Wave transmission at low-crested structures

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Hierbij wil ik de leden van deze commissie
bedanken voor hun begeleiding.

Ivar Daemen

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1. INTRODUCTION

1.1 General

This report contains an analysis of data on wave transmission. It is restricted to wave transmission at low-crested permeable breakwaters. All data used are from tests with irregular waves. These data were earlier gathered in Delft Hydraulics' report: "Data on wave transmission due to overtopping" by J.W. van der Meer (1990).

The study was performed by I.F.R. Daemen, student at the Delft University of Technology, as part of his master's thesis, under the guidance of Prof.ir. K. d'Angremond (TU Delft) and dr.ir. J.W. van der Meer (Delft Hydraulics). In september 1990, the author performed an additional series of tests on wave transmission at Delft Hydraulics.

The phenomenon of wave transmission will first be introduced in chapter 2, where, guided by previous work, the governing parameters and their influence will be discussed. In chapter 3 a short description of the data sets used for the analysis will be given. The above mentioned latest tests on wave transmission will be treated extensively. Finally in chapter 4 the actual analysis will be presented and the results of it discussed.

The author wishes to acknowledge Delft Hydraulics for the use of test facilities and the guidance.

1.2 Aim of the research

Until now wave transmission is described by various formulas in which terms appear which contain more than one parameter. This makes it hard to recognize the influence of an individual parameter. The aim of the analysis presented in this report is to look at all parameters involved in a separate way and to come up with a formula which can predict wave transmission at low-crested breakwaters. This formula should be practically usable and reasonably reliable.

1.3 Conclusions and recommendations

1. The main governing parameters, which determine wave transmission at low-crested and submerged breakwaters, are:

crest freeboard	:	R_c
wave height	:	H_{mo}
wave peak period	:	T_p
crest width	:	B_c

2. Parameters investigated which had little -or no influence are: bulk number (B_n), permeability factor (P) and slope angle ($\cot\alpha$).

3. The crest height, wave height and crest width are made dimensionless by using the nominal diameter of the stone: D_{n50}. The influence of the wave peak period is described by the fictitious wave steepness: s_{op}. The dimensionless governing parameters are:

relative crest height	:	R_c/D_{n50}
relative wave height	:	H_{mo}/D_{n50}
fictitious wave steepness	:	s_{op}
relative crest width	:	B_c/D_{n50}

4. Three structure types were investigated: conventional, homogeneous and reef type breakwaters. A conventional breakwater consists of a core, filter layer(s) and armour layer. A homogeneous breakwater is best described as a homogeneous mound of stones. A reef type breakwater is also homogeneous, but special in a way that it is allowed to deform under wave attack.

5. The wave transmission coefficient K_t of conventional breakwaters is given by:

$$K_t = a * R_c/D_{n50} + b \qquad \text{(eq. 4.1)}$$

In which:

$a = f(H_{mo}/D_{n50})$

$b = f(s_{op}, H_{mo}/D_{n50}, B_c/D_{n50})$

An overall view of the formula for conventional breakwaters is presented in figure 39.

With the use of the range of application a standard deviation of 0.048 is reached, without it the standard deviation amounts to 0.058.

6. The wave transmission coefficient increases from a minimum to a maximum value in the area of the relative crest height ranging from -2 to +2. In this area the influence of the wave steepness on wave transmission is constant and the influence of the relative wave height is dependent on the value of the relative crest height.

7. The influence of the relative crest height seems also to be dependent on the permeability of the crest. This appears when comparing an armour layer of rock and of, more permeable, tetrapods. Further investigations will be needed to confirm, and eventually quantify, this phenomenon. The permeability of the crest is not taken into account in the formulas proposed in this report.

8. The minimum and maximum values of the wave transmission coefficient are set at fixed values. this means independent of any parameter. However the point of reaching this minimum or maximum is dependent on the formula, and thus dependent on the parameters used in it. It is clear that for very large positive and negative values of the relative crest height the wave transmission coefficient will decrease respectively increase further to 0 respectively 1.

9. Caution must be taken with very small and vary large values of the wave steepness and relative wave height. Very small values of the wave steepness ($s_{op} < 0.005$) lead to very long swell, which has a different behaviour towards wave transmission then short wind waves. The upper limit of the wave steepness is physically estimated at about $s_{op} = 0.06$. At higher values of the wave steepness the waves will break. When very small values of the relative wave height are used ($H_{mo}/D_{n50} < 1$), the influence of the permeability of the crest, which is not present in the formula, becomes important. Too large values of the relative wave height ($H_{mo}/D_{n50} > 6$) also lead to less accurate results of the formula. Moreover it can cause instability of the armour units. In this report this matter is treated only qualitatively, further analysis is needed to quantify it. The range of application, given by equations 4.29 and 4.30, is a result of the foregoing. The formula can be used outside of this range, but the reliability will decrease as can be seen by the standard deviations shown in table 13.

10. The parameters, not used in the formulas, such as bulk number, slope angle and permeability factor, did not have much influence. Their influence will probably be present at large positive values of the relative crest height. Since this report concentrates on structures with crest levels around the still water level, these breakwater properties are "hidden" under water. However, in various parts of the analysis the influence of permeability showed up. Also a short look was taken at the influence on wave transmission of wave run-up, in which the slope angle plays a part. A certain trend was observed, but not further analyzed. Therefor further analysis are needed to determine whether these breakwater properties can be brought in account in a proper way.

11. Wave transmission at reef type breakwaters is nearby described in the same way as was done in item 5 for conventional breakwaters:

$$K_t = a * R_c/D_{n50} + b \qquad \text{(eq. 4.1)}$$

In which:

$a = f(H_{mo}/D_{n50})$

$b = f(s_{op}, H_{mo}/D_{n50})$

An overall view of the formulas for reef type structures is presented in figure 40.

For data, at which the crest height, during the test, lowered less then 10 percent of the initial height, a standard deviation of 0.031 is reached in the range of application. Without the range of application the standard deviation amounts to 0.067.

With the use of the range of application a standard deviation of 0.054 is reached for all data on reef type structures, without it the standard deviation amounts to 0.092.

12. At a reef type breakwater the values of H_{mo}/D_{n50} and s_{op} will not have influence on wave transmission only, but on the damage of the structure as well. This damage results,, among other things, in a lowering of the crest height. It is obvious that a lowering of the crest height results in more transmission over the structure. The level of damage is not taken into account in the formulas proposed in this report. It can be expected that wave transmission at reef type breakwaters is better described when the dynamic stability of the structure is taken into account.

13. A general formula for wave transmission at (stable) homogeneous breakwaters could not be derived because of the inaccessibility of the available data on these types of structure.

2. REVIEW ON WAVE TRANSMISSION

2.1 Wave transmission coefficient

Considering a wave, with an incident wave height H_i, approaching a structure, its energy can be determined at 100 percent. At the structure a part of the incident energy is reflected as the reflected wave height H_r. Some of the remaining energy will be transmitted by overtopping and/or transmission through the structure causing a transmitted wave height H_t at the lee side. That proportion of the incident energy that is neither reflected nor transmitted must necessarily be dissipated in the various processes at the structure. In this way the balance of energy is correct. This report will only deal with the phenomenon of wave transmission.

The ratio between incident (H_i) and transmitted (H_t) wave height is given by the wave transmission coefficient K_t:

$$K_t = H_t / H_i \qquad \text{(eq. 2.1)}$$

The incident wave height is measured at the location of the structure, eliminating the effects of reflection. The transmitted wave height is measured behind the structure.

The wave transmission coefficient K_t can be divided in a part of the transmission caused by overtopping and a part caused by transmission through the breakwater. The main part of K_t is estimated by overtopping. Transmission through the breakwater is of importance only when the crest is well above the water level.

2.2 Governing parameters

K_t is determined by wave and breakwater properties. The most important of these properties are shown in figure 1 and given below.

Wave:	significant height	: H_{mo} or H_s
	peak period	: T_p
	water depth at structure	: h
Breakwater:	crest height	: h_c
	crest width	: B_c
	slope angle	: $\cot\alpha$
	materials	: D_{n50}, permeability, porosity

Other governing parameters can be derived or calculated from those mentioned above:

wave steepness : $s_{op} = 2\pi H_{mo} / gT_{p2}$ (eq. 2.2)

crest freeboard : $R_c = h_c - h$ (eq. 2.3)

cross sectional area: $A_t = h_c{}^2\cot\alpha + h_c B_c$ (eq. 2.4)

bulk number : $B_n = A_t / D_{n50}{}^2$ (eq. 2.5)

A very important parameter is the relative crest height: crest freeboard divided by wave height (R_c/H_{mo}). This denotes how much a breakwater is underneath or above the still water level in proportion to the wave height. The usual way of looking at wave transmission is done by creating a figure of K_t versus R_c/H_{mo}, see figures 2 and 3 which are taken from Van der Meer (1990). All data gathered in that report are shown together with the proposed formula of Van der Meer (1990) (equations 3.5 to 3.7) in figure 2 and suggested curves of Ahrens (1987) and Hearn (1987) (equations 3.2 to 3.4) and Powell and Allsop (1985) in figure 3.

Confusing is the fact that also a relative crest height defined as crest freeboard divided by water depth (R_c/h) is used sometimes. In this chapter relative crest height stands for crest freeboard divided by wave height (R_c/H_{mo}).

Before looking at the influence of above mentioned parameters on wave transmission, the structure types used in various tests will be discussed briefly.

2.3 Structure types

Low-crested and submerged breakwaters

A distinction in structure types can be made by looking at the height of the crest relative to the water level. This report will mainly deal with structures which have their crest height around the water level. Many different names are used to describe these types of breakwaters. In this report only the names submerged and low-crested will be used. A submerged breakwater has a negative crest freeboard and is overtopped by all waves. A low-crested breakwater still has a positive crest freeboard. This freeboard, however is that small that waves running up the slope cause frequent overtopping.

These types are special in a way that they allow a considerable amount of overtopping by incident waves. By allowing the structure to be overtopped, the crest height, and hence the volume of material needed, can be reduced. This volume is a quadratic function of the structure height h_c.

It is evident that choosing a low crest level will lead to a considerable wave transmission, and thus to a wave height at the lee side of the breakwater that can not be neglected. The use of low-crested and submerged breakwaters is therefor restricted to situations where the level of wave activity is acceptable in comparison to the functional use. This implies the importance of a reliable method for prediction of transmitted wave height over these kind of breakwaters.

Rubble mound, homogeneous and reef type breakwaters

Another distinction can be made by looking at the construction of breakwaters. The conventional rubble mound breakwater consists of a core, filter layer(s) and armour layer. The structures tested on wave transmission mostly did not have a filter layer, but consisted only of a core and armour layer.

Another structure type tested was the homogeneous breakwater, best described as a homogeneous mound of stones. A reef type breakwater is homogeneous as well, but special in a way that it is allowed to deform under wave attack. This is called dynamic stability. More extensive information about the tested structures will be given in chapter 3.

2.4 Influence of parameters

Hereunder a brief review is given of information from various reports about wave transmission. This information concerns the parameters governing wave transmission at permeable structures. Their influence and importance as well is described in section 2.4.3.

First the phenomena wave run-up and overtopping, which are important for wave transmission, will be defined here. Wave run-up is the height on the slope to which the top of the wave can reach, running up the slope. Run-up can occur at structures with positive crest freeboards only. Overtopping is the phenomenon of masses of water passing over the crest of a breakwater. Run-up and overtopping are related in a way that when the crest freeboard is larger then the run-up, waves are not able to overtop the structure; there will be no overtopping. As the run-up exceeds the crest freeboard, overtopping will occur. From this moment on increasing wave run-up will lead to increased overtopping. As mentioned before, a submerged breakwater is overtopped by all waves. A low-crested breakwater is overtopped by those waves only, which have a run-up exceeding the crest freeboard. A structure with a small crest freeboard, which is attacked by waves that small that they are not able to cause overtopping, is not officially called a low-crested breakwater. This means that the title "low-crested" is dependent on the wave height. Due to reasons of simplicity in namegiving, in this report all structures with small crest freeboards are called low-crested.

This report concentrates on permeable structures, but first a short view is taken at impermeable structures to get a better insight into the mechanics wave transmission.

2.4.1 Impermeable breakwaters

When a breakwater is totally impermeable, wave run up determines the degree of overtopping and thus the wave transmission. The transmission through the structure is of course zero. As long as there is no overtopping there will be no wave transmission. An increasing wave height or decreasing crest freeboard leads to a larger run up and hence, when overtopping occurs, to an increasing wave transmission and a larger K_t. A smaller crest width also gives a larger K_t. Formulas are available to calculate K_t, via run up coefficients, for impermeable structures (Seelig 1980, equations 10 to 12). These formulas can be used for impermeable smooth and rough slopes. According to the same report, Seelig (1980), this method yields good results.

Submerged breakwaters are always overtopped, but here also wave height plays a part. The larger a wave, the more it will be affected by the structure. So in this case a larger wave height gives a smaller transmission coefficient.

2.4.2 Permeable breakwaters

Wave transmission at a permeable breakwater, which is not overtopped, will occur by transmission through the structure only. The other extreme is a submerged breakwater with nearly no transmission through the structure and thus K_t determined by overtopping only. Between a transmission coefficient totally determined by overtopping or on the other hand by transmission through the structure, there is a large area with both phenomena involved. Following section will give a brief review of this area where a number of parameters is involved. The main parameters and their influence on wave transmission will be discussed.

2.4.3 Governing parameters

Wave Height (H_{mo})

At a low-crested breakwater, which is not overtopped, the wave transmission coefficient K_t will decrease with increasing wave height H_{mo} because there will be more dissipation inside the breakwater. However this can depend on the ratio of H_{mo} and the nominal diameter (D_{n50}). At a low-crested breakwater, which is overtopped, K_t will increase with increasing H_{mo} due to increasing masses of water passing over the breakwater. Figure 4 shows this in a qualitative way; the parameters are not dimensionless.

When the structure is submerged, a larger wave will be more affected than a smaller wave. Thus now K_t will decrease with increasing H_{mo}, see figure 4. There must be a point where the structure is that far submerged that most of the passing waves will not note the presence of it anymore. At this point K_t will increase with increasing H_{mo} again.

Wave peak period (T_p)

At a low-crested breakwater the wave transmission coefficient K_t increases with increasing wave period T_p, due to longer wave length which increases the run up. Also a longer wave will propagate better through the structure. The stone size (D_{n50}) relative to the wave length probably has influence.

With submerged structures it is more difficult. Van der Meer (1990) found that longer waves cause a larger K_t. But Powell and Allsop (1985) noted the opposite. From their report, chapter 3.3: "increasing T_p leads to decreasing K_t. Short waves pass unhindered over the structure. Longer waves, which propagate

deeper in the water, will be partially attenuated". Maybe
was a special ratio between wave length and stone size. Any
further on a closer look must be taken at these data.

In the same report Powell and Allsop came up with a new parameter to substitute the old relative crest height R_c/H_{mo}. They introduced R^*_p:

$$R^*_p = R_c/H_{mo} * (s_p/2\pi)^{1/2} \qquad \text{(eq. 2.5)}$$

where s_p is the wave steepness corresponding to the peak period of the wave energy spectrum. In the low crested area the use of R^*_p in stead of R_c/H_{mo} in a figure versus K_t collects data with different wave period T_p together. In the submerged area the use of R^*_p leads to a larger spreading of data with different T_p. This is shown in figure 5 which is taken from Van der Meer (1990). In the same report it was concluded that the wave period has a significant influence on wave transmission, but is not brought into account in a proper way by using R^*_p.

Permeability

A higher permeability of a low-crested breakwater will lead to an increasing wave transmission coefficient K_t. A wave will propagate easier through the structure, but the run up will be smaller because the running up wave will sink into the structure. The height of the core relative to the wave height is important because the core is much less permeable than the armour layer.

At a submerged breakwater increasing permeability will increase K_t, but the influence is small due to domination of overtopping. There is no run up involved, so K_t will not be very sensitive to changes in permeability. Of course this sensitivity will be dependent, just as with low-crested structures, on the height of the core relative to the wave height.

Generally the problem is how to compare permeabilities of different structures. Mostly only the indication permeable/impermeable is given. Van der Meer (1988) introduced the notional permeability factor P which is roughly defined as:

P = 0.1 :impermeable breakwater
P = 0.4 :conventional breakwater, with core, filter- and armour layer
P = 0.5. :conventional breakwater, with large core and armour layer
P = 0.6 :homogeneous breakwater

These permeability factors have proved their use in breakwater stability formulas, perhaps they can be useful in this case too.

Porosity

Porosity and permeability are often hard to separate. The effect of porosity on wave transmission is nearby the same as of permeability. Still it is possible to have a porous armour layer on a structure which is impermeable.

Interesting is the fact that the sensitivity of a submerged breakwater to porosity is small, which implies that the wave transmission coefficient K_t should be equal for more and less porous structures in the submerged area. Figure 3.11 of Powell and Allsop (1985) does not show this tendency. Even at a relative crest height $R_c/D_{n50} = -3$, a difference in K_t of about 0.1 is observed for different porosities.

In general the sensitivity towards porosity increases as R_c/H_{mo} increases. This is because of the fact that with increasing R_c/H_{mo} wave run up gets more important, and hence the degree of overtopping is affected.

Crest width (B_c)

At a low-crested breakwater an increase of the crest width will cause more friction losses at the crest and a longer way for a wave to overtop the structure. Thus a decrease of the wave transmission coefficient. A wider crest can also be explained as a larger cross sectional area. Massie (red.) (1986) state that the crest width should be very large to have any influence. For submerged breakwaters the influence on K_t of the crest width is small.

Finally

Information about slopes (angle, materials and roughness) is presented in theories about wave run up. It is likely that the slope angle has most influence on overtopping because it is an influence on wave run up, but slope angle and roughness are only important for gentle slopes and wide crests. By then they have a significant influence on wave run up and hence on wave transmission.

The main parameters are crest freeboard (R_c), wave height (H_{mo}) and wave period (T_p). The author found some notes about the possible importance of the wave height and length compared to the stone diameter. This suggestion was not treated further. Therefor it can be important to first look at D_{n50} relative to the main parameters before drawing conclusions from test results.

In the foregoing no distinction is made between rubble mound, homogeneous and reef type breakwaters. The influence of the discussed parameters on wave transmission is nearby the same for all structure types. But the absence of a core in homogeneous breakwaters can, and probably will, change its sensitivity towards changes in parameters. A wave propagating through a homogeneous breakwater will not have to cross a core! Furthermore a reef type breakwater is allowed to deform under wave attack, which means it can be reshaped in a more or less different form than its initial form. It is obvious that these facts will change a structure's behaviour towards wave transmission.

3. DESCRIPTION OF LABORATORY TESTS

3.1 Description of previous tests

The analysis on wave transmission, which will be presented in chapter 4, is performed on data sets of various laboratories. These sets were gathered in Van der Meer (1990) and will be described briefly in this section. In that report a new formula for wave transmission was proposed which will be given at the description of the tests of Van der Meer (1988).
A new series of tests on wave transmission was performed at Delft Hydraulics during the time of the present study and will be treated extensively in section 3.2. An overall view of previous and present tests is given in table 1.

Seelig (1980)
Seelig (1980) measured wave transmission for a large number of structure cross sections, mostly with monochromatic waves, but also with random waves. These were one of the first tests in the CERC flume with random waves. Maybe this is the reason why very large values of the wave steepness were measured, up to 0.10, which is physically impossible. At a wave steepness of 0.05 to 0.06 the waves will break. These data must be handled with suspicion. The various cross sections tested with random waves have an armour layer consisting of stone with a large nominal diameter (D_{n50}) compared to other tests. The cross sections are given in figure 6, the test data in table 2.

Allsop (1983)
The structure tested by Allsop (1983) is the only one, of all structures considered in this report, to have a filter layer. All tests were performed with large positive values of the crest freeboard. The cross section is given in figure 8b, the data in table 3.

Powell and Allsop (1985)
The structures described by Powell and Allsop (1985) are

homogeneous breakwaters with a very small bulk number. The curves for wave transmission, suggested in their report, are given in figure 3. The report of Hydraulics Research about the actual tests is confidential, but Allsop was willing to send some data on wave transmission to van der Meer. During the latest investigations on these data it appeared that with given wave height and water depth, severe breaking should have taken place. Allsop was contacted about this matter, but until now no satisfying explanation is found. It can be concluded that the reliability of these data can be questioned. The cross sections are given in figure 7 and 8a, the data in table 4.

Daemrich und Kahle (1985)

The tests of Daemrich and Kahle are the only ones in which artificial armour units were used, namely tetrapods. An armour layer of tetrapods is more permeable than an armour layer of rock, which is used in all other tests described in this report. A large and a small crest width were tested. The cross sections are given in figure 8c, the data in table 5.

Ahrens (1987)

Ahrens (1987) tested reef type structures, both on stability and wave transmission. Hearn (1987) gives a more extensive analysis of Ahrens' data. In this report the parameter P was introduced:

$$P = H_{mo} A_t \; / \; L_p D_{50}{}^2 \qquad \text{(eq. 3.1)}$$

Hearn gives the following relationship for wave transmission:

$$K_t = 1.0 \; / \; (1.0 + P^{0.592}) \qquad \text{for } R_c/H_{mo} > 1 \qquad \text{(eq. 3.2)}$$

$$K_t = 1.0 \; / \; (1.845 + (P^{0.593} - 0.845) \; R_c/H_{mo}) \qquad \text{for } 0 < R_c/H_{mo} < 1 \qquad \text{(eq. 3.3)}$$

$$K_t = 0.9 - 0.358 \; e^{Rc}/H_{mo} \qquad \text{for } R_c/H_{mo} < 0 \qquad \text{(eq. 3.4)}$$

Formula 3.2 was taken from Ahrens (1987). These formulas are given in figure 3 for three values of the parameter P (5, 10 and 15). During a test on wave transmission it was possible that the crest height lowered, sometimes even considerably. This makes it difficult to choose the correct crest height for that test. The crest height used in this report is the height after the test (h_c). These are the only tests available on wave transmission with reef type breakwaters. Table 6a gives all data of Ahrens, table 6b only the ones at which the crest height, during the test, lowered less than ten percent of the initial height. Figure 9 shows an example of a reef type cross section and the basic data on the tests.

Van der Meer (1988)

A very extensive investigation on stability of rock slopes and gravel beaches was performed at Delft Hydraulics between 1983 and 1987. The basic background and all test data was described in van der Meer (1988). A part of the investigation was focussed on stability of low-crested breakwaters. Besides the stability the wave transmission was measured too. Three crest heights were tested, one with the crest well above the water level, one with the crest at the water level and one with the crest well below the water level. Hereby not the water level was changed, but three structures, with different structure heights, were used. The cross sections are given in figure 10, the data in table 7. Van der Meer (1990) proposed a formula for wave transmission in his report "data on wave transmission due to overtopping" which is given by:

$$K_t = 0.80 \qquad \text{for } -2.0 < R_c/H_{mo} < -1.13 \qquad \text{(eq. 3.5)}$$

$$K_t = 0.46 - 0.3\, R_c/H_{mo} \qquad \text{for } -1.13 < R_c/H_{mo} < 1.2 \qquad \text{(eq. 3.6)}$$

$$K_t = 0.10 \qquad \text{for } 1.2 < R_c/H_{mo} < 2.0 \qquad \text{(eq. 3.7)}$$

This formula is given in figure 2.

3.2 Description of present tests

3.2.1 Wave tank

The tests for this study were performed in the "Schelde" flume at Delft Hydraulics. The length of this flume is 50 m, the width 1.0 m and the depth 1.2 m. An overview of the test set-up is given in figure 11.

The wave generator is controlled by signals on magnetic tape which contain a present wave energy spectrum. A system developed by Delft Hydraulics was used to measure and compensate for reflected waves at the wave board. With this system standing waves and basin resonance were avoided. The incident significant wave height was measured with the structure in the flume, by means of two wave gauges placed about a quarter of a wave length apart. In this way the incident and reflected spectra were determined.

In the flume a very smooth foreshore slope of 1:350 was sited which continued to the end of the flume. Here a steeper slope of 1:9 was sited which lead, via an elevation, to a small tank. The 1:9 slope functioned as a wave damping construction which avoided reflections behind the structure. Four wave gauges were used, two at the beginning of the flume and two behind the structure.

3.2.2 Structure

Figure 11 shows a cross section of the structure used for all tests, except for the ones with numbers 41 to 46. The structure consisted of a core of angular stone with a nominal diameter D_{n50} of 0.028 m and an armour layer. The armour layer consisted of angular stone with a nominal diameter of 0.040 m. The differences in the structure used for the tests with numbers 41 to 46 were the nominal diameter of the armour layer, which amounted to 0.061 m in stead of 0.040 m in all other tests, and the crest height relative to the wave tank, which amounted to 0.433 m, instead of 0.463 m in all other tests.

3.2.3 Tests

Wave heights were measured by the spectral method and by time analysis, which means that the wave height (H_{mo}) is defined as: four times the root mean square of the first moment of the wave energy spectrum (4 $(mo)^{1/2}$). In deep water H_{mo} does not differ from the statistical defined wave height, H_s (average of the highest 1/3 of the waves).

The tests concentrated on three parameters: relative crest height (R_c/D_{n50}), relative wave height (H_{mo}/D_{n50}) and fictitious wave steepness (s_{op}). R_c and H_{mo} were separated and made dimensionless by dividing them by the nominal diameter D_{n50}. The reason for this will be explained in chapter 4. To get a good insight in the influence of all parameters especially, only one parameter was changed at the time. To achieve so the tests were performed with two fixed values of the wave steepness, 0.02 and 0.04. For each wave steepness a range of crest freeboard heights was investigated, from a negative to a positive crest height. With a fixed crest freeboard the wave height was varied. In order to vary the crest freeboard heights, the water level was changed.

In total 53 tests were performed. 34 tests with a wave steepness of 0.02, a nominal diameter of 0.040 m and 6 values of the crest freeboard. Another 6 with the same wave steepness, but a nominal diameter of 0.061 m and 3 values of the crest freeboard. 10 tests were performed with a wave steepness of 0.04, a nominal diameter of 0.040 m and 5 values of the crest freeboard.

Finally the 1:9 slope and the small tank at the end of the flume was removed and 3 more tests (nr. 25 to 27) were performed with a fixed water level behind the structure. To achieve so, water, which passed the structure but could not flow back and hence caused a set up behind the structure, was pumped out at the end of the flume and brought in again at the beginning of the flume. This was done to investigate the influence of set up behind the structure during the earlier tests. During the last 3 tests (nr. 25 to 27) a wave damping construction was sited at the end of the flume to avoid reflections behind the structure.

3.2.4 Results

The data on these tests are given in table 8. The incident wave height was determined as the mean value of wave gauges 1 and 2, corrected for reflection. The transmitted wave height was the mean value of wave gauges 3 and 4.

At the end of all tests, data of the two gauges behind the structure (gauges 3 and 4) were filtered to remove long wave components which could be present behind the structure. These long wave components confuse the issue because their existence is not a wave transmission phenomenon, but pure a result of testing circumstances. They occurred mainly when the crest of the structure was above the water level. They can be traced by the fact that the wave heights measured by wave gauges 3 and 4 relative to each other differ very much. Figure 12a shows the measured wave height of gauge 3 (H_{mo} 3) versus the measured wave height of gauge 4 (H_{mo} 4), before and after filtering. All data of the present research are shown in this figure. It shows that the spreading around the line of equal H_{mo} 3 and H_{mo} 4 is much smaller after filtering then it was before. The results of filtering the test data are therefore remarkable, maybe not quantitative, but surely qualitative.

