gauss distribution is 95 %. This again yields according to De Vries (1976):

- for the y-axis, (chance of a value outside the interval of ±2 times the s.d. for y)^2 = (5 % for $H_s)^2$ + (5 % for $\Delta)^2$ + (5 % for $D_{n50})^2$
  chance of a value outside the interval of ±2 times the s.d. = 8.6 %
- for the z -axis, (chance of a value outside the interval of ±2 times the s.d. for z)^2 = (5 % for h)^2 + (5 % for $H_s)^2$
  chance of a value outside the interval of ±2 times the s.d. = 7 %

In the graph of combination 1 the total chance of finding a value inside the interval of ±2 times the standard deviation is, (1-0.086)·(1-0.07) = 0.93, or 93 %.

Which one of these chances the best approximation is not clear and depends on the correctness of the measurement accuracy of the equipment. In this case it will probably lie somewhere in between 25 % and 93 %.

As a concluding remark it would be fair to say that not much can be said about the occurancy of spurious correlation if there is not an accurate knowledge about the standard deviations of the involved measuring devices.

6.5.3 Influence of strip dimensions on the damage level

When discussing the influence of the strip dimensions on the damage level 2 phenomena are to be considered.

The damage level should be independent of the total amount of stones in a strip. Therefore a certain minimum amount of stones is nessecary. As said before in section 6.1 the ideal strip width is one stone diameter. No transport of stones is possible within the strip. A problem is introduced because only a certain amount of stones fit in the 80 cm broad flume. The damage percentage level may or may not be independent of total amount of stones in that one stone strip. One should test this by increasing the flume width and test if there is a finit limit of the occuring damage level. It then would be possible to define a minimum amount of stones to measure damage and to be sure that there would not be any influence towards the damage level. The test just descibed is unfortunately not possible since the width of the flume is not variable.

Secondly when having determined the minimum amount of stones in a strip an investigation about the strip width has to be made. A strip with a width of one stone diameter is not practically possible when experimenting. The strip has to have more workable dimensions. In this study a strip width of 25 cm is chosen. The broader the strip the more damage will occur within the strip. The damage percentage level will therefore decrease and flatten out. This is shown in figure 6.11.

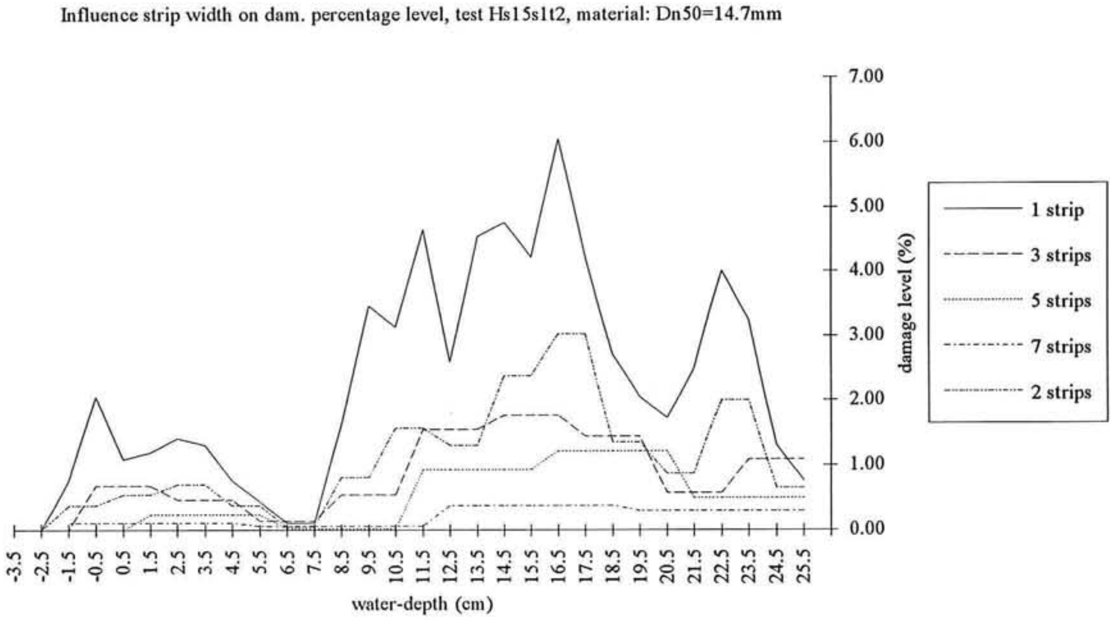


figure 6.11: Influence strip width on damage percentage level

The question is if a strip of 25 cm width is sufficient (small enough) to approximate the 'correct' damage curve. The smaller the strip width the better the approximation. A possibility to research this would be measuring damage in strips on a horizontal bottom. By decreasing the strip width an idea could be formed of the correctness of the 25 cm strip width. This test is not executed in this research.

6.5.4 The shallow water wave height correction factor

In chapter 3 a possible stability relation was derived. The assumption was that the highest 1% of the waves, $H_{1\%}$, causes the damage to the stones. This $H_{1\%}$ was calculated with the Rayleigh probability wave height distribution. For shallow water a correction factor according to Stive (1984) was used to obtain the the proper $H_{1\%}$, wave height. See chapter 3 section 3.41. If this correction factor is valid for the laboratory situation is not clear.

This can be verified by means of a comparison with the wave heights measured in the wave flume and the theoretically calculated wave heights. See figure 6.12.

Two different wave height measurements are compared with the theoretically calculated values. It seems that, at least for this laboratory situation, the correction factor according to Stive (1984) can be used appropriately. Both series of measurements of $H_{1\%}$ are well matched by the calculated $H_{1\%}$ values. All wave heights are local wave heights.

Comparison of H1% measured with H1% calculated for a wave steepness = 3%

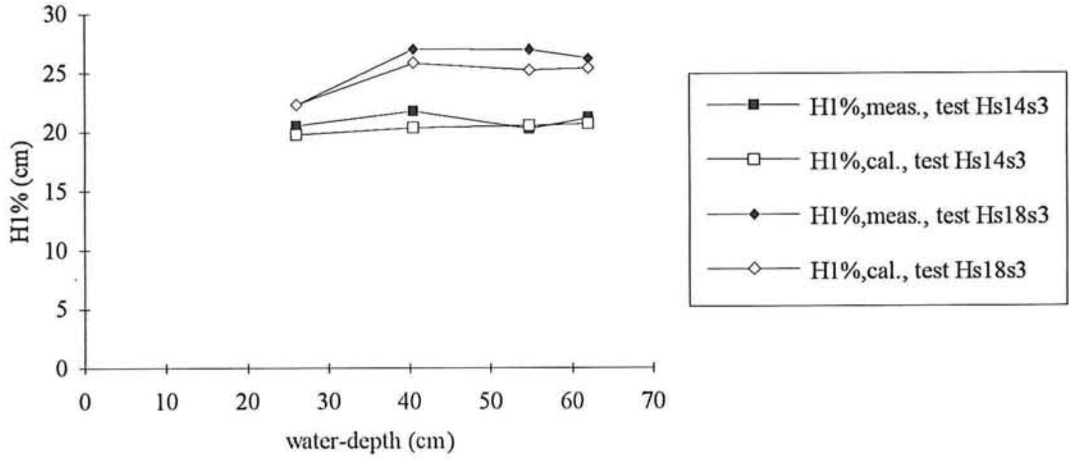


figure 6.12

7 Computer simulation with ODIFLOCS

7.1 Introduction

ODIFLOCS (One Dimensional Flow on and in Coastal Structures) is a numerical model developed by the Delft University of Technology. It can simulate wave motion on and in several types of coastal structures.

The model is based on a one-dimensional description of the flow; known as long wave equations. This means that the depth-averaged velocities are applied. The program uses hydrostatic pressures.

The model is divided into an external part and an internal part; the external part models the motion outside the structure, whereas the internal part models the flow through the porous medium. Regular as well as irregular waves can be applied.

For the simulation of waves on a slope with only a small porous layer as in case of an outfall, it is sufficient to model only the external water motion on the structure. The objective for this thesis is to see wether ODIFLOCS simulates the water motion on gentle slopes correctly. Only regular waves are simulated.

In the experimental fase velocity and wave height measurements were performed which will be compared with the ODIFLOCS results.

7.2 Calculations and comparison with experiments

The geometry used for the ODIFLOCS simulations is the same as that of the laboratory wave flume.

The recommended friction factor when moddeling with ODIFLOCS is given according to Madsen and White by:

$$f=0.29\left(\frac{D}{SWL}\right)^{-0.5}\left(D\tan\frac{\alpha}{R}\right)^{0.7} \tag{7.1}$$

where:

D	=	stone diameter
SWL	=	water-depth in front of the structure
R	=	run-up level
α	=	the slope angle

This factor was developed for breakwaters which implies relatively short, steep slopes. In case of long, gentle slopes the values of the friction factor according to Madsen & White will result in too much energy dissipation. Therefore the smallest value of the friction factor possible in ODIFLOCS, is used (f = 0.005).

Figure 7.1 and 7.2, respectively, shows wave height and measurements in the laboratory compared with ODIFLOCS simulations for exactly the same wave conditions at the toe of the slope. Two wave conditions are simulated, H = 16 cm with T = 1.84 s. and H = 24 cm with T = 2.24 s.

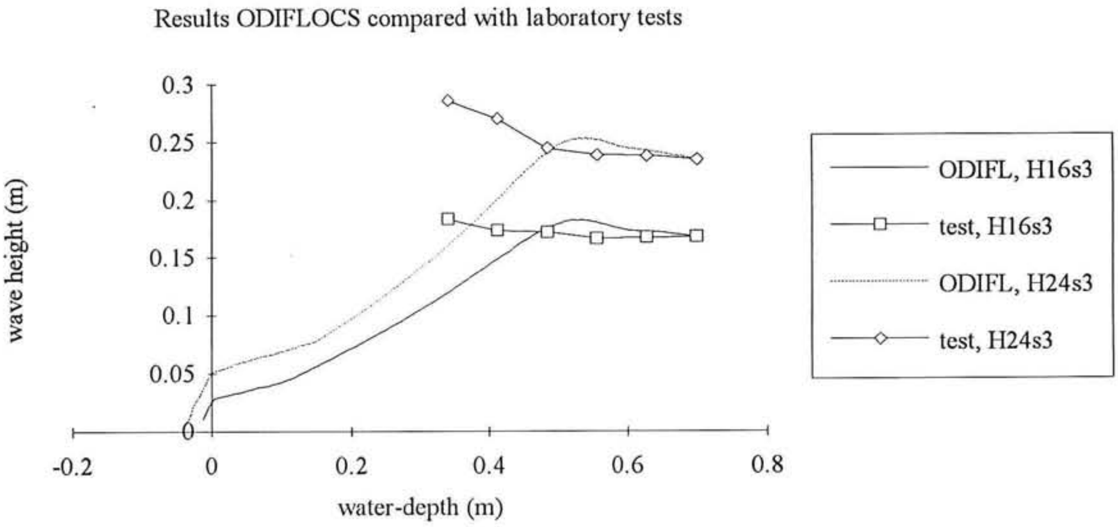


figure 7.1

Figure 7.1 shows that, according to the simulation by ODIFLOCS, the breaking of the wave is induced too early. This also means a decay in velocity after breaking which can be seen in figure 7.2.

From figure 7.2 it can be concluded that the calculated velocities are too high compared with the measurements. This can be explained by the calculation of ODIFLOCS of depth averaged velocities according to the long-wave theory. This is the same phenomenon as described in chapter 3 section 3.2 (comparison with results of Sistermans (1993)). The use of the long-wave theory to calculate the orbital velocities at the bottom will not lead to correct results for relatively steep waves.

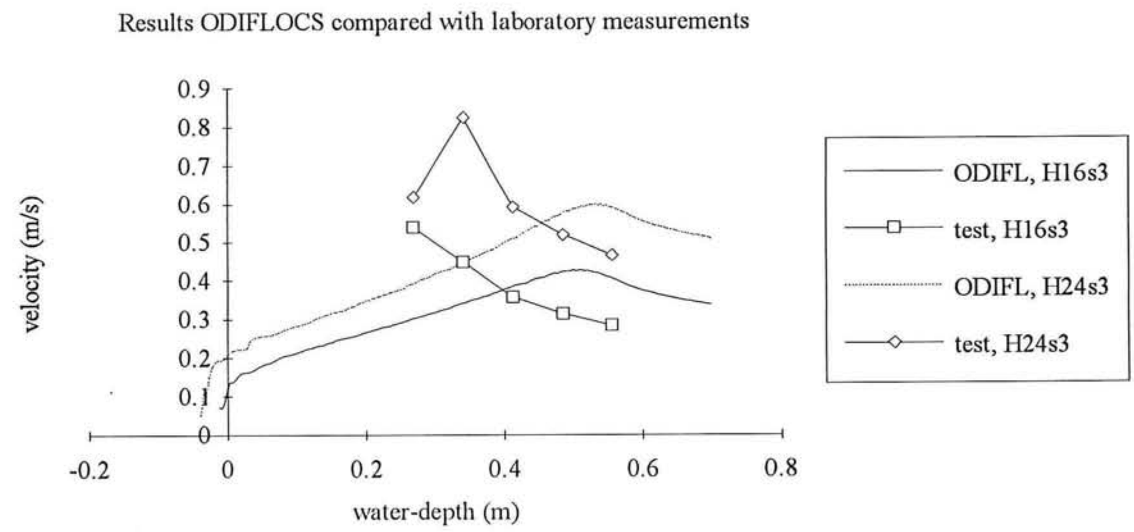


figure 7.2

7.3 Evaluation

ODIFLOCS was developed for the simulation of waves interacting with mainly breakwaters. These are much steeper than the gentle slopes tested in this thesis. Therefore gentle slopes are relatively long structures to ODIFLOCS. This means that the smallest Δx between the gridpoints in the numerical scheme, is relatively large. A large Δx in the numerical scheme causes numerical energy dissipation in the simulation, where in the actual situation no dissipation would occur.

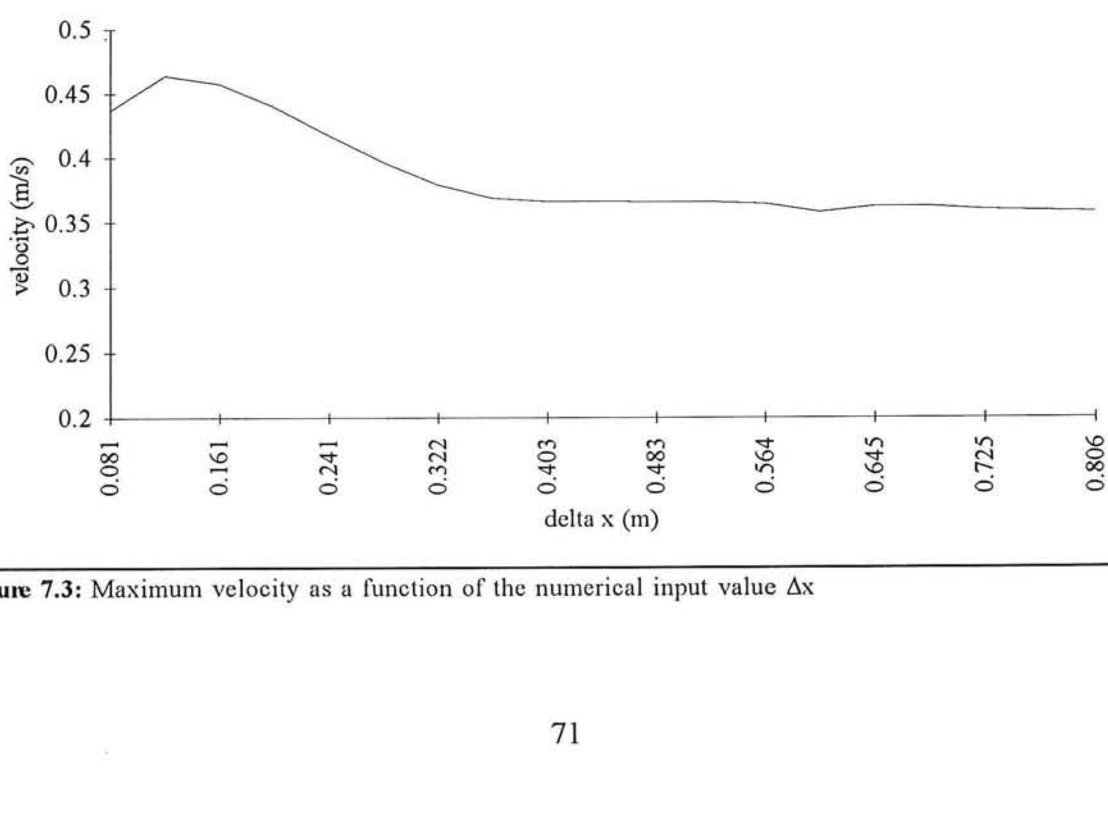


Figure 7.3: Maximum velocity as a function of the numerical input value Δx

Figure 7.3 shows the influence of Δx on the maximum calculated velocities. The arbitrary calculational input was: H=0.18 m, h=0.7 m, T=1.96 s, $\tan\alpha=0.04$.

The smallest Δx shown in the graph is 0.081; this is the smallest value possible in ODIFLOCS. Smaller values will not be accepted by the program, because the memory capacity is limited. The figure shows that the velocity is indeed a function of Δx. It is expected that a smaller Δx yields a more accurate calculation. The opposite effect can however be seen here.

Figure 7.4 shows the influence of the water-depth variation on the velocity.

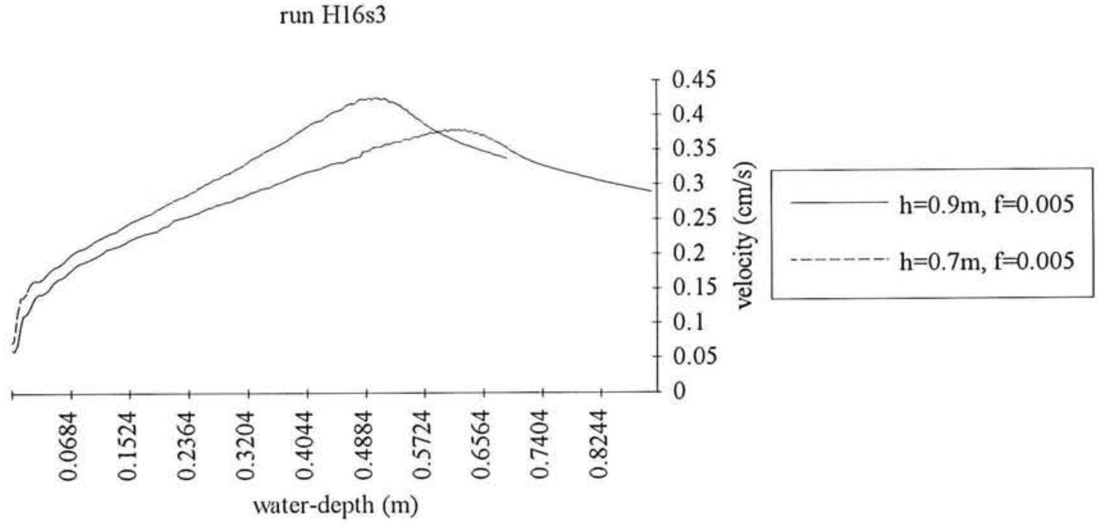


figure 7.4

When varying the water-depth by only 20 cm, the velocity profile changes completely. Breaking is induced earlier when simulating with a water-depth of 0.9 m, compared to a simulation with a water-depth of 0.7 m. Also the maximum velocity decreases to a lower value. Apparently the 5 m extra slope length causes in combination with a larger value of Δx quite a lot of energy dissipation. Of course a change in the water-depth should not cause such a dramatic change in the velocity profile.

The numerical scheme used in ODIFLOCS causes the waves to break too fast. On 'long' gentle slopes this imperfection in ODIFLOCS is emphasized even more than when simulating wave motion on breakwaters with 'short' steep slopes. For more specific details on the numerical scheme used in ODIFLOCS see Van Gent (1993).

7.4 Conclusions

The graphs shown in the previous section present an inconsequent output for the simulated situation. ODIFLOCS, at least in this configuration, seems not suited for simulating wave motion on gentle slopes. The usage of the numerical scheme in the present form implies too fast breaking of the waves combined with numerical dissipation resulting into lower values of the wave height and the velocities.

8 Conclusions and recommendations

8.1 Conclusions

- The linear wave theory has to be fully applied in order to derive correct results for the orbital bottom velocities on gentle slopes.

- The tested relations of Rance & Warren and Jonsson / Sleath derived for the stability of stone on a horizontal bottom, applied to gentle slopes, give approximately the same results.

- The stability of stone on gentle slopes under regular wave attack can be described by formulae derived from stability of stone on horizontal bottoms. That is for values of $h/H > 1$. For values of $h/H < 1$ the theorectical approach is not succesfull.

- For irregular waves, it seems that the derived stability relations, chapter 3, for horizontal bottoms will match the experimentally obtained results for the deeper water region, where no waves are yet broken. More experimental research has to be conducted to confirm or to reject this assumption.

- The stability for waves with low values of the wave steepness is less than for waves with higher values of the wave steepness.

- For values $h/H < 1$ the 'spilling' and the 'plunging' effect by the breaking of waves causes a deviation of the experimental results compared with the theoretical derived stability relations. This applies especially to waves with lower values of the wave steepness.

- The computer simulation program ODIFLOCS is not suited for simulation of wave motion on gentle slopes.

8.2 Recommendations

- In the experiments several variables were not varied, mainly due to a lack of time. Some of them are structural variables such as the grading of the material, D_{85}/D_{15}, and the slope angle α. For the environmental variables the spectral shape and the storm duration were not varied. The effect of these variables on the stability of the stone is unknown. Further experimental reseach is therefore recommended.

- More irregular wave experiments are needed to verify the possible stability relations for irregular waves as derived in chapter 3, especially on the test section where no waves are yet broken.