The results of the three tests without set up behind the structure showed that the set up in the earlier tests have no, or negligible, influence on the results. See figure 12b.

The incident wave heights were measured at the beginning of the flume, so the influence of the foreshore slope is not taken into account. At the other tests, described in this report, the wave height was measured in front of the structure. But because the foreshore slope is very smooth this probably makes no difference. Checking with the computer wave program ENDEC confirms this statement. For all water depths the largest wave heights used at that depth are run with ENDEC. The proportional decrease of these wave heights versus the relative water depth (h/H_{mo}) is given in figure 12c. Only with large waves in shallow water a significant decrease of the wave height occurs. For $h/H_{mo} > 3$ this decrease is less then 10 percent. The tests with smaller relative water depths are:

test number:	95:	h/H_{mo}: 2.6;	decrease H_{mo}:	23 %
	94:	: 2.9;	:	13 %
	20:	: 2.8;	:	16 %
	12:	: 2.9;	:	13 %

As can be seen in table 8 the course of the wave transmission coefficient with increasing wave height does not show abnormalities for these data. Therefor all data of the present tests will be considered in the analysis of chapter 4.

In the following tables and figures the present data are given by the name of "Daemen".

4. ANALYSIS OF DATA

4.1 Introduction

The conventional way of describing wave transmission consists of a figure which shows the wave transmission coefficient K_t versus the relative crest height R_c/H_{mo}, see figure 2. This is not strange since R_c and H_{mo} are the most important parameters determining K_t. But it is not proved that the use of the division R_c/H_{mo} gives the same result with on one hand constant R_c and variable H_{mo} and on the other hand variable R_c and constant H_{mo}. Moreover, when R_c becomes zero, all influence of the wave height H_{mo} is lost, which leads to a large spreading in the figure at $R_c = 0$. For these reasons in the following analysis R_c and H_{mo} will be separated.

Another disadvantage of using the figure of K_t versus R_c/H_{mo} is the fact that much of the (significant) information, such as wave period and remaining breakwater properties, is not taken into account. As stated in section 2.4.3, the wave period T_p has a significant influence on wave transmission. Therefor T_p will be considered in the analysis as well.

At the end of section 2.4.3 it was stated that the main parameters are R_c, H_{mo} and T_p. These parameters are called primary parameters. Because the influence of the remaining breakwater properties is less clear, these are assumed to be secondary parameters.

Following will be an attempt to derive a formula for wave transmission from the test data described in chapter 3. Hereby it is tried to consider all parameters especially. In this way a formula can be found in which the influence of each single parameter clearly appears.

4.2 Selected parameters

By separating the crest height R_c and the wave height H_{mo}, the need is caused for a good parameter to make them dimensionless. This parameter is the nominal diameter D_{n50}. D_{n50} is a breakwater property which is constant by structure. By using R_c/D_{n50} the structure type, low-crested or submerged, is well described. The use of R_c/D_{n50} and H_{mo}/D_{n50} gives a good description of the wave height compared to the crest height. Moreover, as mentioned before, wave height relative to the nominal diameter can be an important parameter for wave transmission. Compared to stability H_s/(delta D_{n50}) is a very important parameter. The relative crest height R_c/H_{mo} is now substituted by a relative crest height defined as R_c/D_{n50} and a relative wave height H_{mo}/D_{n50}.

Finally D_{n50} is a good measuring-staff to describe breakwater properties as crest width B_c, bulk number B_n and of course crest freeboard R_c. One can imagine for example a crest width of so many times a nominal diameter.

The definition of the relative crest height R_c/D_{n50}, or the crest freeboard R_c, should be looked at closer first. It is assumed that in all tests a crest freeboard of zero is reached when all stones of the crest are under water. A few tops of stones extending above the water level is allowed. This definition is very critical while a somewhat different definition will result in a shift of all data points in the figure of K_t versus R_c/D_{n50}. Especially around $R_c/D_{n50} = 0$, where the largest in/decreasing of the wave transmission coefficient takes place, this is important. It can not be retraced if the above mentioned definition agrees with the one used for the test series which were not performed at Delft Hydraulics. It is possible that a definition for R_c is used which lies 0.5 D_{n50} below the value of R_c determined with the above assumed definition. This will cause a shift in the figure of R_c/D_{n50} versus K_t of 0.5 D_{n50} to the left. It must still be analyzed whether definitions of R_c, deviating from the assumed one, have been used in other tests.

The use of D_{n50} excludes the investigation on impermeable structures because it is impossible to determine a nominal diameter. This disadvantage is relative since only a small number of test data are on impermeable structures. Furthermore already formulas are available for wave transmission at impermeable structures. See section 2.4.1.

By relating the wave and crest height to D_{n50}, the influence of the nominal diameter is brought in obviously. However, when a structure is that far submerged that waves will hardly note the presence of it, the nominal diameter will not be a significant parameter anymore. This case will be handled further on in the analysis.

Now R_c and H_{mo} are described as R_c/D_{n50} and H_{mo}/D_{n50}, only the last of primary parameters, T_p, is left. The influence of the wave period T_p can be described by the fictitious wave steepness s_{op}:

$$s_{op} = 2\pi H_{mo} / gT_p^2 \qquad \text{(eq. 2.2)}$$

The remaining (secondary) parameters are all breakwater properties. By using D_{n50} a relative crest width is defined as B_c/D_{n50}. The other parameters are bulk number (eq. 2.4), slope angle and the permeability factor according to Van der Meer (1988).

Now all parameters are defined and they are repeated here.

Primary parameters:	relative crest height :	R_c/D_{n50}
	relative wave height :	H_{mo}/D_{n50}
	fictitious wave steepness:	s_{op}

Secondary parameters :	relative crest width :	B_c/D_{n50}
	bulk number :	B_n
	permeability coefficient:	P
	slope angle :	$\cot\alpha$

4.3 Derivation of formula (basis)

4.3.1 Conventional breakwaters

To start with, the primary parameters will be used to derive a formula which describes wave transmission. Figures are made of the transmission coefficient K_t versus the relative crest height R_c/D_{n50} with data from the available tests. This can be done by grouping the data by constant relative wave height H_{mo}/D_{n50}, or by constant wave steepness s_{op}.

Grouping by wave steepness leads to the clear picture of a higher wave steepness resulting in a smaller transmission coefficient. This can be seen in figure 13. What is more is the fact that this is true for the whole involved area of relative crest heights, negative and positive as well. This is in accordance with theory which states that a larger wave period T_p, with constant wave height, results in a larger transmission coefficient. Since $s_{op} = H_{mo}2\pi / gT_p^2$ (eq. 2.2), a smaller s_{op} leads to a larger transmission coefficient.

Grouping the data by relative wave height leads to some trends to be seen also, see figure 14. But these trends are not as convincing and/or consistent as was seen in figure 13.

By assuming that the influence of the wave steepness is present at the whole area of R_c/D_{n50}, it is possible to take a look at groups of different relative wave height within one single group of constant wave steepness. Doing so a clear trend can be observed for the relative wave height H_{mo}/D_{n50} too. See for example figure 16 and following (further on these figures will be discussed more thorough). For $R_c/D_{n50} < -1$ a larger H_{mo}/D_{n50} gives a larger wave transmission coefficient. For $R_c/D_{n50} > -1$ the opposite occurs: a larger H_{mo}/D_{n50} gives a smaller transmission coefficient.

The behaviour of the wave transmission coefficient towards relative wave height will be explained here. At a low-crested breakwater, where R_c/D_{n50} is positive, the transmission coefficient is primarily determined by overtopping, and thus by wave run up. In this area of R_c/D_{n50} a larger relative wave height gives a higher run up, thus more overtopping and hence a larger transmission coefficient. At a submerged breakwater, where R_c/D_{n50} is negative, higher waves will be more affected by the structure while small waves pass unhindered. In this case a larger relative wave height results in a smaller transmission coefficient.

This can also explain why the use of R^*_p (see section 2.4.2 and figure 5) to describe wave transmission leads to good results in the area of $R_c/H_{mo} > 0$, while it fails for $R_c/H_{mo} < 0$. R^*_p is defined as: $R_c \backslash H_{mo} * (s_{op}/2\pi)^{1/2}$ (eq. 2.5). This term contains the wave steepness s_{op} divided by the wave height H_{mo}: s_{op}/H_{mo}. Now the effect of a change in s_{op} or H_{mo} on the wave transmission coefficient K_t and the division s_{op}/H_{mo} is looked at for a positive and a negative crest height. When $R_c > 0$, with constant H_{mo}, a larger s_{op} leads to a smaller K_t and a larger s_{op}/H_{mo}. With the same (positive) R_c and constant s_{op}, a smaller H_{mo} leads to a smaller K_t and a larger s_{op}/H_{mo}. This is in accordance with each other, so wave transmission is described properly by s_{op}/H_{mo} for positive R_c. When $R_c < 0$, with constant H_{mo}, a larger s_{op} still leads to a smaller K_t and a larger

s_{op}/H_{mo}. With the same (negative) R_c and constant s_{op}, a smaller H_{mo} leads to a larger K_t (!) and a larger s_{op}/H_{mo}. This is not in accordance, so s_{op}/H_{mo} is not the right term to describe wave transmission for negative R_c. When $R_c < 0$, a R^*_p should be used which contains something like $s_{op} * H_{mo}$. In the following R^*_p will not be further looked at.

Figure 15 shows the wave transmission coefficient K_t versus relative crest height R_c/D_{n50} for all data. Going from high positive values to high negative values of R_c/D_{n50}, it appears that the transmission coefficient first stays low, then increases in the area of R_c/D_{n50} = +2 to -2, and finally stays high. Theoretically the increase of the wave transmission coefficient will be a curve with a smooth course from its low to its high value. To come to a simple description of wave transmission, the curve will be assumed to be a straight line. This means that a linear relation between wave transmission coefficient and relative crest height is assumed in the area of the relative crest height of about -2 to +2. The wave transmission coefficient can now be described as:

$$K_t = a * R_c/D_{n50} + b \qquad \text{(eq. 4.1)}$$

In this equation "a" is the coefficient: it determines the slope of the line. "b" is the constant: it is the value of K_t at $R_c/D_{n50} = 0$. The areas of relative crest height in which this relation is not valid, will be looked at closer in section 4.5.

Further assumptions must be made to determine the coefficient "a" and the constant "b". "a" and "b" can be functions of one or more parameters. As stated before a change in the wave steepness s_{op} leads to a constant increase/decrease of the wave transmission coefficient K_t. In other words: lines of constant, but different, s_{op} are lying parallel to each other, see figure

13. This implies that the constant "b" is a function of the wave steepness:

$$b = f(s_{op}) \qquad \text{(eq. 4.2)}$$

In contrast with the wave steepness, a change in the relative wave height H_{mo}/D_{n50} does not result in a constant change in the wave transmission coefficient K_t. This is dependent on the value of the relative crest height R_c/D_{n50}, as explained at the beginning of this chapter. Thus lines of constant, but different, relative wave height are lying rotated to each other, they all have a different slope angle, see figures 16 to 23. This means that the coefficient "a" is a function of the relative wave height:

$$a = f(H_{mo}/D_{n50}) \qquad \text{(eq. 4.3)}$$

To investigate the relationship between "a" and H_{mo}/D_{n50}, and later on the one between "b" and s_{op}, for each series of tests lines are fit through data points with constant s_{op} and H_{mo}/D_{n50}. To do so, for each constant s_{op} at least 2 to 3 data points with constant H_{mo}/D_{n50} are needed to fit a straight line through it. In a figure where various reliable lines have been drawn, and thus a clear pattern is generated, other lines have been "constructed" which correspond to the pattern, with less than 2 or 3 data points. The results are given in figure 16 to 23.

A few remarkable facts in these figures are mentioned here, but will be explained later. In figure 19 and 20 (Daemrich and Kahle (1985)) the pattern of crossing lines is not present. The lines in figure 17b and 18 (Ahrens (1987)) seem to be moved, compared to the position of the lines in other figures, over a distance of about $2*R_c/D_{n50}$ to the positive side of the relative crest height.

Note that not all data have been used. All data of impermeable structures were not used because it is not possible to define a nominal stone diameter D_{n50}. These data were: Seelig BW1 (1980) and Daemrich and Kahle (1985), their tests on a smooth impermeable structure. From the data of Seelig (1980) only the ones of BW4 are used, the other data had values of R_c/D_{n50}, H_{mo}/D_{n50} or s_{op} which were not of interest for this investigation. Very large negative relative crest heights and very small relative wave heights were used. Furthermore the very large values of s_{op}, which are questionable (see section 3.1), make these parts of the data of Seelig (1980) unsuitable to use in the analysis. The same yields for Allsop (1983) who investigated only high positive values of R_c/D_{n50}. From the data of Ahrens (1987) only those ones are used, at which the crest height lowered, during the test, less then 10 percent of the initial crest height (see table 6b).

In total 58 lines were drawn which describe equation 4.1 with constant wave steepness and relative wave height. The range of s_{op} is 0.01 to 0.04, that of H_{mo}/D_{n50} 1.3 to 5. In more detail:

s_{op} = 0.01: 12 lines with 1.25 < H_{mo}/D_{n50} < 5.0
s_{op} = 0.02: 19 lines with 1.25 < H_{mo}/D_{n50} < 4.6
s_{op} = 0.025: 7 lines with 1.50 < H_{mo}/D_{n50} < 2.4
s_{op} = 0.03: 17 lines with 1.50 < H_{mo}/D_{n50} < 5.0
s_{op} = 0.04: 3 lines with 1.3 0< H_{mo}/D_{n50} < 3.0

Now 58 values of the coefficient "a" and the constant "b" are available. These are shown in table 9 as "a-measured" (a_m) and "b-measured 1" (b_m1).

Note that until now no distinction is made in breakwater types and/or properties. By looking at all 58 lines, drawn for various breakwaters, all structures are brought together. This means that the secondary parameters from now on will have influence too. These secondary parameters were: relative crest width, bulk number, permeability factor and slope angle. It must still be analyzed whether their influence becomes significant.

As the coefficient "a" was a function of the relative wave height (eq. 4.3), a figure is made of "a_m" versus H_{mo}/D_{n50}, see figure 24a. A clear trend can be observed of a larger H_{mo}/D_{n50} causing a smaller coefficient "a". To determine the relationship between "a_m" and H_{mo}/D_{n50} the data of Van der Meer (1988) and the present data are primary used, see figure 24b. The reason for this is the fact that the circumstances of the test set-up and the definitions of the parameters used, are known, or can be retraced, by the author. This is important, for example, towards the definition of R_c. Both primary used data sets are from tests performed at Delft Hydraulics. In figure 24b a linear relation is drawn:

$$a = 0.031\ H_{mo}/D_{n50} - 0.24 \qquad \text{(eq. 4.4)}$$

For $H_{mo}/D_{n50} < 1.5$ this line is not accurate anymore.

Data sets which do fit in the line of equation 4.4 are also given in figure 24b. These are Seelig BW4 (1980), a conventional breakwater with a small crest width, and Ahrens (1987), reef type breakwaters. The fact that the reef type data do fit in is remarkable because they concern a different structure type.

The 2 data sets which do not fit in are Powell and Allsop (1985) and Daemrich and Kahle (1985). The data of Powell and Allsop (1985) consider many data with $H_{mo}/D_{n50} < 1.5$ for which the line of equation 4.4 is not accurate. Also the different structure type, homogeneous with a very small bulk number, and the inaccessibility of these data (uncertainty about H_s at the structure) are debt to not fitting in. The data of Daemrich and Kahle are left away because of the small values of H_{mo}/D_{n50} and the different structure properties (the use of tetrapods and a very small and very large crest width). The absence of these 2 data sets will be further discussed at the end of this section.

Looking at the definition of "a", it can be seen that a larger relative wave height causes a less steep slope of the line of equation 4.1. This is in accordance with the earlier explained phenomenon of a larger H_{mo}/D_{n50} which causes more overtopping at a positive relative crest height, but is more affected by the structure at a negative relative crest height.

By putting equation 4.4 in to equation 4.1, so far the formula for wave transmission looks like:

$$K_t = (0.031\ H_{mo}/D_{n50} - 0.24)\ R_c/D_{n50} + b \qquad \text{(eq. 4.5)}$$

To determine the constant "b", again all lines of figure 16 to 23 are drawn, but this time with imposed values of the coefficient "a". These values are calculated from equation 4.4 for each line and shown in table 9 as "a-formula" (a_f). Now again all values of "b" are measured and shown in table 9 as "b-measured 2" (b_m2). This second session of drawing lines is not shown in this report. As can be seen in table 9 the values of "b_m2", measured with imposed coefficient "a_f", do not, in general, differ too much from the values of "b_m1". As the constant "b" was a function of the wave steepness (eq. 4.2), a figure is made of "b_m2" versus s_{op}, see figure 25a. This figure does not show much of a convincing trend. When the data are restricted to the conventional breakwaters used in figure 24b, a clear picture can be seen. Figure 25b only shows the data of Van der Meer (1988), Seelig BW4 (1980) and the present data. The data on reef type structures, Ahrens (1987), are also shown in this figure, but will be treated in section 4.3.2. Two things can be made up from figure 25b. The first is that a larger wave steepness gives a smaller value of "b". This relation is assumed to be a straight line:

$$b = d * s_{op} + c \qquad \text{(eq. 4.6)}$$

In this equation "d" is the coefficient which determines the slope of the line. The constant "c" is the value of "b" when $s_{op} = 0$.

The second thing is the fact that the spreading around the straight line can be explained by looking at the relative wave heights of the data. It appears that, with a fixed value of the wave steepness, a larger relative wave height gives a larger value of "b". This is not shown in the figure, but can be seen in table 9. This means that the constant "c" is a function of the relative wave height:

$$c = f(H_{mo}/D_{n50}) \qquad \text{(eq. 4.7)}$$

Now the influence of H_{mo}/D_{n50} can stay in the formula for situations in which $R_c/D_{n50} = 0$. "b" is namely the value of K_t when $R_c/D_{n50} = 0$, see equation 4.1. The coefficient "d" is determined by measuring in figure 25b:

$$d = -5.42 \qquad \text{(eq. 4.8)}$$

The constant "c", which is a function of the relative wave height (eq. 4.7), can be determined in the same way as the constant "b" is determined. With an imposed value of the coefficient "d", determined by equation 4.8, for each point in figure 25b the line of equation 4.6 is drawn. At $s_{op} = 0$ the constant "c" is measured. These values are given in table 10 and figure 26a. A straight line is fit through the data of figure 26a which is given by:

$$c = 0.0323\ H_{mo}/D_{n50} + 0.44 \qquad \text{(eq. 4.9)}$$

Putting equations 4.8 and 4.9 into equation 4.6 results in:

$$b = -5.42\ s_{op} + 0.0323\ H_{mo}/D_{n50} + 0.44 \qquad \text{(eq. 4.10)}$$

The results of the analysis so far are:

$$K_t = a * R_c/D_{n50} + b \qquad \text{(eq. 4.1)}$$

$$a = 0.031\ H_{mo}/D_{n50} - 0.24 \qquad \text{(eq. 4.4)}$$

$$b = -5.42\ s_{op} + 0.0323\ H_{mo}/D_{n50} + 0.44 \qquad \text{(eq. 4.10)}$$

An overall view of the formulas for conventional breakwaters is given in figure 39. In this figure the results of further analysis, presented in the following sections, are also given.

4.3.2 Reef type breakwaters

Figure 24b showed that the data for reef type breakwaters, Ahrens (1987), fit in the line (eq. 4.4) which describes the coefficient "a". Therefor equation 4.4 is also used for reef structures. To determine the constant "b", the same procedure is followed as was done in the previous section. All data can be found in tables 9 and 10, and in figures 25b and 26a. This leads to:

$$b_{reef} = -2.6\ s_{op} + c_{reef} \qquad \text{(eq. 4.12)}$$

Note that the influence of the wave steepness is about half as small as with conventional breakwaters.

$$c_{reef} = -0.05\ H_{mo}/D_{n50} + 0.85 \qquad \text{(eq. 4.13)}$$

What strikes is the fact that, with a fixed value of the wave steepness, a larger relative wave height gives a smaller value of the constant "b_{reef}". This in contrast with conventional breakwaters where, with a fixed value of the wave steepness, a larger relative wave height results in a larger value of the constant "b". The author can not give a satisfying explanation for this. Fact is however that the pattern of crossing lines in figure 17b to 18 was much less convincing to recognize than it could be done in the same figures of other data sets.

The results for reef type breakwaters now become:

$$K_t = a * R_c/D_{n50} + b \qquad \text{(eq. 4.1)}$$

$$a = 0.031\, H_{mo}/D_{n50} - 0.24 \qquad \text{(eq. 4.4)}$$

$$b = -2.6\, s_{op} - 0.05\, H_{mo}/D_{n50} + 0.85 \qquad \text{(eq. 4.14)}$$

An overall view of the formulas for reef type breakwaters is given in figure 40. In this figure the results of further analysis, presented in the following sections, are also given.

4.3.3 Discarded data sets

There are 2 data sets which are not used in this derivation, namely Powell and Allsop (1985) and Daemrich and Kahle (1985). To start with the data of Powell and Allsop (1985), using these data resulted in a very large spreading of data in all the figures. Moreover the inaccessibility established in advance due to uncertainty about the wave height at the structure, made this data set unsuitable to use for the derivation of a standard formula. Yet the formula of K_{treef} can predict wave transmission coefficients for this data set. To do so, the constant 0.85 in equation 4.14 must be replaced by 0.65. Apparently these homogeneous structures showed the same behaviour towards wave transmission as the reef type structures, which are homogeneous as well. The replacement of 0.85 by 0.65 can be explained by the difference in behaviour of reef type and statical stable breakwaters, a different definition of $R_c = 0$ and last, but not least, the earlier mentioned uncertainty about the wave height at the structure. The use of the formulas for reef type structures on the data of Powell and Allsop (1985) will be discussed further in section 4.7.

The use of the data of Daemrich and Kahle (1985) also lead to a large spreading in the figures, although the coefficients found for the formula and this data set matched reasonably well, see figure 24a. In a figure of the constant "c" versus H_{mo}/D_{n50} the whole group of data points is moved downward for the 1.0 m crest width, and upward for the 0.2 m crest width. This shift, which is structural, is shown in figure 26b. The data on this figure are given in table 10. Figure 26b indicates that the constant 0.44 in equation 4.11 must be replaced by 0.32 for the 1.0 m crest width and by 0.5 for the 0.2 m crest width. Doing so the formula of K_t for conventional breakwaters, used on this data set, leads to good results. These adaptions will be discussed more extensively in chapter 4.4.

4.4 further specification of formula

4.4.1 Derivation

The question now is whether the last part of the formula, the constant 0.44 for conventional (eq. 4.11) and 0.85 for reef type breakwaters (eq. 4.14), can be further specified with reasonable reliability. This should be done by relating the constant to one, or more, of the parameters not used so far. These remaining parameters are all breakwater properties:

relative crest width	$:B_c/D_{n50}$
bulk number	$:B_n$
permeability factor	$:P$
slope angle	$:\cot\alpha$

The formula for wave transmission was given by:

$$K_t = a * R_c/D_{n50} + b \qquad \text{(eq. 4.1)}$$

By replacing the constant 0.44 in equation 4.10 by a "constant" which is still to determine, equation 4.10 can be written as:

$$b = -5.42\ s_{op} + 0.0323\ H_{mo}/D_{n50} + \text{constant} \qquad \text{(eq. 4.15)}$$

The part of "b" which is a function of H_{mo}/D_{n50} and s_{op} is called "b-formula'" (b_f'). With given data it can be calculated. For conventional breakwaters:

$$b_f' = -5.42\ s_{op} + 0.0323\ H_{mo}/D_{n50} \qquad \text{(eq. 4.16)}$$

The value of "b" can be measured in the figures of K_t versus relative crest height, figures 16 to 23, as is done in section 4.3.1. This measured value of "b" was called "b-measured 2" (b_m2). Equation 4.15 can now be written as:

$$b_m2 = b_f' + \text{constant} \qquad \text{(eq. 4.17)}$$

And thus:

$$\text{constant} = b_m2 - b_f' \qquad \text{(eq. 4.18)}$$

All values are given in table 9. To investigate a possible relation between the constant and one of the remaining parameters, figures were made of the constant versus one parameter or a combination of parameters. Only the figure which resulted in a clear relation is shown here. It appeared that the use of the relative crest width (B_c/D_{n50}) gives the best relationship with the constant, see figure 27a. A power curve is fitted through the data points of conventional breakwaters:

$$\text{constant} = 0{,}51 - 0{,}0017\ (B_c/D_{n50})^{1{,}84} \qquad \text{(eq. 4.19)}$$

This leads to a slightly declining line up to a relative crest width of 10. For higher values of the relative crest width the line declines more rapidly. This is in accordance with the theory which states that crest width has little influence on wave transmission for "small and normal" values of the crest width. It explains why a power curve is used, and not a linear fit.

The power curve is fitted through data points of Van der Meer (1988), Daemrich and Kahle (1985), Seelig BW4 (1980) and the present tests. It must be realized that the tests of Daemrich and Kahle (1985) are performed with tetrapods in stead of rock, which is used in the other tests mentioned here. Tetrapods are more permeable than rock. This means that the tests of Daemrich and Kahle (1985) performed with an armour layer of rock, in stead of tetrapods, would result in somewhat smaller values of the wave transmission coefficient K_t. A smaller K_t leads to a smaller value of the constant, see equation 4.18. Looking at the power curve (eq. 4.19) this could imply that the curve of the line is more smooth for a relative crest width smaller than 10, and more steep for a relative crest width larger than 10. Whether this assumption is correct, can not be verified with the available test data.

The data of Ahrens do not fit in the curve at all. This is not surprising while a different formula is used for conventional and reef type breakwaters. While there are no data available for reef type breakwaters with larger crest width, a further specification of the constant in the formula for these structures is not possible. At least not in relation to the relative crest width. One could assume the same curve of the line as the one for conventional breakwaters. This, however, is a questionable assumption which will not be further discussed.

The formula for wave transmission at conventional breakwaters, with equation 4.19, becomes :

$$K_t = a * R_c/D_{n50} + b \qquad \text{(eq. 4.1)}$$

$$a = 0.031\ H_{mo}/D_{n50} - 0.24 \qquad \text{(eq. 4.4)}$$

$$b = -5.42\ s_{op} + 0.0323\ H_{mo}/D_{n50} + 0.51 - 0.0017\ (B_c/D_{n50})^{1.84} \qquad \text{(eq. 4.20)}$$

An overall view of the formulas is given in figure 39.

4.4.2 Discarded parameters

A closer look must be taken at the parameters which are not included in the formula. These are: slope angle, bulk number and permeability factor. All these parameters did not show a more or less clear relation with the constant. Therefor figures of these parameters versus the constant are considered redundant and are not shown in this report. It will be attempted to give an explanation for this.

First it must be mentioned that breakwater properties are local: for the influence of a property on wave transmission it makes a difference what part of the structure is attacked by the waves. This is dependent on the relative crest height. Since "b_m" is measured at a relative crest height of zero, a lot of the breakwater properties are "hidden" under the water level. When the water level is equal to the structure height, a wave will be affected mostly by the upper part, with a size of half the wave height, of the breakwater. At the conventional breakwaters tested this "involved" upper part of the structure was only 10 to 20 percent of the total structure height. Now it becomes more clear why the relative crest width does, and other breakwater properties do not have influence on the constant in the formula.

This will be worked out in more detail.