List of Symbols

a_0	= amplitude of displacement of water particle at bottom		
C	= coefficient of variation		
c_0	= deep water wave celerity		
D	= diameter of material		
	index:	15	= 15% value of sieve curve
		50	= 50% value of sieve curve
		85	= 85% value of sieve curve
		n	= nominal diameter
		s	= equivalent sphere diameter
D_*	= dimensionless grain size		
f	= frequence		
f_p	= peak frequencey		
f_w	= wave friction factor		
Fr	= Froude number		
g	= gravitational acceleration		
h	= local water depth		
H	= wave height		
	index:	s	= significant wave height
		rms	= root mean square wave height
		0	= wave height in deep water, $L_0 \langle 2 \cdot h$
		1%	= 1% value of wave height exceedance curve
k	= wave number, $2 \cdot \pi / L$		
K_s	= roughness length of Nikuradse		
K_{sh}	= shoaling factor		
L	= wave length		
L	= length		
L0	= deep water wave length		
M	= mass		
m_n	= n-th spectral moment		
n_x	= scaling factor of variable x		
N	= number of waves		
N_p	= number of moving particles		
N_{pt}	= total number of particles in the top layer		
r	= correlation factor		
Re	= Reynolds number		
Re_*	= grain related Reynolds number		
s	= fictious wave steepness, H/L_0		
s_0	= fictious wave steepness in deep water		
$S_{\%}$	= percentual number of stones displacing from a strip, related to the number of stones in top layer of strip		
s.d.	= standard deviation		
T	= time		
T	= wave period		
	index:	p	= peak period of spectrum
		s	= significant period

U_0 = orbital velocity at the bottom
U_* = boundary shear velocity
W = weight of the rock
index: 50 = average weight of stone grading
X = co-ordinate along the slope for incoming wave

α = slope angle of structure
β = shape factor of rock
γ_{br} = breaker index
Δ = relative mass density
υ = kinematic viscosity of water
ξ = breaker parameter
Π = dimensionless variable
ρ_a = mass density of the armor
ρ_w = mass density of water
σ = surface tension
σ = shape parameter of spectrum
τ_b = bottom shear stress
τ_{cr} = critical bottom shear stress
τ_* = dimensionless bottom shear stress
ψ_{cr} = critical Shields parameter
ω = angular velocity

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Appendix I

Sieve curves

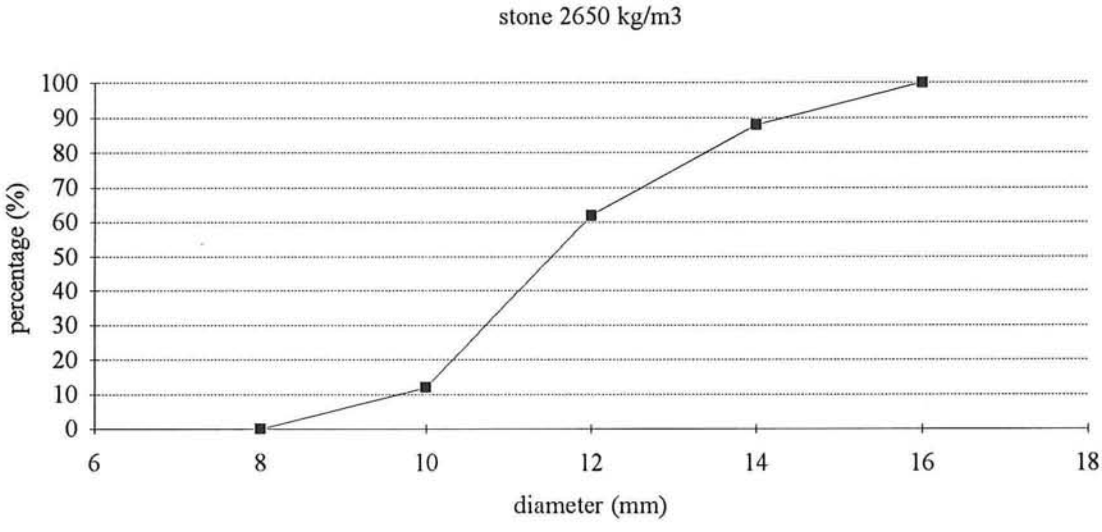


figure I.1: Sieve curve stone D_{50} = 11.4 mm, grading 1.4

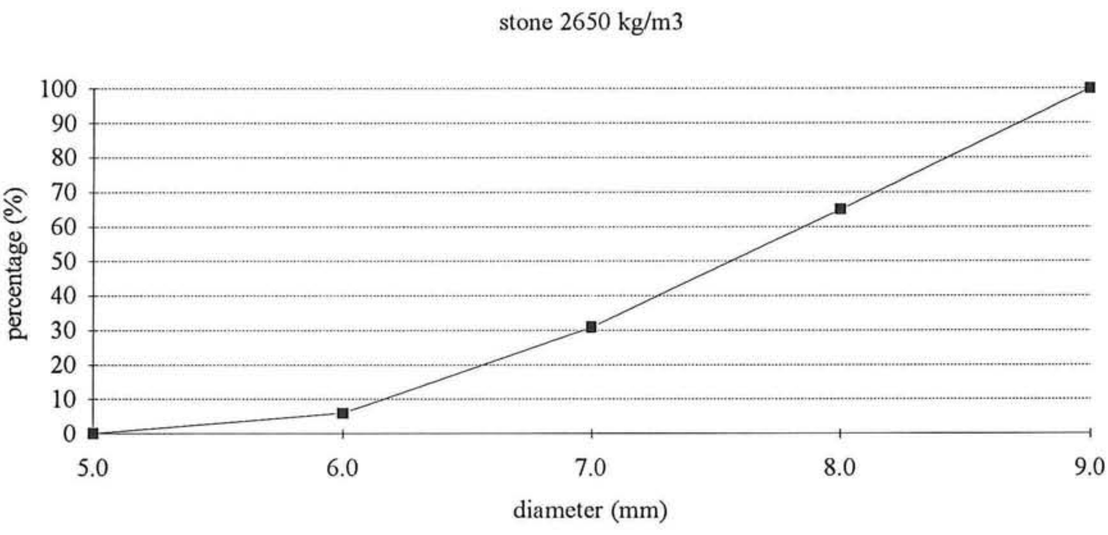


figure I.2: Sieve curve stone D_{50} = 7.5 mm, grading = 1.4

Appendix II

Input files of software package AUKE/pc

For regular waves:

03:39 PM Tuesday 17 May 1994. program = STIR Version 2.01
Licensed user : Technical University Delft / Copyright DELFT HYDRAULICS 1989.

Overview of files
~~~~~~~~~~~~~~~~~

++++ FILE H12s3.pcf ++++ (01)

wavetype,regular
height,0.12
period,1.60
end:wavetype

wave-board,tud
biesel,off
order,first
compensation,off
depth,0.70
data-stir,H12s3
time-step,25,Hz
transform,yes

VARIOUS SIGNAL PARAMETERS

GENERAL information

Regular or deterministic signal

frequency	period	amplitude	phase
.625000E+00	.160000E+01	.600000E-01	.000000E+00

Period is accurate

Resulting frequency Fp : .625000
period Tp : 1.60000
~~~~~~~~~~~~~~~~~

time step in signal= .400000E-01 s (or 25.00 Hz)
number of samples = 0000000040

depth for second order signal : .70
wavelength for the given Fp : 3.42696

Zeroth order signal
H mean .120000E+00
T mean .160000E+01
variance .184615E-02

---- number of waves found 1 ----

Input example for irregular waves:

00:59 PM Wednesday 25 May 1994. program = STIR Version 2.01
Licensed user : Technical University Delft / Copyright DELFT HYDRAULICS 1989.

Overview of files
~~~~~~~~~~~~~~~~~~
++++ FILE hs10s1.pcf ++++ (01)

WAVETYPE,JONSWAP-SPECTRUM
HM0,0.10,PRECISION=0.99
PEAK,TP=2.53
GAMMA,3.3
DURATION,17:29
EXTEND,YES
RANDOM,TYPE=COEFFICIENT
END:WAVETYPE

WAVE-BOARD,TUD.POS
BIESEL,OFF
ORDER,FIRST

** Bij tweede orde krijgen we in de STIR.OUT file een WARNING.
** Deze WARNING luidt o.a: values do not fit in the range (-32767:32752)

COMPENSATION,ON
DEPTH,0.62
DATA-STIR,HS10s1
TIME-STEP,25,Hz
TRANSFORM,YES
~~~~~~~~~~~~~~~~~~

VARIOUS SIGNAL PARAMETERS

GENERAL information

Spectrum type : JONSWAP, gamma= .330000E+01
  Hs : .100000
  Fp : .395257
  Tp : 2.53000

Used duration=00:17:29.76 h
Nyquist frequency
  * before resampling : 4.1667 Hz
  * after resampling : 12.5000 Hz
lowest frequency with energy is   .2848 Hz
highest frequency with energy is 1.0955 Hz
time step in signal= .400000E-01 s (or 25.00 Hz)
number of samples = 26244

depth for second order signal :   .62
wavelength for the given Fp   : 5.83244

Zeroth order signal

parameter	DOMAIN time	DOMAIN frequency
variance	.617229E-03	.617160E-03
Hs	.963453E-01	.994702E-01
Hrms	.688434E-01	.702658E-01
H mean	.612259E-01	.622714E-01
T mean	.211572E+01	.217685E+01
T dominant	--	.248689E+01
Kappa**2	.522188E+00	.333024E+00

---- number of waves found 495 ----

Appendix III

Velocity profiles over the water-depth

To determine the position above the sloping bed, various velocity measurements over the water-depth were taken. It proved that a distance of approximately 2 cm above the mean bed was a good point to measure the orbital velocity motion. If measurements were taken below this point the influence of the turbulent boundary layer would dominate the measurement. An example is given in figure III.1.

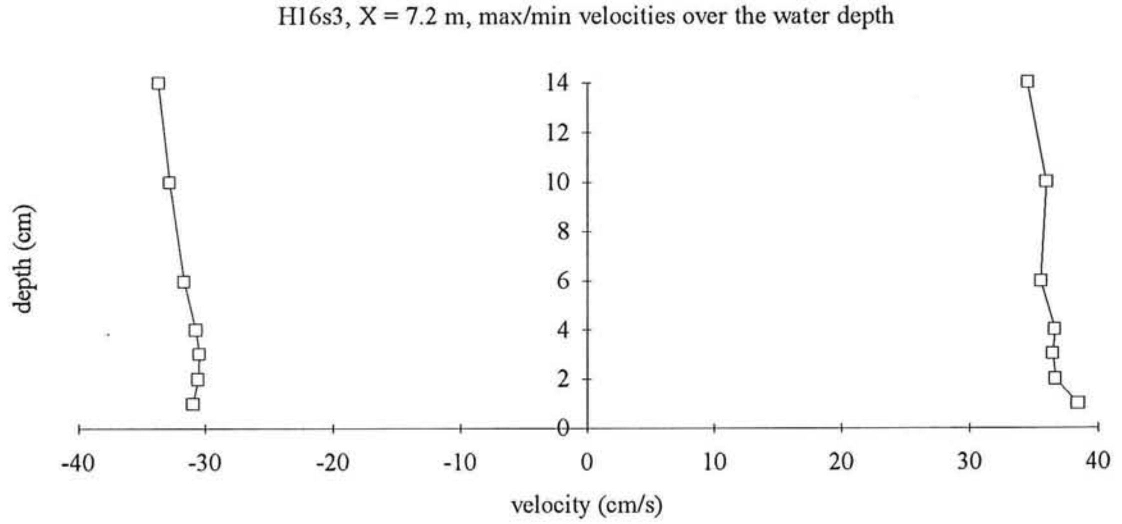


figure III.1: Regular waves, H = 16.6 cm, steepness, s0 = 3 %, water-depth, h = 41.2 cm

Appendix IV

Procedure for both regular and irregular wave tests:

1. Put the stones in their corresponding colored strips and be sure that the top layer is 'loosely' packed as described in paragraph 4.5.

2. Fill the wave flume till the required depth is reached. (70 cm for regular waves and 60 cm for irregular waves)

3. Run the data acquisition set for the determination of the 'drift' factor of the EMS in still water.

4. Run the control file in AUKE/pc for the wave-board controller.

5. Calibrate the wave height gauges.

6. Change the calibration factors in AUKE/pc.

7. Turn on the wave-board controller.

8. Run the data-acquisition set at the required positions.

9. Stop the tests after 750 waves (regular waves) or 2000 waves (irregular waves).

10. Run the data-acquisition set for the determination of the 'drift' factor of the EMS in still water.

11. Let the water out of the flume

12. Determine the damage.

ad. 4: For the determination of the 'drift' factor two files are needed: EMSvoor.log and EMSna.log. EMSvoor.log is obtained by running the data-acquisition set, DACON, in still water before the start of each measurement. The EMS-meter should be in zero
position. Input in DACON: - 1000ms
- 60 samples

ad. 5: The calibration of the wave height meters is executed for every test.
Procedure: - make sure the wave height meters is in zero position

- run five files in DACON
    - CWHMU(up)000.log
    - CWHMU040.log (4cm up)
    - CWHMU060.log (6cm up)

    - CWHMD(down)040.log (4cm down)
    - CWHMD060.log (6cm down)
- input in DACON: - 1000ms
  - 20 samples
- go to c:\auke\analyse and type: EDFM (Elaboration Data File Manually) See also the manual of P. de Wit (1992). Calibration formula for transforming factors to AUKE/pc: $Y = C_1 X + C_0$.
  - C_0 = -b/204.8 [cm]
  - C_1 = 20.48/a [cm/v]
- The accuracy of the wave height meters is: ± 0.5 % of the set range.

ad. 6: The calibration factors of ad 5. should be implemented in the wavestan.seq file of AUKE/pc under the directory analyse. AUKE/pc corrects the wave output automatically.

ad. 7: The measurement of the wave heights:

- run DACON to create file, wave.log
- input in DACON: - 50ms
  - 18000 samples (irregular waves), 1200 samples regular waves)

ad. 8: The determination of the velocities over the profile:

- run DACON to create files
- input in DACON: - 50ms
  - 18000 samples (irregular waves), 1200 samples regular waves)

ad.10: Run DACON to create file EMSna.log. - input in DACON: - 1000ms
- 60ms

Determine the 'drift' factor with EDFM: - input: - one channel
- D/A channel 3
- number of EMS

Appendix V

Experimental Data

The experimental data are presented in two sections. The performed regular wave tests and the performed irregular wave tests.

regular wave experiments

For each regular wave experiment, different variables are presented.

general:	H0	[cm]	wave height measured at the toe of the slope
	T	[sec]	wave period
	L0	[m]	deep water wave length
	s0	[%]	wave steepness at the toe of the slope
	h0	[cm]	water-depth
	test material 1 and 2:		used materials on the slope

colomns:	strip nr.	[-]	strip number 1 is located at the toe of the slope
	hor. pos.	[m]	horizontal position, of middle of strip, with respect to the toe of the slope
	w.level.	[cm]	still water-depth, h, at middle of strip
	stones up	[-]	number of stones displaced from strip in up-ward direction after 750 waves
	down	[-]	number of stones displaced from strip in down-ward direction after 750 waves
	totaal 1	[-]	total number of stones displaced from strip with test material 2
	totaal 2	[-]	total number of stones displaces from strip with test material 1
	h/H0	[-]	ratio of water-depth over wave height at toe of slope

experiment H 12 s3t2				H0=11.8 cm	L0 = 4.0 m		
				T = 1.6 s	s0 = 2.95 %	h0 = 70 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. level	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	69.5			0		5.88
2	0.375	68.5			0		5.80
3	0.625	67.5			0		5.72
4	0.875	66.5			0		5.63
5	1.125	65.5			0		5.55
6	1.375	64.5			0		5.46
7	1.625	63.5			0		5.38
8	1.875	62.5			0		5.29
9	2.125	61.5			0		5.21
10	2.375	60.5			0		5.12
11	2.625	59.5			0		5.04
12	2.875	58.5			0		4.95
13	3.125	57.5			0		4.87
14	3.375	56.5			0		4.78
15	3.625	55.5			0		4.70
16	3.875	54.5			0		4.61
17	4.125	53.5			0		4.53
18	4.375	52.5			0		4.44
19	4.625	51.5			0		4.36
20	4.875	50.5			0		4.27
21	5.125	49.5			0		4.19
22	5.375	48.5			0		4.11
23	5.625	47.5			0		4.02
24	5.875	46.5			0		3.94
25	6.125	45.5			0		3.85
26	6.375	44.5			0		3.77
27	6.625	43.5			0		3.68
28	6.875	42.5			0		3.60
29	7.125	41.5			0		3.51
30	7.375	40.5			0		3.43
31	7.625	39.5			0		3.34
32	7.875	38.5			0		3.26
33	8.125	37.5			0		3.17
34	8.375	36.5			0		3.09

35	8.625	35.5			0		3.00
36	8.875	34.5			0		2.92
37	9.125	33.5			0		2.83
38	9.375	32.5			0		2.75
39	9.625	31.5			0		2.66
40	9.875	30.5			0		2.58
41	10.125	29.5			0		2.5
42	10.375	28.5			0		2.41
43	10.625	27.5			0		2.33
44	10.875	26.5			0		2.24
45	11.125	25.5			0		2.16
46	11.375	24.5			0		2.07
47	11.625	23.5			0		1.99
48	11.875	22.5			0		1.90
49	12.125	21.5			0		1.82
50	12.375	20.5			0		1.73
51	12.625	19.5			0		1.65
52	12.875	18.5			0		1.5
53	13.125	17.5			0		1.48
54	13.375	16.5			0		1.39
55	13.625	15.5			0		1.31
56	13.875	14.5			0		1.22
57	14.125	13.5			0		1.14
58	14.375	12.5			0		1.05
59	14.625	11.5			0		0.97
60	14.875	10.5			0		0.88
61	15.125	9.5			0		0.80
62	15.375	8.5			0		0.72
63	15.625	7.5			0		0.63
64	15.875	6.5			0		0.55
65	16.125	5.5			0		0.46
66	16.375	4.5			0		0.38
67	16.625	3.5			0		0.29
68	16.875	2.5			0		0.21
69	17.125	1.5			0		0.12
70	17.375	0.5			0		0.04
71	17.625	-0.5			0		-0.04
72	17.875	-1.5			0		-0.12
73	18.125	-2.5			0		-0.21
74	18.375	-3.5			0		-0.29

experiment H 16 s3 t1					H0=16.8 cm	L0 = 5.29 m	
					T = 1.84 s	s0 = 3.18 %	h0 = 70 cm
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	69.5			0		4.14
2	0.375	68.5			0		4.08
3	0.625	67.5			0		4.02
4	0.875	66.5			0		3.96
5	1.125	65.5			0		3.90
6	1.375	64.5			0		3.84
7	1.625	63.5			0		3.78
8	1.875	62.5			0		3.72
9	2.125	61.5			0		3.66
10	2.375	60.5			0		3.60
11	2.625	59.5			0		3.54
12	2.875	58.5			0		3.48
13	3.125	57.5			0		3.42
14	3.375	56.5			0		3.36
15	3.625	55.5			0		3.30
16	3.875	54.5			0		3.24
17	4.125	53.5			0		3.18
18	4.375	52.5	1		1		3.13
19	4.625	51.5			0		3.07
20	4.875	50.5			0		3.01
21	5.125	49.5			0		2.95
22	5.375	48.5			0		2.89
23	5.625	47.5			0		2.83
24	5.875	46.5			0		2.77
25	6.125	45.5			0		2.71
26	6.375	44.5	1		1		2.65
27	6.625	43.5	2		2		2.59
28	6.875	42.5	2		2		2.53
29	7.125	41.5	1		1		2.47
30	7.375	40.5	2		2		2.41
31	7.625	39.5	1		3		2.35
32	7.875	38.5	3	2	5		2.29
33	8.125	37.5	2	2	4		2.23
34	8.375	36.5	2	2	5		2.17

35	8.625	35.5	5	3	5		2.11
36	8.875	34.5	5		8		2.05
37	9.125	33.5	3	3	5		1.99
38	9.375	32.5	13	2	15		1.93
39	9.625	31.5	5	2	6		1.88
40	9.875	30.5	19	1	20		1.82
41	10.125	29.5	7		7		1.76
42	10.375	28.5	3	2	5		1.70
45	11.125	25.5				0	1.52
46	11.375	24.5	3	2		5	1.46
47	11.625	23.5		2		2	1.40
48	11.875	22.5	3	1		4	1.34
49	12.125	21.5				0	1.28
50	12.375	20.5	3	2		5	1.22
51	12.625	19.5	3	3		6	1.16
52	12.875	18.5	5	4		9	1.10
53	13.125	17.5	1			1	1.04
54	13.375	16.5				0	0.98
55	13.625	15.5				0	0.92
56	13.875	14.5				0	0.86
57	14.125	13.5				0	0.80
58	14.375	12.5				0	0.74
59	14.625	11.5				0	0.68
60	14.875	10.5				0	0.63
61	15.125	9.5				0	0.57
62	15.375	8.5				0	0.51
63	15.625	7.5				0	0.45
64	15.875	6.5				0	0.39
65	16.125	5.5				0	0.33
66	16.375	4.5				0	0.27
67	16.625	3.5				0	0.21
68	16.875	2.5				0	0.15
69	17.125	1.5				0	0.09
70	17.375	0.5				0	0.03
71	17.625	-0.5				0	-0.03
72	17.875	-1.5				0	-0.09
73	18.125	-2.5				0	-0.15
74	18.375	-3.5				0	-0.21
75	18.625	-4.5				0	-0.27

experiment H 20 s3 t1					H0=20.3 cm	L0 = 6.75 m	
				T = 2.08 s	s0 = 3.0 %	h0 = 70 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	69.5			0		3.42
2	0.375	68.5			0		3.37
3	0.625	67.5			0		3.32
4	0.875	66.5			0		3.27
5	1.125	65.5			0		3.22
6	1.375	64.5			0		3.17
7	1.625	63.5			0		3.12
8	1.875	62.5			0		3.07
9	2.125	61.5			0		3.02
10	2.375	60.5			0		2.97
11	2.625	59.5			0		2.93
12	2.875	58.5			0		2.88
13	3.125	57.5			0		2.83
14	3.375	56.5			0		2.78
15	3.625	55.5			0		2.73
16	3.875	54.5			0		2.68
17	4.125	53.5			0		2.63
18	4.375	52.5			0		2.58
19	4.625	51.5			0		2.53
20	4.875	50.5	2		2		2.48
21	5.125	49.5			0		2.43
22	5.375	48.5			0		2.38
23	5.625	47.5			0		2.34
24	5.875	46.5	1		1		2.29
25	6.125	45.5		1	1		2.24
26	6.375	44.5			0		2.19
27	6.625	43.5			0		2.14
28	6.875	42.5			0		2.09
29	7.125	41.5	4	0	4		2.04
30	7.375	40.5	1	0	1		1.99
31	7.625	39.5	5	0	5		1.94
32	7.875	38.5	3	0	3		1.89
33	8.125	37.5	6	0	6		1.84
34	8.375	36.5	5	0	5		1.79