Slope angle

According to various sources in literature the slope angle has little or no influence on wave transmission. Only a very steep or very smooth slope will affect a structure's behaviour towards wave transmission. All slope angles of the structures tested were within a rather limited range of values, namely 1:1.5 to 1:3. Furthermore the influence of the slope angle on wave transmission is an influence on wave run up which can only take place with high, positive, values of the crest height. With a relative crest height of zero, wave run up, and hence slope angle, is not of much importance.

Bulk number

The bulk number is defined as:

$$B_n = A_t / D_{n50}^2 \qquad \text{(eq. 2.4)}$$

So this breakwater property is derived from the whole structure, while at a relative crest height of zero, the upper part of the structure is most involved. In this case the bulk number is not a significant breakwater property.

Permeability factor

The permeability factor defined by Van der Meer (1988) is, among other things, derived from the ratio of the nominal stone diameter of armour layer and core. But, as the upper part of the structure is most involved, the waves will be mostly affected by the permeability of the armour layer. The permeability factor is not a significant parameter in this case.

Finally

The fact that the three above mentioned parameters have no influence on wave transmission when the crest height is equal to the water level does not imply that they have no influence at all. At high, positive, crest heights there probably will be an influence. But it can be assumed that the influence of relative crest height R_c/D_{n50}, relative wave height H_{mo}/D_{n50} and wave steepness s_{op} is dominant in the case of low-crested and submerged breakwaters.

4.5 Minima and maxima

The derived formula stands for a straight line in the figure of the wave transmission coefficient K_t versus the relative crest height R_c/D_{n50}. It can produce values of K_t which are larger than 1 for large negative values of R_c/D_{n50} and which are smaller than 0 for large positive values of R_c/D_{n50}. As this is physically impossible, and hence not in accordance with the test data, the formula must be restricted. This can be done in a "horizontal" or in a "vertical" manner, or in both horizontal and vertical manner. Figure 27b gives an idea of these methods of restriction.

First the vertical method will be discussed. The vertical method means that at fixed values of $+R_c/D_{n50}$ and $-R_c/D_{n50}$ the minimum respectively the maximum of the wave transmission coefficient is reached. From the formula of Van der Meer (1990), see equations 3.5 to 3.7 and figure 2, conditions for vertical restriction can be derived, only a relative crest height is used which is defined as R_c/H_{mo}. The minimum is valid for $R_c/H_{mo} > 1.2$, the maximum for $R_c/H_{mo} < -1.1$. This can be rewritten as:

$$R_c/D_{n50} > +1.2\ H_{mo}/D_{n50} \qquad \text{:minimum } K_t = 0.10 \qquad \text{(eq. 4.21a)}$$
$$R_c/D_{n50} < -1.1\ H_{mo}/D_{n50} \qquad \text{:maximum } K_t = 0.80 \qquad \text{(eq. 4.21b)}$$

An unsurmountable problem of this method is the connection with the formula for wave transmission proposed in this report (eq. 4.1). There will be discontinuities at $R_c/D_{n50} = +1.2$ and $R_c/D_{n50} = -1.1$. Furthermore it does not guarantee a wave transmission coefficient between 0 and 1.

This guarantee can be provided by the horizontal method of restriction. With this method the wave transmission coefficient becomes the value of a fixed minimum/maximum when this value is under/overrated by the formula. At first sight this seems to be quite a rough method, but it offers the security of a wave transmission coefficient between the fixed minimum and maximum. Furthermore it contains, via the formula, all significant parameters. This means that a combination of the vertical and horizontal method becomes needless since the relative crest height is already taken in to account in the formula.

Now the values of the minimum and maximum must be determined. This can be done in two different manners. The one is a fixed value for all structures and wave circumstances, the other is a value as a function of one or more parameters. With a value for the minimum/maximum as a function of one or more parameters, one returns to the problems of a vertical restriction. So it is tried to find fixed values for all cases. To do so, in figures 16 to 23, where possible, minima and maxima are measured for constant wave steepness and relative wave height. These data are shown in table 11. Figure 28a shows the minimum/maximum wave transmission coefficients of table 11 versus relative wave height. It can be seen that the minima and maxima do not fluctuate to much with increasing relative wave height, although certain trends can be recognized. As the values of the minima and maxima were measured at different relative crest heights, however, it is difficult to draw conclusions out of these trends. Figure 28b shows the minimum/maximum wave transmission coefficients versus the wave steepness. The same, nearby, constant values of the minimum and maximum K_t are observed. Because of reasons of simplicity as well, the minimum and maximum are assumed to be fixed values. In figures 28a and 28b lines are drawn for the mean minimum and maximum K_t, for conventional breakwaters (solid line), as well for reef type breakwaters (dash line). The results:

Conventional breakwaters: minimum $K_t = 0.075$ (eq. 4.22a)

maximum $K_t = 0.75$ (eq. 4.22b)

Reef type breakwaters: minimum $K_t = 0.15$ (eq. 4.23a)

maximum $K_t = 0.60$ (eq. 4.23b)

Table 13 shows some statistics on the use of equation 4.22 and 4.23. It is seen that the standard deviations of the minimum and maximum in general are smaller than the ones of the formulas derived in this report. The standard deviations of the various formulas will be discussed in section 4.7. The restrictions on H_{mo}/D_{n50} and s_{op}, which are used in table 13, will be discussed in sections 4.6.1, respectively 4.6.2.

The fixed maximum of 0.75 (eq. 4.22b) for conventional breakwaters gives less good results then the minimum (eq. 4.22a). This probably is caused by the fact that the relative wave height and the wave steepness do have some influence on the value of the maximum. Figures 28a and 28b show a large spreading of data around the line of $K_t$max = 0.75. Figure 29a shows all data of conventional breakwaters with the minimum and maximum of equation 4.22. In this figure again it is seen that the spreading of data points around the minimum is smaller than the spreading around the maximum. For positive relative crest heights data are available up to $R_c/D_{n50} = +5$, for negative R_c/D_{n50} only down to $R_c/D_{n50} = -3$. This makes it hard to perform further analysis on the definition of the maximum. It can be assumed that the wave transmission coefficient will increase to its absolute maximum of 1.0 for even smaller negative values of R_c/D_{n50} then the ones used in the tests. The range of investigation, for conventional breakwaters, is given by:

$$-3 < R_c/D_{n50} < +5 \qquad \text{(eq. 4.24a)}$$

Figures 30a and 30b show all data, respectively the data at which the crest height, during the test, lowered less then 10 percent of the initial height, of Ahrens (1987). These data concern reef type breakwaters. The minimum and maximum of equation 4.23 are also shown. Figure 30a shows a large spreading around the maximum. However, for negative R_c/D_{n50}, the mean value of K_t is about 0.6. This spreading is caused by tests at which a severe lowering of the crest height occurred. In figure 30b this spreading is much smaller. The large spreading in both figures around the minimum is caused by the use of very small values of the wave steepness. This is seen as the standard deviation of the minimum decreases dramaticly when data with these small values of s_{op} are not taken into account. The exclusion of data because of very small values of s_{op} will be discussed in section 4.6.2. The range of investigation, for reef type breakwaters at which the crest height, during the test, lowered less then 10 percent of the initial height, is given by:

$$-2 < R_c/D_{n50} < 6 \qquad \text{(eq. 4.24b)}$$

The range of investigation, for all reef structures, is given by:

$$-6 < R_c/D_{n50} < 6 \qquad \text{(eq. 4.24c)}$$

The definition of the minimum as a fixed value excludes the influence on it of parameters. Thus the influence of the nominal diameter D_{n50} too. The objection mentioned in section 4.2 to the use of D_{n50} because it has no influence on wave transmission at well submerged structures, is thereby of less importance.

In the scope of determining the minimum, the method of Hamer and Hamer (1982) can be mentioned. They relate wave transmission to wave run up. As the minimum is reached for large positive values of R_c/D_{n50}, wave run up can be the main parameter because at these values of the relative crest height wave run up determines, against transmission through the structure, the transmission coefficient. Hamer and Hamer (1982) assume a linear relation between the wave transmission coefficient and the relative run-up. The relative run-up is defined as:

$$R_c/Ru = R_c / H_{mo}\ Xi \qquad \text{(eq. 4.25)}$$

In which Xi is the surf similarity parameter:

$$Xi = \tan\alpha / s_{op}^{0.5} \qquad \text{(eq. 4.26)}$$

Stam (1988) relates run-up to levels of run-up. For example the 2 percent or the significant run-up. The formulas of Stam (1988) in general are given by:

$$Ru/H_{mo} = a\ Xi^{b} \qquad \text{(eq.4.27)}$$

a and b are coefficients for various levels of run-up. These formulas are used on the method of Hamer and Hamer (1982) in an attempt to find a minimum which is related to the relative run-up. Figure 31a shows the use of the method of Hamer and Hamer (1982) for the 2 percent run-up level of Stam (1988) on the data of Van der Meer (1988) and the present data. For this run-up level the coefficients a and b in equation 4.27 are respectively 0.96 and 1.17. In figure 31a positive crest heights are used only. It is seen that not much of a linear relation is present. By fitting a curve through the data it is seen that the data points which do not fit in this curve represent wave transmission through the structure, instead of transmission by overtopping. In this way the use of the relative run-up provides some insight in the reaching of the minimum. The fact that the relation between relative run-up and transmission coefficient is more of an exponential kind, can be explained by looking at the definition of the relative run-up. Using equations 4.25 and 4.26 the relative run-up is given by:

$$R_c/Ru = R_c/H_{mo} \, (s_{op}{}^{0.5} \, / \, \tan\alpha). \qquad \text{(eq. 4.28)}$$

In section 2.4.3 a relative crest height R^*_p was given by:

$$R^*_p = R_c/H_{mo} \, (s_{op}{}^{0.5} \, / \, 2\pi) \qquad \text{(eq. 2.5)}$$

The use of R^*_p versus K_t on the data of Van der Meer (1988) is given in figure 5b. Equations 4.28 and 2.5 are almost identical. Therefor it is not surprising that the figures of relative run-up and R^*_p show the same tendency. It is concluded that relative run-up describes wave transmission in the same way as the relative crest height R^*_p. Further analysis is needed to determine whether the minimum transmission coefficient is better described by using the relative run-up or by a fixed value of the minimum. During the present study, this analysis is not performed.

4.6 Applicability of wave transmission formula

A first analysis of the results of the formulas, equations 4.1, 4.4 and 4.20 for conventional and 4.1, 4.4 and 4.14 for reef type breakwaters, showed that the reliability became less when using very small or very large values of the relative wave height and wave steepness. Therefor the results of the formulas are shown in two manners. In the first all values of H_{mo}/D_{n50} and s_{op} are allowed, in the second these values are restricted between certain boundaries. This range of application is determined in the next 2 sections. The case of a small relative wave height is treated more extensively because it often showed up in the analysis of section 4.3.

The actual results of the formulas are discussed in a statistical way in section 4.7 and shown in table 13 and figures

33 to 36. In these table and figures the results of using the range of application is also shown.

4.6.1 Relative wave height

A special group of data is formed by data with a relative wave height smaller then about 1.5. Figure 24a and 24b showed that this group of data did not fit in the line which was drawn for the data with a relative wave height larger then 1.5. It will be analyzed here whether the formula for wave transmission can be used for these data, or if adaptions are needed and can be made.

For a relative wave height between 1 and 2 enough data are available to draw lines of constant wave steepness and relative wave height. This has already been done in figures 16 to 23. It becomes more difficult for $H_{mo}/D_{n50} < 1$, where only single data points are available, see table 12 and figure 31b.

First the consequences of the use of the formula for K_t on data with small H_{mo}/D_{n50} will be discussed. Therefore the formula will be repeated here:

$$K_t = a * R_c/D_{n50} + b \qquad \text{(eq. 4.1)}$$

$$a = 0.031\ H_{mo}/D_{n50} - 0.24 \qquad \text{(eq. 4.4)}$$

$$b = -5.42\ s_{op} + 0.0323\ H_{mo}/D_{n50} + 0.51 - 0.0017\ (B_c/D_{n50})^{1.84} \qquad \text{(eq. 4.20)}$$

When H_{mo}/D_{n50} becomes smaller then 2, the coefficient "a" will have a value of about 0.18 to 0.24. This is slightly lower than in figure 24b in which these data have coefficients of 0.23 to 0.27. This means that the formula results in a slope which is a little too flatly.

While the relative crest width is constant per structure and

H_{mo}/D_{n50} is smaller then 2, the constant "b" will now only be a function of the wave steepness s_{op}. This means that large values of s_{op}, with small values of H_{mo}/D_{n50}, will lead to somewhat small values of "b".

Now the real test results will be looked at. Again it is noted that too less data are available to make reliable statements about the situation of $H_{mo}/D_{n50} < 1$. So it is chosen here to discuss the situation of $H_{mo}/D_{n50} < 1$ in a more qualitative way.

In figure 31b all data with $H_{mo}/D_{n50} < 1$, shown in table 12, are plotted. The lines of the formulas for wave transmission are also given. These lines have been drawn with the following data:

Daemrich and Kahle (1985), B_c = 0.2 m: upper 2 dash lines:

$s_{op} = 0.01$; $H_{mo}/D_{n50} = 0.40$

$s_{op} = 0.02$; $H_{mo}/D_{n50} = 0.80$

Present data: left solid line:

$s_{op} = 0.02$; $H_{mo}/D_{n50} = 0.80$

Daemrich and Kahle (1985), B_c = 1.0 m: lower 2 dash lines:

$s_{op} = 0.01$; $H_{mo}/D_{n50} = 0.40$

$s_{op} = 0.02$; $H_{mo}/D_{n50} = 0.80$

Ahrens (1987): right solid line:

$s_{op} = 0.001$; $H_{mo}/D_{n50} = 0.80$

From these lines it is seen that the data points are reasonably well described by the lines. Even the data of Ahrens (1987), which have an extreme small wave steepness of 0.001, are not to far removed from their line. The case of a very small wave steepness ($s_{op} < 0.01$) is treated in section 4.6.2.

Figure 31b also shows the difference in behaviour of structures with a more and less permeable armour layer. This concerns the data points plotted, not the lines of the formulas. The data of the present study, with an armour layer of stone, D_{n50} = 0.040 m, increase slightly with decreasing relative crest height. The data of Daemrich and Kahle (1985), with an armour layer of tetrapods, D_{n50} = 0.078 m, have already reached higher values of K_t at R_c/D_{n50} = 0. Apparently small waves have much trouble passing a relative impermeable armour layer at positive relative crest heights. It can be expected that, when the relative crest height decreases that waves can pass unhindered, the value of K_t will increase rapidly to its maximum. This results in a steep curve of the K_t versus R_c/D_{n50} line. A less steep curve is caused by the permeable tetrapods, used by Daemrich and Kahle (1985). With a positive relative crest height, small waves can pass more easy through the armour layer, and hence cause already larger values of K_t at positive values of R_c/D_{n50}. It must be mentioned here that around R_c = 0 the definition of R_c/D_{n50} is very important. The question is what definition is used by Daemrich and Kahle (1985) for tetrapods. A definition which differs from the one assumed in this report, will cause a small shift in the K_t versus R_c/D_{n50} figure. The foregoing described trend however, will keep its value.

Another interesting figure which can provide more insight in situations of H_{mo}/D_{n50} <1 is figure 32a. This figure shows the relative wave height versus the wave transmission coefficient for various classes of R_c/D_{n50} and a wave steepness of 0.02. Also the lines of the formula for K_t (eq. 4.1, 4.4 and 4.20) are drawn, according to the given fixed values of R_c/D_{n50} and as a function of H_{mo}/D_{n50}. The data are given per R_c/D_{n50}. From this figure it can be concluded that the general trend is described well. For a negative R_c/D_{n50} (-0.98), the measured K_t becomes larger than the predicted K_t in the area of H_{mo}/D_{n50} < 2. With a positive R_c/D_{n50} (0.24 and 0.73) the measured K_t becomes smaller than the predicted K_t when H_{mo}/D_{n50} < 2. When the relative crest height becomes an even larger positive value (1.22 and 2.34), with decreasing H_{mo}/D_{n50}, the data tend to go more quickly to their minimum. This minimum apparently is somewhat higher than the fixed minimum of equation 4.22a due to the use of a relative permeable core in the structure tested for the present study. From this figure it can be confirmed what was already seen in figure 24b: when the relative wave height becomes smaller then about 2, the coefficient "a" of the formula must be larger.

Figure 32b again shows transmission coefficient versus relative wave height, but now the data are given for a wave steepness of 0.02 and 0.04, with each 3 crest height classes. The lines of the formula are drawn in too. This figure confirms the above described trend.

The formula for wave transmission can be used for small relative wave heights. Figures 32a and 32b however showed a structural deviation between measured and calculated K_t for $H_{mo}/D_{n50} < 1$ to 2. So the reliability of the predicted wave transmission coefficients will be less than the ones calculated for $H_{mo}/D_{n50} > 1$ to 2. The lower boundary of the relative wave height is determined at $H_{mo}/D_{n50} = 1$.

Very few large values of the relative wave height were present in the data sets. For conventional breakwaters the largest was 6.7, for reef type 8.6. Up to $H_{mo}/D_{n50} = 6$ the formulas lead to good results, higher values give less reliable results. The problem of large wave heights is probably that the stability of the armour units is brought in danger. So the upper boundary of the relative wave height is related to stability of the structure. The upper boundary of the relative wave height is determined at $H_{mo}/D_{n50} = 6$.

The range of application for the relative wave height is given by:

$$1 < H_{mo}/D_{n50} < 6 \qquad \text{(eq. 4.29)}$$

4.6.2 Wave steepness

Very large values of the wave steepness will lead to breaking of the waves. Physically the upper boundary of the wave steepness is about 0.05 to 0.06. The formulas give good results up to a value of 0.05. Larger values can be used, but will lead to less reliability of the predicted transmission coefficient. The upper boundary of the wave steepness is determined at $s_{op} = 0.05$.

Very small values of the wave steepness ($s_{op} < 0.005$) lead to very long swell, which has a different behaviour towards wave transmission then short wind waves. The formula can not predict the very high transmission coefficients caused by swell. Down to a value of 0.01 of the wave steepness the formula gives good results, between 0.005 and 0.01 the results are less reliable. The lower boundary of the wave steepness is determined at 0.01.

The range of application for the wave steepness is given by:

$$0.01 < s_{op} < 0.05 \qquad \text{(eq. 4.30)}$$

4.7 Validity and reliability of formulas

An overall view of the formulas for wave transmission at conventional and reef type breakwaters is given in figure 39, respectively figure 40. The results of using the formulas on the test data are presented in figures of the measured versus the calculated wave transmission coefficient. See figures 33 to 36. These figures are made with (b-figures), and without (a-figures) the above described range of application. This range was defined as:

$$1 < H_{mo}/D_{n50} < 6 \qquad \text{(eq. 4.29)}$$
$$0.01 < s_{op} < 0.05 \qquad \text{(eq. 4.30)}$$

This is the range in which the relative wave height and the wave steepness are usually situated. In table 13 the statistical data on the figures are given.

Figure 33 shows the conventional breakwaters. These are: Seelig BW4 (1980), Daemrich and Kahle (1985), Van der Meer (1988) and the present data. What can be seen is that the value of the maximum is too rough for the data of Daemrich and Kahle (1985). This probably is caused by the larger permeability of the armour layer (tetrapods) used on their structures. The use of a different definition of R_c for tetrapods can also be a reason for the larger spreading of these data around the maximum. Furthermore figure 33b shows a smaller spreading for the data of Daemrich and Kahle (1985). In several tests they used relative wave heights smaller than 1.

The data of Seelig BW4 (1980) do fit in nicely in figure 33a, except for some data with a very large wave steepness which are left away in figure 33b.

The data of Van der Meer (1988) and the present data are shown together in figure 34. A smaller spreading than in figure 33 is reached. This was to be expected because the lines drawn in earlier figures of these data showed a clear pattern which corresponded to the theories mentioned in chapter 2 and on which basis the formula was derived. In figures 16 to 17a and 21, it is seen that the pattern of crossing lines do fit in in the data points. Data sets which do not show such a pattern, for example Daemrich and Kahle (1985) figures 19 and 20, will therefor have a larger difference in measured and calculated wave transmission coefficient. Whether this different pattern in figures 19 and 20 is a result of breakwater properties or testing circumstances is hard to say. Probably the large permeability of the armour layer is of great influence. At negative crest heights large waves are much less affected by a crest of tetrapods then by a crest of rock. In this way lines of constant relative wave height will not have to cross each other, but just come more near to each other with decreasing relative crest height, as is seen in figures 19 and 20.

The standard deviation of the formulas used on all conventional breakwaters, in the range of application, is 0.048. For the tests of Van der Meer and the present research this is 0.029.

Figure 35a shows the data of Ahrens (1987) from tests at which the crest height lowered, during the test, less then 10 percent of the initial height. The formula for reef type breakwaters is used. Still a large spreading is present. With a restriction of the wave steepness between 0,01 and 0,05 a smaller spreading is observed, but now very few data points are left. The same effect of a decreasing standard deviation, by using the range of application, is observed for all data of Ahrens (1987), see figure 35b and table 13. Ahrens (1987) used many values of s_{op} smaller than 0.01, even down to 0.001. Although a reasonable accuracy for reef type breakwaters is reached, a remark about wave transmission at these types of structures must be made. At a reef type breakwater the values of H_{mo}/D_{n50} and s_{op} will not have influence on wave transmission only, but on the damage of the structure as well. This damage results, among other things, in a lowering of the crest height. It is obvious that a lowering of the crest height results in more transmission over the structure. A larger wave, which causes more transmission at positive - and less transmission at negative values of R_c/D_{n50}, will cause more damage to the structure and hence a larger decrease of the crest height so the wave can pass more easily. The same yields for the wave steepness. A smaller wave steepness causes more transmission, but also less damage to the structure which leads on his turn to less transmission. So the phenomena which determine wave transmission at reef type breakwaters can be competitive. This explains, for example, the minor influence of s_{op} which was noted in equation 4.12. Figure 37 shows R_c/D_{n50} versus K_t per s_{op}, for the data of Ahrens (1987) used in figure 35. Comparing this figure to figure 13, the minor importance of

s_{op} on wave transmission at reef type breakwaters is obtained. It can be expected that wave transmission at reef type breakwaters is better described when the dynamic stability of the structure is taken into account.

The standard deviation of the formulas used on all reef type breakwaters, in the range of application, is 0.054. For the tests at which the crest height lowered less then 10 percent of the initial height this is 0.031.

Figure 38 shows data sets which are not used in the derivation of the formulas. They will be briefly discussed hereunder.

The data of Powell and Allsop (1985) are calculated with the formula for reef type breakwaters, only the constant 0.85 is replaced by 0.65. The maximum for this data set is determined at K_t = 0.85. With these adaptions a reasonable spreading is reached, but at the same time the use of adaptions makes it hard, if not impossible, to draw conclusions out of the results. In a way this is not important because this formula was derived for such a special data set that its use for other homogeneous breakwaters probable is not possible.

The data of Allsop (1983) are calculated with the formula for conventional breakwaters. The structure tested by Allsop was the only one to have a filter layer. What strikes is the fact that with high positive values of the relative crest height, $R_c/D_{n50} > 2$, still high transmission coefficients were measured. All the other data sets have already reached their minimum at $R_c/D_{n50} > 2$. This difference can be a result of more transmission through the structure or (much) more wave run up. It is also possible that Allsop (1983) used a different definition of the crest height then is done in this report. This last item would explain a lot.

The data of Seelig BW5 and BW10 (1980) are calculated with the formula for conventional breakwaters. Seelig used small values of H_{mo}/D_{n50} only, approximately from 0.7 to 1.6. At the same time very high values of the wave steepness were measured. In the range of application the data of BW10 do fit in nicely. The data of BW5 cause a large spreading, especially for a relative crest height of R_c/D_{n50} = -1.08. Since in this area of the relative crest height the definition of R_c is very important, probably a different definition is used for the tests on BW5. This assumption becomes even more reliable when it is noted that all calculated transmission coefficients at R_c/D_{n50} = -1.08 consequently are too large compared to the measured K_t. Again it is noted that for the use of the formulas, proposed in this report, the definition of R_c is very important. Especially with a water level near to the crest height, this is true.

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NOTATION

a	= coefficient	(-)
A_t	= cross sectional area	(m^2)
b	= constant	(-)
B_c	= crest width	(m)
B_n	= bulk number, $A_t/(D_{n50})^2$	(-)
c	= constant	(-)
d	= coefficient	(-)
D_{n50}	= nominal diameter, $(M/rho)^{1/3}$	(m)
g	= gravitational acceleration	(m/s^2)
h	= water depth	(m)
h_c', h_c	= armour crest level relative to seabed, before respectively after wave attack	(m)
H_i	= incident significant wave height	(m)
H_{mo}	= significant wave height based on wave energy spectrum, $(mo)^{1/2}$	(m)
H_s	= significant wave height, average of highest 1/3 of all waves	(m)
H_t	= transmitted significant wave height	(m)
K_t	= wave transmission coefficient	(-)
L_p	= local wave length calculated with T_p	(m)
M_{50}	= mass of unit given by 50% on mass distribution curve	(kg)
mo	= zeroth moment of wave energy density spectrum	(-)
P	= parameter, $(H_{mo}A_t)/(L_pD_{n50}^2)$ (Hearn 1987)	(-)
P	= permeability coefficient (Van der Meer 1988)	(-)
R_c	= crest freeboard	(-)
R^*_p	= dimensionless freeboard, $(R_c/H_{mo}) * (s_{op}/2\pi)^{1/2}$	(-)
Ru	= wave run-up	(m)
s_{op}	= fictitious wave steepness, $(2\pi H_{mo})/(gT_p^2)$	(-)
T_p	= peak wave period	(s)
α	= structure front face angle	(-)
rho_a	= mass density of armour	(kg/m^3)
xi	= surf similarity parameter	(-)

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	Dn50	Rc/Dn50	Hmo/Dn50	sop	Kt	Bc/Dn50	Bn	# tests	type
vd Meer	.034	.20	2.30 - 4.90	.008 - .028	.38 - .50	8.7	374	11	conv.
	.034	3.70	2.30 - 4.10	.008 - .024	.05 - .11	8.7	607	9	conv.
	.034	-2.60	2.90 - 6.70	.010 - .039	.54 - .81	8.7	234	11	conv.
DaKa 0.2m	.078	-2.55 - .00	.30 - 2.70	.008 - .024	.36 - .90	2.6	98	51	conv.
DaKa 1.0m	.078	-2.55 - .00	.30 - 2.80	.007 - .025	.14 - .86	12.8	163	44	conv.
Daemen	.004	-.98 - 4.78	.78 - 3.61	.010 - .042	.05 - .63	8.5	220	47	conv.
	.061	-1.43 - -.66	1.37 - 1.95	.021 - .022	.47 - .61	8.5	95	6	conv.
Ahrens	.019	-1.70 - -.20	1.60 - 8.60	.003 - .035	.54 - .79	3.0	337	30	reef
	.019	.90 - 2.40	1.60 - 8.60	.001 - .024	.23 - .78	3.0	450	41	reef
	.019	3.90 - 5.90	1.10 - 8.60	.001 - .036	.18 - .74	3.0	631	52	reef
	.029	1.40 - 2.70	.70 - 5.50	.001 - .035	.24 - .60	3.0	222	64	reef
	.029	-.20 - .60	1.00 - 6.10	.003 - .036	.55 - .86	3.0	222	18	reef
See bw4	.111	-.70 - 1.90	1.10 - 1.50	.002 - .106	.07 - .54	3.6	94	20	conv.
bw5	.111	-3.80 - -1.10	.90 - 1.60	.010 - .076	.66 - .92	3.6	27	30	conv.
bw10	.161	-.60 - 1.30	.10 - 1.10	.004 - .060	.06 - .55	1.9	33	24	conv.
PoAl 2	.076	-1.90 - 1.00	1.60 - 2.40	.022 - .028	.25 - .80	1.8	30	6	homog.
3	.076	-1.60 - .90	1.30 - 2.00	.022 - .028	.33 - .86	1.0	19	6	homog.
4	.090	-1.90 - 1.00	1.60 - 2.40	.022 - .028	.24 - .88	1.8	38	6	homog.
5	.076	-2.50 - .40	1.60 - 2.90	.022 - .029	.36 - .86	2.7	26	18	homog.
6	.076	-3.10 - -.20	1.60 - 2.40	.022 - .028	.40 - .89	2.3	18	6	homog.
7	.076	-3.70 - -.80	1.60 - 2.40	.022 - .028	.49 - .95	1.9	11	6	homog.
8	.076	-2.50 - .40	1.60 - 2.40	.022 - .028	.30 - .98	4.2	31	16	homog.
Allsop	.040	2.00 - 3.90	1.50 - 4.80	.003 - .030	-	4.0	285	27	conv.