35	8.625	35.5	5	0	5		1.75
36	8.875	34.5	17	0	17		1.70
37	9.125	33.5	21	0	21		1.65
38	9.375	32.5	32	0	32		1.60
39	9.625	31.5	10	0	10		1.55
40	9.875	30.5	37	0	37		1.50
43	10.625	27.5	4	0		4	1.35
44	10.875	26.5	0	0		0	1.30
45	11.125	25.5	0	1		1	1.25
46	11.375	24.5	1	1		2	1.20
47	11.625	23.5	13	6		19	1.16
48	11.875	22.5	6	15		21	1.11
49	12.125	21.5	0	4		4	1.06
50	12.375	20.5	1	0		1	1.01
51	12.625	19.5	1	2		3	0.96
52	12.875	18.5	0	0		0	0.91
53	13.125	17.5	0	0		0	0.86
54	13.375	16.5	0	0		0	0.81
55	13.625	15.5	0	0		0	0.76
56	13.875	14.5	0	0		0	0.71
57	14.125	13.5	0	0		0	0.66
58	14.375	12.5	0	0		0	0.61
59	14.625	11.5	0	0		0	0.57
60	14.875	10.5	0	0		0	0.52
61	15.125	9.5	0	0		0	0.47
62	15.375	8.5	0	0		0	0.42
63	15.625	7.5	0	0		0	0.37
64	15.875	6.5	0	0		0	0.32
65	16.125	5.5	0	0		0	0.27
66	16.375	4.5	1	0		1	0.22
67	16.625	3.5	1	0		1	0.17
68	16.875	2.5	3	0		3	0.12
69	17.125	1.5	12	0		12	0.07
70	17.375	0.5	0	0		0	0.02
71	17.625	-0.5	0	0		0	-0.02
72	17.875	-1.5	0	0		0	-0.07
73	18.125	-2.5	0	0		0	-0.12
74	18.375	-3.5	0	0		0	-0.17
75	18.625	-4.5	0	0		0	-0.22

experiment H 24 s3 t2					H0 = 22.6 cm	L0 = 7.83 m	
					T = 2.24 s	s0 = 2.89 %	h0 = 70 cm
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	69.5			0		3.07
2	0.375	68.5			0		3.03
3	0.625	67.5			0		2.98
4	0.875	66.5			0		2.94
5	1.125	65.5			0		2.89
6	1.375	64.5			0		2.85
7	1.625	63.5	1		1		2.80
8	1.875	62.5	1		1		2.76
9	2.125	61.5			0		2.72
10	2.375	60.5	2	1	3		2.67
11	2.625	59.5			0		2.63
12	2.875	58.5	2		2		2.58
13	3.125	57.5	1		1		2.54
14	3.375	56.5	1		1		2.5
15	3.625	55.5	2		2		2.45
16	3.875	54.5			0		2.41
17	4.125	53.5			0		2.36
18	4.375	52.5	4		4		2.32
19	4.625	51.5	2		2		2.27
20	4.875	50.5	2		2		2.23
21	5.125	49.5	3		3		2.19
22	5.375	48.5	1		1		2.14
23	5.625	47.5	4		4		2.10
24	5.875	46.5	2		2		2.05
25	6.125	45.5	4		4		2.01
26	6.375	44.5	3		3		1.96
27	6.625	43.5	1		1		1.92
28	6.875	42.5	10		10		1.88
29	7.125	41.5	2		2		1.83
30	7.375	40.5	14		14		1.79
31	7.625	39.5	15		15		1.74
32	7.875	38.5	13	0	13		1.70
33	8.125	37.5	17	0	17		1.65

36	8.875	34.5	3	0		3	1.52
37	9.125	33.5	2	0		2	1.48
38	9.375	32.5	4	0		4	1.43
39	9.625	31.5	2	0		2	1.39
40	9.875	30.5	4	0		4	1.34
41	10.125	29.5	3	0		3	1.30
42	10.375	28.5	2	0		2	1.26
43	10.625	27.5	1	0		1	1.21
44	10.875	26.5	1	6		7	1.17
45	11.125	25.5	5	9		14	1.12
46	11.375	24.5	7	16		23	1.08
47	11.625	23.5	5	9		14	1.03
48	11.875	22.5	0	2		2	0.99
49	12.125	21.5	2	2		4	0.95
50	12.375	20.5	0	0		0	0.90
51	12.625	19.5	0	0		0	0.86
52	12.875	18.5	0	0		0	0.81
53	13.125	17.5	0	0		0	0.77
54	13.375	16.5	0	0		0	0.73
55	13.625	15.5	0	0		0	0.68
56	13.875	14.5	0	0		0	0.64
57	14.125	13.5	0	1		1	0.59
58	14.375	12.5	0	0		0	0.55
59	14.625	11.5	0	0		0	0.50
60	14.875	10.5	0	0		0	0.46
61	15.125	9.5	0	0		0	0.42
62	15.375	8.5	0	0		0	0.37
63	15.625	7.5	0	0		0	0.33
64	15.875	6.5	0	0		0	0.28
65	16.125	5.5	0	0		0	0.24
66	16.375	4.5	0	0		0	0.19
67	16.625	3.5	0	0		0	0.15
68	16.875	2.5	0	0		0	0.11
69	17.125	1.5	2	0		2	0.06
70	17.375	0.5	8	0		8	0.02
71	17.625	-0.5	11	0		11	-0.02
72	17.875	-1.5	4	0		4	-0.06
73	18.125	-2.5	0	0		0	-0.11
74	18.375	-3.5	0	0		0	-0.15

experiment H 24 s3 t3					H0=23.5 cm	L0 = 7.83 m	
				T = 2.24 s	s0 = 3.0 %	h0 = 70 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	69.5			0		2.96
2	0.375	68.5			0		2.91
3	0.625	67.5			0		2.87
4	0.875	66.5			0		2.83
5	1.125	65.5			0		2.79
6	1.375	64.5			0		2.74
7	1.625	63.5			0		2.70
8	1.875	62.5			0		2.66
9	2.125	61.5			0		2.62
10	2.375	60.5			0		2.57
11	2.625	59.5			0		2.53
12	2.875	58.5			0		2.49
13	3.125	57.5			0		2.45
14	3.375	56.5			0		2.40
15	3.625	55.5			0		2.36
16	3.875	54.5			0		2.32
17	4.125	53.5			0		2.28
18	4.375	52.5			0		2.23
19	4.625	51.5			0		2.19
20	4.875	50.5			0		2.15
21	5.125	49.5	1		1		2.11
22	5.375	48.5	3		3		2.06
23	5.625	47.5	1		1		2.02
24	5.875	46.5	1		1		1.98
25	6.125	45.5	1		1		1.94
26	6.375	44.5	2		2		1.89
27	6.625	43.5	6		6		1.85
28	6.875	42.5	6		6		1.81
29	7.125	41.5	13		13		1.77
30	7.375	40.5	6		6		1.72
31	7.625	39.5	7		7		1.68
32	7.875	38.5	19	0	19		1.64
33	8.125	37.5	35	0	35		1.60

36	8.875	34.5	1	0		1	1.47
37	9.125	33.5	2	0		2	1.43
38	9.375	32.5	2	0		4	1.38
39	9.625	31.5	3	2		4	1.34
40	9.875	30.5	3	1		4	1.30
41	10.125	29.5	1	2		3	1.26
42	10.375	28.5	1	1		2	1.21
43	10.625	27.5	2	8		10	1.17
44	10.875	26.5	3	18		21	1.13
45	11.125	25.5	2	22		24	1.09
46	11.375	24.5	15	29		44	1.04
47	11.625	23.5	2	3		5	1.00
48	11.875	22.5	0	0		0	0.96
49	12.125	21.5	0	1		1	0.91
50	12.375	20.5	0	0		0	0.87
51	12.625	19.5	0	0		0	0.83
52	12.875	18.5	0	0		0	0.79
53	13.125	17.5	0	0		0	0.74
54	13.375	16.5	0	0		0	0.70
55	13.625	15.5	0	0		0	0.66
56	13.875	14.5	0	0		0	0.62
57	14.125	13.5	0	0		0	0.57
58	14.375	12.5	0	0		0	0.53
59	14.625	11.5	0	0		0	0.49
60	14.875	10.5	0	0		0	0.45
61	15.125	9.5	0	0		0	0.40
62	15.375	8.5	0	0		0	0.36
63	15.625	7.5	0	0		0	0.32
64	15.875	6.5	1	0		1	0.28
65	16.125	5.5	3	0		3	0.23
66	16.375	4.5	5	0		5	0.19
67	16.625	3.5	5	0		5	0.15
68	16.875	2.5	2	0		2	0.11
69	17.125	1.5	1	0		1	0.06
70	17.375	0.5	1	0		1	0.02
71	17.625	-0.5	2	0		2	-0.02
72	17.875	-1.5	3	0		3	-0.06
73	18.125	-2.5	0	0		0	-0.11
74	18.375	-3.5	0	0		0	-0.15
75	18.625	-4.5	0	0		0	-0.19

experiment H 26 s3 t1					H0=27.3 cm	L0 = 8.73 m	
				T = 2.36 s	s0 = 3.13 %	h0 = 70 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	69.5			0		2.55
2	0.375	68.5			0		2.51
3	0.625	67.5			0		2.47
4	0.875	66.5			0		2.44
5	1.125	65.5			0		2.40
6	1.375	64.5			0		2.36
7	1.625	63.5			0		2.33
8	1.875	62.5			0		2.29
9	2.125	61.5			0		2.25
10	2.375	60.5			0		2.22
11	2.625	59.5			0		2.18
12	2.875	58.5			0		2.14
13	3.125	57.5			0		2.11
14	3.375	56.5			0		2.07
15	3.625	55.5			0		2.03
16	3.875	54.5			0		2.00
17	4.125	53.5	2		2		1.96
18	4.375	52.5	12		12		1.92
19	4.625	51.5	10		10		1.89
20	4.875	50.5	5		5		1.85
21	5.125	49.5	8		8		1.81
22	5.375	48.5	12		12		1.78
23	5.625	47.5	11		11		1.74
24	5.875	46.5	8		8		1.70
25	6.125	45.5	15		15		1.67
26	6.375	44.5	13		13		1.63
27	6.625	43.5	31	3	34		1.59
28	6.875	42.5	40	1	41		1.56
29	7.125	41.5	31	2	33		1.52
30	7.375	40.5	71	2	73		1.48
31	7.625	39.5	119	4	123		1.45
32	7.875	38.5	115	7	122		1.41
33	8.125	37.5	175	31	206		1.37
34	8.375	36.5			0		1.34

37	9.125	33.5				0	1.23
38	9.375	32.5		2		2	1.19
39	9.625	31.5	2	4		6	1.15
40	9.875	30.5	2	10		12	1.12
41	10.125	29.5		2		2	1.08
42	10.375	28.5				0	1.04
43	10.625	27.5				0	1.01
44	10.875	26.5		3		3	0.97
45	11.125	25.5	4	4		8	0.93
46	11.375	24.5				0	0.90
47	11.625	23.5				0	0.86
48	11.875	22.5		1		1	0.82
49	12.125	21.5				0	0.79
50	12.375	20.5				0	0.75
51	12.625	19.5				0	0.71
52	12.875	18.5				0	0.68
53	13.125	17.5				0	0.64
54	13.375	16.5				0	0.60
55	13.625	15.5				0	0.57
56	13.875	14.5				0	0.53
57	14.125	13.5	2			2	0.49
58	14.375	12.5				0	0.46
59	14.625	11.5	1			1	0.42
60	14.875	10.5		3		3	0.38
61	15.125	9.5				0	0.35
62	15.375	8.5	1			1	0.31
63	15.625	7.5	1			1	0.27
64	15.875	6.5	3			3	0.24
65	16.125	5.5				0	0.20
66	16.375	4.5				0	0.16
67	16.625	3.5				0	0.13
68	16.875	2.5				0	0.09
69	17.125	1.5				0	0.05
70	17.375	0.5				0	0.02
71	17.625	-0.5	4			4	-0.02
72	17.875	-1.5	8			8	-0.05
73	18.125	-2.5	2			2	-0.09
74	18.375	-3.5	1			1	-0.13
75	18.625	-4.5				0	-0.16

experiment H16 s3 t1b					Hs=15.9 cm	L0 = 5.12 m	
					T = 1.81 sec	s0 = 3.1 %	h0 = 70 cm
stones:							
	test material 2, Dn50 = 0.61 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	68			0		4.28
2	0.375	67			0		4.21
3	0.625	66			0		4.15
4	0.875	65			0		4.09
5	1.125	64			0		4.03
6	1.375	63			0		3.96
7	1.625	62			0		3.90
8	1.875	61			0		3.84
9	2.125	60			0		3.77
10	2.375	59			0		3.71
11	2.625	58			0		3.65
12	2.875	57			0		3.58
13	3.125	56			0		3.52
14	3.375	55			0		3.46
15	3.625	54			0		3.40
16	3.875	53			0		3.33
17	4.125	52			0		3.27
18	4.375	51			0		3.21
19	4.625	50			0		3.14
20	4.875	49			0		3.08
21	5.125	48			0		3.02
22	5.375	47			0		2.96
23	5.625	46			0		2.89
24	5.875	45			0		2.83
25	6.125	44			0		2.77
26	6.375	43			0		2.70
27	6.625	42			0		2.64
28	6.875	41			0		2.58
29	7.125	40			0		2.52
30	7.375	39			0		2.45
31	7.625	38			0		2.39
32	7.875	37			0		2.33
33	8.125	36	0		0		2.26
34	8.375	35	1		1		2.20
35	8.625	34	2		2		2.14
36	8.875	33	4		4		2.08
37	9.125	32					2.01

experiment H 20 s3t1b					Hs=21.5 cm	L0 = 7.28 m	
					T = 2.08 sec	h0 = 70 cm	
stones:							
	test material 2, Dn50 = 0.61 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	68			0		3.17
2	0.375	67			0		3.12
3	0.625	66			0		3.08
4	0.875	65			0		3.03
5	1.125	64			0		2.98
6	1.375	63			0		2.94
7	1.625	62			0		2.89
8	1.875	61			0		2.84
9	2.125	60			0		2.80
10	2.375	59			0		2.75
11	2.625	58			0		2.70
12	2.875	57			0		2.66
13	3.125	56			0		2.61
14	3.375	55			0		2.56
15	3.625	54			0		2.52
16	3.875	53			0		2.47
17	4.125	52			0		2.42
18	4.375	51			0		2.38
19	4.625	50			0		2.33
20	4.875	49			0		2.28
21	5.125	48			0		2.24
22	5.375	47			0		2.19
23	5.625	46			0		2.14
24	5.875	45			0		2.10
25	6.125	44			0		2.05
26	6.375	43			0		2.00
27	6.625	42			0		1.96
28	6.875	41			0		1.91
29	7.125	40			0		1.86
30	7.375	39	1		1		1.82
31	7.625	38	2		2		1.77
32	7.875	37	2		2		1.72
33	8.125	36	7		7		1.68
34	8.375	35	8		8		1.63
35	8.625	34	8		8		1.58
36	8.875	33	11		11		1.54
37	9.125	32					1.49

experiment H24 s3 t1b					Hs = 25.13 cm	L0 = 7.28 m	
				T = 2.24 sec	s0 = 3.2 %	h0 = 70 cm	
stones:							
	test material 2, Dn50 = 0.61 cm, basalt						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	68			0		2.71
2	0.375	67			0		2.67
3	0.625	66			0		2.63
4	0.875	65			0		2.59
5	1.125	64			0		2.55
6	1.375	63			0		2.51
7	1.625	62			0		2.47
8	1.875	61			0		2.43
9	2.125	60			0		2.39
10	2.375	59			0		2.35
11	2.625	58			0		2.31
12	2.875	57			0		2.27
13	3.125	56			0		2.23
14	3.375	55			0		2.19
15	3.625	54			0		2.15
16	3.875	53			0		2.11
17	4.125	52			0		2.07
18	4.375	51			0		2.03
19	4.625	50			0		1.99
20	4.875	49			0		1.95
21	5.125	48			0		1.91
22	5.375	47			0		1.87
23	5.625	46	3		3		1.83
24	5.875	45	7		7		1.79
25	6.125	44	5		5		1.75
26	6.375	43	2		2		1.71
27	6.625	42	15		15		1.67
28	6.875	41	11		11		1.63
29	7.125	40	15		15		1.59
30	7.375	39	8		8		1.55
31	7.625	38	23		23		1.51
32	7.875	37	21		21		1.47
33	8.125	36	66		66		1.43
34	8.375	35	23		23		1.39
35	8.625	34	30		30		1.35
36	8.875	33	57	2	59		1.31

experiment H 5 t2b				H0=5cm	L0=6.25 m		
				T = 2 s	s0=0.8%	h0 = 65 cm	
stones:	test material 1, Dn50 = 0.61 cm, basalt						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	63			0		12.6
2	0.375	62			0		12.4
3	0.625	61			0		12.2
4	0.875	60			0		12
5	1.125	59			0		11.8
6	1.375	58			0		11.6
7	1.625	57			0		11.4
8	1.875	56			0		11.2
9	2.125	55			0		11
10	2.375	54			0		10.8
11	2.625	53			0		10.6
12	2.875	52			0		10.4
13	3.125	51			0		10.2
14	3.375	50			0		10
15	3.625	49			0		9.8
16	3.875	48			0		9.6
17	4.125	47			0		9.4
18	4.375	46			0		9.2
19	4.625	45			0		9
20	4.875	44			0		8.8
21	5.125	43			0		8.6
22	5.375	42			0		8.4
23	5.625	41			0		8.2
24	5.875	40			0		8
25	6.125	39			0		7.8
26	6.375	38			0		7.6
27	6.625	37			0		7.4
28	6.875	36			0		7.2
29	7.125	35			0		7
30	7.375	34			0		6.8
31	7.625	33			0		6.6
32	7.875	32			0		6.4
33	8.125	31			0		6.2
34	8.375	30			0		6
35	8.625	29			0		5.8
36	8.875	28			0		5.6
37	9.125	27			0		5.4

38	9.375	26			0		5.2
39	9.625	25			0		5
40	9.875	24			0		4.8
41	10.125	23			0		4.6
42	10.375	22			0		4.4
43	10.625	21			0		4.2
44	10.875	20			0		4
45	11.125	19			0		3.8
46	11.375	18			0		3.6
47	11.625	17			0		3.4
48	11.875	16			0		3.2
49	12.125	15			0		3
50	12.375	14			0		2.8
51	12.625	13			0		2.6
52	12.875	12			0		2.4
53	13.125	11			0		2.2
54	13.375	10			0		2

experiment H 10 t2b				H0=9.86cm	L0=6.25 m		
				T = 2 s	s0=1.6 %	h0=65 cm	
stones:	test material 1, Dn50 = 0.61 cm						
	basalt						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.13	63.00			0		6.39
2	0.38	62.00			0		6.29
3	0.63	61.00			0		6.19
4	0.88	60.00			0		6.09
5	1.13	59.00			0		5.98
6	1.38	58.00			0		5.88
7	1.63	57.00			0		5.78
8	1.88	56.00			0		5.68
9	2.13	55.00			0		5.58
10	2.38	54.00			0		5.48
11	2.63	53.00			0		5.38
12	2.88	52.00			0		5.27
13	3.13	51.00			0		5.17
14	3.38	50.00			0		5.07
15	3.63	49.00			0		4.97
16	3.88	48.00			0		4.87
17	4.13	47.00			0		4.77
18	4.38	46.00			0		4.67
19	4.63	45.00			0		4.56
20	4.88	44.00			0		4.46
21	5.13	43.00			0		4.36
22	5.38	42.00			0		4.26
23	5.63	41.00			0		4.16
24	5.88	40.00			0		4.06
25	6.13	39.00			0		3.96
26	6.38	38.00			0		3.85
27	6.63	37.00			0		3.75
28	6.88	36.00			0		3.65
29	7.13	35.00			0		3.55
30	7.38	34.00			0		3.45
31	7.63	33.00			0		3.35
32	7.88	32.00			0		3.25
33	8.13	31.00			0		3.14
34	8.38	30.00			0		3.04
35	8.63	29.00			0		2.94
36	8.88	28.00			0		2.84
37	9.13	27.00			0		2.74