Table 1 Overall view of data sets

test section	Rc m	Hmo m	Tp s	sop -	Kt -	Rc/Hmo -	Rc/Dn50 -	Hmo/Dn50 -
bw1	.15	.158	1.60	.040	.103	.949		
cota=1.5	.15	.169	1.62	.041	.176	.888		
smooth	.15	.113	3.32	.007	.039	1.327		
impermeable	.15	.120	3.32	.007	.045	1.250		
B=0.30 m	.15	.172	1.46	.052	.151	.872		
	.15	.082	3.08	.006	.035	1.829		
	.15	.128	2.05	.020	.068	1.172		
	.15	.155	2.02	.024	.160	.968		
	.00	.156	1.34	.056	.319	0		
	.00	.165	1.56	.043	.347	0		
	.00	.075	3.28	.004	.253	0		
	.00	.115	2.00	.018	.356	0		
	.00	.167	1.45	.051	.355	0		
	.00	.111	3.32	.006	.303	0		
	.00	.125	1.33	.045	.291	0		
	.00	.133	1.34	.047	.305	0		
bw4	-.08	.133	2.12	.019	.543	-.602	-.721	1.198
cota=2.6	-.08	.161	2.03	.025	.495	-.497	-.721	1.450
Dn50=0.111 m	-.08	.146	1.44	.045	.501	-.548	-.721	1.315
permeable	-.08	.156	.97	.106	.488	-.513	-.721	1.405
B=0.40 m	-.08	.156	1.53	.043	.484	-.513	-.721	1.405
rock	.06	.150	2.23	.019	.231	.400	.541	1.351
	.06	.150	1.53	.041	.193	.400	.541	1.351
	.06	.146	2.12	.021	.229	.411	.541	1.315
	.06	.170	2.03	.026	.233	.353	.541	1.532
	.06	.146	1.44	.045	.188	.411	.541	1.315
	.06	.147	2.12	.021	.226	.408	.541	1.324
	.06	.174	1.38	.059	.237	.345	.541	1.568
	.06	.146	1.44	.045	.187	.411	.541	1.315
	.06	.148	2.23	.019	.228	.405	.541	1.333
	.06	.154	1.38	.052	.209	.390	.541	1.387
	.21	.164	2.35	.019	.113	1.280	1.892	1.477
	.21	.124	1.30	.047	.071	1.694	1.892	1.117
	.21	.121	2.12	.017	.113	1.736	1.892	1.090
	.21	.149	1.53	.041	.084	1.409	1.892	1.342
	.21	.124	1.70	.027	.109	1.694	1.892	1.117
bw4w	-.14	.174	1.38	.059	.658	-.805	-1.261	1.568
cota=2.6	-.19	.170	1.82	.033	.766	-1.118	-1.712	1.532
Dn50=0.111 m	-.19	.152	1.44	.047	.786	-1.250	-1.712	1.369
impermeable	-.19	.167	1.53	.046	.755	-1.138	-1.712	1.505
B=0.40 m	-.19	.153	1.94	.026	.768	-1.242	-1.712	1.378
rock	-.10	.164	1.02	.101	.551	-.610	-.901	1.477
	-.10	.157	1.30	.060	.518	-.637	-.901	1.414
bw5	-.42	.151	1.88	.027	.769	-2.781	-3.784	1.360
cota=1.5	-.42	.167	1.19	.076	.846	-2.515	-3.784	1.505
Dn50=0.111	-.42	.098	2.44	.011	.803	-4.286	-3.784	.883
permeable	-.42	.095	1.45	.029	.807	-4.421	-3.784	.856
B=0.40 m	-.42	.178	1.34	.063	.898	-2.360	-3.784	1.604
rock	-.42	.153	1.88	.028	.823	-2.745	-3.784	1.378
bw5	-.42	.168	1.19	.076	.844	-2.500	-3.784	1.514
cota=1.5	-.42	.099	2.46	.010	.843	-4.242	-3.784	.892
Dn50=0.111	-.42	.096	1.45	.029	.825	-4.375	-3.784	.865
permeable	-.42	.177	1.34	.063	.885	-2.373	-3.784	1.595
B=0.40 m	-.42	.173	1.26	.070	.922	-2.428	-3.784	1.559
rock	-.42	.153	1.88	.028	.826	-2.745	-3.784	1.378
	-.27	.125	2.64	.011	.777	-2.160	-2.432	1.126
	-.27	.152	1.55	.041	.815	-1.776	-2.432	1.369
	-.27	.134	1.16	.064	.663	-2.015	-2.432	1.207
	-.27	.126	2.64	.012	.804	-2.143	-2.432	1.135
	-.27	.153	1.55	.041	.815	-1.765	-2.432	1.378
	-.27	.134	1.16	.064	.652	-2.015	-2.432	1.207
	-.27	.158	1.26	.064	.792	-1.709	-2.432	1.423
	-.27	.17	1.97	.028	.814	-1.588	-2.432	1.532
	-.27	.131	2.84	.010	.713	-2.061	-2.432	1.180
	-.27	.16	1.26	.065	.791	-1.688	-2.432	1.441
	-.27	.171	1.97	.028	.810	-1.579	-2.432	1.541
	-.12	.122	2.12	.017	.798	-.984	-1.081	1.099
	-.12	.158	2.35	.018	.685	-.759	-1.081	1.423
	-.12	.122	1.30	.046	.710	-.984	-1.081	1.099
	-.12	.123	2.12	.018	.842	-.976	-1.081	1.108
	-.12	.144	2.23	.019	.735	-.833	-1.081	1.297
	-.12	.148	1.53	.040	.662	-.811	-1.081	1.333
	-.12	.08	.91	.062	.708	-1.500	-1.081	.721
bw10	-.09	.16	1.34	.057	.408	-.563	-.559	.994
cota=1.5	-.09	.17	1.72	.037	.418	-.529	-.559	1.056
Dn50=0.161 m	-.09	.067	2.61	.006	.625	-1.343	-.559	.416
permeable	-.09	.11	2.00	.018	.475	-.818	-.559	.683
B=0.30 m	-.09	.162	1.45	.049	.447	-.556	-.559	1.006
one layer ro	-.09	.103	2.64	.009	.552	-.874	-.559	.640
	-.09	.125	1.33	.045	.405	-.720	-.559	.776
	-.09	.13	1.34	.046	.458	-.692	-.559	.807
	.06	.021	1.95	.004	.381	2.857	.373	.130
	.06	.162	1.51	.046	.191	.370	.373	1.006
	.06	.074	3.12	.005	.305	.811	.373	.460
	.06	.122	1.14	.060	.190	.492	.373	.758
	.06	.144	3.24	.009	.286	.417	.373	.894
	.06	.146	1.54	.039	.229	.411	.373	.907
	.06	.169	1.64	.040	.215	.355	.373	1.050
	.06	.112	3.32	.007	.268	.536	.373	.696
	.06	.113	3.66	.005	.232	.531	.373	.702
	.21	.158	1.36	.055	.062	1.329	1.304	.981
	.21	.067	3.12	.004	.213	3.134	1.304	.416
	.21	.125	2.21	.016	.098	1.680	1.304	.776
	.21	.154	2.21	.020	.090	1.364	1.304	.957
	.21	.161	1.67	.037	.082	1.304	1.304	1.000
	.21	.109	3.28	.006	.155	1.927	1.304	.677
	.21	.123	3.46	.007	.126	1.707	1.304	.764

Table 2. Data of Seelig (1980) with random waves

	test	Rc m	Hs m	Tp s	sop -	Kt -	Rc/Hs -	Rc/Dn50 -	Hmo/Dn50 -
short regime	1	.08	.163	1.86	.030	.380	.490	2.000	4.075
	2	.08	.136	1.70	.030	.270	.590	2.000	3.400
	3	.08	.108	1.51	.030	.140	.740	2.000	2.700
	4	.08	.081	1.31	.030	.120	.990	2.000	2.025
	5	.121	.173	1.91	.030	.190	.700	3.025	4.325
	6	.121	.148	1.77	.030	.200	.820	3.025	3.700
	7	.121	.146	1.76	.030	.180	.830	3.025	3.650
	8	.121	.127	1.64	.030	.120	.950	3.025	3.175
	9	.121	.127	1.64	.030	.110	.950	3.025	3.175
	10	.121	.095	1.42	.030	.090	1.270	3.025	2.375
	11	.121	.099	1.45	.030	.075	1.220	3.025	2.475
	12	.121	.073	1.24	.030	.070	1.660	3.025	1.825
	13	.121	.049	1.02	.030	.070	2.450	3.025	1.225
	14	.154	.132	1.67	.030	.100	1.170	3.850	3.300
	15	.154	.117	1.57	.030	.150	1.320	3.850	2.925
	16	.154	.097	1.43	.030	.055	1.580	3.850	2.425
	17	.154	.067	1.19	.030	.050	2.300	3.850	1.675
	18	.154	.049	1.02	.030	.050	3.150	3.850	1.225
long regime	19	.121	.130	3.17	.008	.220	.930	3.025	3.250
	20	.121	.123	3.17	.008	.190	.980	3.025	3.075
	21	.121	.083	3.17	.005	.130	1.450	3.025	2.075
	22	.121	.059	3.17	.004	.130	2.060	3.025	1.475
	23	.156	.115	3.17	.007	.115	1.360	3.900	2.875
	24	.156	.111	3.17	.007	.120	1.410	3.900	2.775
	25	.156	.100	3.17	.006	.085	1.560	3.900	2.500
	26	.156	.074	3.17	.005	.075	2.110	3.900	1.850
	27	.156	.050	3.17	.003	.080	3.150	3.900	1.250

Table 3. Data op Allsop (1983)
Data points taken from Fig. 3.5 of Powell and Allsop (1985)
Rock structure with filter layer and core
Slope angle 1:2

Section	Rc	Hs	Tp	sop	Kt	Rc/Hs	Rc/Dn50	Hs/Dn50	Section	Rc	Hs	Tp	sop	Kt	Rc/Hs	Rc/Dn50	Hs/Dn50
	m	m	s	-	-	-	-	-		m	m	s	-	-	-	-	-
2	.079	.118	1.64	.028	.254	.665	1.035	1.555	5 final	.033	.189	2.30	.023	.433	.175	.437	2.488
	.000	.115	1.64	.027	.520	.000	.000	1.507		-.045	.221	2.30	.027	.487	-.205	-.598	2.913
	-.141	.117	1.64	.028	.802	-1.202	-1.854	1.543		-.150	.243	2.30	.029	.708	-.617	-1.974	3.200
	.079	.164	2.16	.022	.297	.481	1.035	2.153		-.186	.222	2.30	.027	.738	-.838	-2.452	2.925
	.000	.182	2.16	.025	.455	.000	.000	2.392	6	-.012	.118	1.64	.028	.412	-.104	-.161	1.555
	-.141	.184	2.16	.025	.755	-.767	-1.854	2.416		-.091	.115	1.64	.027	.679	-.794	-1.196	1.507
3	.079	.118	1.64	.028	.327	.665	.874	1.313		-.232	.117	1.64	.028	.891	-1.977	-3.050	1.543
	.000	.115	1.64	.027	.556	.000	.000	1.273		-.012	.164	2.16	.022	.400	-.075	-.161	2.153
	-.141	.117	1.64	.028	.864	-1.202	-1.566	1.303		-.091	.182	2.16	.025	.560	-.500	-1.196	2.392
	.079	.164	2.16	.022	.344	.481	.874	1.818		-.232	.184	2.16	.025	.829	-1.262	-3.050	2.416
	.000	.182	2.16	.025	.478	.000	.000	2.020	7	-.058	.118	1.64	.028	.631	-.488	-.760	1.555
	-.141	.184	2.16	.025	.755	-.767	-1.566	2.040		-.136	.115	1.64	.027	.813	-1.190	-1.794	1.507
4	.079	.118	1.64	.028	.235	.665	1.035	1.555		-.277	.117	1.64	.028	.946	-2.364	-3.648	1.543
	.000	.115	1.64	.027	.512	.000	.000	1.507		-.058	.164	2.16	.022	.492	-.353	-.760	2.153
	-.141	.117	1.64	.028	.876	-1.202	-1.854	1.543		-.136	.182	2.16	.025	.683	-.750	-1.794	2.392
	.079	.164	2.16	.022		.481	1.035	2.153		-.277	.184	2.16	.025	.879	-1.510	-3.648	2.416
	.000	.182	2.16	.025	.458	.000	.000	2.392	8	.033	.090	1.39	.030	.302	.367	.437	1.190
	-.141	.184	2.16	.025	.730	-.767	-1.854	2.416		-.045	.091	1.39	.030	.545	-.500	-.598	1.196
5	.033	.118	1.64	.028	.358	.281	.437	1.555		-.150	.095	1.39	.031	.870	-1.587	-1.974	1.244
	-.045	.115	1.64	.027	.595	-.397	-.598	1.507		-.186	.092	1.39	.031	.980	-2.020	-2.452	1.214
	-.186	.117	1.64	.028	.857	-1.589	-2.452	1.543		.033	.118	1.64	.028	.338	.281	.437	1.555
	.033	.164	2.16	.022	.356	.203	.437	2.153		-.045	.115	1.64	.027	.536	-.397	-.598	1.507
	-.045	.182	2.16	.025	.488	-.250	-.598	2.392		-.150	.120	1.64	.029	.766	-1.245	-1.974	1.585
	-.186	.184	2.16	.025	.775	-1.015	-2.452	2.416		-.186	.117	1.64	.028	.837	-1.589	-2.452	1.543
5 final	.033	.153	1.86	.028	.485	.217	.437	2.010		.033	.141	1.86	.026	.348	.235	.437	1.854
	-.045	.147	1.86	.027	.627	-.309	-.598	1.938		-.045	.151	1.86	.028	.482	-.301	-.598	1.986
	-.150	.151	1.86	.028	.813	-.994	-1.974	1.986		-.150	.154	1.86	.029	.693	-.973	-1.974	2.028
	-.186	.143	1.86	.027	.851	-1.302	-2.452	1.884		-.186	.150	1.86	.028	.743	-1.239	-2.452	1.980
	.033	.184	2.16	.025	.446	.181	.437	2.416		.033	.164	2.16	.022	.358	.203	.437	2.153
	-.045	.206	2.16	.028	.520	-.220	-.598	2.715		-.045	.182	2.16	.025	.475	-.250	-.598	2.392
	-.150	.229	2.16	.031	.704	-.655	-1.974	3.014		-.150	.203	2.16	.028	.649	-.738	-1.974	2.673
	-.186	.197	2.16	.027	.770	-.945	-2.452	2.596		-.186	.184	2.16	.025	.728	-1.015	-2.452	2.416

Table 4. Data of Powell and Allsop (1985)
Data released by Allsop
Foreshore slope about 1:65

smooth impermeable			Bc=0.20 m cota=2.0		
Rc	Hmo	Tp	sop	Kt	Rc/Hmo
m	m	s	-	-	-
.00	.027	1.23	.011	.414	.00
.00	.055	1.23	.023	.437	.00
.00	.068	1.63	.016	.494	.00
.00	.097	1.63	.023	.563	.00
.00	.1	1.63	.024	.570	.00
.00	.082	2.04	.013	.552	.00
.00	.121	2.04	.019	.616	.00
.00	.155	2.04	.024	.653	.00
.00	.118	2.45	.013	.621	.00
.00	.168	2.45	.018	.680	.00
.00	.194	2.45	.021	.715	.00
.00	.131	2.86	.010	.667	.00
.00	.174	2.86	.014	.713	.00
.00	.192	2.86	.015	.747	.00
.00	.177	3.27	.011	.694	.00
.00	.194	3.27	.012	.724	.00
.00	.204	3.27	.012	.724	.00
-.10	.024	1.23	.010	.837	-4.17
-.10	.055	1.23	.023	.772	-1.82
-.10	.044	1.63	.011	.731	-2.27
-.10	.071	1.63	.017	.713	-1.41
-.10	.099	1.63	.024	.708	-1.01
-.10	.101	2.04	.016	.752	-.99
-.10	.132	2.04	.020	.793	-.76
-.10	.155	2.04	.024	.801	-.65
-.10	.116	2.45	.012	.782	-.86
-.10	.16	2.45	.017	.809	-.63
-.10	.196	2.45	.021	.835	-.51
-.10	.197	2.86	.015	.763	-.51
-.10	.16	2.86	.013	.805	-.63
-.10	.212	2.86	.017	.825	-.47
-.10	.128	3.27	.008	.793	-.78
-.10	.188	3.27	.011	.664	-.53
-.10	.206	3.27	.012	.828	-.49
-.20	.025	1.23	.011	.917	-8.00
-.20	.061	1.23	.026	.885	-3.28
-.20	.051	1.63	.012	.825	-3.92
-.20	.078	1.63	.019	.782	-2.56
-.20	.104	1.63	.025	.800	-1.92
-.20	.065	2.04	.010	.763	-3.08
-.20	.099	2.04	.015	.749	-2.02
-.20	.129	2.04	.020	.749	-1.55
-.20	.16	2.04	.025	.805	-1.25
-.20	.205	2.45	.022	.772	-.98
-.20	.206	2.45	.022	.846	-.97
-.20	.082	2.86	.006	.759	-2.44
-.20	.124	2.86	.010	.738	-1.61
-.20	.162	2.86	.013	.782	-1.23
-.20	.2	2.86	.016	.823	-1.00

breakwater Tetrapods				Bc=0.20 m cota=2			
Rc	Hmo	Tp	sop	Kt	Rc/Hmo	Rc/Dn5	Hmo/Dn
m	m	s	-	-	-	-	-
.00	.024	1.23	.010	.416	.00	.00	.31
.00	.055	1.23	.023	.372	.00	.00	.70
.00	.040	1.63	.010	.361	.00	.00	.51
.00	.072	1.63	.017	.366	.00	.00	.92
.00	.100	1.63	.024	.391	.00	.00	1.28
.00	.098	2.04	.015	.400	.00	.00	1.25
.00	.128	2.04	.020	.444	.00	.00	1.63
.00	.154	2.04	.024	.483	.00	.00	1.97
.00	.118	2.45	.013	.462	.00	.00	1.51
.00	.161	2.45	.017	.506	.00	.00	2.06
.00	.188	2.45	.020	.522	.00	.00	2.40
.00	.098	2.86	.008	.481	.00	.00	1.25
.00	.160	2.86	.013	.570	.00	.00	2.04
.00	.192	2.86	.015	.598	.00	.00	2.45
.00	.127	3.27	.008	.508	.00	.00	1.62
.00	.164	3.27	.010	.552	.00	.00	2.09
.00	.189	3.27	.011	.575	.00	.00	2.41
-.10	.025	1.23	.011	.763	-4.00	-1.28	.32
-.10	.051	1.23	.022	.766	-1.96	-1.28	.65
-.10	.037	1.63	.009	.690	-2.70	-1.28	.47
-.10	.068	1.63	.016	.676	-1.47	-1.28	.87
-.10	.097	1.63	.023	.703	-1.03	-1.28	1.24
-.10	.096	2.04	.015	.671	-1.04	-1.28	1.23
-.10	.127	2.04	.020	.690	-.79	-1.28	1.62
-.10	.155	2.04	.024	.722	-.65	-1.28	1.98
-.10	.143	2.45	.015	.669	-.70	-1.28	1.83
-.10	.158	2.45	.017	.735	-.63	-1.28	2.02
-.10	.187	2.45	.020	.784	-.53	-1.28	2.39
-.10	.099	2.86	.008	.667	-1.01	-1.28	1.26
-.10	.158	2.86	.012	.738	-.63	-1.28	2.02
-.10	.212	2.86	.017	.752	-.47	-1.28	2.71
-.10	.137	3.27	.008	.678	-.73	-1.28	1.75
-.10	.176	3.27	.011	.745	-.57	-1.28	2.25
-.10	.210	3.27	.013	.736	-.48	-1.28	2.68
-.20	.023	1.23	.010	.897	-8.70	-2.55	.29
-.20	.051	1.23	.022	.832	-3.92	-2.55	.65
-.20	.039	1.63	.009	.800	-5.13	-2.55	.50
-.20	.070	1.63	.017	.752	-2.86	-2.55	.89
-.20	.097	1.63	.023	.745	-2.06	-2.55	1.24
-.20	.093	2.04	.014	.722	-2.15	-2.55	1.19
-.20	.123	2.04	.019	.729	-1.63	-2.55	1.57
-.20	.153	2.04	.024	.747	-1.31	-2.55	1.95
-.20	.112	2.45	.012	.726	-1.79	-2.55	1.43
-.20	.157	2.45	.017	.779	-1.27	-2.55	2.01
-.20	.196	2.45	.021	.809	-1.02	-2.55	2.50
-.20	.101	2.86	.008	.736	-1.98	-2.55	1.29
-.20	.169	2.86	.013	.786	-1.18	-2.55	2.16
-.20	.225	2.86	.018	.841	-.89	-2.55	2.87
-.20	.129	3.27	.008	.747	-1.55	-2.55	1.65
-.20	.165	3.27	.010	.807	-1.21	-2.55	2.11
-.20	.205	3.27	.012	.800	-.98	-2.55	2.62

breakwater Tetrapods				Bc=1.00 m cota=2			
Rc	Hmo	Tp	sop	Kt	Rc/Hmo	Rc/Dn5	Hmo/Dn
m	m	s	-	-	-	-	-
.00	.023	1.23	.010	.251	.00	.00	.29
.00	.051	1.23	.022	.161	.00	.00	.65
.00	.040	1.63	.010	.209	.00	.00	.51
.00	.070	1.63	.017	.138	.00	.00	.89
.00	.097	1.63	.023	.149	.00	.00	1.24
.00	.095	2.04	.015	.166	.00	.00	1.21
.00	.124	2.04	.019	.218	.00	.00	1.58
.00	.151	2.04	.023	.26	.00	.00	1.93
.00	.115	2.45	.012	.276	.00	.00	1.47
.00	.095	2.86	.007	.276	.00	.00	1.21
.00	.186	2.86	.015	.418	.00	.00	2.38
.00	.125	3.27	.007	.324	.00	.00	1.60
.00	.182	3.27	.011	.386	.00	.00	2.32
-.10	.024	1.23	.010	.646	-4.17	-1.28	.31
-.10	.055	1.23	.023	.632	-1.82	-1.28	.70
-.10	.071	1.63	.017	.554	-1.41	-1.28	.91
-.10	.099	1.63	.024	.549	-1.01	-1.28	1.26
-.10	.098	2.04	.015	.485	-1.02	-1.28	1.25
-.10	.128	2.04	.020	.52	-.78	-1.28	1.63
-.10	.158	2.04	.024	.566	-.63	-1.28	2.02
-.10	.116	2.45	.012	.529	-.86	-1.28	1.48
-.10	.160	2.45	.017	.582	-.63	-1.28	2.04
-.10	.197	2.45	.021	.634	-.51	-1.28	2.52
-.10	.160	2.86	.013	.609	-.63	-1.28	2.04
-.10	.216	2.86	.017	.658	-.46	-1.28	2.76
-.10	.129	3.27	.008	.582	-.78	-1.28	1.65
-.10	.171	3.27	.010	.641	-.58	-1.28	2.18
-.20	.024	1.23	.010	.855	-8.33	-2.55	.31
-.20	.055	1.23	.023	.8	-3.64	-2.55	.70
-.20	.041	1.63	.010	.706	-4.88	-2.55	.52
-.20	.074	1.63	.018	.671	-2.70	-2.55	.95
-.20	.104	1.63	.025	.662	-1.92	-2.55	1.33
-.20	.097	2.04	.015	.635	-2.06	-2.55	1.24
-.20	.158	2.04	.024	.683	-1.27	-2.55	2.02
-.20	.118	2.45	.013	.641	-1.69	-2.55	1.51
-.20	.162	2.45	.017	.703	-1.23	-2.55	2.07
-.20	.205	2.45	.022	.745	-.98	-2.55	2.62
-.20	.097	2.86	.008	.632	-2.06	-2.55	1.24
-.20	.130	2.86	.010	.658	-1.54	-2.55	1.66
-.20	.161	2.86	.013	.703	-1.24	-2.55	2.06
-.20	.218	2.86	.017	.745	-.92	-2.55	2.78
-.20	.130	3.27	.008	.669	-1.54	-2.55	1.66
-.20	.173	3.27	.010	.713	-1.16	-2.55	2.21
-.20	.217	3.27	.013	.731	-.92	-2.55	2.77