38	9.38	26.00			0		2.64
39	9.63	25.00			0		2.54
40	9.88	24.00			0		2.43
41	10.13	23.00			0		2.33
42	10.38	22.00			0		2.23
43	10.63	21.00			0		2.13
44	10.88	20.00			0		2.03
45	11.13	19.00	2		2		1.93
46	11.38	18.00	3		3		1.83
47	11.63	17.00	2		2		1.72
48	11.88	16.00	18		18		1.62
49	12.13	15.00	13		13		1.52
50	12.38	14.00	2	1	3		1.42
51	12.63	13.00	3	2	5		1.32
52	12.88	12.00	8	3	11		1.22
53	13.13	11.00	4	58	62		1.12
54	13.38	10.00	15	3	18		1.01

experiment H 15 t2b				H0=14.8cm	L0=6.25m		
				T = 2 s	s0=2.37%	h0=65 cm	
stones:	test material 1, Dn50 = 0.61 cm						
	basalt						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	63			0		4.25
2	0.375	62			0		4.18
3	0.625	61			0		4.11
4	0.875	60			0		4.05
5	1.125	59			0		3.98
6	1.375	58			0		3.91
7	1.625	57			0		3.84
8	1.875	56			0		3.78
9	2.125	55			0		3.71
10	2.375	54			0		3.64
11	2.625	53			0		3.57
12	2.875	52			0		3.51
13	3.125	51			0		3.44
14	3.375	50			0		3.37
15	3.625	49			0		3.30
16	3.875	48			0		3.24
17	4.125	47			0		3.17
18	4.375	46			0		3.10
19	4.625	45			0		3.03
20	4.875	44			0		2.97
21	5.125	43			0		2.90
22	5.375	42			0		2.83
23	5.625	41			0		2.76
24	5.875	40			0		2.70
25	6.125	39			0		2.63
26	6.375	38			0		2.56
27	6.625	37			0		2.49
28	6.875	36			0		2.43
29	7.125	35			0		2.36
30	7.375	34			0		2.29
31	7.625	33			0		2.23
32	7.875	32			0		2.16
33	8.125	31	1		1		2.09
34	8.375	30			0		2.02
35	8.625	29	3		3		1.96
36	8.875	28	3		3		1.89
37	9.125	27	6		6		1.82

38	9.375	26	19		19		1.75
39	9.625	25	8	7	15		1.69
40	9.875	24	3		3		1.62
41	10.125	23	15		15		1.55
42	10.375	22	22	2	24		1.48
43	10.625	21	17		17		1.42
44	10.875	20	21	1	22		1.35
45	11.125	19	12		12		1.28
46	11.375	18	12	14	26		1.21
47	11.625	17	15	96	111		1.15
48	11.875	16	60	321	381		1.08
49	12.125	15	5	42	47		1.01
50	12.375	14	22	75	97		0.94
51	12.625	13	9	14	23		0.88
52	12.875	12	3	22	25		0.81
53	13.125	11	3	1	4		0.74
54	13.375	10	2	1	3		0.67

experiment H 20 t2b				H0=19.3cm	L0 = 6.25 m		
				T = 2 s	s0 = 3.09%	h0 = 65 cm	
stones:	test material 1, Dn50 = 0.61 cm						
	basalt						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	63			0		3.26
2	0.375	62			0		3.21
3	0.625	61			0		3.16
4	0.875	60			0		3.11
5	1.125	59			0		3.06
6	1.375	58			0		3.00
7	1.625	57			0		2.95
8	1.875	56			0		2.90
9	2.125	55			0		2.85
10	2.375	54			0		2.80
11	2.625	53			0		2.74
12	2.875	52			0		2.69
13	3.125	51			0		2.64
14	3.375	50			0		2.59
15	3.625	49			0		2.54
16	3.875	48			0		2.49
17	4.125	47			0		2.43
18	4.375	46			0		2.38
19	4.625	45			0		2.33
20	4.875	44			0		2.28
21	5.125	43			0		2.23
22	5.375	42			0		2.18
23	5.625	41			0		2.12
24	5.875	40	1		1		2.07
25	6.125	39			0		2.02
26	6.375	38	1		1		1.97
27	6.625	37	2		2		1.92
28	6.875	36	2		2		1.86
29	7.125	35	2		2		1.81
30	7.375	34	4		4		1.76
31	7.625	33	4		4		1.71
32	7.875	32	4		4		1.66
33	8.125	31	4		4		1.61
34	8.375	30	2	2	4		1.55
35	8.625	29	16		16		1.50
36	8.875	28	10	2	12		1.45
37	9.125	27	20		20		1.40

38	9.375	26	34	2	36		1.35
39	9.625	25	40	0	40		1.29
40	9.875	24	35	47	82		1.24
41	10.125	23	100	100	200		1.19
42	10.375	22	200	200	400		1.14
43	10.625	21	150	150	300		1.09
44	10.875	20	20	100	120		1.04
45	11.125	19	14	100	114		0.98
46	11.375	18	21	100	121		0.93
47	11.625	17	9	84	93		0.88
48	11.875	16	20	130	150		0.83
49	12.125	15	15	7	22		0.78
50	12.375	14	6	10	16		0.73
51	12.625	13	10	4	14		0.67
52	12.875	12	6	4	10		0.62
53	13.125	11	1	3	4		0.57
54	13.375	10	17	1	18		0.52

experiment H 25 t2b				H0=25.1cm	L0=6.346 m		
				T = 2 s	s0 = 3.95%	h0 = 65 cm	
stones:	test material 1, Dn50 = 0.61 cm						
	basalt						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	63			0		2.51
2	0.375	62			0		2.47
3	0.625	61			0		2.43
4	0.875	60			0		2.39
5	1.125	59			0		2.35
6	1.375	58			0		2.31
7	1.625	57			0		2.27
8	1.875	56			0		2.23
9	2.125	55			0		2.19
10	2.375	54			0		2.15
11	2.625	53			0		2.11
12	2.875	52			0		2.07
13	3.125	51			0		2.03
14	3.375	50			0		1.99
15	3.625	49			0		1.95
16	3.875	48			0		1.92
17	4.125	47			0		1.88
18	4.375	46	1		1		1.84
19	4.625	45			0		1.80
20	4.875	44	1		1		1.76
21	5.125	43	2		2		1.72
22	5.375	42	3		3		1.68
23	5.625	41	3		3		1.64
24	5.875	40	8		8		1.60
25	6.125	39	10		10		1.56
26	6.375	38	11		11		1.52
27	6.625	37	9		9		1.48
28	6.875	36	16		16		1.44
29	7.125	35	14		14		1.40
30	7.375	34	30	5	35		1.36
31	7.625	33	38	4	42		1.32
32	7.875	32	19	7	26		1.28
33	8.125	31	50	6	56		1.24
34	8.375	30	60	34	94		1.20
35	8.625	29	100	100	200		1.16
36	8.875	28	120	120	240		1.12
37	9.125	27	130	134	264		1.08

38	9.375	26	140	124	264		1.04
39	9.625	25	150	130	280		1.00
40	9.875	24	140	140	280		0.96
41	10.125	23	140	135	275		0.92
42	10.375	22	120	130	250		0.88
43	10.625	21	100	125	225		0.84
44	10.875	20	100	120	220		0.80
45	11.125	19	100	120	220		0.76
46	11.375	18	14	110	124		0.72
47	11.625	17	10	18	28		0.68
48	11.875	16	41	50	91		0.64
49	12.125	15	21	8	29		0.60
50	12.375	14	15		15		0.56
51	12.625	13	17	1	18		0.52
52	12.875	12	7	3	10		0.48
53	13.125	11	12		12		0.44
54	13.375	10	7	7	14		0.40

experiment H 30 T2b				H0=31.7cm	L0=6.25m		
				T = 2 s	s0=5.08%	h0=65 cm	
stones:	test material 1, Dn50 = 0.61 cm						
basalt							
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	63			0		1.99
2	0.375	62			0		1.95
3	0.625	61			0		1.92
4	0.875	60			0		1.89
5	1.125	59			0		1.86
6	1.375	58			0		1.83
7	1.625	57			0		1.80
8	1.875	56			0		1.76
9	2.125	55			0		1.73
10	2.375	54			0		1.70
11	2.625	53			0		1.67
12	2.875	52			0		1.64
13	3.125	51			0		1.61
14	3.375	50			0		1.58
15	3.625	49	13		13		1.54
16	3.875	48	15		15		1.51
17	4.125	47	19		19		1.48
18	4.375	46	22		22		1.45
19	4.625	45	25		25		1.42
20	4.875	44	28		28		1.39
21	5.125	43	29		29		1.36
22	5.375	42	33		33		1.32
23	5.625	41	44		44		1.29
24	5.875	40	44		44		1.26
25	6.125	39	61		61		1.23
26	6.375	38	62		62		1.20
27	6.625	37	100		100		1.17
28	6.875	36	120		120		1.13
29	7.125	35	140		140		1.10
30	7.375	34	160		160		1.07
31	7.625	33	180		180		1.04
32	7.875	32	200		200		1.01
33	8.125	31	220		220		0.98
34	8.375	30	240		240		0.95
35	8.625	29	260		260		0.91
36	8.875	28	280		280		0.88
37	9.125	27	300		300		0.85

38	9.375	26	280		280		0.82
39	9.625	25	260		260		0.79
40	9.875	24	240		240		0.76
41	10.125	23	220		220		0.72
42	10.375	22	200		200		0.69
43	10.625	21	180		180		0.66
44	10.875	20	160		160		0.63
45	11.125	19	140		140		0.60
46	11.375	18	120		120		0.57
47	11.625	17	100		100		0.54
48	11.875	16	60		60		0.50
49	12.125	15	19	10	29		0.47
50	12.375	14	33	5	38		0.44
51	12.625	13	30	6	36		0.41
52	12.875	12	27	10	37		0.38
53	13.125	11	11	10	21		0.35
54	13.375	10	34	10	44		0.32

Irregular waves experiments

For each irregular wave experiment, different variables are presented.

general:	Hs	[cm]	significant wave height measured at the toe of the slope
	T	[sec]	wave period
	L0	[m]	deep water wave length
	s0	[%]	wave steepness at the toe of the slope
	h0	[cm]	water-depth
	test material 1 and 2:		used materials on the slope

colomns:	strip nr.	[-]	strip number 1 is located at the toe of the slope
	hor. pos.	[m]	horizontal position, of middle of strip, with respect to the toe of the slope
	w.level.	[cm]	still water-depth, h, at middle of strip
	stones up	[-]	number of stones displaced from strip in up-ward direction after 750 waves
	down	[-]	number of stones displaced from strip in down-ward direction after 750 waves
	totaal 1	[-]	total number of stones displaced from strip with test material 2
	totaal 2	[-]	total number of stones displaces from strip with test material 1
	h/H0	[-]	ratio of water-depth over wave height at toe of slope

experiment Hs10 s1 t1					Hs=10.7 cm	L0 = 9.22 m	
				T = 2.43 sec	s0 = 1.15 %	h0 = 62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	61.5			0		5.76
2	0.375	60.5			0		5.67
3	0.625	59.5			0		5.58
4	0.875	58.5			0		5.48
5	1.125	57.5			0		5.39
6	1.375	56.5			0		5.30
7	1.625	55.5			0		5.20
8	1.875	54.5			0		5.11
9	2.125	53.5			0		5.01
10	2.375	52.5			0		4.92
11	2.625	51.5			0		4.83
12	2.875	50.5			0		4.73
13	3.125	49.5	1		1		4.64
14	3.375	48.5	1		1		4.55
15	3.625	47.5	2		2		4.45
16	3.875	46.5			0		4.36
17	4.125	45.5			0		4.26
18	4.375	44.5			0		4.17
19	4.625	43.5			0		4.08
20	4.875	42.5			0		3.98
21	5.125	41.5			0		3.89
22	5.375	40.5			0		3.80
23	5.625	39.5			0		3.70
24	5.875	38.5			0		3.61
25	6.125	37.5			0		3.51
26	6.375	36.5			0		3.42
27	6.625	35.5			0		3.33
28	6.875	34.5			0		3.23
29	7.125	33.5			0		3.14
30	7.375	32.5			0		3.05
31	7.625	31.5			0		2.95
32	7.875	30.5			0		2.86
33	8.125	29.5			0		2.76
34	8.375	28.5			0		2.67
37	9.125	25.5				0	2.39
38	9.375	24.5	1			1	2.30

39	9.625	23.5		1			1	2.20
40	9.875	22.5					0	2.11
41	10.125	21.5	1				1	2.01
42	10.375	20.5					0	1.92
43	10.625	19.5					0	1.83
44	10.875	18.5					0	1.73
45	11.125	17.5	1				1	1.64
46	11.375	16.5	4				4	1.55
47	11.625	15.5					0	1.45
48	11.875	14.5	1				1	1.36
49	12.125	13.5					0	1.27
50	12.375	12.5					0	1.17
51	12.625	11.5	2				2	1.08
52	12.875	10.5					0	0.98
53	13.125	9.5	1				1	0.89
54	13.375	8.5					0	0.80
55	13.625	7.5	2				2	0.70
56	13.875	6.5	4				4	0.61
57	14.125	5.5	2				2	0.52
58	14.375	4.5	4				4	0.42
59	14.625	3.5	2				2	0.33
60	14.875	2.5	1				1	0.23
61	15.125	1.5					0	0.14
62	15.375	0.5					0	0.05
63	15.625	-0.5					0	-0.05
64	15.875	-1.5					0	-0.14
65	16.125	-2.5					0	-0.23
66	16.375	-3.5					0	-0.33
67	16.625	-4.5					0	-0.42
68	16.875	-5.5					0	-0.52
69	17.125	-6.5					0	-0.61
70	17.375	-7.5					0	-0.70
71	17.625	-8.5					0	-0.80
72	17.875	-9.5					0	-0.89
73	18.125	-10.5					0	-0.98
74	18.375	-11.5					0	-1.08
75	18.625	-12.5					0	-1.17
76	18.875	-13.5					0	-1.27
77	19.125	-14.5					0	-1.36
78	19.375	-15.5					0	-1.45
79	19.625	-16.5					0	-1.55
80	19.875	-17.5					0	-1.64
81	20.125	-18.5					0	-1.73

experiment Hs12 s1 t2					Hs=12.5 cm	L0 = 12.07 m	
				T = 2.78 sec	s0 = 1.04 %	h0 = 62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	61.5			0		4.90
2	0.375	60.5			0		4.82
3	0.625	59.5			0		4.74
4	0.875	58.5			0		4.67
5	1.125	57.5			0		4.59
6	1.375	56.5			0		4.51
7	1.625	55.5			0		4.43
8	1.875	54.5			0		4.35
9	2.125	53.5			0		4.27
10	2.375	52.5			0		4.19
11	2.625	51.5			0		4.11
12	2.875	50.5			0		4.03
13	3.125	49.5			0		3.95
14	3.375	48.5			0		3.87
15	3.625	47.5			0		3.79
16	3.875	46.5			0		3.71
17	4.125	45.5			0		3.63
18	4.375	44.5			0		3.55
19	4.625	43.5			0		3.47
20	4.875	42.5			0		3.39
21	5.125	41.5			0		3.31
22	5.375	40.5			0		3.23
23	5.625	39.5			0		3.15
24	5.875	38.5			0		3.07
25	6.125	37.5			0		2.99
26	6.375	36.5	1		1		2.91
27	6.625	35.5	5		5		2.83
28	6.875	34.5	5		5		2.75
29	7.125	33.5	6		6		2.67
30	7.375	32.5	7		7		2.59
31	7.625	31.5	14		14		2.51
32	7.875	30.5	20		20		2.43
33	8.125	29.5	21		21		2.35
34	8.375	28.5	25		25		2.27
37	9.125	25.5	2			2	2.03

38	9.375	24.5	3				3	1.95
39	9.625	23.5	6				6	1.87
40	9.875	22.5	8	1			9	1.79
41	10.125	21.5	8	1			9	1.71
42	10.375	20.5	7	5			12	1.63
43	10.625	19.5	2				2	1.56
44	10.875	18.5	4	2			6	1.48
45	11.125	17.5	7	1			8	1.40
46	11.375	16.5	7				7	1.32
47	11.625	15.5	4				4	1.24
48	11.875	14.5	4				4	1.16
49	12.125	13.5	13				13	1.08
50	12.375	12.5	4				4	1.00
51	12.625	11.5	4				4	0.92
52	12.875	10.5	7				7	0.84
53	13.125	9.5	4				4	0.76
54	13.375	8.5	8				8	0.68
55	13.625	7.5	3				3	0.60
56	13.875	6.5	4				4	0.52
57	14.125	5.5	9				9	0.44
58	14.375	4.5	5				5	0.36
59	14.625	3.5	15				15	0.28
60	14.875	2.5	5				5	0.20
61	15.125	1.5	8				8	0.12
62	15.375	0.5	7				7	0.04
63	15.625	-0.5	1				1	-0.04
64	15.875	-1.5					0	-0.12
65	16.125	-2.5					0	-0.20
66	16.375	-3.5					0	-0.28
67	16.625	-4.5					0	-0.36
68	16.875	-5.5					0	-0.44
69	17.125	-6.5					0	-0.52
70	17.375	-7.5					0	-0.60
71	17.625	-8.5					0	-0.68
72	17.875	-9.5					0	-0.76
73	18.125	-10.5					0	-0.84
74	18.375	-11.5					0	-0.92
75	18.625	-12.5					0	-1.00
76	18.875	-13.5					0	-1.08

experiment Hs14 s1 t1					Hs=14 cm	L0 = 12.07 m	
				T = 2.78 sec	s0 = 1.15 %	h0 = 62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	61.5			0		4.41
2	0.375	60.5			0		4.34
3	0.625	59.5			0		4.27
4	0.875	58.5			0		4.19
5	1.125	57.5			0		4.12
6	1.375	56.5			0		4.05
7	1.625	55.5			0		3.98
8	1.875	54.5			0		3.91
9	2.125	53.5			0		3.84
10	2.375	52.5			0		3.76
11	2.625	51.5			0		3.69
12	2.875	50.5			0		3.62
13	3.125	49.5			0		3.55
14	3.375	48.5			0		3.48
15	3.625	47.5	1		1		3.41
16	3.875	46.5	1		1		3.33
17	4.125	45.5	1		1		3.26
18	4.375	44.5	1		1		3.19
19	4.625	43.5	1		1		3.12
20	4.875	42.5	1		1		3.05
21	5.125	41.5	4		4		2.97
22	5.375	40.5	12		12		2.90
23	5.625	39.5	4		4		2.83
24	5.875	38.5	7		7		2.76
25	6.125	37.5	9		9		2.69
26	6.375	36.5	13		13		2.62
27	6.625	35.5	27		27		2.54
28	6.875	34.5	39		39		2.47
29	7.125	33.5	18		18		2.40
30	7.375	32.5	20	2	22		2.33
31	7.625	31.5	36		36		2.26
32	7.875	30.5	47		47		2.19
33	8.125	29.5	31		31		2.11
34	8.375	28.5	64		64		2.04
37	9.125	25.5	6			6	1.83

38	9.375	24.5	4				4	1.76
39	9.625	23.5	13				13	1.68
40	9.875	22.5	20	1			21	1.61
41	10.125	21.5	10	1			11	1.54
42	10.375	20.5	9				9	1.47
43	10.625	19.5	12				12	1.40
44	10.875	18.5	18				18	1.33
45	11.125	17.5	35	11			46	1.25
46	11.375	16.5	25	4			29	1.18
47	11.625	15.5	35	1			36	1.11
48	11.875	14.5	47	1			48	1.04
49	12.125	13.5	21				21	0.97
50	12.375	12.5	23				23	0.90
51	12.625	11.5	31				31	0.82
52	12.875	10.5	31				31	0.75
53	13.125	9.5	13				13	0.68
54	13.375	8.5	13				13	0.61
55	13.625	7.5	3				3	0.54
56	13.875	6.5	4				4	0.47
57	14.125	5.5	5				5	0.39
58	14.375	4.5	24				24	0.32
59	14.625	3.5	10				10	0.25
60	14.875	2.5	9				9	0.18
61	15.125	1.5	8				8	0.11
62	15.375	0.5	10				10	0.04
63	15.625	-0.5	15				15	-0.04
64	15.875	-1.5	4				4	-0.11
65	16.125	-2.5					0	-0.18
66	16.375	-3.5					0	-0.25
67	16.625	-4.5					0	-0.32
68	16.875	-5.5					0	-0.39
69	17.125	-6.5					0	-0.47
70	17.375	-7.5					0	-0.54
71	17.625	-8.5					0	-0.61
72	17.875	-9.5					0	-0.68
73	18.125	-10.5					0	-0.75
74	18.375	-11.5					0	-0.82
75	18.625	-12.5					0	-0.90
76	18.875	-13.5					0	-0.97
77	19.125	-14.5					0	-1.04
78	19.375	-15.5					0	-1.11
79	19.625	-16.5					0	-1.18
80	19.875	-17.5					0	-1.25

experiment Hs15 s1 t2					Hs=14.6 cm	L0 = 12.07 m	
				T = 2.78 sec	s0 = 1.21 %	h0 = 62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	61.5			0		4.21
2	0.375	60.5			0		4.14
3	0.625	59.5			0		4.08
4	0.875	58.5			0		4.01
5	1.125	57.5			0		3.94
6	1.375	56.5			0		3.87
7	1.625	55.5			0		3.80
8	1.875	54.5			0		3.73
9	2.125	53.5			0		3.66
10	2.375	52.5			0		3.60
11	2.625	51.5			0		3.53
12	2.875	50.5			0		3.46
13	3.125	49.5			0		3.39
14	3.375	48.5			0		3.32
15	3.625	47.5	1		1		3.25
16	3.875	46.5	1		1		3.18
17	4.125	45.5	1		1		3.12
18	4.375	44.5	3		3		3.05
19	4.625	43.5	3		3		2.98
20	4.875	42.5	2		2		2.91
21	5.125	41.5	5		5		2.84
22	5.375	40.5	8		8		2.77
23	5.625	39.5	15		15		2.71
24	5.875	38.5	8		8		2.64
25	6.125	37.5	33		33		2.57
26	6.375	36.5	38		38		2.50
27	6.625	35.5	39		39		2.43
28	6.875	34.5	47		47		2.36
29	7.125	33.5	26		26		2.29
30	7.375	32.5	28		28		2.23
31	7.625	31.5	65		65		2.16
32	7.875	30.5	72	2	74		2.09
33	8.125	29.5	105	7	112		2.02
34	8.375	28.5	104	10	114		1.95
37	9.125	25.5	7			7	1.75

38	9.375	24.5	12				12	1.68
39	9.625	23.5	29	1			30	1.61
40	9.875	22.5	37				37	1.54
41	10.125	21.5	23				23	1.47
42	10.375	20.5	16				16	1.40
43	10.625	19.5	18	1			19	1.34
44	10.875	18.5	25				25	1.27
45	11.125	17.5	39				39	1.20
46	11.375	16.5	51	5			56	1.13
47	11.625	15.5	39				39	1.06
48	11.875	14.5	44				44	0.99
49	12.125	13.5	42				42	0.92
50	12.375	12.5	24				24	0.86
51	12.625	11.5	43				43	0.79
52	12.875	10.5	29				29	0.72
53	13.125	9.5	32				32	0.65
54	13.375	8.5	15				15	0.58
55	13.625	7.5	1				1	0.51
56	13.875	6.5	1				1	0.45
57	14.125	5.5	4				4	0.38
58	14.375	4.5	7				7	0.31
59	14.625	3.5	12				12	0.24
60	14.875	2.5	13				13	0.17
61	15.125	1.5	11				11	0.10
62	15.375	0.5	10				10	0.03
63	15.625	-0.5	19				19	-0.03
64	15.875	-1.5	7				7	-0.10
65	16.125	-2.5					0	-0.17
66	16.375	-3.5					0	-0.24
67	16.625	-4.5					0	-0.31
68	16.875	-5.5					0	-0.38
69	17.125	-6.5					0	-0.45
70	17.375	-7.5					0	-0.51
71	17.625	-8.5					0	-0.58
72	17.875	-9.5					0	-0.65
73	18.125	-10.5					0	-0.72
74	18.375	-11.5					0	-0.79
75	18.625	-12.5					0	-0.86
76	18.875	-13.5					0	-0.92
77	19.125	-14.5					0	-0.99
78	19.375	-15.5					0	-1.06
79	19.625	-16.5					0	-1.13
80	19.875	-17.5					0	-1.20

experiment Hs10 s3 t1					Hs=10.0 cm	L0 = 3.47 m	
				T = 1.49 sec	s0 = 2.9 %	h0 = 62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	61.5			0		6.15
2	0.375	60.5			0		6.05
3	0.625	59.5			0		5.95
4	0.875	58.5			0		5.85
5	1.125	57.5			0		5.75
6	1.375	56.5			0		5.65
7	1.625	55.5			0		5.55
8	1.875	54.5			0		5.45
9	2.125	53.5			0		5.35
10	2.375	52.5			0		5.25
11	2.625	51.5			0		5.15
12	2.875	50.5			0		5.05
13	3.125	49.5			0		4.95
14	3.375	48.5			0		4.85
15	3.625	47.5			0		4.75
16	3.875	46.5			0		4.65
17	4.125	45.5			0		4.55
18	4.375	44.5			0		4.45
19	4.625	43.5			0		4.35
20	4.875	42.5			0		4.25
21	5.125	41.5			0		4.15
22	5.375	40.5			0		4.05
23	5.625	39.5			0		3.95
24	5.875	38.5			0		3.85
25	6.125	37.5			0		3.75
26	6.375	36.5			0		3.65
27	6.625	35.5			0		3.55
28	6.875	34.5			0		3.45
29	7.125	33.5			0		3.35
30	7.375	32.5			0		3.25
31	7.625	31.5			0		3.15
32	7.875	30.5			0		3.05
33	8.125	29.5			0		2.95
34	8.375	28.5			0		2.85
37	9.125	25.5				0	2.55

38	9.375	24.5				0	2.45
39	9.625	23.5				0	2.35
40	9.875	22.5				0	2.25
41	10.125	21.5				0	2.15
42	10.375	20.5				0	2.05
43	10.625	19.5				0	1.95
44	10.875	18.5	1			1	1.85
45	11.125	17.5				0	1.75
46	11.375	16.5				0	1.65
47	11.625	15.5				0	1.55
48	11.875	14.5				0	1.45
49	12.125	13.5				0	1.35
50	12.375	12.5				0	1.25
51	12.625	11.5				0	1.15
52	12.875	10.5				0	1.05
53	13.125	9.5				0	0.95
54	13.375	8.5				0	0.85
55	13.625	7.5				0	0.75
56	13.875	6.5				0	0.65
57	14.125	5.5				0	0.55
58	14.375	4.5				0	0.45
59	14.625	3.5				0	0.35
60	14.875	2.5				0	0.25
61	15.125	1.5				0	0.15
62	15.375	0.5				0	0.05
63	15.625	-0.5				0	-0.05
64	15.875	-1.5				0	-0.15
65	16.125	-2.5				0	-0.25
66	16.375	-3.5				0	-0.35
67	16.625	-4.5				0	-0.45
68	16.875	-5.5				0	-0.55
69	17.125	-6.5				0	-0.65
70	17.375	-7.5				0	-0.75
71	17.625	-8.5				0	-0.85
72	17.875	-9.5				0	-0.95
73	18.125	-10.5				0	-1.05
74	18.375	-11.5				0	-1.15
75	18.625	-12.5				0	-1.25
76	18.875	-13.5				0	-1.35
77	19.125	-14.5				0	-1.45
78	19.375	-15.5				0	-1.55
79	19.625	-16.5				0	-1.65
80	19.875	-17.5				0	-1.75

experiment Hs14 s3 t1					Hs=14.6 cm	L0=4.89 m	
				T=1.77sec	s0 = 3.0%	h0=62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	61.5			0		4.20
2	0.375	60.5			0		4.14
3	0.625	59.5			0		4.07
4	0.875	58.5			0		4.00
5	1.125	57.5			0		3.93
6	1.375	56.5			0		3.86
7	1.625	55.5			0		3.79
8	1.875	54.5			0		3.73
9	2.125	53.5			0		3.66
10	2.375	52.5			0		3.59
11	2.625	51.5			0		3.52
12	2.875	50.5			0		3.45
13	3.125	49.5			0		3.38
14	3.375	48.5			0		3.32
15	3.625	47.5			0		3.25
16	3.875	46.5			0		3.18
17	4.125	45.5			0		3.11
18	4.375	44.5			0		3.04
19	4.625	43.5			0		2.97
20	4.875	42.5			0		2.90
21	5.125	41.5			0		2.84
22	5.375	40.5			0		2.77
23	5.625	39.5			0		2.70
24	5.875	38.5	1		1		2.63
25	6.125	37.5	1		1		2.56
26	6.375	36.5	1		1		2.49
27	6.625	35.5	2		2		2.43
28	6.875	34.5	1		1		2.36
29	7.125	33.5	1		1		2.29
30	7.375	32.5	1		1		2.22
31	7.625	31.5	3		3		2.15
32	7.875	30.5	1		1		2.08
33	8.125	29.5	6		6		2.02
34	8.375	28.5	6		6		1.95
37	9.125	25.5				0	1.74

38	9.375	24.5				0	1.67
39	9.625	23.5	1	2		3	1.61
40	9.875	22.5	2	1		3	1.54
41	10.125	21.5	1			1	1.47
42	10.375	20.5				0	1.40
43	10.625	19.5	1			1	1.33
44	10.875	18.5	2			2	1.26
45	11.125	17.5				0	1.20
46	11.375	16.5				0	1.13
47	11.625	15.5				0	1.06
48	11.875	14.5				0	0.99
49	12.125	13.5				0	0.92
50	12.375	12.5				0	0.85
51	12.625	11.5	1			1	0.79
52	12.875	10.5				0	0.72
53	13.125	9.5	2			2	0.65
54	13.375	8.5	1			1	0.58
55	13.625	7.5	1			1	0.51
56	13.875	6.5	2			2	0.44
57	14.125	5.5	2			2	0.38
58	14.375	4.5	1			1	0.31
59	14.625	3.5	4			4	0.24
60	14.875	2.5	2			2	0.17
61	15.125	1.5	2			2	0.10
62	15.375	0.5	1			1	0.03
63	15.625	-0.5				0	-0.03
64	15.875	-1.5				0	-0.10
65	16.125	-2.5				0	-0.17
66	16.375	-3.5				0	-0.24
67	16.625	-4.5				0	-0.31
68	16.875	-5.5				0	-0.38
69	17.125	-6.5				0	-0.44
70	17.375	-7.5				0	-0.51
71	17.625	-8.5				0	-0.58
72	17.875	-9.5				0	-0.65
73	18.125	-10.5				0	-0.72
74	18.375	-11.5				0	-0.79
75	18.625	-12.5				0	-0.85
76	18.875	-13.5				0	-0.92
77	19.125	-14.5				0	-0.99
78	19.375	-15.5				0	-1.06
79	19.625	-16.5				0	-1.13
80	19.875	-17.5				0	-1.20

experiment Hs18 s3 t1					Hs=18.2 cm	L0 = 5.91 m	
				T = 1.95 sec	s0 = 3.09 %	h0 = 62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal	h/H0
1	0.125	61.5			0		3.37
2	0.375	60.5			0		3.32
3	0.625	59.5			0		3.26
4	0.875	58.5			0		3.21
5	1.125	57.5			0		3.15
6	1.375	56.5			0		3.10
7	1.625	55.5			0		3.04
8	1.875	54.5			0		2.99
9	2.125	53.5			0		2.93
10	2.375	52.5			0		2.88
11	2.625	51.5			0		2.82
12	2.875	50.5			0		2.77
13	3.125	49.5			0		2.71
14	3.375	48.5			0		2.66
15	3.625	47.5			0		2.60
16	3.875	46.5			0		2.55
17	4.125	45.5	1		1		2.49
18	4.375	44.5	1		1		2.44
19	4.625	43.5	7		7		2.38
20	4.875	42.5	1		1		2.33
21	5.125	41.5	5		5		2.28
22	5.375	40.5	5		5		2.22
23	5.625	39.5	8		8		2.17
24	5.875	38.5	7		7		2.11
25	6.125	37.5	7		7		2.06
26	6.375	36.5	6	1	7		2.00
27	6.625	35.5	9	2	11		1.95
28	6.875	34.5	10	2	12		1.89
29	7.125	33.5	13	11	24		1.84
30	7.375	32.5	19	5	24		1.78
31	7.625	31.5	25	29	54		1.73
32	7.875	30.5	55	5	60		1.67
33	8.125	29.5	53	14	67		1.62
34	8.375	28.5	50	47	97		1.56
37	9.125	25.5	1			1	1.40

38	9.375	24.5	2				2	1.34
39	9.625	23.5	7				7	1.29
40	9.875	22.5	8	2			10	1.23
41	10.125	21.5	2				2	1.18
42	10.375	20.5	3				3	1.12
43	10.625	19.5	4				4	1.07
44	10.875	18.5	4				4	1.01
45	11.125	17.5	4				4	0.96
46	11.375	16.5	2				2	0.90
47	11.625	15.5	3				3	0.85
48	11.875	14.5	2				2	0.79
49	12.125	13.5	4				4	0.74
50	12.375	12.5	1				1	0.69
51	12.625	11.5	2				2	0.63
52	12.875	10.5	10				10	0.58
53	13.125	9.5	3				3	0.52
54	13.375	8.5	8				8	0.47
55	13.625	7.5	14	2			16	0.41
56	13.875	6.5	3				3	0.36
57	14.125	5.5	5				5	0.30
58	14.375	4.5	3				3	0.25
59	14.625	3.5	4				4	0.19
60	14.875	2.5	2				2	0.14
61	15.125	1.5	3				3	0.08
62	15.375	0.5	2				2	0.03
63	15.625	-0.5	4				4	-0.03
64	15.875	-1.5					0	-0.08
65	16.125	-2.5					0	-0.14
66	16.375	-3.5					0	-0.19
67	16.625	-4.5					0	-0.25
68	16.875	-5.5					0	-0.30
69	17.125	-6.5					0	-0.36
70	17.375	-7.5					0	-0.41
71	17.625	-8.5					0	-0.47
72	17.875	-9.5					0	-0.52
73	18.125	-10.5					0	-0.58
74	18.375	-11.5					0	-0.63
75	18.625	-12.5					0	-0.69
76	18.875	-13.5					0	-0.74
77	19.125	-14.5					0	-0.79
78	19.375	-15.5					0	-0.85
79	19.625	-16.5					0	-0.90
80	19.875	-17.5					0	-0.96

experiment Hs20 s3 t2					Hs=19.4 cm	L0 = 7.28 m	
				T = 2.16 sec	s0 = 2.66 %	h0 = 62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	61.5			0		3.17
2	0.375	60.5			0		3.12
3	0.625	59.5			0		3.07
4	0.875	58.5			0		3.02
5	1.125	57.5			0		2.96
6	1.375	56.5			0		2.91
7	1.625	55.5			0		2.86
8	1.875	54.5			0		2.81
9	2.125	53.5			0		2.76
10	2.375	52.5			0		2.71
11	2.625	51.5			0		2.65
12	2.875	50.5			0		2.60
13	3.125	49.5			0		2.55
14	3.375	48.5			0		2.50
15	3.625	47.5			0		2.45
16	3.875	46.5	1		1		2.40
17	4.125	45.5	2		2		2.35
18	4.375	44.5	2		2		2.29
19	4.625	43.5	3		3		2.24
20	4.875	42.5	3		3		2.19
21	5.125	41.5	2		2		2.14
22	5.375	40.5	5	1	6		2.09
23	5.625	39.5	10	1	11		2.04
24	5.875	38.5	6	1	7		1.98
25	6.125	37.5	8		8		1.93
26	6.375	36.5	16		16		1.88
27	6.625	35.5	31	3	34		1.83
28	6.875	34.5	70	27	97		1.78
29	7.125	33.5	36	17	53		1.73
30	7.375	32.5	57	7	64		1.68
31	7.625	31.5	104	25	129		1.62
32	7.875	30.5	76	25	101		1.57
33	8.125	29.5	90	22	112		1.52
34	8.375	28.5	73	24	97		1.47
37	9.125	25.5	3			3	1.31

38	9.375	24.5	1				1	1.26
39	9.625	23.5	4	2			6	1.21
40	9.875	22.5	6	3			9	1.16
41	10.125	21.5	1	1			2	1.11
42	10.375	20.5	1				1	1.06
43	10.625	19.5	4	1			5	1.01
44	10.875	18.5	6				6	0.95
45	11.125	17.5	3				3	0.90
46	11.375	16.5	8				8	0.85
47	11.625	15.5	3				3	0.80
48	11.875	14.5	5				5	0.75
49	12.125	13.5	6				6	0.70
50	12.375	12.5	6				6	0.64
51	12.625	11.5	2				2	0.59
52	12.875	10.5	2				2	0.54
53	13.125	9.5	3				3	0.49
54	13.375	8.5	2				2	0.44
55	13.625	7.5	2				2	0.39
56	13.875	6.5	3				3	0.34
57	14.125	5.5	8	1			9	0.28
58	14.375	4.5	18	2			20	0.23
59	14.625	3.5	10	2			12	0.18
60	14.875	2.5	4				4	0.13
61	15.125	1.5	8				8	0.08
62	15.375	0.5	8				8	0.03
63	15.625	-0.5	9				9	-0.03
64	15.875	-1.5	1				1	-0.08
65	16.125	-2.5					0	-0.13
66	16.375	-3.5					0	-0.18
67	16.625	-4.5					0	-0.23
68	16.875	-5.5					0	-0.28
69	17.125	-6.5					0	-0.34
70	17.375	-7.5					0	-0.39
71	17.625	-8.5					0	-0.44
72	17.875	-9.5					0	-0.49
73	18.125	-10.5					0	-0.54
74	18.375	-11.5					0	-0.59
75	18.625	-12.5					0	-0.64
76	18.875	-13.5					0	-0.70
77	19.125	-14.5					0	-0.75
78	19.375	-15.5					0	-0.80
79	19.625	-16.5					0	-0.85
80	19.875	-17.5					0	-0.90

experiment Hs16 s5 t1					Hs=16.2 cm	L0 = 3.06 m	
				T = 1.4 s	s0 = 5.3 %	h0 = 62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	61.5			0		3.80
2	0.375	60.5			0		3.74
3	0.625	59.5			0		3.68
4	0.875	58.5			0		3.61
5	1.125	57.5			0		3.55
6	1.375	56.5			0		3.49
7	1.625	55.5			0		3.43
8	1.875	54.5			0		3.37
9	2.125	53.5			0		3.30
10	2.375	52.5			0		3.24
11	2.625	51.5			0		3.18
12	2.875	50.5			0		3.12
13	3.125	49.5			0		3.06
14	3.375	48.5			0		3.00
15	3.625	47.5			0		2.93
16	3.875	46.5			0		2.87
17	4.125	45.5			0		2.81
18	4.375	44.5			0		2.75
19	4.625	43.5			0		2.69
20	4.875	42.5			0		2.63
21	5.125	41.5			0		2.56
22	5.375	40.5			0		2.50
23	5.625	39.5			0		2.44
24	5.875	38.5			0		2.38
25	6.125	37.5			0		2.32
26	6.375	36.5			0		2.25
27	6.625	35.5			0		2.19
28	6.875	34.5			0		2.13
29	7.125	33.5			0		2.07
30	7.375	32.5			0		2.01
31	7.625	31.5			0		1.95
32	7.875	30.5			0		1.88
33	8.125	29.5	2		2		1.82
34	8.375	28.5	2		2		1.76
37	9.125	25.5				0	1.58

38	9.375	24.5					0	1.51
39	9.625	23.5					0	1.45
40	9.875	22.5					0	1.39
41	10.125	21.5					0	1.33
42	10.375	20.5					0	1.27
43	10.625	19.5					0	1.20
44	10.875	18.5					0	1.14
45	11.125	17.5					0	1.08
46	11.375	16.5					0	1.02
47	11.625	15.5					0	0.96
48	11.875	14.5					0	0.90
49	12.125	13.5					0	0.83
50	12.375	12.5					0	0.77
51	12.625	11.5					0	0.71
52	12.875	10.5					0	0.65
53	13.125	9.5					0	0.59
54	13.375	8.5					0	0.53
55	13.625	7.5					0	0.46
56	13.875	6.5					0	0.40
57	14.125	5.5					0	0.34
58	14.375	4.5					0	0.28
59	14.625	3.5	2				2	0.22
60	14.875	2.5					0	0.15
61	15.125	1.5	2				2	0.09
62	15.375	0.5					0	0.03
63	15.625	-0.5					0	-0.03
64	15.875	-1.5					0	-0.09
65	16.125	-2.5					0	-0.15
66	16.375	-3.5					0	-0.22
67	16.625	-4.5					0	-0.28
68	16.875	-5.5					0	-0.34
69	17.125	-6.5					0	-0.40
70	17.375	-7.5					0	-0.46
71	17.625	-8.5					0	-0.53
72	17.875	-9.5					0	-0.59
73	18.125	-10.5					0	-0.65
74	18.375	-11.5					0	-0.71
75	18.625	-12.5					0	-0.77
76	18.875	-13.5					0	-0.83
77	19.125	-14.5					0	-0.90
78	19.375	-15.5					0	-0.96
79	19.625	-16.5					0	-1.02
80	19.875	-17.5					0	-1.08

experiment Hs18 s5 t1					Hs=17.9 cm	L0 = 3.51 m	
				T = 2.36 s	s0 = 5.0 %	h0 = 62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	61.5			0		2.25
2	0.375	60.5			0		2.22
3	0.625	59.5			0		2.18
4	0.875	58.5			0		2.14
5	1.125	57.5			0		2.11
6	1.375	56.5			0		2.07
7	1.625	55.5			0		2.03
8	1.875	54.5			0		2.00
9	2.125	53.5			0		1.96
10	2.375	52.5			0		1.92
11	2.625	51.5			0		1.89
12	2.875	50.5			0		1.85
13	3.125	49.5			0		1.81
14	3.375	48.5			0		1.78
15	3.625	47.5			0		1.74
16	3.875	46.5			0		1.70
17	4.125	45.5			0		1.67
18	4.375	44.5			0		1.63
19	4.625	43.5			0		1.59
20	4.875	42.5			0		1.56
21	5.125	41.5			0		1.52
22	5.375	40.5			0		1.48
23	5.625	39.5			0		1.45
24	5.875	38.5	1		1		1.41
25	6.125	37.5	1		1		1.37
26	6.375	36.5			0		1.34
27	6.625	35.5	2		2		1.30
28	6.875	34.5	3	2	5		1.26
29	7.125	33.5	1		1		1.23
30	7.375	32.5	1		1		1.19
31	7.625	31.5	9		9		1.15
32	7.875	30.5	5		5		1.12
33	8.125	29.5	3		3		1.08
34	8.375	28.5	5	2	7		1.04
37	9.125	25.5				0	0.93