Table 5. Data of Daemrich and Kahle (1985). Data taken from Figures.
Tetrapods Dn50 = 0.0783 m

sub-set	test	Rc	Hmo	Tp	sop	Kt	Rc/Hmo	Rc/Dn50	Hmo/Dn5
		m	m	s	-	-	-	-	-
1	1	-.031	.110	1.45	.034	.586	-.280	-1.656	5.919
1	2	-.020	.101	1.46	.030	.560	-.196	-1.070	5.452
1	3	-.015	.080	1.43	.025	.558	-.188	-.806	4.301
1	4	-.006	.057	1.45	.017	.571	-.105	-.323	3.081
1	5	-.011	.029	1.44	.009	.585	-.373	-.575	1.543
1	6	-.043	.134	2.23	.017	.613	-.320	-2.312	7.220
1	7	-.035	.115	2.23	.015	.627	-.308	-1.903	6.183
1	8	-.012	.091	2.25	.011	.639	-.136	-.661	4.876
1	9	-.004	.061	2.27	.008	.568	-.066	-.215	3.274
1	10	-.005	.029	2.28	.004	.543	-.158	-.247	1.565
1	11	-.050	.131	2.23	.017	.601	-.382	-2.694	7.059
1	13	-.080	.158	3.00	.011	.593	-.508	-4.312	8.484
1	14	-.074	.144	3.00	.010	.592	-.516	-3.984	7.715
1	15	-.052	.114	2.78	.009	.633	-.453	-2.774	6.118
1	16	-.024	.078	2.76	.007	.645	-.312	-1.312	4.199
1	17	-.006	.039	2.75	.003	.607	-.144	-.301	2.091
1	18	-.079	.157	2.95	.012	.583	-.503	-4.247	8.452
1	20	-.012	.055	3.53	.003	.623	-.220	-.645	2.935
1	21	-.061	.101	3.52	.005	.679	-.609	-3.296	5.414
1	22	-.085	.143	3.60	.007	.624	-.597	-4.575	7.661
1	23	-.091	.161	3.64	.008	.588	-.566	-4.903	8.656
1	25	-.031	.115	1.45	.035	.553	-.269	-1.656	6.156
1	26	-.031	.101	1.46	.030	.568	-.310	-1.677	5.419
1	27	-.032	.088	2.24	.011	.640	-.360	-1.710	4.747
1	28	-.057	.116	2.80	.009	.653	-.494	-3.070	6.210
1	29	-.067	.104	3.59	.005	.687	-.649	-3.624	5.581
1	30	-.083	.150	3.63	.007	.606	-.554	-4.462	8.054
2	12	-.050	.059	2.24	.007	.710	-.853	-2.694	3.156
2	19	-.081	.059	2.23	.008	.785	-1.387	-4.376	3.156
2	24	-.091	.060	2.23	.008	.788	-1.528	-4.887	3.199
3	31	-.003	.114	1.47	.034	.456	-.025	-.151	6.108
3	32	.014	.095	1.45	.029	.427	.151	.769	5.086
3	33	.030	.078	1.44	.024	.309	.389	1.634	4.204
3	34	.044	.055	1.44	.017	.233	.796	2.355	2.957
3	35	.045	.028	1.44	.009	.255	1.596	2.419	1.516
3	36	-.057	.156	2.98	.011	.526	-.367	-3.086	8.403
3	37	-.052	.138	3.00	.010	.580	-.379	-2.806	7.398
3	38	-.027	.110	2.81	.009	.563	-.242	-1.430	5.903
3	39	.009	.075	2.82	.006	.502	.117	.473	4.027
3	40	.035	.037	2.79	.003	.337	.959	1.898	1.978
3	41	-.033	.134	2.23	.017	.537	-.244	-1.758	7.194
3	42	-.010	.112	2.27	.014	.546	-.088	-.527	6.005
3	43	.010	.084	2.25	.011	.496	.120	.538	4.489
3	44	.030	.057	2.29	.007	.362	.521	1.602	3.075
3	45	.043	.029	2.28	.004	.298	1.484	2.306	1.554
3	46	.031	.055	3.56	.003	.392	.557	1.651	2.962
3	47	-.042	.106	3.58	.005	.663	-.391	-2.231	5.704
3	48	-.036	.102	3.52	.005	.619	-.354	-1.935	5.468
3	49	-.067	.146	3.57	.007	.570	-.455	-3.575	7.855
3	50	-.076	.158	3.6	.008	.578	-.482	-4.102	8.505
3	51	.038	.026	3.52	.001	.341	1.456	2.043	1.403
3	52	-.029	.132	2.25	.017	.544	-.221	-1.575	7.113
3	54	-.056	.156	2.9	.012	.532	-.356	-2.984	8.382
3	56	-.070	.158	3.52	.008	.556	-.441	-3.758	8.516
3	67	-.009	.104	1.43	.033	.442	-.085	-.478	5.602
3	68	.009	.111	1.46	.033	.448	.082	.489	5.946
3	69	.016	.084	2.25	.011	.488	.191	.866	4.532
3	70	-.030	.109	2.91	.008	.569	-.275	-1.608	5.855
3	71	.031	.026	3.59	.001	.355	1.197	1.667	1.392
4	55	-.056	.055	2.26	.007	.713	-1.018	-3.016	2.962
4	57	-.070	.027	2.24	.003	.779	-2.581	-3.774	1.462
4	58	-.072	.055	2.22	.007	.772	-1.316	-3.855	2.930
4	59	-.072	.084	2.23	.011	.722	-.862	-3.871	4.489
4	60	-.071	.112	2.23	.014	.656	-.639	-3.839	6.011
4	61	-.070	.133	2.23	.017	.606	-.527	-3.758	7.134
4	62	-.071	.032	1.44	.010	.669	-2.243	-3.823	1.704
4	63	-.073	.056	1.44	.017	.716	-1.306	-3.903	2.989
4	64	-.073	.080	1.44	.025	.653	-.916	-3.935	4.296
4	65	-.074	.092	1.44	.028	.663	-.807	-4.000	4.957
4	66	-.073	.112	1.46	.034	.597	-.651	-3.919	6.016
5	72	.044	.109	1.46	.033	.232	.409	2.387	5.839
5	73	.072	.094	1.45	.029	.179	.767	3.866	5.043
5	74	.089	.079	1.42	.025	.145	1.124	4.780	4.253
5	75	.096	.075	1.46	.023	.132	1.271	5.140	4.043
5	76	.096	.055	1.41	.018	.132	1.749	5.134	2.935
5	77	-.049	.157	3.58	.008	.489	-.310	-2.624	8.452
5	78	.086	.088	1.41	.028	.177	.971	4.602	4.742
5	79	.103	.028	1.44	.008	.207	3.731	5.516	1.478
5	80	-.008	.130	2.27	.016	.445	-.062	-.430	6.968
5	81	.016	.109	2.28	.013	.397	.147	.860	5.855
5	82	.037	.096	2.3	.012	.359	.382	1.978	5.183
5	83	.086	.068	2.3	.008	.212	1.265	4.618	3.651
5	84	.094	.040	2.3	.005	.208	2.333	5.054	2.167
5	85	-.034	.153	3	.011	.471	-.221	-1.823	8.247
5	86	-.028	.141	2.96	.010	.490	-.202	-1.527	7.570
5	87	-.020	.128	2.86	.010	.496	-.154	-1.054	6.855
5	88	-.001	.112	2.84	.009	.240	-.012	-.070	6.000
5	89	.047	.076	2.85	.006	.354	.623	2.538	4.075
5	90	.104	.038	2.78	.003	.262	2.738	5.565	2.032
5	91	-.040	.143	3.56	.007	.482	-.278	-2.134	7.683
5	92	-.014	.101	3.57	.005	.528	-.142	-.774	5.446
5	93	.020	.053	3.56	.003	.435	.377	1.081	2.866
5	94	.109	.026	3.57	.001	.295	4.209	5.839	1.387
5	95	.104	.043	1.44	.013	.152	2.435	5.602	2.301
5	96	.103	.070	1.44	.022	.128	1.472	5.554	3.774
5	97	.068	.100	1.33	.036	.198	.677	3.634	5.371
5	98	.045	.114	1.45	.035	.270	.400	2.441	6.102
5	99	.094	.055	2.29	.007	.188	1.723	5.075	2.946

Table 6a Data of Ahrens (1987)
Foreshore 1:15, then horizontal
Reef breakwater structure, i.e. homogeneous structure

sub-set	test	Rc	Hmo	Tp	sop	Kt	Rc/Hmo	Rc/Dn50	Hmo/Dn5
		m	m	s	-	-	-	-	-
5	100	.053	.082	2.29	.010	.292	.641	2.833	4.419
5	101	.023	.110	2.28	.014	.400	.212	1.258	5.930
5	102	.063	.069	2.29	.008	.194	.916	3.403	3.715
5	103	-.010	.130	2.28	.016	.466	-.073	-.511	7.000
5	104	.107	.018	2.78	.002	.343	5.906	5.747	.973
5	105	.068	.057	2.81	.005	.280	1.190	3.634	3.054
5	106	.022	.093	2.85	.007	.441	.232	1.161	5.005
5	107	-.028	.139	2.86	.011	.469	-.203	-1.511	7.457
5	108	-.037	.156	2.91	.012	.470	-.238	-2.000	8.392
5	109	.109	.026	3.56	.001	.305	4.258	5.860	1.376
5	110	.020	.081	3.56	.004	.393	.244	1.059	4.333
5	111	-.046	.145	3.54	.007	.507	-.321	-2.495	7.774
5	112	-.052	.160	3.58	.008	.493	-.326	-2.806	8.597
6	113	-.052	.028	1.43	.009	.708	-1.827	-2.790	1.527
6	114	-.054	.090	1.43	.028	.539	-.597	-2.903	4.860
6	115	-.054	.056	1.40	.018	.626	-.961	-2.887	3.005
6	116	-.055	.081	1.44	.025	.555	-.672	-2.935	4.366
6	117	-.054	.100	1.44	.031	.525	-.538	-2.887	5.366
6	118	-.050	.115	1.45	.035	.495	-.439	-2.710	6.167
6	119	-.052	.025	2.22	.003	.739	-2.096	-2.806	1.339
6	120	-.052	.052	2.23	.007	.707	-1.002	-2.790	2.785
6	121	-.052	.080	2.22	.010	.627	-.652	-2.790	4.280
6	122	-.050	.107	2.25	.013	.572	-.473	-2.710	5.731
6	123	-.053	.129	2.23	.017	.519	-.408	-2.823	6.925
7	124	.062	.114	1.45	.035	.342	.543	2.119	3.904
7	125	.066	.100	1.45	.031	.293	.654	2.235	3.420
7	126	.064	.080	1.44	.025	.249	.791	2.167	2.741
7	127	.066	.056	1.43	.018	.238	1.180	2.256	1.911
7	128	.067	.026	1.43	.008	.315	2.562	2.273	.887
7	129	.067	.130	2.23	.017	.380	.511	2.273	4.447
7	130	.070	.111	2.30	.013	.365	.627	2.379	3.792
7	131	.067	.086	2.28	.011	.345	.773	2.276	2.945
7	132	.067	.056	2.28	.007	.308	1.206	2.297	1.904
7	133	.066	.027	2.26	.003	.368	2.408	2.235	.928
7	134	.047	.157	3.04	.011	.432	.301	1.611	5.345
7	135	.048	.140	2.88	.011	.436	.339	1.621	4.788
7	136	.065	.112	2.79	.009	.438	.585	2.232	3.812
7	137	.065	.074	2.82	.006	.384	.881	2.232	2.532
7	138	.061	.036	2.78	.003	.380	1.724	2.089	1.212
7	139	-.007	.159	3.58	.008	.505	-.043	-.232	5.413
7	140	.041	.142	3.52	.007	.451	.291	1.413	4.857
7	141	.052	.104	3.55	.005	.433	.502	1.778	3.543
7	142	.062	.051	3.57	.003	.359	1.218	2.119	1.741
7	143	.067	.024	3.60	.001	.417	2.834	2.273	.802
7	144	.066	.040	1.42	.013	.269	1.668	2.266	1.358
7	145	.068	.067	1.39	.022	.236	1.007	2.317	2.300
7	146	.068	.100	1.45	.030	.288	.682	2.324	3.406
7	147	.067	.114	1.45	.035	.317	.589	2.297	3.898
7	148	.066	.041	2.29	.005	.322	1.631	2.266	1.389
7	149	.065	.071	2.29	.009	.331	.914	2.205	2.413
7	150	.064	.113	2.26	.014	.375	.562	2.171	3.863
7	151	.055	.131	2.23	.017	.389	.420	1.881	4.474
7	152	.067	.017	2.78	.001	.485	4.055	2.283	.563
7	153	.060	.057	2.79	.005	.357	1.065	2.058	1.932
7	154	.060	.098	2.8	.008	.434	.615	2.048	3.328
7	155	.046	.142	2.81	.012	.424	.325	1.580	4.860
7	156	.036	.154	2.88	.012	.451	.233	1.225	5.263
7	157	.078	.024	3.58	.001	.426	3.306	2.652	.802
7	158	.075	.078	3.6	.004	.373	.955	2.546	2.666
7	159	.020	.145	3.55	.007	.471	.136	.672	4.952
7	160	.019	.160	3.58	.008	.479	.117	.642	5.474
7	161	.033	.144	3.54	.007	.463	.227	1.119	4.922
8	162	.034	.011	1.43	.003	.523	3.101	1.154	.372
8	163	.032	.024	1.43	.008	.395	1.313	1.089	.829
8	164	.032	.040	1.44	.012	.356	.789	1.075	1.362
8	165	.032	.054	1.44	.017	.355	.599	1.099	1.836
8	166	.032	.078	1.45	.024	.355	.409	1.089	2.662
8	167	.034	.098	1.46	.029	.382	.343	1.143	3.338
8	168	.032	.110	1.45	.034	.395	.286	1.078	3.765
8	169	.032	.012	2.28	.001	.603	2.725	1.079	.396
8	170	.033	.026	2.27	.003	.467	1.275	1.109	.870
8	171	.032	.039	2.26	.005	.447	.810	1.089	1.345
8	172	.032	.054	2.3	.007	.460	.592	1.099	1.857
8	173	.032	.087	2.26	.011	.456	.369	1.099	2.980
8	174	.033	.113	2.28	.014	.457	.292	1.123	3.843
8	175	.027	.133	2.24	.017	.475	.199	.904	4.543
8	176	.026	.016	2.78	.001	.568	1.611	.891	.553
8	177	.026	.036	2.8	.003	.459	.727	.881	1.212
8	178	.026	.056	2.8	.005	.470	.466	.891	1.911
8	179	.027	.076	2.83	.006	.502	.349	.904	2.590
8	180	.027	.113	2.84	.009	.481	.234	.904	3.870
8	181	.030	.142	2.8	.012	.472	.213	1.027	4.833
8	182	.026	.133	1.8	.026	.447	.191	.870	4.546
8	183	.030	.023	3.58	.001	.502	1.338	1.027	.768
8	184	.026	.050	3.59	.002	.501	.515	.881	1.710
8	185	.027	.075	3.56	.004	.525	.359	.918	2.560
8	186	.026	.099	3.54	.005	.516	.260	.881	3.389
8	187	.025	.123	3.54	.006	.493	.203	.850	4.184
9	188	-.004	.105	3.56	.005	.636	-.018	-.150	3.597
9	189	.015	.058	1.43	.018	.545	.311	.526	1.966
9	190	.013	.109	1.5	.031	.551	.141	.440	3.734
9	191	.010	.126	1.5	.036	.550	.098	.338	4.311
9	192	.013	.058	2.2	.008	.553	.262	.433	1.980
9	193	.008	.120	2.19	.016	.593	.088	.276	4.102
9	194	-.006	.145	2.22	.019	.579	-.024	-.201	4.935
9	195	.015	.082	2.99	.006	.621	.215	.515	2.799
9	196	-.036	.161	3.08	.011	.596	-.211	-1.242	5.491
9	197	-.047	.182	3.06	.012	.569	-.247	-1.618	6.201
9	198	.018	.052	3.37	.003	.556	.395	.618	1.782
9	199	-.016	.134	3.31	.008	.626	-.102	-.549	4.567
9	200	-.050	.176	3.28	.010	.595	-.272	-1.720	6.007
10	201	-.050	.026	2.21	.003	.864	-1.857	-1.720	.881
10	202	-.051	.056	2.22	.007	.774	-.865	-1.730	1.901
10	203	-.051	.088	2.22	.011	.723	-.558	-1.751	2.986
10	204	-.053	.123	2.22	.016	.653	-.411	-1.805	4.181
10	205	-.052	.144	2.22	.019	.619	-.346	-1.785	4.918

Table 6a continued. Data of Ahrens (1987)

sub-set	test	Rc	Hmo	Tp	sop	Kt	Rc/Hmo	Rc/Dn50	Hmo/Dn5
		m	m	s	-	-	-	-	-
1	2	-.020	.101	1.46	.030	.56	-.196	-1.07	5.45
	3	-.015	.080	1.43	.025	.56	-.188	-.81	4.30
	4	-.006	.057	1.45	.017	.57	-.104	-.32	3.08
	5	-.011	.029	1.44	.009	.59	-.377	-.58	1.54
	8	-.012	.091	2.25	.011	.64	-.135	-.66	4.88
	9	-.004	.061	2.27	.008	.57	-.067	-.22	3.27
	10	-.005	.029	2.28	.004	.54	-.160	-.25	1.56
	17	-.006	.039	2.75	.003	.61	-.144	-.30	2.09
	20	-.012	.055	3.53	.003	.62	-.221	-.65	2.94
	25	-.031	.115	1.45	.035	.55	-.269	-1.66	6.16
3	33	.030	.078	1.44	.024	.31	.388	1.63	4.20
	34	.044	.055	1.44	.017	.23	.794	2.35	2.96
	35	.045	.028	1.44	.009	.26	1.592	2.42	1.52
	40	.035	.037	2.79	.003	.34	.960	1.90	1.98
	44	.030	.057	2.29	.007	.36	.519	1.60	3.08
	45	.043	.029	2.28	.004	.30	1.490	2.31	1.55
	46	.031	.055	3.56	.003	.39	.557	1.65	2.96
	51	.038	.026	3.52	.001	.34	1.457	2.04	1.40
	69	.016	.084	2.25	.011	.49	.192	.87	4.53
	71	.031	.026	3.59	.001	.36	1.201	1.67	1.39
5	73	.072	.094	1.45	.029	.18	.768	3.87	5.04
	74	.089	.079	1.42	.025	.15	1.125	4.78	4.25
	75	.096	.075	1.46	.023	.13	1.272	5.14	4.04
	76	.095	.055	1.41	.018	.13	1.745	5.13	2.94
	78	.086	.088	1.41	.028	.18	.970	4.60	4.74
	79	.103	.028	1.44	.008	.21	3.730	5.52	1.48
	83	.086	.068	2.30	.008	.21	1.266	4.62	3.65
	84	.094	.040	2.30	.005	.21	2.327	5.05	2.17
	90	.103	.038	2.78	.003	.26	2.739	5.56	2.03
	94	.109	.026	3.57	.001	.29	4.201	5.84	1.39
	95	.104	.043	1.44	.013	.15	2.435	5.60	2.30
	96	.103	.070	1.44	.022	.13	1.472	5.55	3.77
	97	.068	.100	1.33	.036	.20	.676	3.63	5.37
	99	.094	.055	2.29	.007	.19	1.722	5.08	2.95
	104	.107	.018	2.78	.002	.34	5.928	5.75	.97
	109	.109	.026	3.56	.001	.30	4.246	5.86	1.38
7	124	.062	.114	1.45	.035	.34	.544	2.12	3.90
	125	.066	.100	1.45	.031	.29	.655	2.24	3.42
	126	.064	.080	1.44	.025	.25	.792	2.17	2.74
	127	.066	.056	1.43	.018	.24	1.183	2.26	1.91
	128	.067	.026	1.43	.008	.32	2.551	2.27	.89
	129	.067	.130	2.23	.017	.38	.510	2.27	4.45
	130	.070	.111	2.30	.013	.37	.628	2.38	3.79
	131	.067	.086	2.28	.011	.35	.773	2.28	2.95
	132	.067	.056	2.28	.007	.31	1.211	2.30	1.90
	133	.066	.027	2.26	.003	.37	2.409	2.24	.93
	134	.047	.156	3.04	.011	.43	.301	1.61	5.34
	135	.047	.140	2.88	.011	.44	.338	1.62	4.79
	136	.065	.112	2.79	.009	.44	.585	2.23	3.81
	137	.065	.074	2.82	.006	.38	.881	2.23	2.53
	138	.061	.035	2.78	.003	.38	1.727	2.09	1.21
	140	.041	.142	3.52	.007	.45	.290	1.41	4.86
	141	.052	.104	3.55	.005	.43	.503	1.78	3.54
	142	.062	.051	3.57	.003	.36	1.218	2.12	1.74
	143	.067	.023	3.60	.001	.42	2.838	2.27	.80
	144	.067	.040	1.42	.013	.27	1.669	2.27	1.36
	145	.068	.067	1.39	.022	.24	1.009	2.32	2.30
	146	.068	.100	1.45	.030	.29	.680	2.32	3.41
	147	.067	.114	1.45	.035	.32	.590	2.30	3.90
	148	.067	.041	2.29	.005	.32	1.633	2.27	1.39
	149	.064	.071	2.29	.009	.33	.913	2.20	2.41
	150	.064	.113	2.26	.014	.38	.562	2.17	3.86
	151	.055	.131	2.23	.017	.39	.421	1.88	4.47
	152	.067	.016	2.78	.001	.48	4.071	2.28	.56
	153	.060	.057	2.79	.005	.36	1.067	2.06	1.93
	154	.060	.098	2.80	.008	.43	.616	2.05	3.33
	155	.046	.142	2.81	.012	.42	.325	1.58	4.86
	157	.078	.023	3.58	.001	.43	3.313	2.65	.80
	158	.075	.078	3.60	.004	.37	.955	2.55	2.67
9	188	-.004	.244	3.56	.005	.64	-.018	-.15	8.33
	189	.016	.050	1.43	.018	.55	.314	.53	1.69
	190	.013	.092	1.50	.031	.55	.141	.44	3.13
	191	.010	.101	1.50	.036	.55	.099	.34	3.44
	192	.013	.048	2.20	.008	.55	.261	.43	1.65
	193	.008	.092	2.19	.016	.59	.089	.28	3.13
	194	-.006	.251	2.22	.019	.58	-.023	-.20	8.56
	195	.015	.070	2.99	.006	.62	.217	.52	2.40
	198	.018	.046	3.37	.003	.56	.395	.62	1.57

Table 6b Data of Ahrens (1987)
Tests at which the crest height lowered less then 10 percent of its initial height

test	Rc	Hmoi	Tp	sop	Kt	Rc/Hmoi	Rc/Dn50	Hmoi/Dn50
	m	m	s	-	-	-	-	-
1	.006	.101	1.96	.017	.375	.059	.174	2.936
2	.006	.121	1.96	.020	.390	.050	.174	3.517
3	.003	.139	1.98	.023	.401	.022	.087	4.041
4	.005	.170	1.96	.028	.407	.029	.145	4.942
5	.014	.082	1.96	.014	.379	.171	.407	2.384
6	.011	.118	2.56	.012	.459	.093	.320	3.430
7	.014	.137	2.56	.013	.464	.102	.407	3.983
8	.000	.171	2.56	.017	.459	.000	.000	4.971
9	.007	.100	2.56	.010	.442	.070	.203	2.907
10	.003	.075	2.53	.008	.424	.040	.087	2.180
11	.000	.151	2.56	.015	.497	.000	.000	4.390
12	.132	.119	2.60	.011	.082	1.109	3.837	3.459
13	.128	.140	2.60	.013	.106	.914	3.721	4.070
14	.123	.100	2.56	.010	.078	1.230	3.576	2.907
15	.128	.076	2.50	.008	.087	1.684	3.721	2.209
16	.131	.127	2.56	.012	.093	1.031	3.808	3.692
17	.125	.122	1.94	.021	.052	1.025	3.634	3.547
18	.126	.102	1.96	.017	.050	1.235	3.663	2.965
19	.125	.081	1.94	.014	.059	1.543	3.634	2.355
20	.126	.142	1.96	.024	.060	.887	3.663	4.128
21	-.088	.141	1.96	.024	.682	-.624	-2.558	4.099
22	-.092	.167	1.94	.028	.635	-.551	-2.674	4.855
23	-.095	.199	1.96	.033	.567	-.477	-2.762	5.785
24	-.094	.231	1.96	.039	.537	-.407	-2.733	6.715
25	-.094	.112	1.94	.019	.737	-.839	-2.733	3.256
26	-.092	.157	1.98	.026	.664	-.586	-2.674	4.564
27	-.087	.166	2.53	.017	.678	-.524	-2.529	4.826
28	-.090	.137	2.56	.013	.737	-.657	-2.616	3.983
29	-.090	.118	2.56	.012	.770	-.763	-2.616	3.430
30	-.088	.099	2.56	.010	.810	-.889	-2.558	2.878
31	-.095	.192	2.60	.018	.660	-.495	-2.762	5.581

Table 7. Data of Van der Meer (1988)

Armour layer	rock
Slope angle	1:2
Diameter armour	Dn50 = 0.0344 m
Permeability structure	permeable
Width of crest	0.30 m
Slope of foreshore	1:30
Water depth at structure	0.40 m
Water depth in flume	0.80 m

test	h	Rc	Hmoi	Tp	sop	Hmot	Kt	Rc/Hmo	Rc/Dn50	Hmo/Dn50
	m	m	m	s	-	m	-	-	-	-
91	.267	.196	.049	1.29	.019	.006	.118	4.027	4.900	1.217
92	.267	.196	.065	1.46	.019	.008	.117	3.031	4.900	1.617
93	.267	.196	.086	1.58	.022	.009	.105	2.279	4.900	2.150
94	.267	.196	.093	1.70	.020	.010	.107	2.115	4.900	2.317
95	.267	.196	.103	1.82	.020	.011	.107	1.909	4.900	2.567
19	.367	.096	.033	.99	.022	.002	.064	2.909	2.400	.825
81	.367	.096	.051	1.32	.019	.007	.133	1.895	2.400	1.267
82	.367	.096	.067	1.44	.021	.009	.131	1.440	2.400	1.667
83	.367	.096	.087	1.58	.023	.010	.119	1.099	2.400	2.183
84	.367	.096	.093	1.70	.020	.012	.124	1.036	2.400	2.317
85	.367	.096	.109	1.86	.020	.014	.128	.878	2.400	2.733
20	.367	.096	.131	2.88	.010	.017	.130	.733	2.400	3.275
8	.413	.050	.033	1.01	.021	.004	.117	1.515	1.250	.825
9	.413	.050	.059	1.44	.018	.010	.164	.847	1.250	1.475
10	.413	.050	.088	1.74	.019	.016	.182	.568	1.250	2.200
11	.413	.050	.117	2.05	.018	.028	.235	.427	1.250	2.925
12	.413	.050	.143	2.88	.011	.039	.273	.350	1.250	3.575
15	.433	.030	.032	.98	.021	.004	.130	.938	.750	.800
71	.433	.030	.052	1.32	.019	.010	.189	.577	.750	1.300
72	.433	.030	.067	1.45	.021	.013	.193	.446	.750	1.683
73	.433	.030	.089	1.58	.023	.022	.248	.338	.750	2.217
74	.433	.030	.096	1.70	.021	.028	.292	.313	.750	2.400
75	.433	.030	.112	1.86	.021	.038	.339	.268	.750	2.800
16	.433	.030	.143	2.28	.018	.048	.332	.210	.750	3.575
1	.453	.010	.032	.99	.021	.005	.148	.313	.250	.800
2	.453	.010	.060	1.41	.019	.016	.258	.167	.250	1.500
3	.453	.010	.088	1.74	.019	.030	.341	.114	.250	2.200
4	.453	.010	.118	2.05	.018	.043	.364	.085	.250	2.950
5	.453	.010	.148	2.28	.018	.057	.385	.068	.250	3.700
61	.503	-.040	.061	1.39	.020	.039	.628	-.652	-1.000	1.533
62	.503	-.040	.083	1.55	.022	.048	.581	-.484	-1.000	2.067
63	.503	-.040	.103	1.83	.020	.059	.575	-.390	-1.000	2.567
64	.503	-.040	.114	1.86	.021	.063	.548	-.351	-1.000	2.850
65	.503	-.040	.135	1.99	.022	.072	.528	-.296	-1.000	3.383
21	.367	.096	.058	1.01	.036	.003	.049	1.655	2.400	1.450
22	.367	.096	.110	1.44	.034	.010	.086	.873	2.400	2.750
13	.413	.050	.061	.99	.040	.005	.084	.820	1.250	1.525
14	.413	.050	.117	1.46	.035	.017	.145	.427	1.250	2.925
17	.433	.030	.060	.98	.040	.006	.106	.500	.750	1.500
18	.433	.030	.115	1.44	.036	.026	.222	.261	.750	2.875
6	.453	.010	.061	.99	.040	.012	.189	.164	.250	1.525
7	.453	.010	.118	1.46	.035	.037	.309	.085	.250	2.950
23	.503	-.040	.064	.99	.042	.032	.500	-.625	-1.000	1.600
24	.503	-.040	.117	1.44	.036	.053	.453	-.342	-1.000	2.925
26	.413	.050	.141	2.28	.017	.038	.266	.355	1.250	3.525
25	.453	.010	.148	2.28	.018	.058	.389	.068	.250	3.700
27	.503	-.040	.119	1.46	.036	.055	.458	-.336	-1.000	2.975
41	.473	-.040	.115	1.82	.022	.056	.488	-.349	-.656	1.880
42	.473	-.040	.083	1.58	.022	.040	.474	-.480	-.656	1.366
43	.503	-.070	.126	1.91	.022	.071	.560	-.556	-1.148	2.066
44	.503	-.070	.119	1.86	.022	.067	.565	-.590	-1.148	1.945
45	.520	-.087	.127	1.91	.022	.075	.592	-.687	-1.426	2.077
46	.520	-.087	.111	1.86	.021	.068	.614	-.786	-1.426	1.814

Armour layer : rock
Dn50 = 0.040 m
Tests 41-46 : Dn50 = 0.061 m

Core : Dn50 = 0.028 m
Crest width : 0.34 m
Foreshore slope: 1:350
Slope angle : 1:1.5

Table 8 Present data (Daemen)

	sop -	Hmo/Dn50 -	am -	bm1 -	af -	bm2 -	bf' -	bm2-bf' -
vd Meer	.010	2.90	-.14	.44	-.15	.45	.04	.41
	.010	3.40	-.10	.47	-.14	.48	.06	.42
	.010	4.00	-.09	.50	-.12	.52	.08	.45
	.020	3.40	-.14	.40	-.14	.40	.00	.40
	.020	4.10	-.12	.42	-.12	.42	.02	.40
	.020	4.90	-.09	.45	-.09	.44	.05	.40
	.030	4.60	-.10	.41	-.10	.42	-.01	.44
	.030	4.90	-.08	.42	-.09	.43	.00	.43
DaKa 0.2	.010	1.25	-.16	.47	-.20	.46	-.01	.47
	.010	1.50	-.15	.49	-.19	.49	-.01	.49
	.010	2.00	-.14	.52	-.18	.53	.01	.51
	.010	2.50	-.13	.57	-.16	.55	.03	.52
	.020	1.25	-.22	.40	-.20	.42	-.07	.48
	.020	1.50	-.20	.44	-.19	.44	-.06	.50
	.020	2.00	-.18	.49	-.18	.50	-.04	.54
	.020	2.50	-.16	.57	-.16	.57	-.03	.60
DaKa 1.0	.010	1.50	-.20	.30	-.19	.30	-.01	.31
	.010	2.30	-.18	.41	-.17	.41	.02	.38
	.020	1.25	-.27	.15	-.20	.27	-.07	.34
	.020	1.50	-.27	.21	-.19	.28	-.06	.34
	.020	2.00	-.23	.27	-.18	.36	-.04	.40
Daemen	.020	1.40	-.26	.37	-.20	.39	-.06	.45
	.020	2.10	-.18	.40	-.17	.40	-.04	.44
	.020	2.90	-.15	.42	-.15	.42	-.01	.43
	.020	3.50	-.12	.43	-.13	.43	.00	.43
	.040	1.50	-.25	.28	-.19	.28	-.17	.44
	.040	2.90	-.13	.32	-.15	.34	-.12	.46
Ahrens	.010	3.00	-.13	.66	-.15	.69	-.18	.87
	.010	4.00	-.10	.58	-.12	.65	-.23	.88
	.010	5.00	-.07	.55	-.09	.58	-.28	.86
	.020	2.00	-.17	.71	-.18	.64	-.15	.79
	.020	3.00	-.14	.67	-.15	.56	-.20	.76
	.020	4.00	-.12	.64	-.12	.55	-.25	.80
	.030	3.00	-.15	.64	-.15	.63	-.23	.85
	.030	4.00	-.13	.60	-.12	.61	-.28	.88
	.030	5.00	-.10	.56	-.09	.54	-.33	.86
See bw4	.020	1.25	-.25	.39	-.20	.39	-.07	.45
	.026	1.50	-.22	.34	-.19	.35	-.09	.44
	.045	1.30	-.23	.31	-.20	.33	-.20	.53
PoAl 2	.028	1.54	-.26	.47	-.19	.49	-.15	.63
	.025	2.40	-.15	.45	-.17	.46	-.19	.64
PoAl 3	.028	1.30	-.21	.53	-.20	.55	-.14	.69
	.025	2.00	-.16	.49	-.18	.49	-.17	.65
PoAl 4	.028	1.54	-.23	.48	-.19	.51	-.15	.66
	.025	2.40	-.18	.45	-.17	.44	-.19	.63
PoAl 5	.028	1.54	-.24	.44	-.19	.49	-.15	.63
	.025	2.40	-.15	.40	-.17	.41	-.19	.60
PoAl 5f	.028	2.00	-.14	.54	-.18	.55	-.17	.72
	.028	2.80	-.13	.45	-.15	.43	-.21	.64
	.028	3.00	-.14	.40	-.15	.40	-.22	.62
	.024	2.50			-.16	.51	-.19	.70
PoAl 6	.028	1.54	-.25	.43	-.19	.39	-.15	.53
	.025	2.40	-.14	.38	-.17	.36	-.19	.55
PoAl 7	.028	1.54	-.18	.57	-.19	.48	-.15	.62
	.025	2.40	-.18	.42	-.17	.38	-.19	.56
PoAl 8	.030	1.20	-.24	.40	-.20	.44	-.14	.58
	.028	1.55	-.18	.41	-.19	.42	-.15	.57
	.028	2.00	-.14	.40	-.18	.34	-.17	.51
	.025	2.40	-.13	.41	-.17	.41	-.19	.59
Allsop	.030	1.50			-.19	.48	-.15	.63
	.030	2.50			-.16	.46	-.20	.66
	.030	3.50			-.13	.53	-.25	.78
	.030	4.00			-.12	.59	-.28	.87

Table 9 Coefficients "am" and "af" ; constants "bm1","bm2","bf'"and "bm2-bf'" for data with constant sop and Hmo/Dn50

	sop	bm2	Hmo/Dn50	c
	-	-	-	-
vdMeer	.010	.45	2.90	.505
	.010	.48	3.45	.535
	.010	.52	4.00	.575
	.020	.40	2.90	.510
	.020	.42	4.10	.530
	.020	.44	4.80	.550
	.030	.42	4.60	.580
	.030	.43	4.80	.590
Daemen	.020	.39	1.40	.500
	.020	.40	2.10	.510
	.020	.42	2.90	.530
	.020	.43	3.50	.540
	.040	.28	1.50	.500
	.040	.34	2.90	.560
See bw4	.020	.39	1.25	.500
	.026	.35	1.50	.490
	.045	.33	1.30	.575
Ahrens	.010	.69	3.00	.715
	.010	.65	4.00	.675
	.010	.58	5.00	.605
	.020	.64	2.00	.695
	.020	.56	3.00	.615
	.020	.55	4.00	.605
	.030	.63	3.00	.710
	.030	.61	4.00	.690
	.030	.54	5.00	.620
DaKa 0.2	.010	.46	1.25	.505
	.010	.49	1.50	.535
	.010	.53	2.00	.575
	.010	.55	2.50	.595
	.020	.42	1.25	.530
	.020	.44	1.50	.550
	.020	.50	2.00	.610
	.020	.57	2.50	.680
DaKa 1.0	.010	.30	1.50	.355
	.010	.41	2.30	.465
	.020	.27	1.25	.375
	.020	.28	1.50	.385
	.020	.36	2.00	.465

Table 10 constant "c" and "bm2"
for data with constant sop and Hmo/Dn50

	Rc/Dn50 -	sop -	Hmo/Dn50 -	Kt max -
vd Meer	-2.60	.010	3.00	.81
	-2.60	.010	4.00	.73
	-2.60	.020	3.00	.74
	-2.60	.020	4.00	.68
	-2.60	.020	5.00	.67
	-2.60	.030	5.00	.66
	-2.60	.030	6.00	.57
DaKa 0.2	-2.55	.010	1.50	.73
	-2.55	.010	2.00	.80
	-2.55	.010	2.50	.80
	-2.55	.020	1.50	.74
	-2.55	.020	2.00	.76
	-2.55	.020	2.50	.83
DaKa 1.0	-2.55	.010	1.50	.66
	-2.55	.010	2.00	.71
	-2.55	.020	1.50	.66
	-2.55	.020	2.00	.70
Ahrens	-1.00	.010	5.00	.65
	-1.00	.020	3.00	.58
	-1.00	.020	4.00	.58
	-1.00	.020	5.00	.58
	-1.00	.030	4.00	.56
	-1.00	.030	5.00	.56
	-1.00	.030	6.00	.56

	Rc/Dn50 -	sop -	Hmo/Dn50 -	Kt min -
vd Meer	3.70	.010	3.00	.08
	3.70	.010	4.00	.11
	3.70	.020	3.00	.05
	3.70	.020	4.00	.07
Daemen	2.00	.020	2.00	.11
	2.00	.020	3.00	.11
	2.00	.040	1.50	.08
	2.00	.040	3.00	.11
See bw4	2.00	.020	1.50	.10
	2.00	.045	1.30	.08
Ahrens	5.00	.010	2.00	.15
	5.00	.020	3.00	.14
	5.00	.030	4.00	.15
	5.00	.030	5.00	.19

Table 11 Maxima and minima

	Rc/Dn50	sop	Hmo/Dn50	Kt	af	bf	bm
	-	-	-	-	-	-	-
Daemen	2.34	.022	.81	.06	.22	.35	
	1.22	.021	.81	.12	.22	.35	.37
	.73	.021	.78	.13	.22	.35	.28
	.24	.021	.78	.15	.22	.35	.21
DaKa 0.2	.00	.010	.31	.42	.23	.46	.42
	.00	.023	.70	.37	.22	.40	.37
	.00	.010	.51	.36	.22	.46	.36
	.00	.017	.92	.37	.21	.44	.37
	-1.28	.011	.32	.76	.23	.45	.46
	-1.28	.022	.65	.77	.22	.40	.46
	-1.28	.009	.47	.69	.23	.47	.41
	-1.28	.016	.87	.68	.21	.44	.40
	-2.55	.010	.29	.90	.23	.46	
	-2.55	.022	.65	.83	.22	.40	
	-2.55	.009	.50	.80	.22	.47	
	-2.55	.017	.89	.75	.21	.44	
DaKa 1.0	.00	.010	.29	.25	.23	.28	.25
	.00	.022	.65	.16	.22	.22	.16
	.00	.010	.51	.21	.22	.28	.21
	.00	.017	.89	.14	.21	.26	.14
	-1.28	.010	.31	.65	.23	.28	.38
	-1.28	.023	.70	.63	.22	.22	.37
	-1.28	.017	.91	.55	.21	.26	.29
	-2.55	.010	.31	.86	.23	.28	
	-2.55	.023	.70	.80	.22	.22	
	-2.55	.010	.52	.71	.22	.28	
	-2.55	.018	.95	.67	.21	.25	
Ahrens	2.27	.008	.89	.32	.21	.78	.79
	2.24	.003	.93	.37	.21	.79	.83
	2.27	.001	.80	.42	.22	.81	.91
	2.28	.001	.56	.49	.22	.82	.98
	2.65	.001	.80	.43	.22	.81	1.01

Table 12 Data with Hmo/Dn50 < 1.0

Data sets	formulas Daemen	vdMeer	Hearn	Daemen min.	max.
conv. bw's	.058	.093		.026	.066
conv. bw's *	.048	.089		.027	.053
vdMeer,Daemen	.033	.067		.027	.030
vdMeer,Daemen *	.029	.065		.029	.016
reef bw's (all)	.092	.100	.073	.068	.080
reef bw's (all) *	.054	.067	.065	.017	.060
reef bw's (lim.)	.067	.080	.050	.066	.031
reef bw's (lim.) *	.031	.058	.042	.018	.032
PoAl	.058	.050			
PoAl *	.058	.050			
Allsop	.051	.040			
Allsop *	.045	.041			
See bw5+bw10	.093	.097			
See bw5+bw10 *	.068	.086			

conv. bw's = vdMeer, DaKa 0.2, DaKa 1.0, See bw4, Daemen

reef bw's (all) = Ahrens

reef bw's (lim.) = Ahrens, tests at which the crest height lowered less then 10 percent of its initial height

* = data in range of application: $1 < Hmo/Dn50 < 6$

$0.01 < sop < 0.05$

FORMULAS:

Daemen conv: equations 4.1, 4.4, 4.20, 4.22

Daemen reef: equations 4.1, 4.4, 4.14, 4.23

vdMeer (1990): equations 3.5, 3.6, 3.7

Hearn (1987): equations 3.2, 3.3, 3.4

Daemen min: equations 4.22a, 4.23a

Daemen max: equations 4.22b, 4.23b

Table 13 Statistical data on various formulas

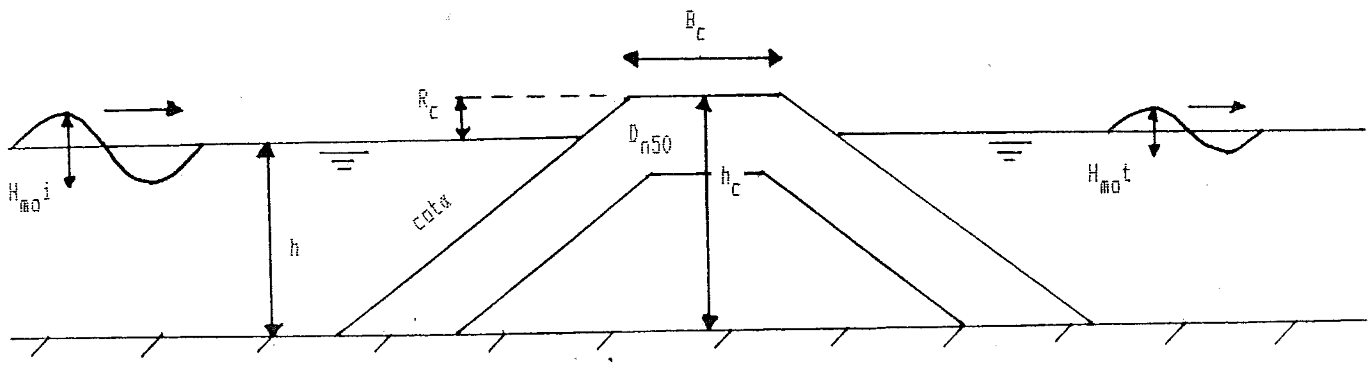
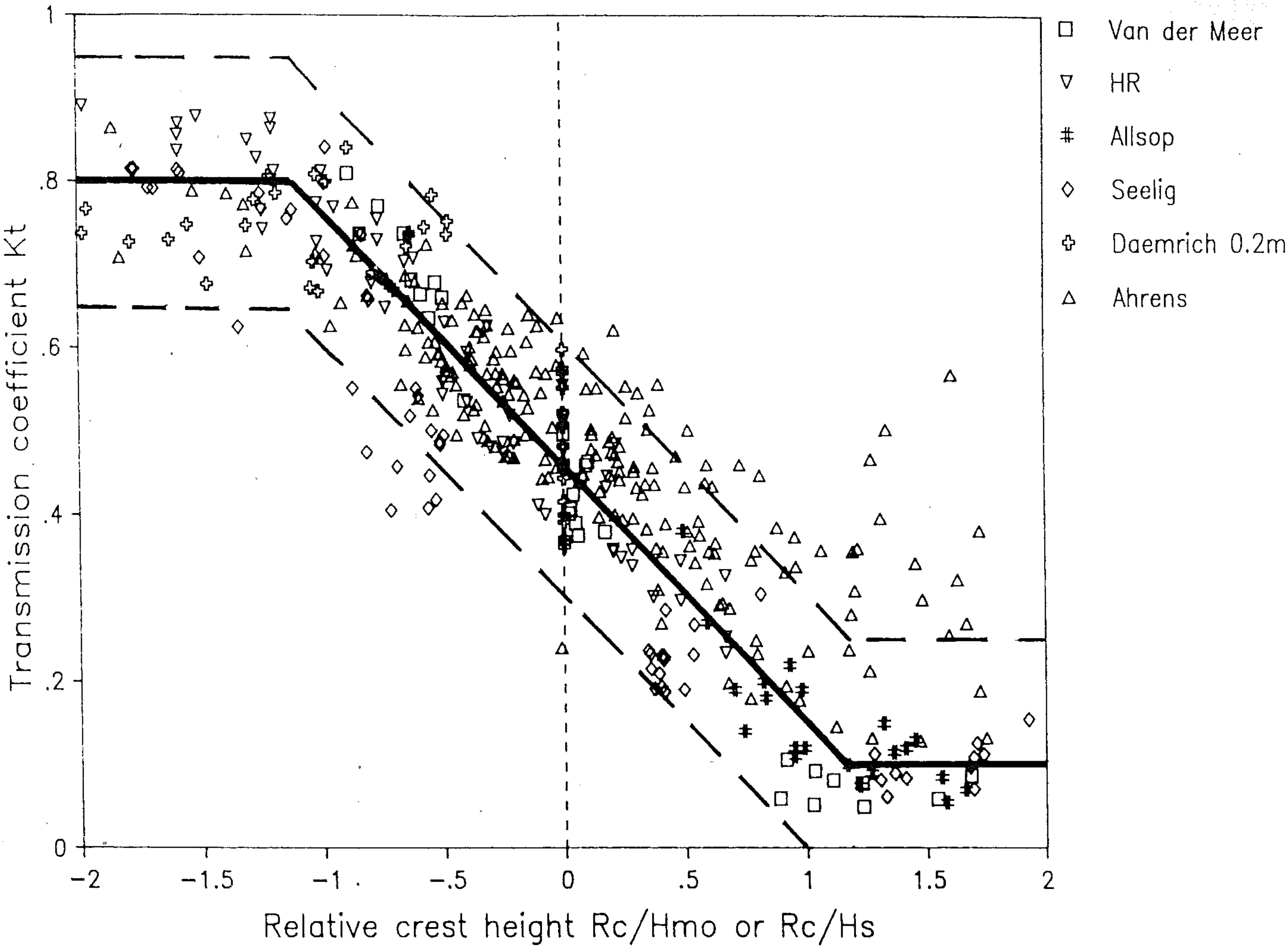


fig 1. Example of breakwater cross section and governing parameters



Van der Meer (1990)

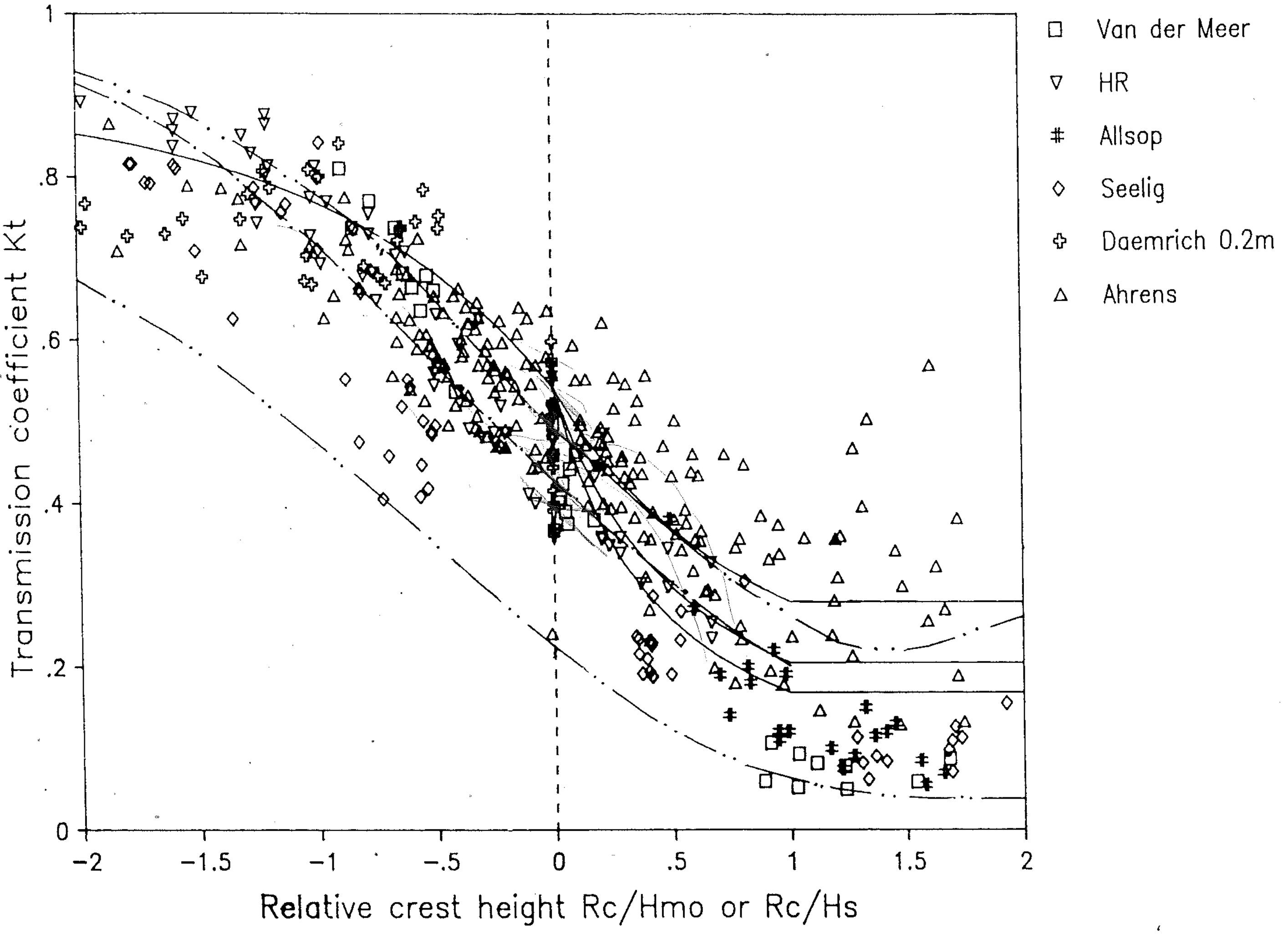
90% confidence levels

$-2.0 < R_c/H_s < -1.13$ $K_t = 0.80$

$-1.13 < R_c/H_s < 1.2$ $K_t = 0.46 - 0.3\, R_c/H_s$

$1.2 < R_c/H_s < 2.0$ $K_t = 0.10$

fig 2. Proposed formula for wave transmission of Van der Meer (1990)



Ahrens (1987),

Hearn (1987), upper curve: P=5
middle curve: P=10
lower curve: P=15

Powell and Allsop (1985), breakwater with porosity of 0.4

Powell and Allsop (1985), upper boundary, porosity of 0.5
lower boundary, porosity of 0.0

fig 3. Suggested curves of Ahrens (1987) and Hearn (1987) and Powell and Allsop (1985)

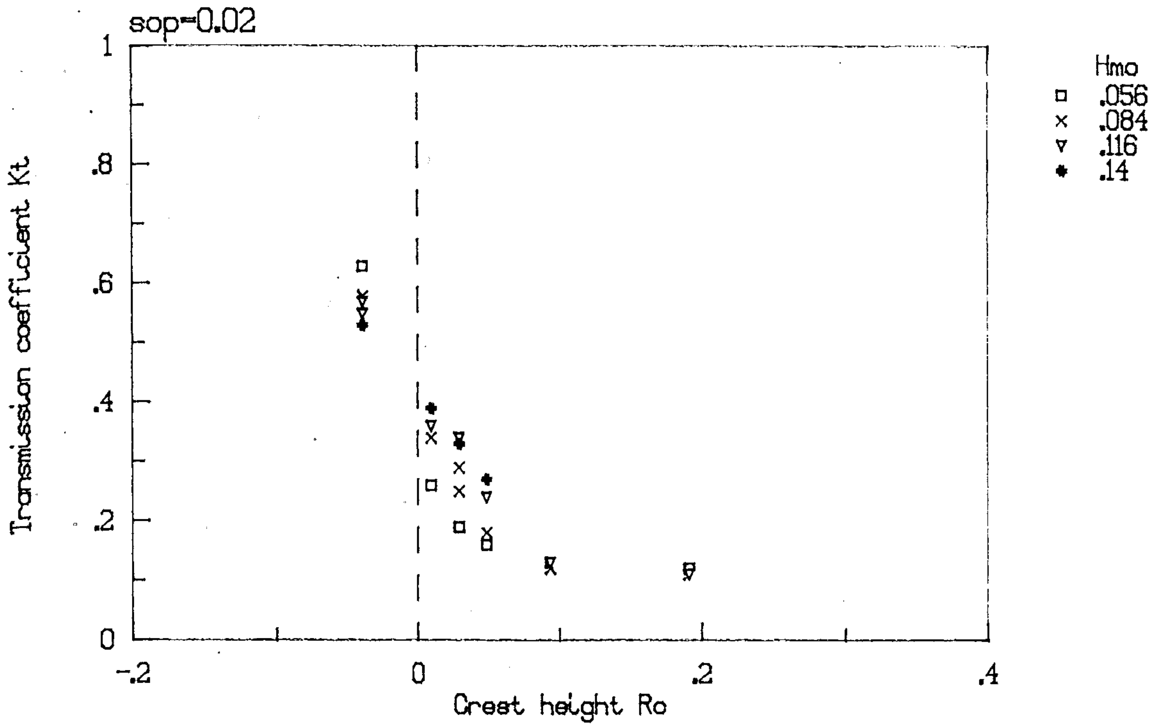


fig 4. Influence of wave height, Present data

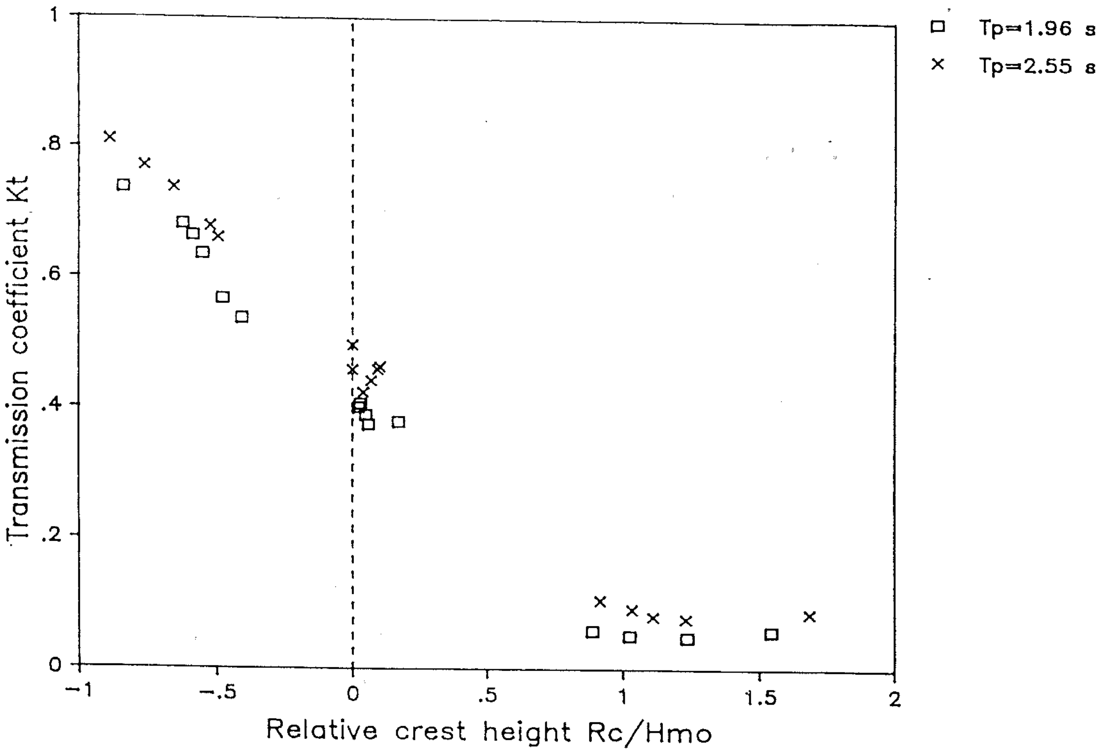


fig 5a. Influence of wave period using relative crest height R_c/H_{mo}, Data of Van der Meer (1988)