38	9.375	24.5					0	0.90
39	9.625	23.5					0	0.86
40	9.875	22.5					0	0.82
41	10.125	21.5					0	0.79
42	10.375	20.5					0	0.75
43	10.625	19.5					0	0.71
44	10.875	18.5					0	0.68
45	11.125	17.5					0	0.64
46	11.375	16.5					0	0.60
47	11.625	15.5					0	0.57
48	11.875	14.5					0	0.53
49	12.125	13.5					0	0.49
50	12.375	12.5					0	0.46
51	12.625	11.5					0	0.42
52	12.875	10.5					0	0.38
53	13.125	9.5					0	0.35
54	13.375	8.5					0	0.31
55	13.625	7.5					0	0.27
56	13.875	6.5					0	0.24
57	14.125	5.5					0	0.20
58	14.375	4.5	3				3	0.16
59	14.625	3.5	5				5	0.13
60	14.875	2.5	2				2	0.09
61	15.125	1.5	5				5	0.05
62	15.375	0.5					0	0.02
63	15.625	-0.5					0	-0.02
64	15.875	-1.5					0	-0.05
65	16.125	-2.5					0	-0.09
66	16.375	-3.5					0	-0.13
67	16.625	-4.5					0	-0.16
68	16.875	-5.5					0	-0.20
69	17.125	-6.5					0	-0.24
70	17.375	-7.5					0	-0.27
71	17.625	-8.5					0	-0.31
72	17.875	-9.5					0	-0.35
73	18.125	-10.5					0	-0.38
74	18.375	-11.5					0	-0.42
75	18.625	-12.5					0	-0.46
76	18.875	-13.5					0	-0.49
77	19.125	-14.5					0	-0.53
78	19.375	-15.5					0	-0.57
79	19.625	-16.5					0	-0.60
80	19.875	-17.5					0	-0.64

experiment Hs23 s5 t1					Hs=20.13cm	L0 = 4.1 m	
				T = 1.62 sec	s0 = 5.0 %	h0 = 62 cm	
stones:	test material 1, Dn50 = 1.5 cm						
	test material 2, Dn50 = 0.63 cm						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	61.5			0		3.06
2	0.375	60.5			0		3.01
3	0.625	59.5			0		2.96
4	0.875	58.5			0		2.91
5	1.125	57.5			0		2.86
6	1.375	56.5			0		2.81
7	1.625	55.5			0		2.76
8	1.875	54.5			0		2.71
9	2.125	53.5			0		2.66
10	2.375	52.5			0		2.61
11	2.625	51.5			0		2.56
12	2.875	50.5			0		2.51
13	3.125	49.5	1		1		2.46
14	3.375	48.5	1		1		2.41
15	3.625	47.5	2		2		2.36
16	3.875	46.5			0		2.31
17	4.125	45.5			0		2.26
18	4.375	44.5			0		2.21
19	4.625	43.5	1		1		2.16
20	4.875	42.5	1		1		2.11
21	5.125	41.5	3		3		2.06
22	5.375	40.5	11		11		2.01
23	5.625	39.5	5		5		1.96
24	5.875	38.5	3	3	6		1.91
25	6.125	37.5	5	1	6		1.86
26	6.375	36.5	1		1		1.81
27	6.625	35.5	2	2	4		1.76
28	6.875	34.5	9		9		1.71
29	7.125	33.5	10	4	14		1.66
30	7.375	32.5	11	1	12		1.61
31	7.625	31.5	32	5	37		1.56
32	7.875	30.5	13	30	43		1.52
33	8.125	29.5	16	7	23		1.47
34	8.375	28.5	19	35	54		1.42
37	9.125	25.5				0	1.27

38	9.375	24.5				0	1.22
39	9.625	23.5				0	1.17
40	9.875	22.5				0	1.12
41	10.125	21.5				0	1.07
42	10.375	20.5				0	1.02
43	10.625	19.5				0	0.97
44	10.875	18.5				0	0.92
45	11.125	17.5				0	0.87
46	11.375	16.5				0	0.82
47	11.625	15.5				0	0.77
48	11.875	14.5				0	0.72
49	12.125	13.5				0	0.67
50	12.375	12.5				0	0.62
51	12.625	11.5				0	0.57
52	12.875	10.5				0	0.52
53	13.125	9.5				0	0.47
54	13.375	8.5	2			2	0.42
55	13.625	7.5				0	0.37
56	13.875	6.5				0	0.32
57	14.125	5.5				0	0.27
58	14.375	4.5	12			12	0.22
59	14.625	3.5	7			7	0.17
60	14.875	2.5	20			20	0.12
61	15.125	1.5	7			7	0.07
62	15.375	0.5	10			10	0.02
63	15.625	-0.5	6			6	-0.02
64	15.875	-1.5				0	-0.07
65	16.125	-2.5				0	-0.12
66	16.375	-3.5				0	-0.17
67	16.625	-4.5				0	-0.22
68	16.875	-5.5				0	-0.27
69	17.125	-6.5				0	-0.32
70	17.375	-7.5				0	-0.37
71	17.625	-8.5				0	-0.42
72	17.875	-9.5				0	-0.47
73	18.125	-10.5				0	-0.52
74	18.375	-11.5				0	-0.57
75	18.625	-12.5				0	-0.62
76	18.875	-13.5				0	-0.67
77	19.125	-14.5				0	-0.72
78	19.375	-15.5				0	-0.77
79	19.625	-16.5				0	-0.82
80	19.875	-17.5				0	-0.87

experiment Hs9s1 t1b					Hs=9.84 cm	L0 = 9.22 m	
				T = 2.43 sec	s0 = 1.07 %	h0 = 60 cm	
stones:	test material 1, Dn50 = 1.0 cm						
	test material 2, Dn50 = 0.61 cm,						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	59.5			0		6.05
2	0.375	58.5			0		5.95
3	0.625	57.5			0		5.84
4	0.875	56.5			0		5.74
5	1.125	55.5			0		5.64
6	1.375	54.5			0		5.54
7	1.625	53.5			0		5.44
8	1.875	52.5			0		5.34
9	2.125	51.5			0		5.23
10	2.375	50.5			0		5.13
11	2.625	49.5			0		5.03
12	2.875	48.5			0		4.93
13	3.125	47.5			0		4.83
14	3.375	46.5			0		4.73
15	3.625	45.5			0		4.62
16	3.875	44.5			0		4.52
17	4.125	43.5			0		4.42
18	4.375	42.5			0		4.32
19	4.625	41.5			0		4.22
20	4.875	40.5			0		4.12
21	5.125	39.5			0		4.01
22	5.375	38.5			0		3.91
23	5.625	37.5			0		3.81
24	5.875	36.5			0		3.71
25	6.125	35.5			0		3.61
26	6.375	34.5			0		3.51
27	6.625	33.5			0		3.40
28	6.875	32.5			0		3.30
29	7.125	31.5			0		3.20
30	7.375	30.5			0		3.10
31	7.625	29.5			0		3.00
32	7.875	28.5			0		2.90
33	8.125	27.5	6		6		2.79
34	8.375	26.5	7		7		2.69
37	9.125	23.5				0	2.39
38	9.375	22.5				0	2.29

39	9.625	21.5	6			6	2.18
40	9.875	20.5	5			5	2.08
41	10.125	19.5	14			14	1.98
42	10.375	18.5	10			10	1.88
43	10.625	17.5	8			8	1.78
44	10.875	16.5	16			16	1.68
45	11.125	15.5	17			17	1.58
46	11.375	14.5	10			10	1.47
47	11.625	13.5	17			17	1.37
48	11.875	12.5	6			6	1.27
49	12.125	11.5	8			8	1.17
50	12.375	10.5	25			25	1.07
51	12.625	9.5	15			15	0.97
52	12.875	8.5	35			35	0.86
53	13.125	7.5	45			45	0.76
54	13.375	6.5	16			16	0.66
55	13.625	5.5	31			31	0.56
56	13.875	4.5	5			5	0.46
57	14.125	3.5	13			13	0.36
58	14.375	2.5	59			59	0.25
59	14.625	1.5	59			59	0.15
60	14.875	0.5	26			26	0.05
61	15.125	-0.5	8			8	-0.05
62	15.375	-1.5	2			2	-0.15
63	15.625	-2.5				0	-0.25
64	15.875	-3.5				0	-0.36
65	16.125	-4.5				0	-0.46
66	16.375	-5.5				0	-0.56
67	16.625	-6.5				0	-0.66
68	16.875	-7.5				0	-0.76
69	17.125	-8.5				0	-0.86
70	17.375	-9.5				0	-0.97
71	17.625	-10.5				0	-1.07
72	17.875	-11.5				0	-1.17
73	18.125	-12.5				0	-1.27
74	18.375	-13.5				0	-1.37
75	18.625	-14.5				0	-1.47
76	18.875	-15.5				0	-1.58
77	19.125	-16.5				0	-1.68
78	19.375	-17.5				0	-1.78
79	19.625	-18.5				0	-1.88
80	19.875	-19.5				0	-1.98
81	20.125	-20.5				0	-2.08

experiment Hs10s1 t1b					Hs=10.52cm	L0 = 9.22 m	
				T = 2.43 sec	s0 = 1.14 %	h0 = 60 cm	
stones:	test material 1, Dn50 = 1.0 cm						
	test material 2, Dn50 = 0.61 cm,						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	59.5			0		5.66
2	0.375	58.5			0		5.56
3	0.625	57.5			0		5.47
4	0.875	56.5			0		5.37
5	1.125	55.5			0		5.28
6	1.375	54.5			0		5.18
7	1.625	53.5			0		5.09
8	1.875	52.5			0		4.99
9	2.125	51.5			0		4.90
10	2.375	50.5			0		4.80
11	2.625	49.5			0		4.71
12	2.875	48.5			0		4.61
13	3.125	47.5			0		4.52
14	3.375	46.5			0		4.42
15	3.625	45.5			0		4.33
16	3.875	44.5			0		4.23
17	4.125	43.5			0		4.13
18	4.375	42.5			0		4.04
19	4.625	41.5			0		3.94
20	4.875	40.5			0		3.85
21	5.125	39.5			0		3.75
22	5.375	38.5			0		3.66
23	5.625	37.5	2		2		3.56
24	5.875	36.5	2		2		3.47
25	6.125	35.5	2	1	3		3.37
26	6.375	34.5	1		1		3.28
27	6.625	33.5	4		4		3.18
28	6.875	32.5	4		4		3.09
29	7.125	31.5	3		3		2.99
30	7.375	30.5	3		3		2.90
31	7.625	29.5	2	1	3		2.80
32	7.875	28.5	4		4		2.71
33	8.125	27.5	4		4		2.61
34	8.375	26.5	5	2	7		2.52
35	8.625	25.5			0		2.42
36	8.875	24.5				0	2.33

33	8.125	27.5	4		4		2.61
34	8.375	26.5	5	2	7		2.52
35	8.625	25.5			0		2.42
36	8.875	24.5				0	2.33
37	9.125	23.5	3			3	2.23
38	9.375	22.5	8	3		11	2.14
39	9.625	21.5	10			10	2.04
40	9.875	20.5	6			6	1.95
41	10.125	19.5	8			8	1.85
42	10.375	18.5	3	1		4	1.76
43	10.625	17.5	13	1		14	1.66
44	10.875	16.5	22	1		23	1.57
45	11.125	15.5	11			11	1.47
46	11.375	14.5	22			22	1.38
47	11.625	13.5	8			8	1.28
48	11.875	12.5	7			7	1.19
49	12.125	11.5	14			14	1.09
50	12.375	10.5	21			21	1.00
51	12.625	9.5	11	4		15	0.90
52	12.875	8.5	43	1		44	0.81
53	13.125	7.5	41			41	0.71
54	13.375	6.5	9			9	0.62
55	13.625	5.5	16			16	0.52
56	13.875	4.5	9			9	0.43
57	14.125	3.5	17			17	0.33
58	14.375	2.5	67	7		74	0.24
59	14.625	1.5	77	1		78	0.14
60	14.875	0.5	25			25	0.05
61	15.125	-0.5	15			15	-0.05
62	15.375	-1.5	3			3	-0.14
63	15.625	-2.5	3			3	-0.24
64	15.875	-3.5				0	-0.33
65	16.125	-4.5				0	-0.43
66	16.375	-5.5				0	-0.52
67	16.625	-6.5				0	-0.62
68	16.875	-7.5				0	-0.71
69	17.125	-8.5				0	-0.81
70	17.375	-9.5				0	-0.90
71	17.625	-10.5				0	-1.00
72	17.875	-11.5				0	-1.09
73	18.125	-12.5				0	-1.19
74	18.375	-13.5				0	-1.28
75	18.625	-14.5				0	-1.38

experiment Hs14s1t1.b					Hs=12.72cm	L0 = 12.07 m	
				T = 2.78 sec	s0 = 1.05 %	h0 = 60 cm	
stones:	test material 1, Dn50 = 1.0 cm						
	test material 2, Dn50 = 0.61 cm,						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	59.5			0		4.68
2	0.375	58.5			0		4.60
3	0.625	57.5			0		4.52
4	0.875	56.5			0		4.44
5	1.125	55.5			0		4.36
6	1.375	54.5			0		4.28
7	1.625	53.5			0		4.21
8	1.875	52.5			0		4.13
9	2.125	51.5			0		4.05
10	2.375	50.5			0		3.97
11	2.625	49.5			0		3.89
12	2.875	48.5			0		3.81
13	3.125	47.5			0		3.73
14	3.375	46.5			0		3.66
15	3.625	45.5			0		3.58
16	3.875	44.5			0		3.50
17	4.125	43.5			0		3.42
18	4.375	42.5			0		3.34
19	4.625	41.5	1		1		3.26
20	4.875	40.5	3		3		3.18
21	5.125	39.5	1		1		3.11
22	5.375	38.5	1		1		3.03
23	5.625	37.5	4		4		2.95
24	5.875	36.5	8		8		2.87
25	6.125	35.5	10		10		2.79
26	6.375	34.5	12		12		2.71
27	6.625	33.5	27		27		2.63
28	6.875	32.5	7		7		2.56
29	7.125	31.5	12		12		2.48
30	7.375	30.5	12		12		2.40
31	7.625	29.5	16		16		2.32
32	7.875	28.5	22		22		2.24
33	8.125	27.5	21		21		2.16
34	8.375	26.5	31	2	33		2.08
37	9.125	23.5	23	12		35	1.85

38	9.375	22.5	27			27	1.77
39	9.625	21.5	30			30	1.69
40	9.875	20.5	38			38	1.61
41	10.125	19.5	63			63	1.53
42	10.375	18.5	39			39	1.45
43	10.625	17.5	59			59	1.38
44	10.875	16.5	64			64	1.30
45	11.125	15.5	105			105	1.22
46	11.375	14.5	103			103	1.14
47	11.625	13.5	112			112	1.06
48	11.875	12.5	183			183	0.98
49	12.125	11.5	189			189	0.90
50	12.375	10.5	102			102	0.83
51	12.625	9.5	69			69	0.75
52	12.875	8.5	83			83	0.67
53	13.125	7.5	58			58	0.59
54	13.375	6.5	22			22	0.51
55	13.625	5.5	33			33	0.43
56	13.875	4.5	41			41	0.35
57	14.125	3.5	69	1		70	0.28
58	14.375	2.5	104	3		107	0.20
59	14.625	1.5	151	2		153	0.12
60	14.875	0.5	91			91	0.04
61	15.125	-0.5	69			69	-0.04
62	15.375	-1.5	68			68	-0.12
63	15.625	-2.5	3			3	-0.20
64	15.875	-3.5				0	-0.28
65	16.125	-4.5	7			7	-0.35
66	16.375	-5.5				0	-0.43
67	16.625	-6.5				0	-0.51
68	16.875	-7.5				0	-0.59
69	17.125	-8.5				0	-0.67
70	17.375	-9.5				0	-0.75
71	17.625	-10.5				0	-0.83
72	17.875	-11.5				0	-0.90
73	18.125	-12.5				0	-0.98
74	18.375	-13.5				0	-1.06
75	18.625	-14.5				0	-1.14
76	18.875	-15.5				0	-1.22
77	19.125	-16.5				0	-1.30
78	19.375	-17.5				0	-1.38
79	19.625	-18.5				0	-1.45
80	19.875	-19.5				0	-1.53

experiment Hs15s1 t1.b					Hs=13.29cm	L0 = 12.07 m	
				T = 2.78 sec	s0 = 1.10 %	h0 = 60 cm	
stones:	test material 1, Dn50 = 1.0 cm						
	test material 2, Dn50 = 0.61 cm,						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	59.5			0		4.48
2	0.375	58.5			0		4.40
3	0.625	57.5			0		4.33
4	0.875	56.5			0		4.25
5	1.125	55.5			0		4.18
6	1.375	54.5			0		4.10
7	1.625	53.5			0		4.03
8	1.875	52.5			0		3.95
9	2.125	51.5			0		3.88
10	2.375	50.5			0		3.80
11	2.625	49.5			0		3.72
12	2.875	48.5			0		3.65
13	3.125	47.5			0		3.57
14	3.375	46.5			0		3.50
15	3.625	45.5			0		3.42
16	3.875	44.5			0		3.35
17	4.125	43.5			0		3.27
18	4.375	42.5			0		3.20
19	4.625	41.5	3		3		3.12
20	4.875	40.5	7		7		3.05
21	5.125	39.5	5		5		2.97
22	5.375	38.5			0		2.90
23	5.625	37.5			0		2.82
24	5.875	36.5	11		11		2.75
25	6.125	35.5	8		8		2.67
26	6.375	34.5	18		18		2.60
27	6.625	33.5	19		19		2.52
28	6.875	32.5	15		15		2.45
29	7.125	31.5	9		9		2.37
30	7.375	30.5	8		8		2.29
31	7.625	29.5	23		23		2.22
32	7.875	28.5	21		21		2.14
33	8.125	27.5	45		45		2.07
34	8.375	26.5	50	4	54		1.99
35	8.625	25.5	70	9	79		1.92
36	8.875	24.5	172	4	176		1.84

39	9.625	21.5	52			52	1.62
40	9.875	20.5	45			45	1.54
41	10.125	19.5	61			61	1.47
42	10.375	18.5	57			57	1.39
43	10.625	17.5	55			55	1.32
44	10.875	16.5	164			164	1.24
45	11.125	15.5	150			150	1.17
46	11.375	14.5	131			131	1.09
47	11.625	13.5	145			145	1.02
48	11.875	12.5	378			378	0.94
49	12.125	11.5	226			226	0.87
50	12.375	10.5	161			161	0.79
51	12.625	9.5	108			108	0.71
52	12.875	8.5	130			130	0.64
53	13.125	7.5	87			87	0.56
54	13.375	6.5	18			18	0.49
55	13.625	5.5	48			48	0.41
56	13.875	4.5	23			23	0.34
57	14.125	3.5	38			38	0.26
58	14.375	2.5	92			92	0.19
59	14.625	1.5	132			132	0.11
60	14.875	0.5	59			59	0.04
61	15.125	-0.5	55			55	-0.04
62	15.375	-1.5	64			64	-0.11
63	15.625	-2.5	40			40	-0.19
64	15.875	-3.5	7			7	-0.26
65	16.125	-4.5				0	-0.34
66	16.375	-5.5				0	-0.41
67	16.625	-6.5				0	-0.49
68	16.875	-7.5				0	-0.56
69	17.125	-8.5				0	-0.64
70	17.375	-9.5				0	-0.71
71	17.625	-10.5				0	-0.79
72	17.875	-11.5				0	-0.87
73	18.125	-12.5				0	-0.94
74	18.375	-13.5				0	-1.02
75	18.625	-14.5				0	-1.09
76	18.875	-15.5				0	-1.17
77	19.125	-16.5				0	-1.24
78	19.375	-17.5				0	-1.32
79	19.625	-18.5				0	-1.39
80	19.875	-19.5				0	-1.47

experiment Hs10s3 t1b					Hs = 9.9 cm	L0 = 3.49 m	
				T = 1.50 sec	s0 = 2.81 %	h0 = 60 cm	
stones:	test material 1, Dn50 = 1.0 cm						
	test material 2, Dn50 = 0.61 cm,						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	59.5			0		6.01
2	0.375	58.5			0		5.91
3	0.625	57.5			0		5.81
4	0.875	56.5			0		5.71
5	1.125	55.5			0		5.61
6	1.375	54.5			0		5.51
7	1.625	53.5			0		5.40
8	1.875	52.5			0		5.30
9	2.125	51.5			0		5.20
10	2.375	50.5			0		5.10
11	2.625	49.5			0		5.00
12	2.875	48.5			0		4.90
13	3.125	47.5			0		4.80
14	3.375	46.5			0		4.70
15	3.625	45.5			0		4.60
16	3.875	44.5			0		4.49
17	4.125	43.5			0		4.39
18	4.375	42.5			0		4.29
19	4.625	41.5			0		4.19
20	4.875	40.5			0		4.09
21	5.125	39.5			0		3.99
22	5.375	38.5			0		3.89
23	5.625	37.5			0		3.79
24	5.875	36.5			0		3.69
25	6.125	35.5			0		3.59
26	6.375	34.5			0		3.48
27	6.625	33.5			0		3.38
28	6.875	32.5			0		3.28
29	7.125	31.5			0		3.18
30	7.375	30.5			0		3.08
31	7.625	29.5			0		2.98
32	7.875	28.5			0		2.88
33	8.125	27.5			0		2.78
34	8.375	26.5			0		2.68
37	9.125	23.5				0	2.37