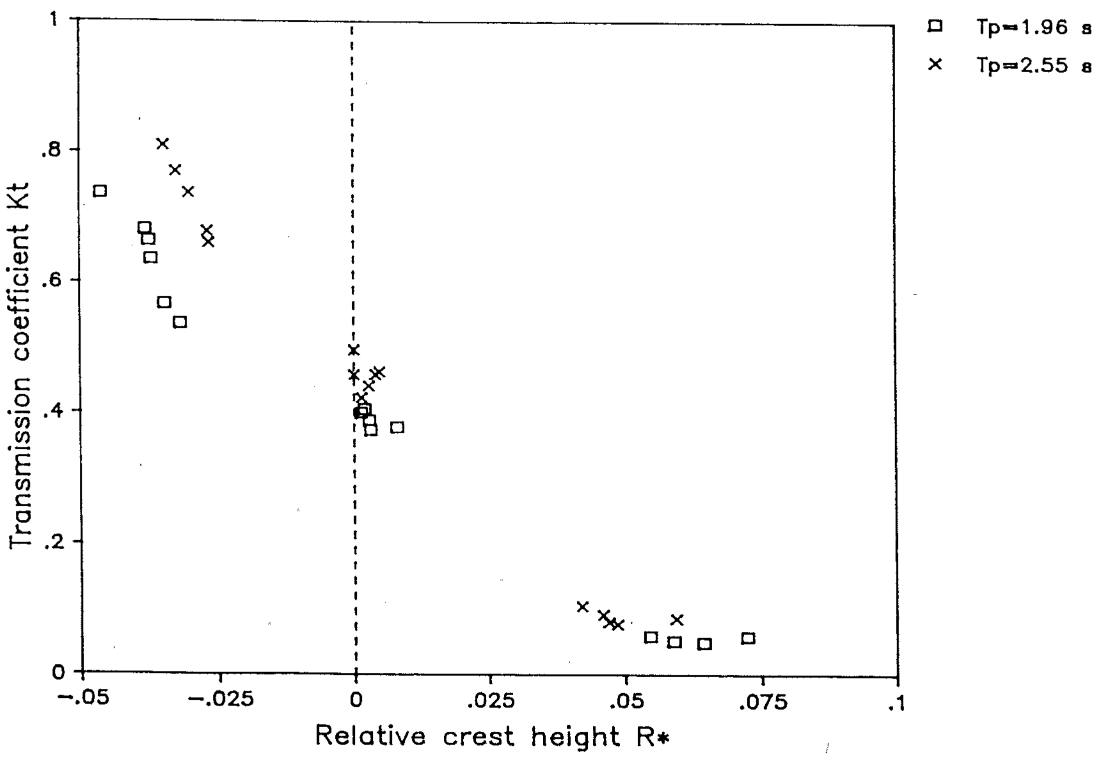
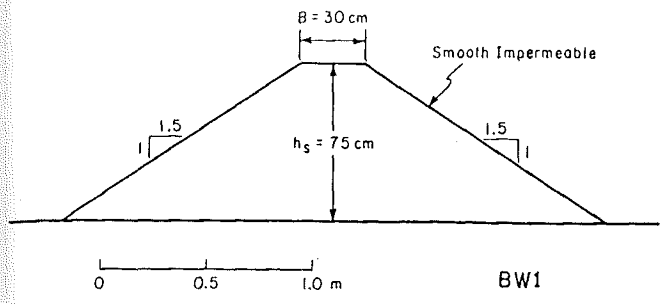
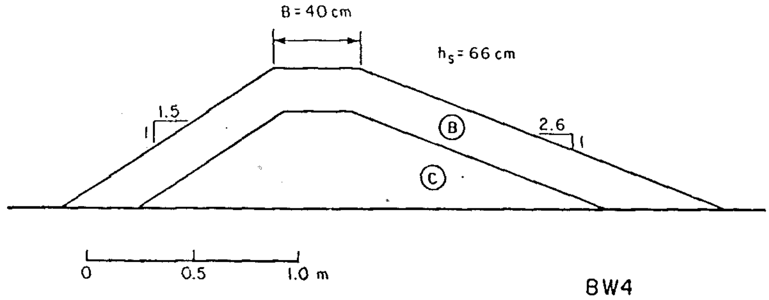


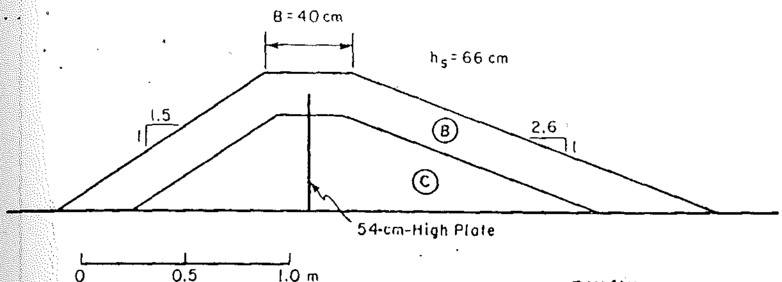
fig 5b. Influence of wave period using relative crest height R^*_p, Data of Van der Meer (1988)



BW1

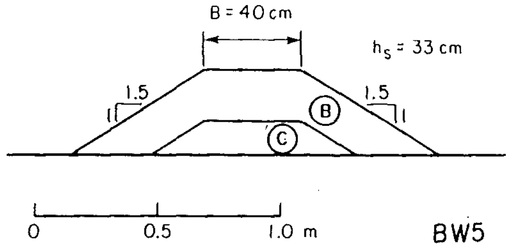


BW4



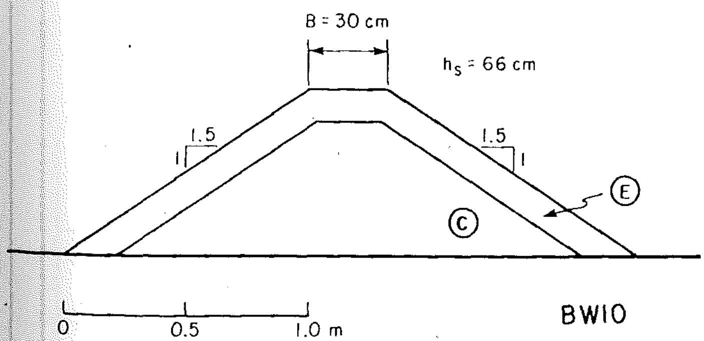
BW4W

BW4W is similar to BW4, but includes a 54-centimeter-high impermeable plat in the center of the structure.



BW5

BW5 is typical of a breakwater built in relatively shallow water. The armor unit size is large compared to the structure height and the core size relatively small.



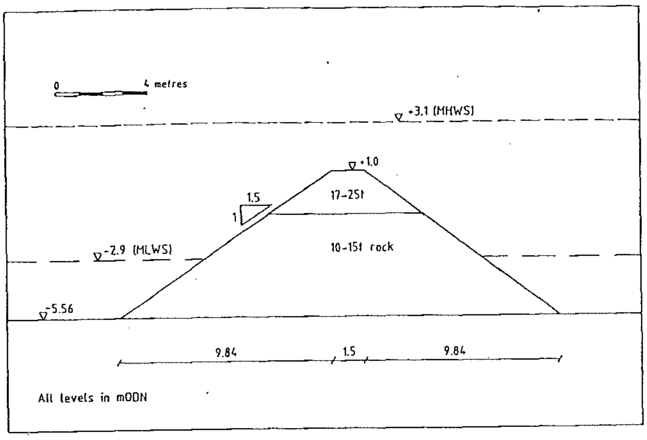
BW10

BW10 was made with an armor one unit thick of well-fitted rectangular rock. The material was placed with one surface parallel to the structure face.

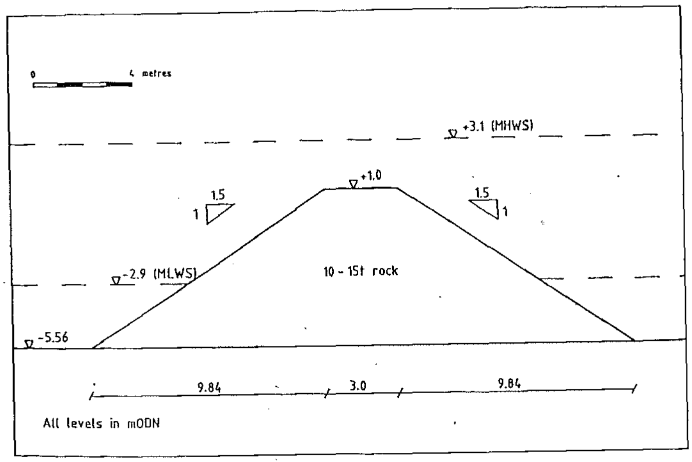
Material characteristics.

Material	Description	W_{85} [1] (g)	W_{50} [2] (g)	W_{15} [3] (g)	d_{50} [4] (cm)
A	Angular stone	2,520	1,530	990	8.3
B	Angular stone	4,680	3,690	2,900	11.1
C	Angular stone	180	68	31	2.9
D	Dolos	405	390	390	----
E	Flat stone	13,200	11,200	8,100	16.1
F	Angular stone	7,600	4,900	2,500	12.2

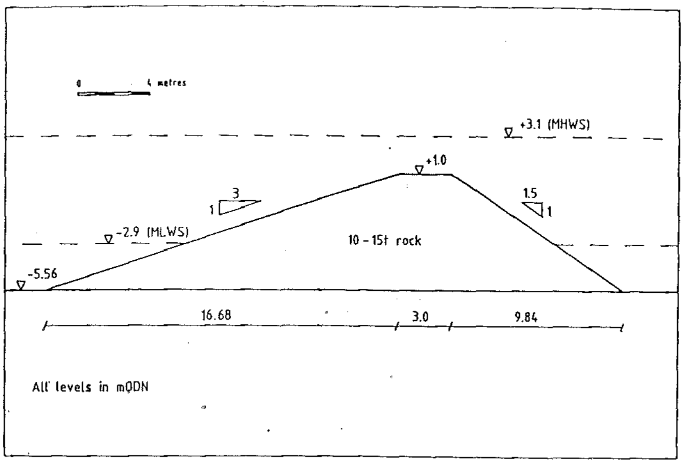
fig 6. Cross-sections of Seelig (1980)



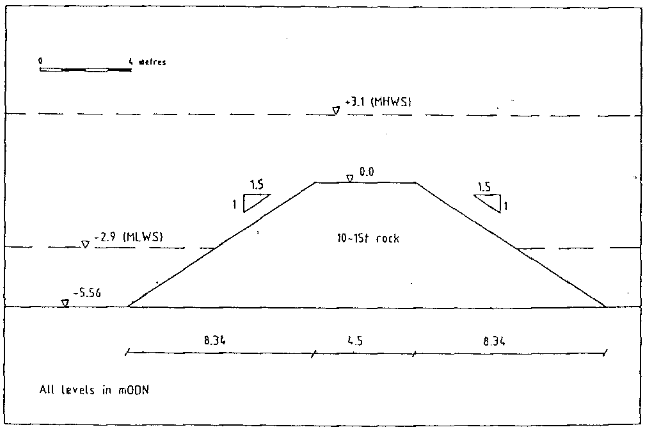
Section III 1 : 1.5 slope, Crest @ +1.0mODN



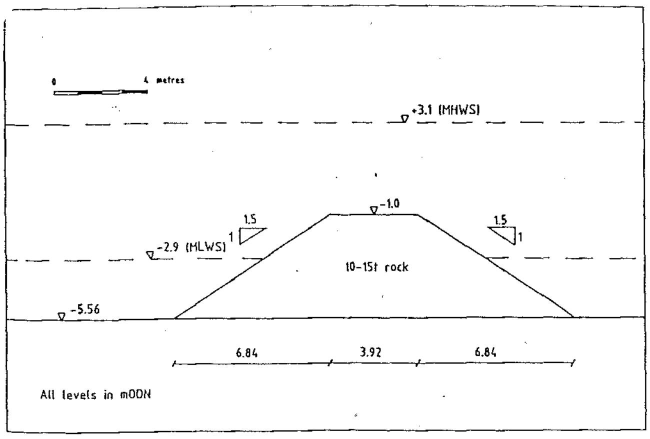
Section II 1:1.5 slope, Crest @ +1.0mODN



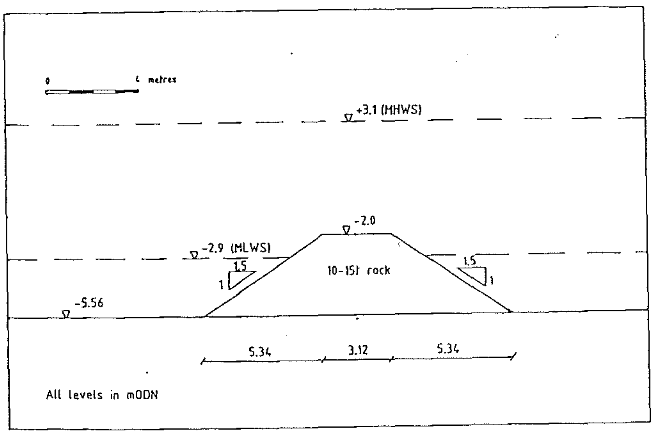
Sections I and IV 1:3 slope, Crest @ +1.0mODN



Section V 1 : 1.5 slope, Crest @ 0.0mODN



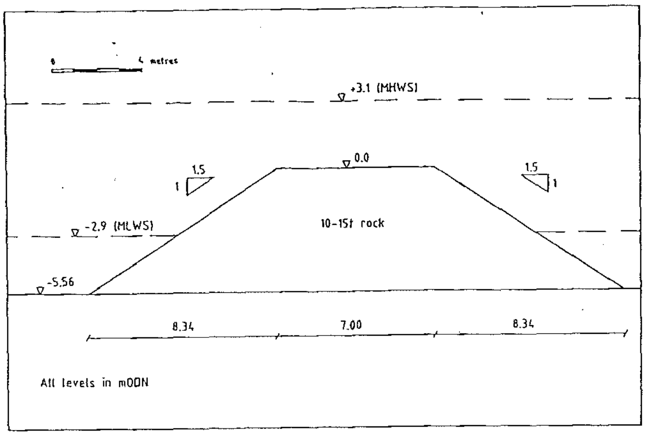
Section VI 1 : 1.5 slope, Crest @ -1.0mODN



Section VII 1 : 1.5 slope, Crest @ -2.0mODN

scale 1:22

fig 7. Cross-sections of Powell and Allsop (1985) scale 1:22



Section VIII 1:1.5 slope, Crest @ 0.0mODN

fig 8a. Cross-section of Powell and Allsop (1985)

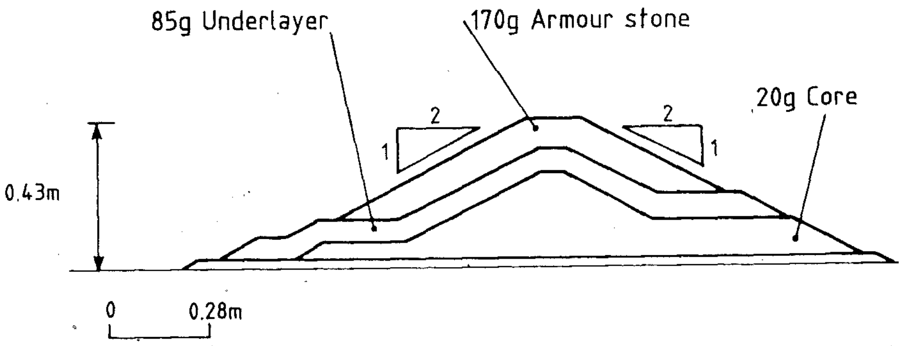


fig 8b. Cross section of Allsop (1983)

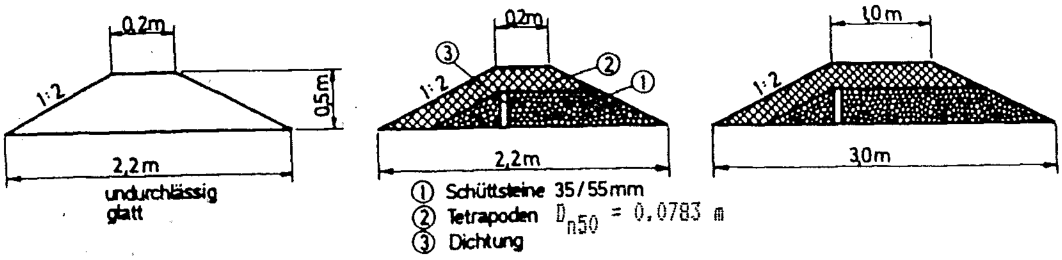
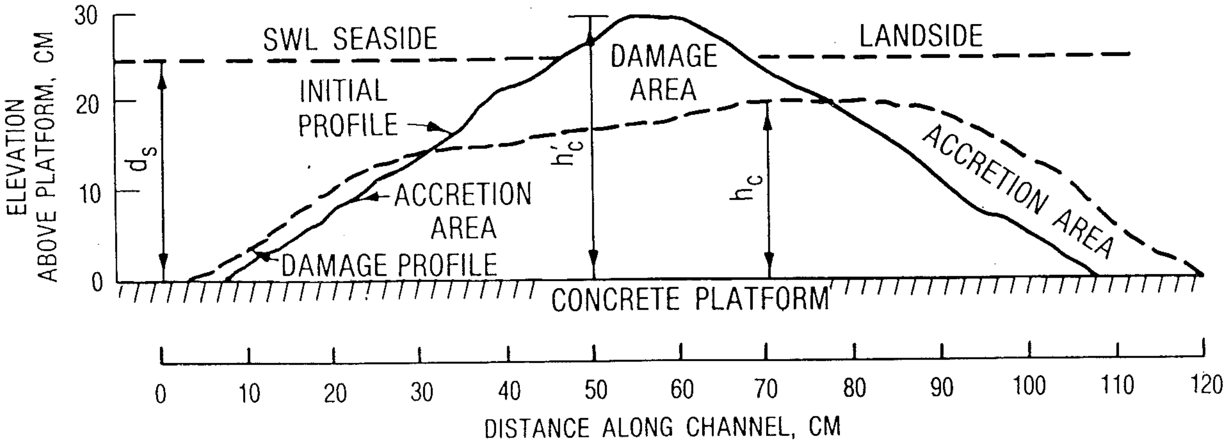


fig 8c. Cross sections of Daemrich and Kahle (1985)



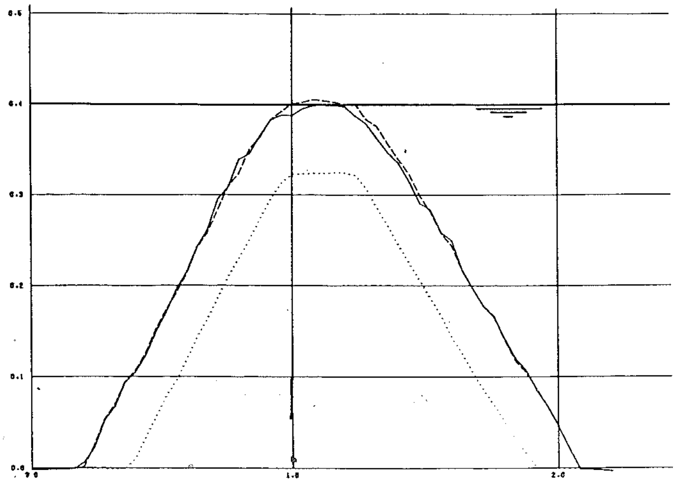
Cross-sectional view of initial and typical damaged reef profiles (swl denotes still-water level)

Basic Data for Each Subset

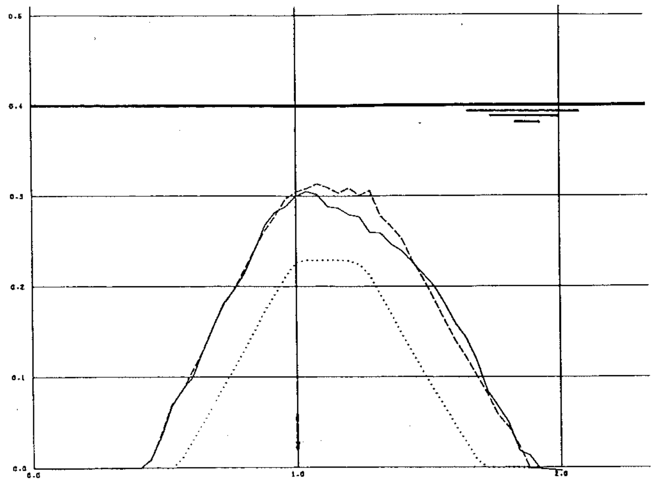
Subset No.	No. of Tests	Water Depth d_s, cm	Crest Height "as built" h_c', cm	Median Stone Weight W_{50}, g	Area of Breakwater Cross Section A_t, cm^2
1	27	25	25	17	1,170
2	3	25	NA*	17	1,170
3	29	25	30	17	1,560
4	12	25	NA	17	1,560
5	41	25	35	17	2,190
6	11	25	NA	17	2,190
7	38	25	32	71	1,900
8	26	25	NA	71	1,900
9	13	30	32	71	1,900
10	5	30	NA	71	1,900

* NA denotes not applicable to previous damage test series.

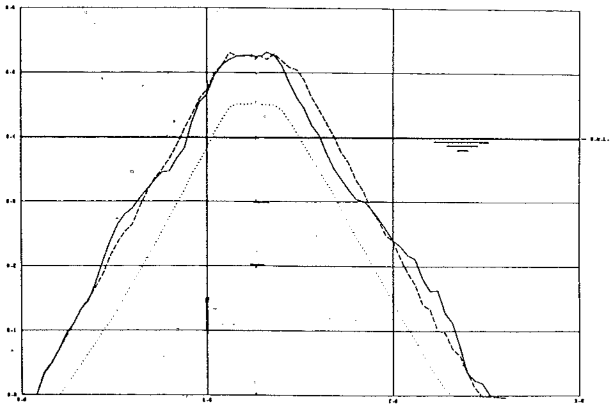
fig 9. Cross-sections and basic test data of Ahrens (1987)



R_c = 0.0 m   Tests 1-11



R_c = -0.09 m   Tests 21-31



R_c = 0.125 m   Tests 12-20

Armour layer	rock
Slope angle	1:2
Diameter armour	D_{n50} = 0.0344 m
Permeability structure	permeable
Width of crest	0.30 m
Slope of foreshore	1:30
Water depth at structure	0.40 m
Water depth in flume	0.80 m

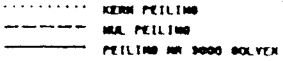


fig 10. Cross-sections of Van der Meer (1988)

All measures in metres and relative to wave tank

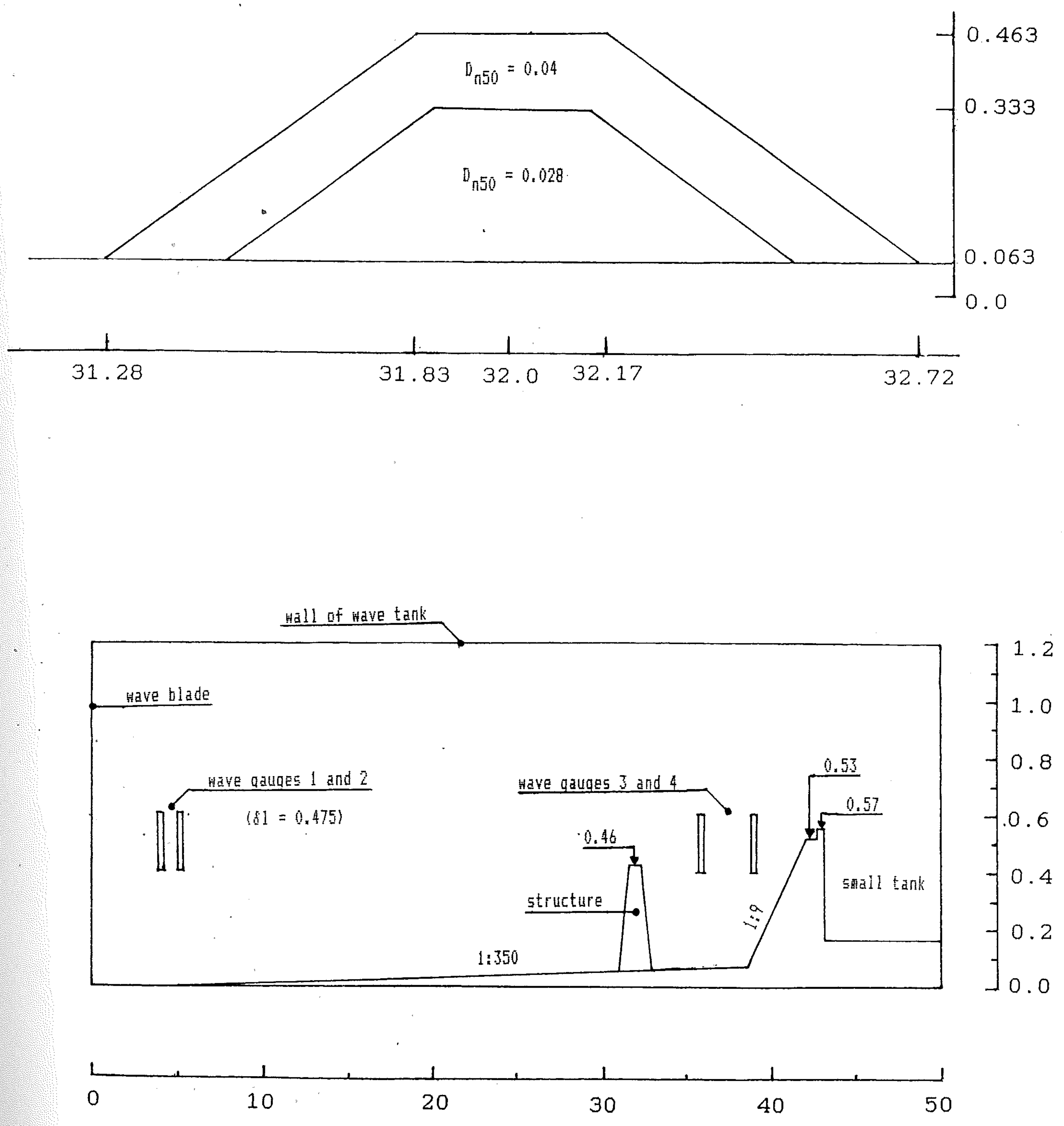


fig 11. Cross-section and overview of test set-up of present tests

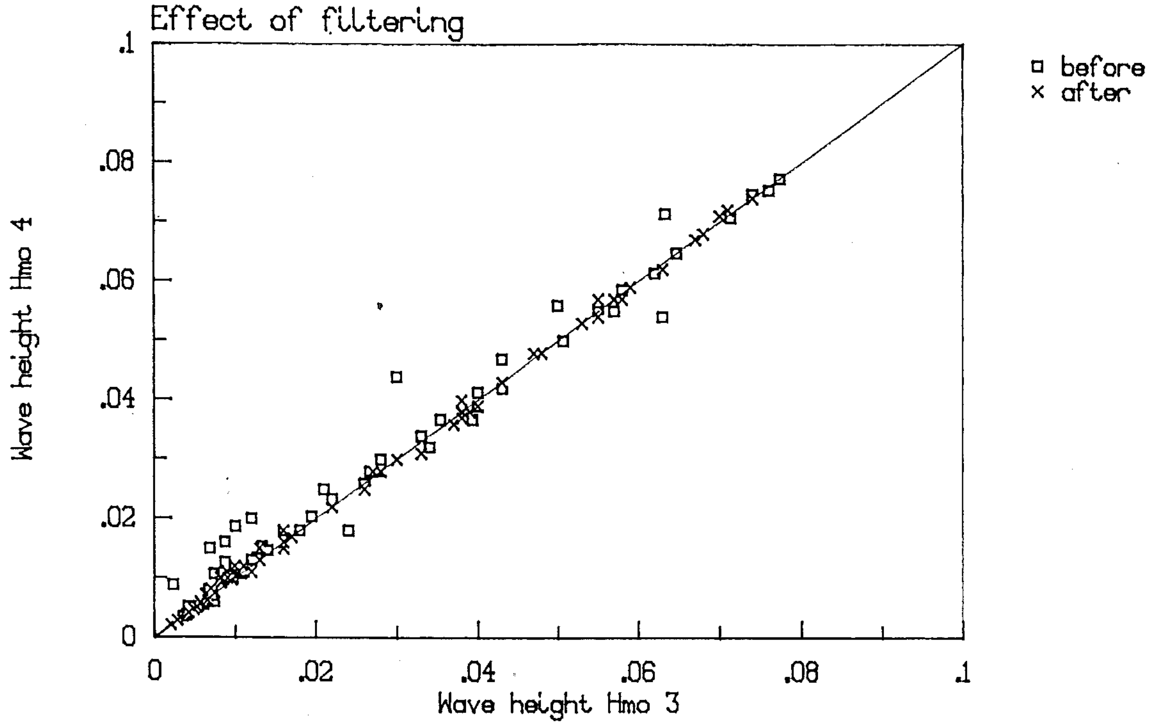


fig 12a.Effect of filtering data of wave gauges behind the structure, Present data