38	9.375	22.5					0	2.27
39	9.625	21.5					0	2.17
40	9.875	20.5					0	2.07
41	10.125	19.5					0	1.97
42	10.375	18.5					0	1.87
43	10.625	17.5					0	1.77
44	10.875	16.5					0	1.67
45	11.125	15.5					0	1.57
46	11.375	14.5					0	1.46
47	11.625	13.5					0	1.36
48	11.875	12.5					0	1.26
49	12.125	11.5					0	1.16
50	12.375	10.5					0	1.06
51	12.625	9.5					0	0.96
52	12.875	8.5					0	0.86
53	13.125	7.5					0	0.76
54	13.375	6.5	2				2	0.66
55	13.625	5.5	3				3	0.56
56	13.875	4.5	2				2	0.45
57	14.125	3.5					0	0.35
58	14.375	2.5	9				9	0.25
59	14.625	1.5	2				2	0.15
60	14.875	0.5					0	0.05
61	15.125	-0.5					0	-0.05
62	15.375	-1.5					0	-0.15
63	15.625	-2.5					0	-0.25
64	15.875	-3.5					0	-0.35
65	16.125	-4.5					0	-0.45
66	16.375	-5.5					0	-0.56
67	16.625	-6.5					0	-0.66
68	16.875	-7.5					0	-0.76
69	17.125	-8.5					0	-0.86
70	17.375	-9.5					0	-0.96
71	17.625	-10.5					0	-1.06
72	17.875	-11.5					0	-1.16
73	18.125	-12.5					0	-1.26
74	18.375	-13.5					0	-1.36
75	18.625	-14.5					0	-1.46
76	18.875	-15.5					0	-1.57
77	19.125	-16.5					0	-1.67
78	19.375	-17.5					0	-1.77
79	19.625	-18.5					0	-1.87
80	19.875	-19.5					0	-1.97

experiment Hs14s3 t1b					Hs=13.79cm	L0 = 4.88 m	
				T=1.768 sec	s0 = 2.81 %	h0 = 60 cm	
stones:	test material 1, Dn50 = 1.0 cm						
	test material 2, Dn50 = 0.61 cm,						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	59.5			0		4.31
2	0.375	58.5			0		4.24
3	0.625	57.5			0		4.17
4	0.875	56.5			0		4.10
5	1.125	55.5			0		4.02
6	1.375	54.5			0		3.95
7	1.625	53.5			0		3.88
8	1.875	52.5			0		3.81
9	2.125	51.5			0		3.73
10	2.375	50.5			0		3.66
11	2.625	49.5			0		3.59
12	2.875	48.5			0		3.52
13	3.125	47.5			0		3.44
14	3.375	46.5			0		3.37
15	3.625	45.5			0		3.30
16	3.875	44.5			0		3.23
17	4.125	43.5			0		3.15
18	4.375	42.5			0		3.08
19	4.625	41.5			0		3.01
20	4.875	40.5			0		2.94
21	5.125	39.5			0		2.86
22	5.375	38.5			0		2.79
23	5.625	37.5			0		2.72
24	5.875	36.5			0		2.65
25	6.125	35.5			0		2.57
26	6.375	34.5			0		2.50
27	6.625	33.5			0		2.43
28	6.875	32.5			0		2.36
29	7.125	31.5			0		2.28
30	7.375	30.5			0		2.21
31	7.625	29.5	3		3		2.14
32	7.875	28.5	4		4		2.07
33	8.125	27.5	5		5		1.99
34	8.375	26.5	6	0	6		1.92
35	8.625	25.5	6	1	7		1.85
36	8.875	24.5		4	4		1.78

39	9.625	21.5				0	1.56
40	9.875	20.5	2			2	1.49
41	10.125	19.5	3			3	1.41
42	10.375	18.5	1			1	1.34
43	10.625	17.5	4	1		5	1.27
44	10.875	16.5	6			6	1.20
45	11.125	15.5	4			4	1.12
46	11.375	14.5	3			3	1.05
47	11.625	13.5	6			6	0.98
48	11.875	12.5	2			2	0.91
49	12.125	11.5	5			5	0.83
50	12.375	10.5	5			5	0.76
51	12.625	9.5	3			3	0.69
52	12.875	8.5	3			3	0.62
53	13.125	7.5	5			5	0.54
54	13.375	6.5	1			1	0.47
55	13.625	5.5	6			6	0.40
56	13.875	4.5	1			1	0.33
57	14.125	3.5	3			3	0.25
58	14.375	2.5	11			11	0.18
59	14.625	1.5	25	1		26	0.11
60	14.875	0.5	42			42	0.04
61	15.125	-0.5	13			13	-0.04
62	15.375	-1.5				0	-0.11
63	15.625	-2.5				0	-0.18
64	15.875	-3.5				0	-0.25
65	16.125	-4.5				0	-0.33
66	16.375	-5.5				0	-0.40
67	16.625	-6.5				0	-0.47
68	16.875	-7.5				0	-0.54
69	17.125	-8.5				0	-0.62
70	17.375	-9.5				0	-0.69
71	17.625	-10.5				0	-0.76
72	17.875	-11.5				0	-0.83
73	18.125	-12.5				0	-0.91
74	18.375	-13.5				0	-0.98
75	18.625	-14.5				0	-1.05
76	18.875	-15.5				0	-1.12
77	19.125	-16.5				0	-1.20
78	19.375	-17.5				0	-1.27
79	19.625	-18.5				0	-1.34
80	19.875	-19.5				0	-1.41

experiment Hs18s3 t1b					Hs=17.97cm	L0 = 5.91 m	
				T=1.945 sec	s0 = 3.04 %	h0 = 60 cm	
stones:	test material 1, Dn50 = 1.0 cm						
	test material 2, Dn50 = 0.61 cm,						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	59.5			0		3.31
2	0.375	58.5			0		3.26
3	0.625	57.5			0		3.20
4	0.875	56.5			0		3.14
5	1.125	55.5			0		3.09
6	1.375	54.5			0		3.03
7	1.625	53.5			0		2.98
8	1.875	52.5			0		2.92
9	2.125	51.5			0		2.87
10	2.375	50.5			0		2.81
11	2.625	49.5			0		2.75
12	2.875	48.5			0		2.70
13	3.125	47.5			0		2.64
14	3.375	46.5			0		2.59
15	3.625	45.5			0		2.53
16	3.875	44.5			0		2.48
17	4.125	43.5			0		2.42
18	4.375	42.5			0		2.37
19	4.625	41.5			0		2.31
20	4.875	40.5			0		2.25
21	5.125	39.5			0		2.20
22	5.375	38.5			0		2.14
23	5.625	37.5			0		2.09
24	5.875	36.5			0		2.03
25	6.125	35.5			0		1.98
26	6.375	34.5			0		1.92
27	6.625	33.5	4		4		1.86
28	6.875	32.5	5		5		1.81
29	7.125	31.5	7	3	10		1.75
30	7.375	30.5	11	10	21		1.70
31	7.625	29.5	15	13	28		1.64
32	7.875	28.5	16	10	26		1.59
33	8.125	27.5	15	25	40		1.53
34	8.375	26.5	26	15	41		1.47
35	8.625	25.5	34	23	57		1.42
36	8.875	24.5	35	4	39		1.36

39	9.625	21.5	9	2		11	1.20
40	9.875	20.5	13			13	1.14
41	10.125	19.5	25			25	1.09
42	10.375	18.5	15			15	1.03
43	10.625	17.5	18			18	0.97
44	10.875	16.5	18			18	0.92
45	11.125	15.5	19			19	0.86
46	11.375	14.5	22			22	0.81
47	11.625	13.5	11			11	0.75
48	11.875	12.5	9			9	0.70
49	12.125	11.5	11			11	0.64
50	12.375	10.5	10			10	0.58
51	12.625	9.5	7			7	0.53
52	12.875	8.5	7			7	0.47
53	13.125	7.5	21			21	0.42
54	13.375	6.5	25			25	0.36
55	13.625	5.5	28			28	0.31
56	13.875	4.5	15			15	0.25
57	14.125	3.5	10			10	0.19
58	14.375	2.5	49			49	0.14
59	14.625	1.5	61			61	0.08
60	14.875	0.5	33			33	0.03
61	15.125	-0.5	94			94	-0.03
62	15.375	-1.5	42	4		46	-0.08
63	15.625	-2.5	69			69	-0.14
64	15.875	-3.5	40			40	-0.19
65	16.125	-4.5	3			3	-0.25
66	16.375	-5.5				0	-0.31
67	16.625	-6.5				0	-0.36
68	16.875	-7.5				0	-0.42
69	17.125	-8.5				0	-0.47
70	17.375	-9.5				0	-0.53
71	17.625	-10.5				0	-0.58
72	17.875	-11.5				0	-0.64
73	18.125	-12.5				0	-0.70
74	18.375	-13.5				0	-0.75
75	18.625	-14.5				0	-0.81
76	18.875	-15.5				0	-0.86
77	19.125	-16.5				0	-0.92
78	19.375	-17.5				0	-0.97
79	19.625	-18.5				0	-1.03
80	19.875	-19.5				0	-1.09

experiment Hs20s3 t1b					Hs = 18.83 cm	L0 =7.28 m	
				T = 2.16 sec	s0 = 2.6 %	h0 = 60 cm	
stones:	test material 1, Dn50 = 1.0 cm						
	test material 2, Dn50 = 0.61 cm,						
strip nr.	hor. pos.	w. depth	stones up	down	totaal 1	totaal 2	h/H0
1	0.125	59.5			0		3.16
2	0.375	58.5			0		3.11
3	0.625	57.5			0		3.05
4	0.875	56.5			0		3.00
5	1.125	55.5			0		2.95
6	1.375	54.5			0		2.89
7	1.625	53.5			0		2.84
8	1.875	52.5			0		2.79
9	2.125	51.5			0		2.73
10	2.375	50.5			0		2.68
11	2.625	49.5			0		2.63
12	2.875	48.5			0		2.58
13	3.125	47.5			0		2.52
14	3.375	46.5			0		2.47
15	3.625	45.5			0		2.42
16	3.875	44.5	3		3		2.36
17	4.125	43.5	2		2		2.31
18	4.375	42.5	4		4		2.26
19	4.625	41.5	11		11		2.20
20	4.875	40.5	8	1	9		2.15
21	5.125	39.5	10		10		2.10
22	5.375	38.5	1		1		2.04
23	5.625	37.5	3	1	4		1.99
24	5.875	36.5	4		4		1.94
25	6.125	35.5	9		9		1.89
26	6.375	34.5	3	3	6		1.83
27	6.625	33.5	25	10	35		1.78
28	6.875	32.5	29	8	37		1.73
29	7.125	31.5	29	45	74		1.67
30	7.375	30.5	42	17	59		1.62
31	7.625	29.5	42	12	54		1.57
32	7.875	28.5	25	43	68		1.51
33	8.125	27.5	55	41	96		1.46
34	8.375	26.5	32	7	39		1.41
35	8.625	25.5	66	31	97		1.35

36	8.875	24.5	73	30	103		1.30
39	9.625	21.5	11	1		12	1.14
40	9.875	20.5	8	4		12	1.09
41	10.125	19.5	10			10	1.04
42	10.375	18.5	14			14	0.98
43	10.625	17.5	14			14	0.93
44	10.875	16.5	27			27	0.88
45	11.125	15.5	34			34	0.82
46	11.375	14.5	23	1		24	0.77
47	11.625	13.5	30			30	0.72
48	11.875	12.5	47	1		48	0.66
49	12.125	11.5	14			14	0.61
50	12.375	10.5	24			24	0.56
51	12.625	9.5	6			6	0.50
52	12.875	8.5	18			18	0.45
53	13.125	7.5	30			30	0.40
54	13.375	6.5	23			23	0.35
55	13.625	5.5	29			29	0.29
56	13.875	4.5	52			52	0.24
57	14.125	3.5	58			58	0.19
58	14.375	2.5	107			107	0.13
59	14.625	1.5	57			57	0.08
60	14.875	0.5	53			53	0.03
61	15.125	-0.5	171			171	-0.03
62	15.375	-1.5	70			70	-0.08
63	15.625	-2.5	32			32	-0.13
64	15.875	-3.5	14			14	-0.19
65	16.125	-4.5		5		5	-0.24
66	16.375	-5.5				0	-0.29
67	16.625	-6.5				0	-0.35
68	16.875	-7.5				0	-0.40
69	17.125	-8.5				0	-0.45
70	17.375	-9.5				0	-0.50
71	17.625	-10.5				0	-0.56
72	17.875	-11.5				0	-0.61
73	18.125	-12.5				0	-0.66
74	18.375	-13.5				0	-0.72
75	18.625	-14.5				0	-0.77
76	18.875	-15.5				0	-0.82
77	19.125	-16.5				0	-0.88
78	19.375	-17.5				0	-0.93
79	19.625	-18.5				0	-0.98

Appendix VI

Damage distribution graph's

In chapter 5 some examples of damage distributions were presented. In this appendix a selection of some more distribution graphs will be presented. Only a limited number of figures is plotted. For regular waves a distribution graph of test H20T2b is plotted, for irregular waves several distribution graphs are presented with different wave steepnesses.

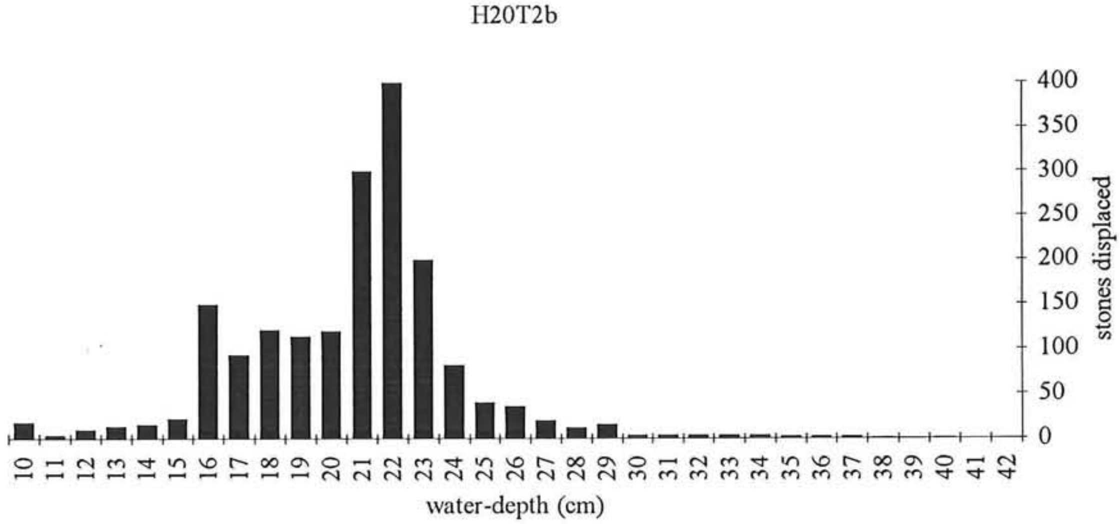


figure VI.1: Damage distribution for regular waves, experiment, H20T2b

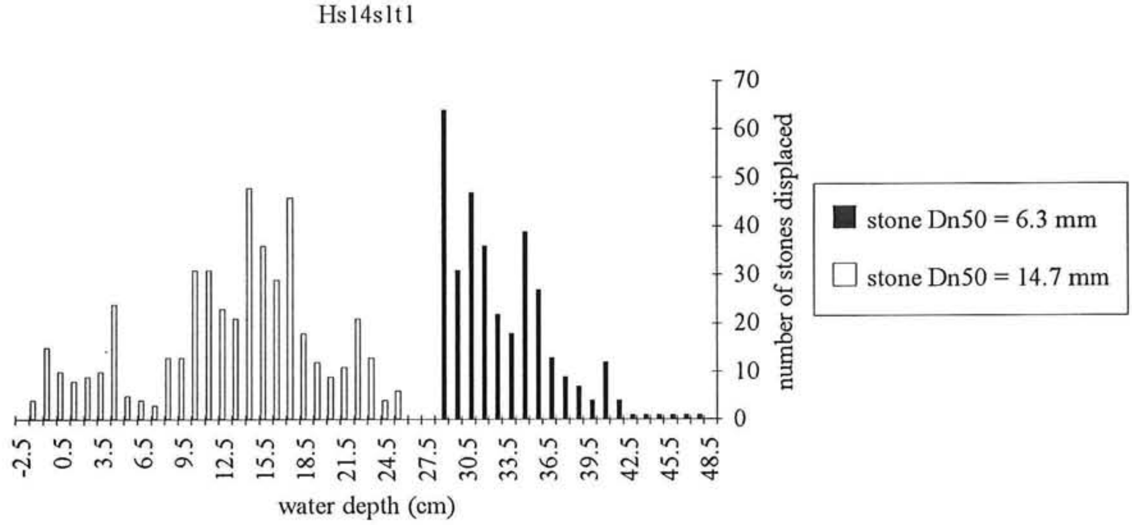


figure VI.2: Distribution of damage for irregular waves, s0=1%

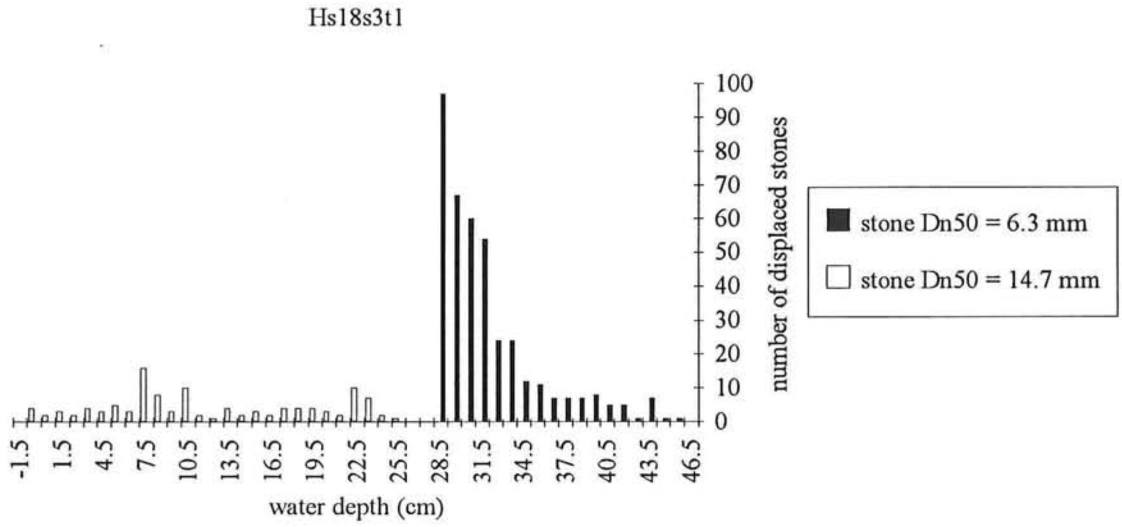


figure VI.3: Distribution of damage, for irregular waves, s0=3%

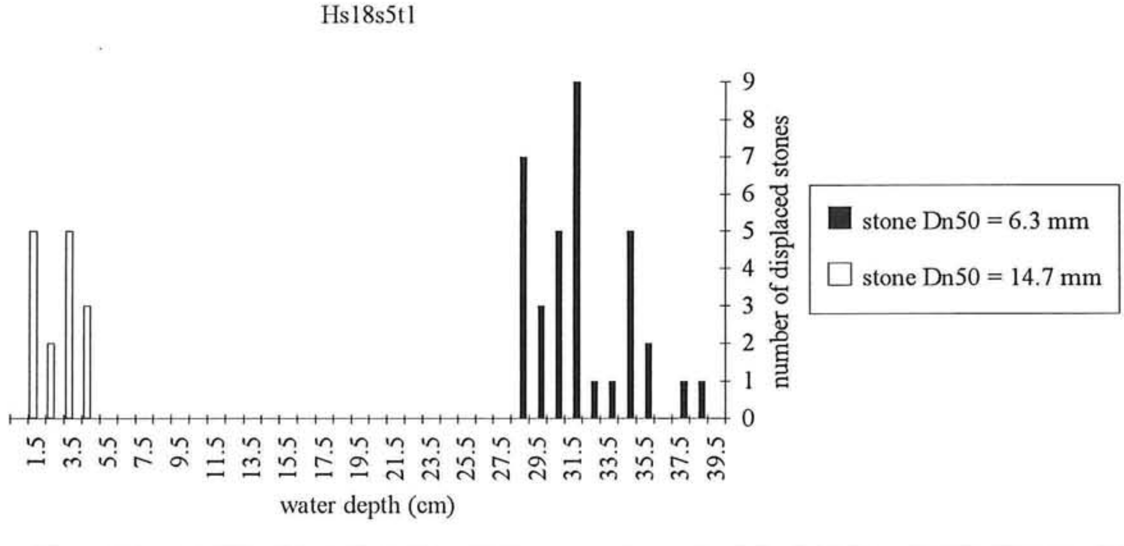


figure VI.4: Distribution of damage, for irregular waves, s0=5%

Appendix VII

Damage-percentage curves for regular and irregular waves

In chapter 6 examples of damage-percentage curves were already presented. An other example for regular waves is given in figure VII.1. For irregular waves see figure VII.2.

Regular waves

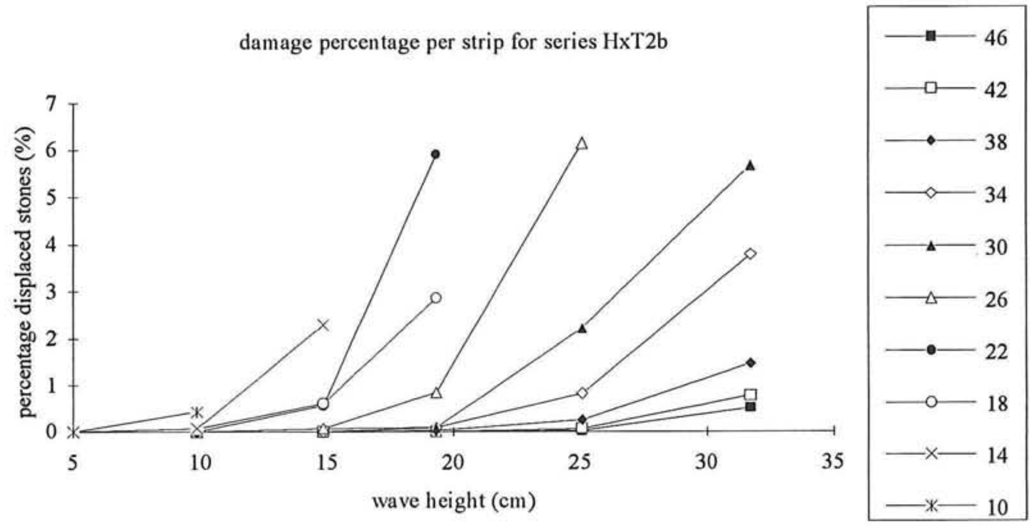


figure VII.1: Stone, Dn50 = 6.1mm, Δ = 1.95

Irregular waves

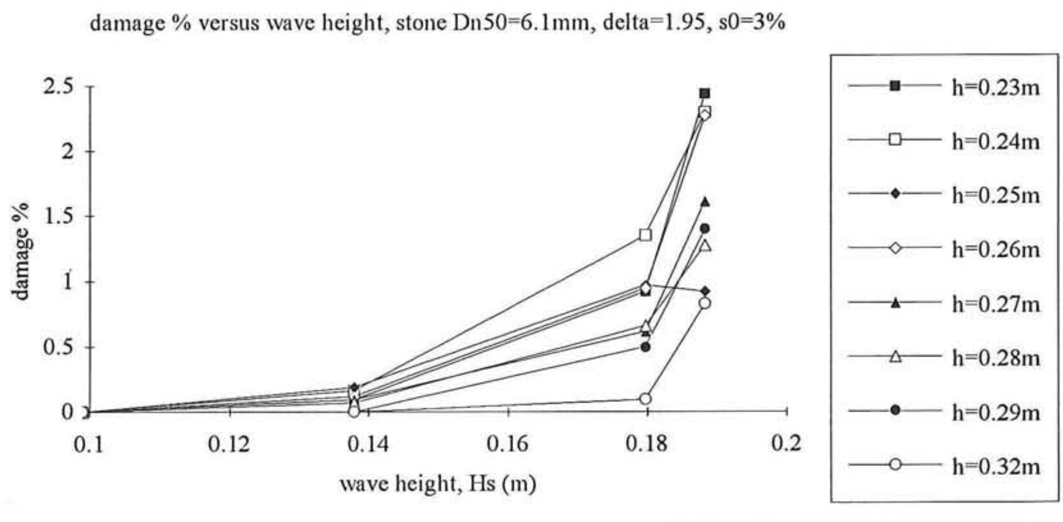


figure VII.2: wave steepness, s0=3%

Appendix VIII

Comparison experimental results with theory

In this appendix are the remaining experimental results, which were not presented in chapter 6, compared with the theoretical calculated stability relations.

Regular waves

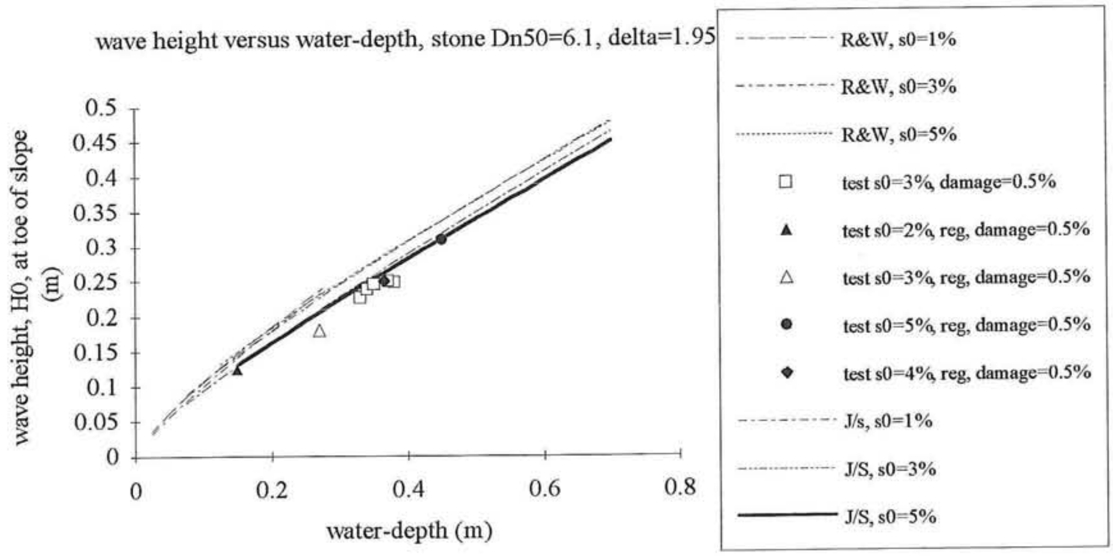


figure VIII.1: The wave height is defined at the toe of the slope

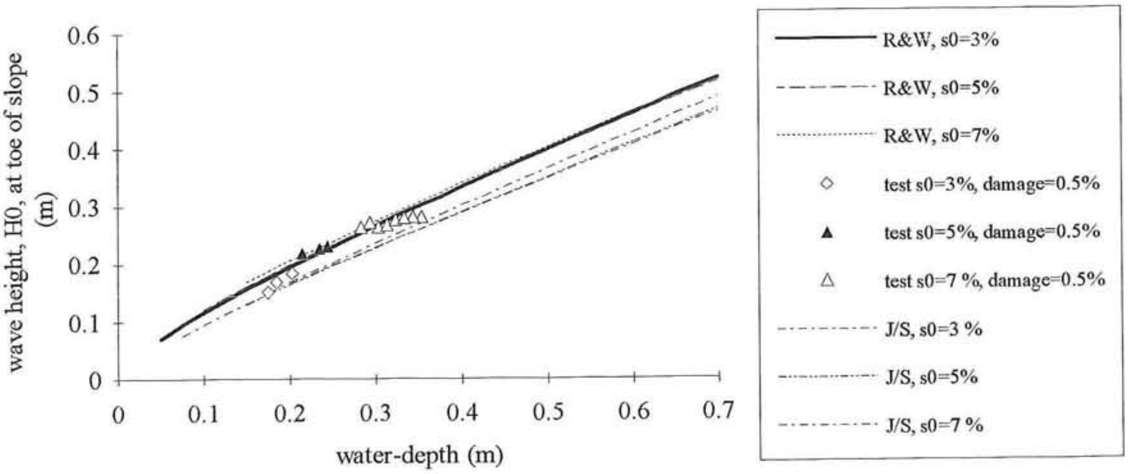


figure VIII.2: The wave height is defined at the toe of the slope

Figure VIII.2 show's the experimental results found by Sistermans (1993).

Irregular waves

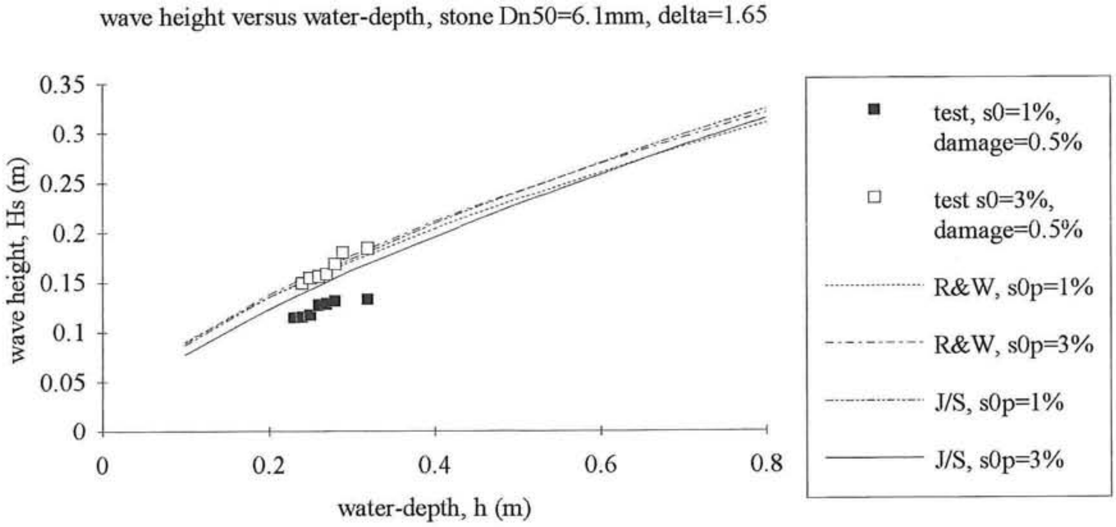


figure VIII.3: The wave heigth is defined at the toe of the slope

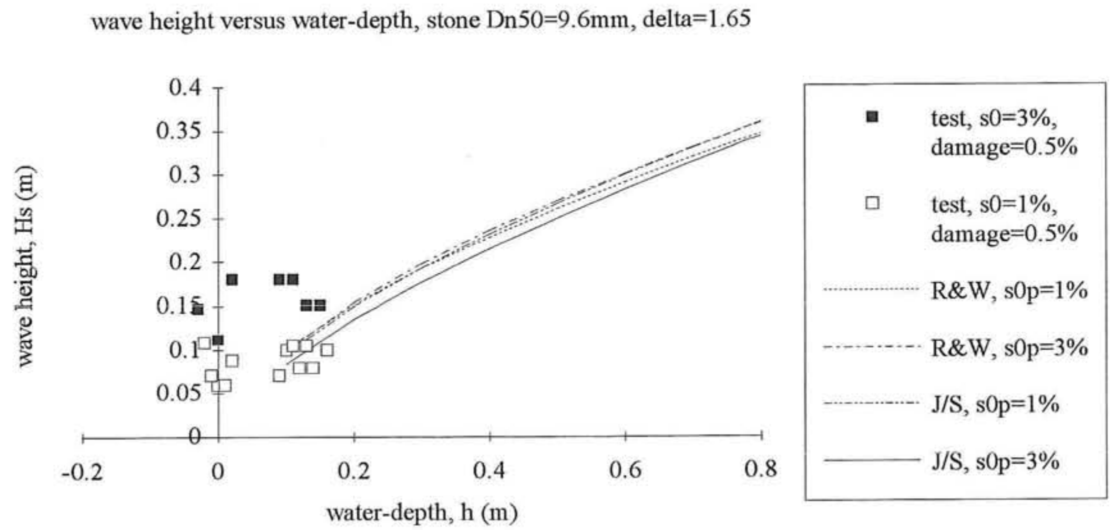


figure VIII.4: The wave height is defined at the toe of the slope

Appendix IX

Comparison of theories

In chapter 6, for irregular waves, the theoretically derived relations only are presented according to Rance & Warren, in order to show the results in a surveable way. The results from Rance & Warren compared to those found with Jonsson / Sleath can be seen in figure IX.1. As it can be seen, there is not much difference between the two theories.

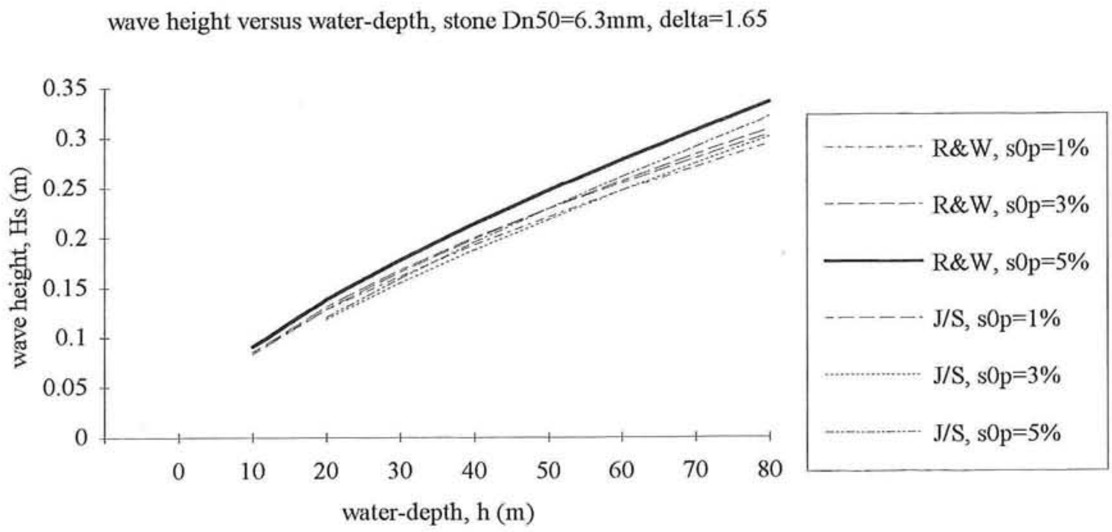
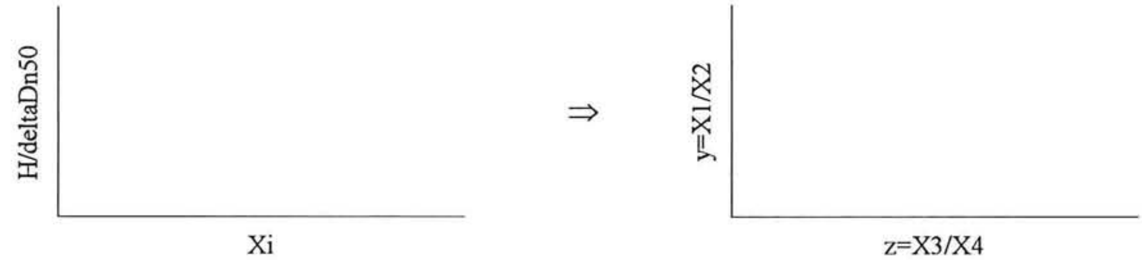


figure IX.1: The significant wave height, H_s, is defined at the toe of the slope

Appendix X

Spurious correlation

The second combination as mentioned in chapter 6 was: $H/\Delta D_{n50}$ as a function of ξ, schematically be represented as:



With $X_1 = H$, $X_2 = \Delta D_{n50}$.
$Xi = \tan\alpha/(H/L_0)^{1/2}$ can be written as: $\tan\alpha(L_0)^{1/2}/H^{1/2}$. This yields $X_3 = \tan\alpha(L_0)^{1/2}$ and $X_4 = H^{1/2}$.The coefficients C_{x1} and C_{x2} were already known. $C_{x3}^2 \approx C_\alpha^2 + 0.25\ C_{L0}^2$, according to De Vries (1976). For C_{x4} this gives, $C_{x4}^2 \approx 0.25\ C_H^2$.

Again according to Benson (1965), the correlation coefficient of y and z is defined by:

$$r_{yz} \approx \frac{r_{13}C_1C_3 - r_{14}C_1C_4 - r_{23}C_2C_3 + r_{24}C_2C_4}{(C_1^2+C_2^2-2r_{12}C_1C_2)^{\frac{1}{2}}(C_3^2+C_4^2-2r_{34}C_3C_4)^{\frac{1}{2}}} \tag{X.1}$$

With: $r_{13} = 0$
$r_{23} = 0$
$r_{24} = 0$
$r_{12} = 0$
$r_{34} = 0$
and r_{14} is defined, De Vries (1976) as:

$$r_{14} \approx \frac{C_{X1}}{(C_{X1}^2+C_{X4}^2)^{\frac{1}{2}}} \tag{X.2}$$

This yields a correlation coefficient, $r_{14} \approx 0.89$.

The correlation coefficient, r_{yz}, of the second graph presented yields:

$$r_{yz} \approx \frac{-r_{14}C_1C_4}{(C_1^2+C_2^2)^{\frac{1}{2}}(C_3^2+C_4^2)^{\frac{1}{2}}} \tag{X.3}$$

Substitution of the coefficients of variation gives: $r_{yz} \approx -0.11$

Again it could be said that this value is small when stating that spurious correlation occurs between $0.5 \leq |r_{yz}| \leq 1.0$. But one could investigate how the accuracies of the variables influence formula X.3 as is done with combination 1 in chapter 6.

- C_1 could be 1.0 % instead of 0.5 % (see combination 1).
- C_2 could decrease from 1.6 % to approximately 1.0 % (see combination 1).
- C_3 consists of the coefficients of variation of α and L_0. When stating that the coefficient of variation of L_0 is not likely to change, C_3 could vary because of a larger error made in the slope angle. Instead of having an error of ±5 mm over 1 m height increase over the slope, an error of ±1 cm could be introduced. The value of C_3 would increase from approximately 0.54 % to 1.0 %.
- C_4 is defined as: $(C_4)^2 = 0.25\ (C_1)^2$, which yields, with the change of C_1, to a value of C_4 = 0.5 %.

Combinations of C_1, C_2, C_3 and C_4 resulting in different values of r_{yz} are given in table X.1.

second combination	1	2	3	4	5	6
C_1	0.5 %	1.0 %	0.5 %	0.5 %	0.5 %	1.0 %
C_2	1.6 %	1.6 %	1.1 %	1.6 %	1.6 %	1.1 %
C_3	0.54 %	0.54 %	0.54 %	1.0 %	0.54 %	0.54 %
C_4	0.25 %	0.25 %	0.25 %	0.25 %	0.5 %	0.5 %
r_{14}	0.89	0.97	0.89	0.89	0.71	0.89
r_{yz}	-0.11	-0.22	-0.15	-0.06	-0.14	-0.41

Table X.1 shows an increase in correlation with a decreasing accuracy for the wave height meter combined with an increasing accuracy for the determination of the diameter, D_{n50}. The influence of the decreasing accuracy of the determination of the slope angle, α, on the spurious correlation is positive, that is, the value of r_{yz} decreases. All the values of r_{yz} of the combinations of C_1, C_2, C_3 and C_4 remain low and are below the imaginary value of $|r_{yz}| \leq 0.5$ to avoid spurious correlation.

For the second combination it's also possible to give judgement of the confidence interval of the values plotted in the graph. This can be done by stating that the accuracies are equal to ±1 times the standard deviation, 68 % of the area under the normal distribution or stating that the accuracies are equal to ±2 times the standard deviation, 95 % of the area under the normal distribution.

In the first case (accuracies ±1 times the standard deviation), the chance of a value outside the interval is 32 %. According to the De Vries (1967):

- for the y -axis, - (see the first combination), the chance of a value outside the interval of ± s.d. = 55 %
- for the z - axis, - (chance of a value outside the interval of ± s.d. for z)^2 = (chance of a value outside the interval of ± s.d. for

$X_3)^2$ + (chance of a value outside the interval of ± s.d. for $X_4)^2$

- (chance for $X_3)^2$ = (32 % for $\alpha)^2$ + 0.25 · (chance for $L_0)^2$
- (chance for $L_0)^2$ = 4 · (32 % for $T_p)^2$
- (chance for $X_4)^2$ = 0.25 · (32 % for $H_s)^2$
- chance of a value outside the interval of ± s.d. for z = 48 %

In the graph of combination 2 the total chance of finding a value inside the interval of ± the standard deviation is, (1-0.55)·(1-0.48) = 0.234, or 23.4 %.

The second case is when stating that the accuracy measured is ±2 times the standard deviation. The marked area under the Gauss distribution is 95 %. This yields according to De Vries (1976):

- for the y -axis,
  - (see the first combination), the chance of a value outside the interval of ± s.d. = 8.6 %
- for the z- axis,
  - (chance of a value outside the interval of ±2 · s.d. for $z)^2$ = (chance of a value outside the interval of ±2 · s.d. for $X_3)^2$ + (chance of a value outside the interval of ±2 · s.d. for $X_4)^2$
    - (chance for $X_3)^2$ = (5 % for $\alpha)^2$ + 0.25 · (chance for $L_0)^2$
      - (chance for $L_0)^2$ = 4 · (5 % for $T_p)^2$
    - (chance for $X_4)^2$ = 0.25 · (5 % for $H_s)^2$
  - chance of a value outside the interval of ± s.d. for z = 7.5 %

In the graph of combination 2 the total chance of finding a value inside the interval of ±2 times the standard deviation is, (1-0.086)·(1-0.075) = 0.846, or 84.6 %.

Which of these two approximations, 23.4 % or 84.6 %, is the most reliable one depends on the correctness of the measurement accuracy of the equipment.

Appendix XI

Stability caluculations according to Rance & Warren and Jonsson / Sleath with the software package Mathcad.

$\delta := 1.65$ $\qquad g := 9.81$ $\qquad L := 1$ $\qquad d := 0.1$

given $\quad L = \dfrac{g \cdot T^2}{2 \cdot \pi} \cdot \tanh\left(\dfrac{2 \cdot \pi}{L} \cdot h\right)$ $\qquad$ (iteration of wave length)

given $\quad d = \dfrac{\exp\left[-6 + 5.2 \cdot \left(\dfrac{ab}{1.024 \cdot d}\right)^{-0.19}\right] \cdot ub^2}{2 \cdot \delta \cdot g \cdot 0.056}$ $\qquad Lh(T, h) := \text{find}(L)$

(iteration of stone diameter)

$diam(ab, ub) := \text{find}(d)$

$i := 0 .. 3$ $\qquad j := 0 .. 9$ $\qquad H0 := 0.2$

$s_i := \dfrac{2 \cdot i + 1}{100}$ $\qquad h_j := \dfrac{j + 5}{20}$

$T_i := \sqrt{\dfrac{H0}{1.56 \cdot s_i}}$

$\lambda_{i,j} := Lh(T_i, h_j)$ $\qquad \omega_i := \dfrac{2 \cdot \pi}{T_i}$ $\qquad k_{i,j} := \dfrac{2 \cdot \pi}{\lambda_{i,j}}$

$kh_{i,j} := k_{i,j} \cdot h_j$ $\qquad$ (shoaling factor)

$$Ksh_{i,j} := \frac{1}{\sqrt{\tanh(kh_{i,j}) \cdot \left(1 + 2 \cdot \dfrac{kh_{i,j}}{\sinh(2 \cdot kh_{i,j})}\right)}}$$

$H_{i,j} := Ksh_{i,j} \cdot \dfrac{H0}{Ksh_{i,9}}$

$ab_{i,j} := \dfrac{H_{i,j}}{2 \cdot \sinh(kh_{i,j})}$ $\qquad ub_{i,j} := \omega_i \cdot ab_{i,j}$

(stone diameter according to Rance & Warren)

$DnRW_{i,j} := 0.84 \cdot 2.56 \cdot \left[\dfrac{(ub_{i,j})^{2.5}}{\sqrt{T_i} \cdot (\delta \cdot g)^{1.5}}\right]$

(stone diameter according to Jonsson / Sleath)

$DnJS_{i,j} := 0.84 \cdot diam(ab_{i,j}, ub_{i,j})$

$Hdiep_i := \dfrac{H0}{Ksh_{i,9}}$

(H/deltaDn50 values of R&W and J/S)

$HD\_RW_{i,j} := \dfrac{Hdiep_i}{\delta \cdot DnRW_{i,j}}$ $\qquad HD\_JS_{i,j} := \dfrac{Hdiep_i}{\delta \cdot DnJS_{i,j}}$