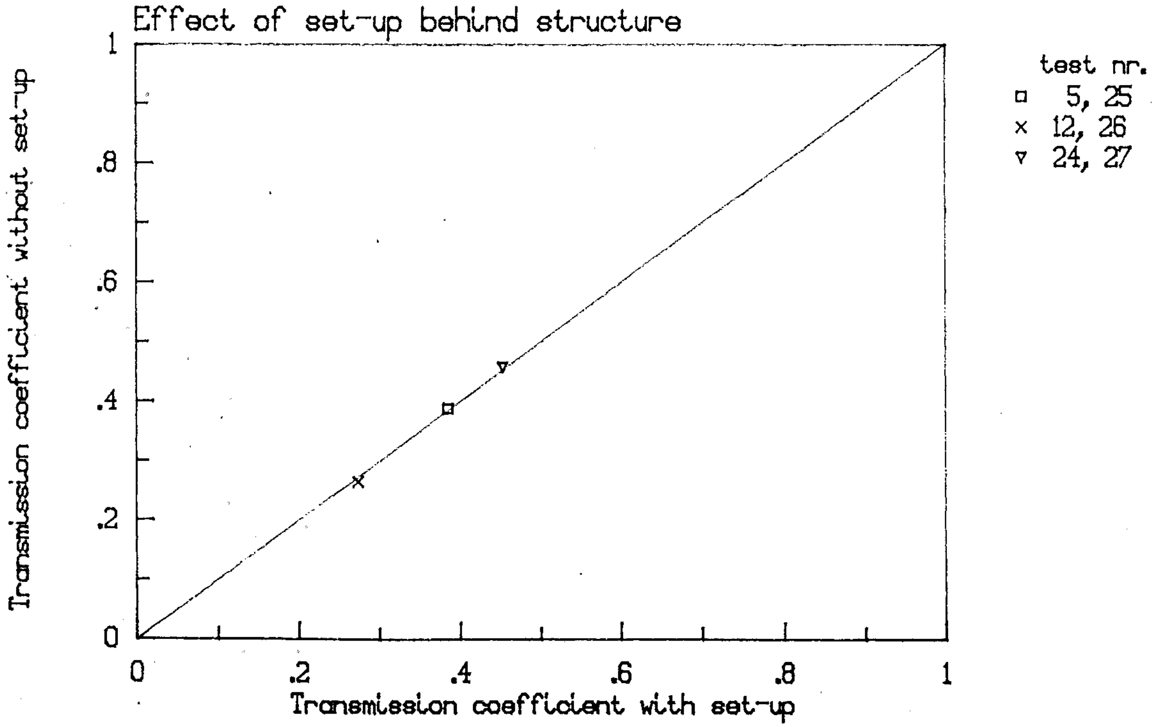


fig 12b.Effect of set-up behind the structure, Present data

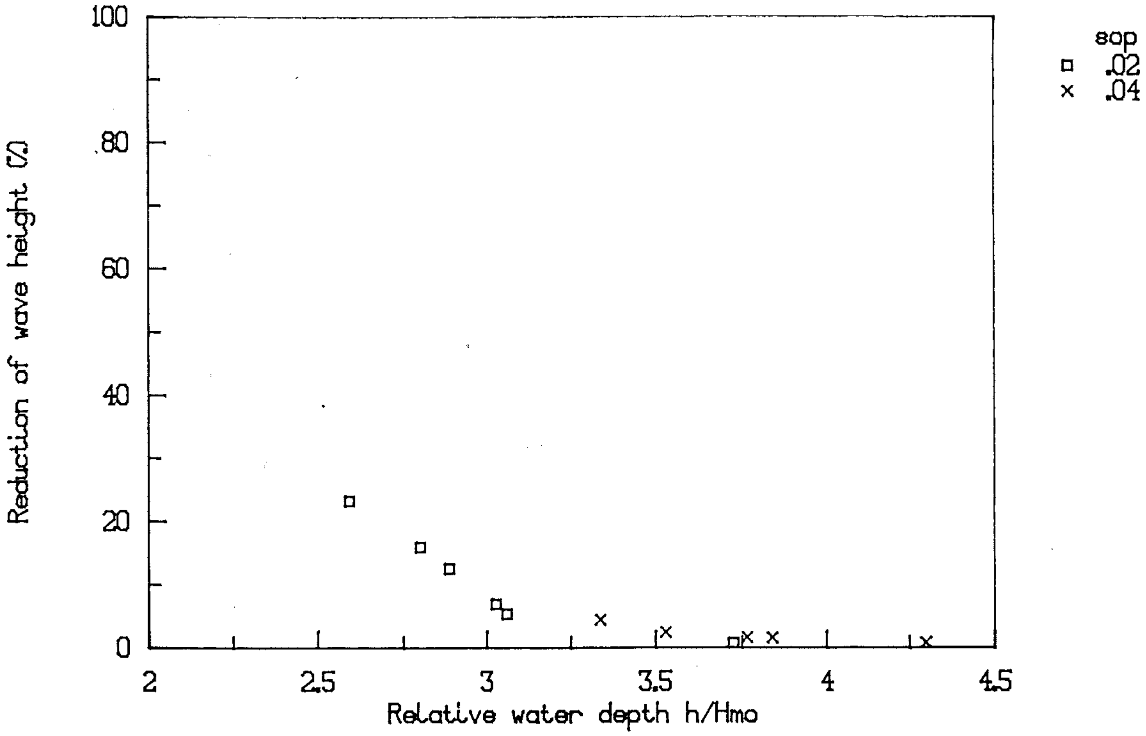


fig 12c.Reduction of wave height due to foreshore slope for all largest wave heights used per water depth, according to computer wave program ENDEC, Present data

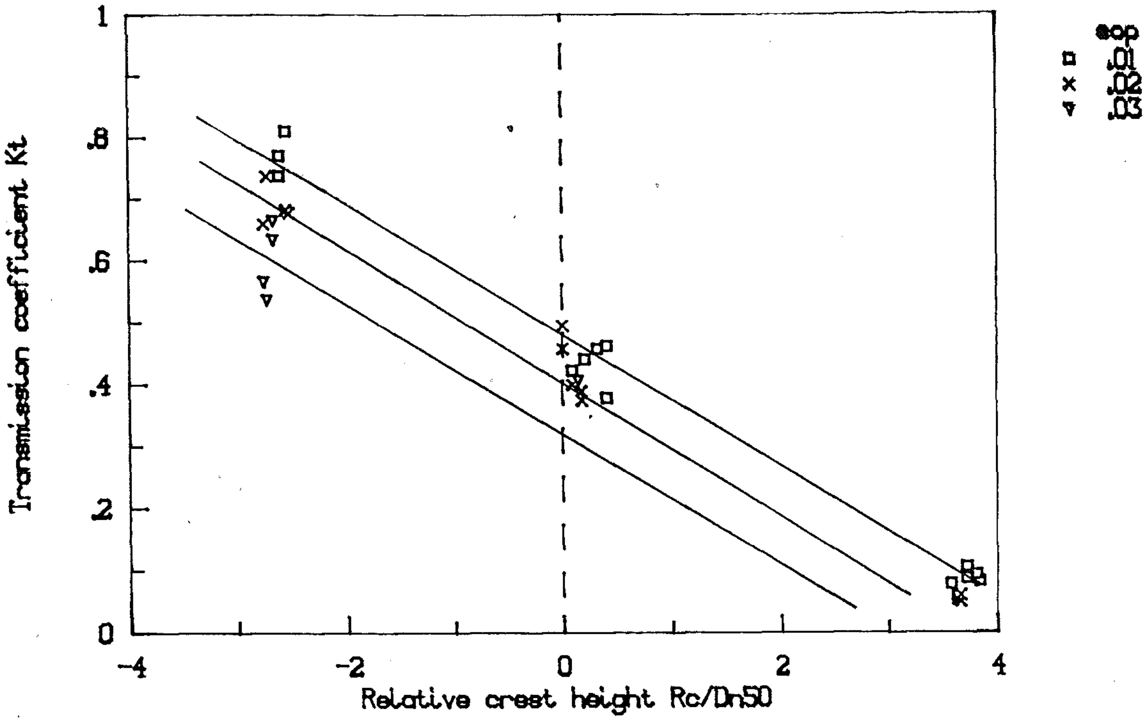


fig 13a. Influence of wave steepness, Data of Van der Meer (1988)

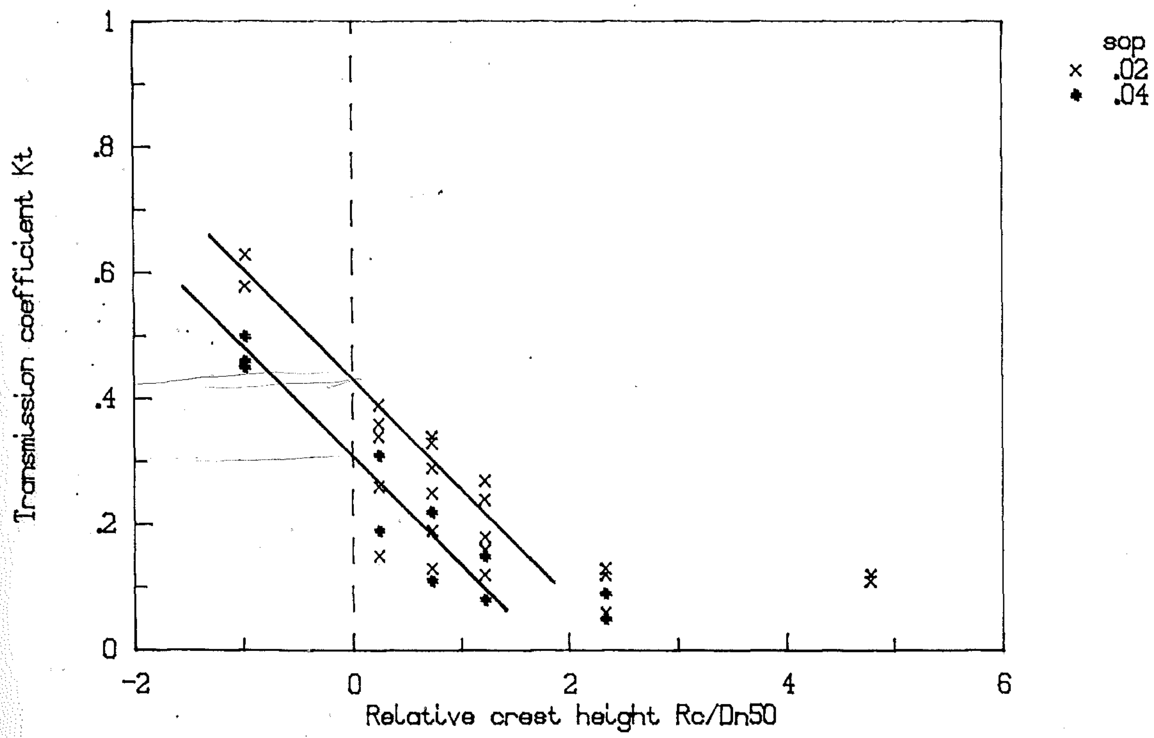


fig 13b. Influence of wave steepness, Present data

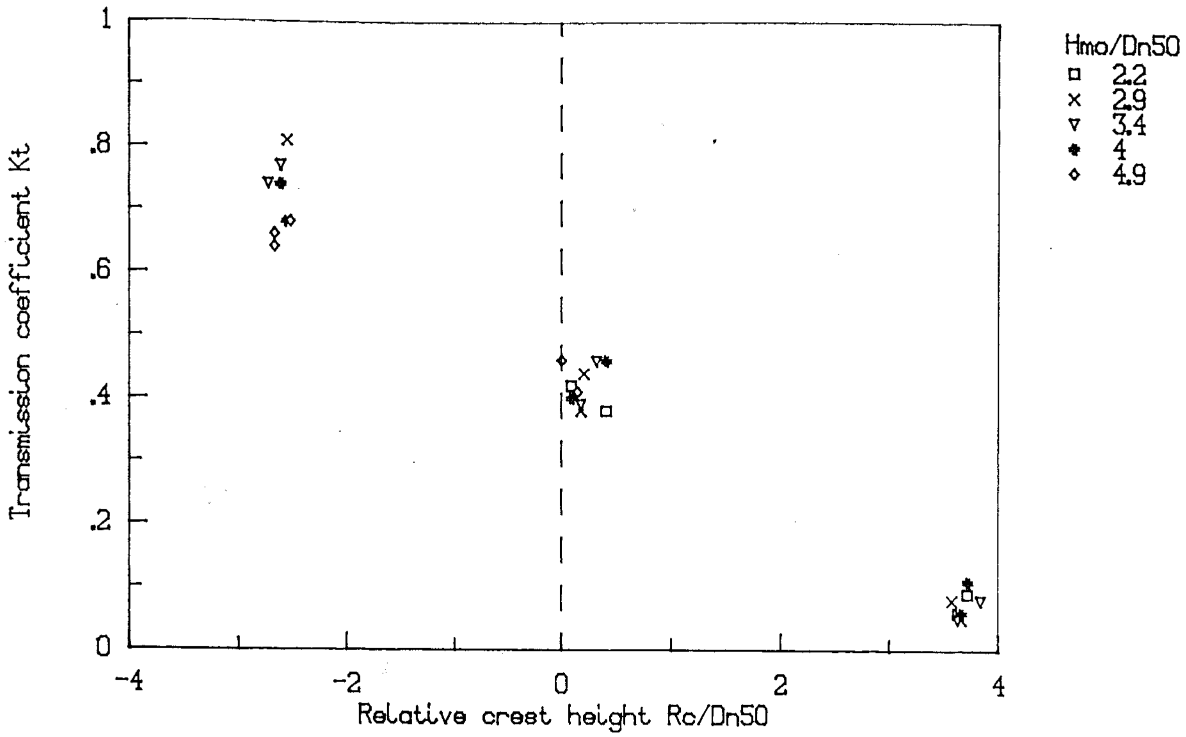


fig 14a. Influence of relative wave height, Data of Van der Meer (1988)

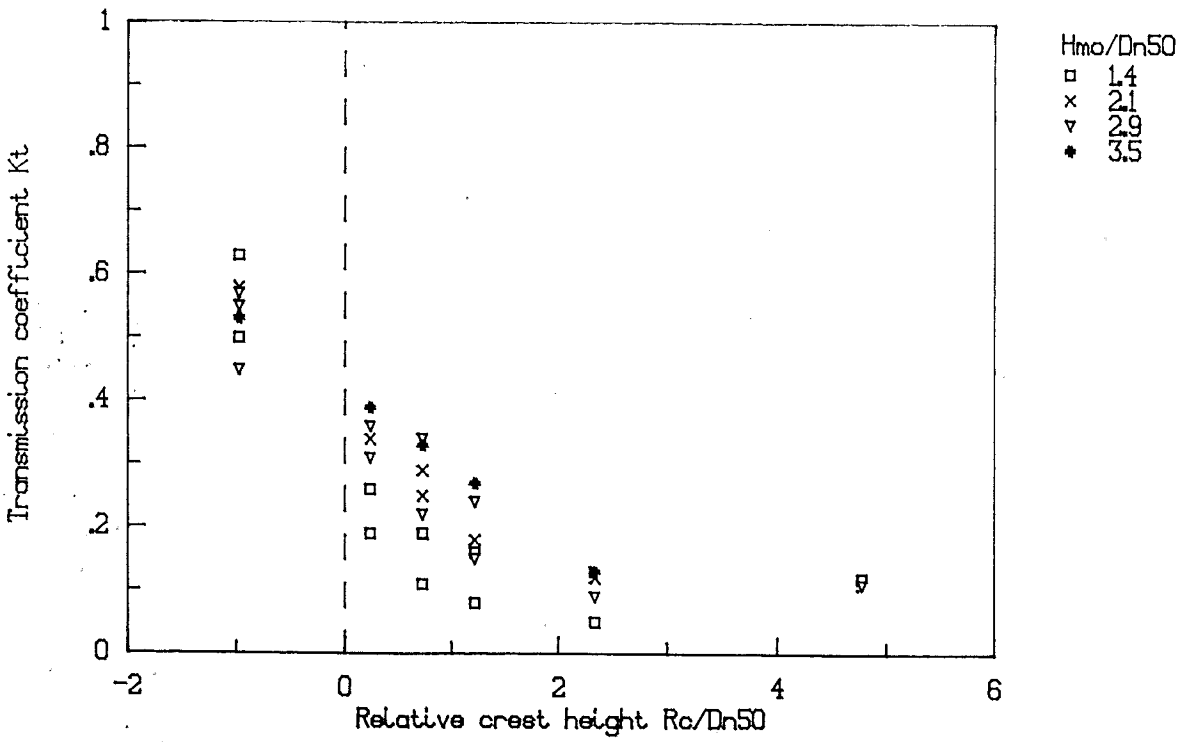


fig 14b. Influence of relative wave height, Present data

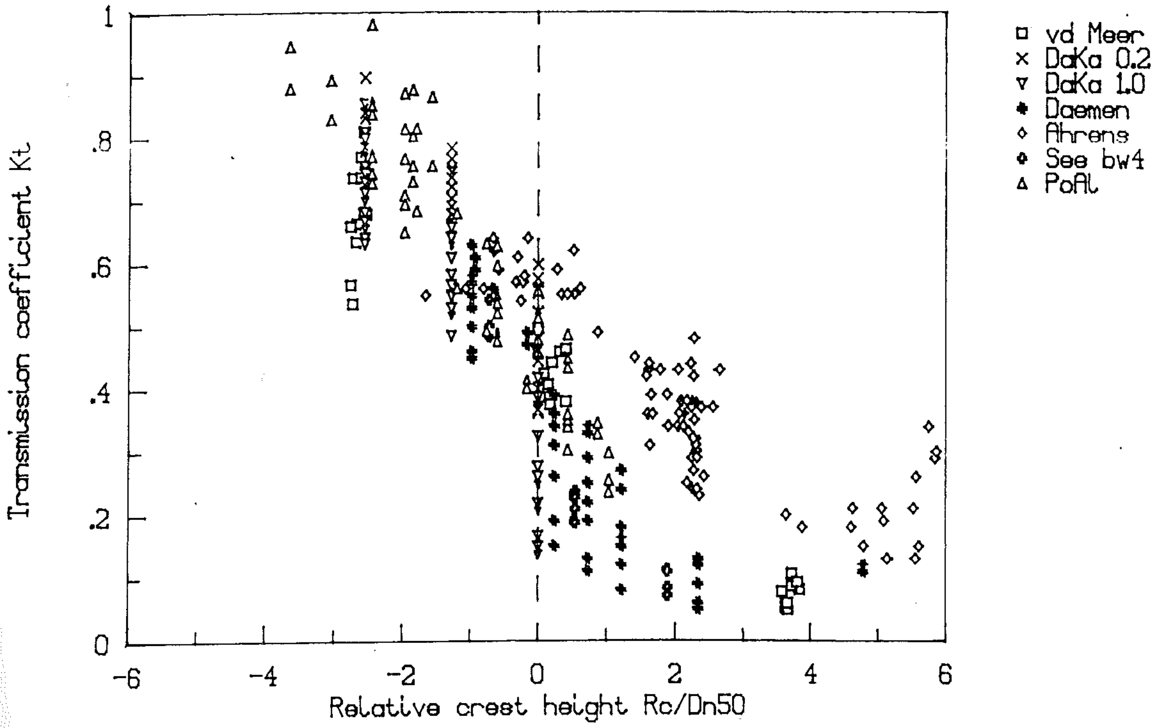


fig 15. Transmission coefficient as a function of relative crest height R_c/D_{n50}. All data

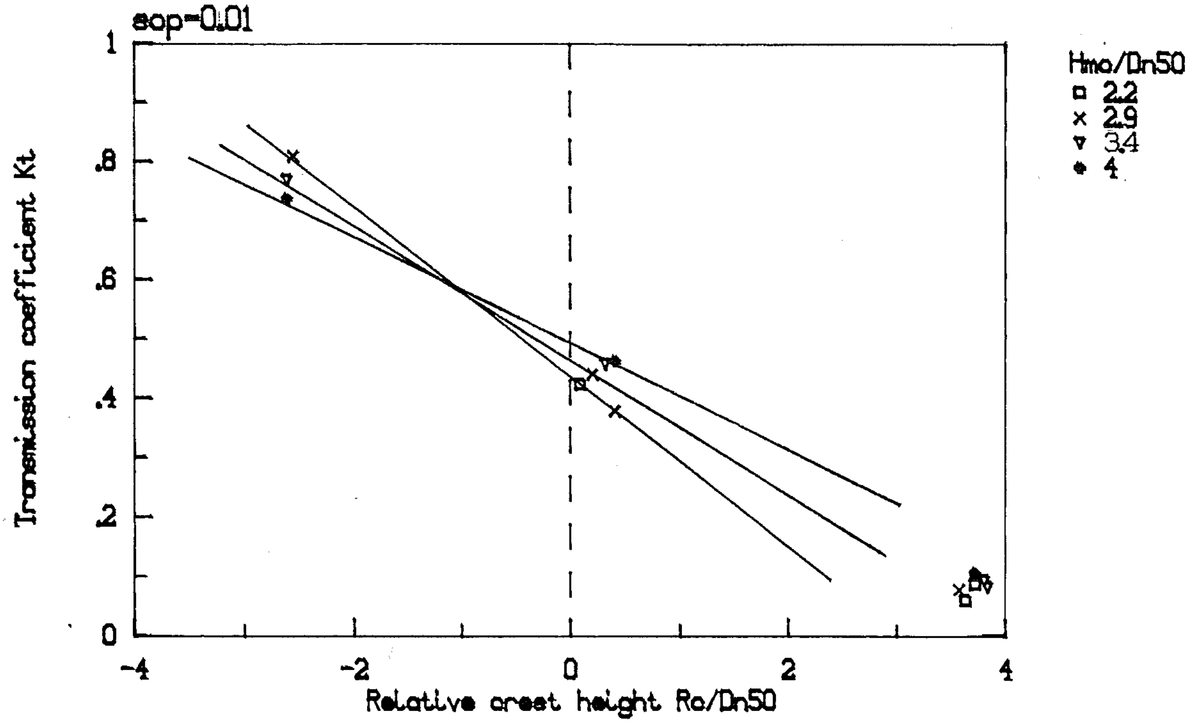


fig 16a.Influence of relative wave height for wave steepness 0.01, Data of Van der Meer (1988)

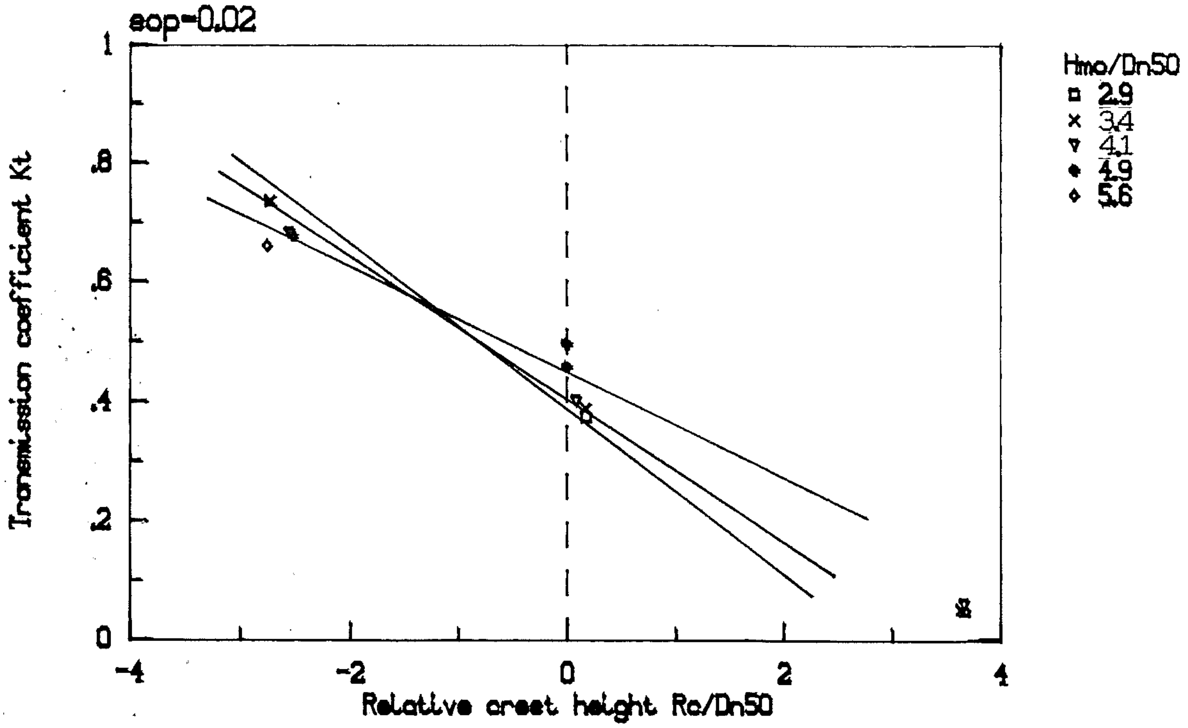


fig 16b.Influence of relative wave height for wave steepness 0.02, Data of Van der Meer (1988)

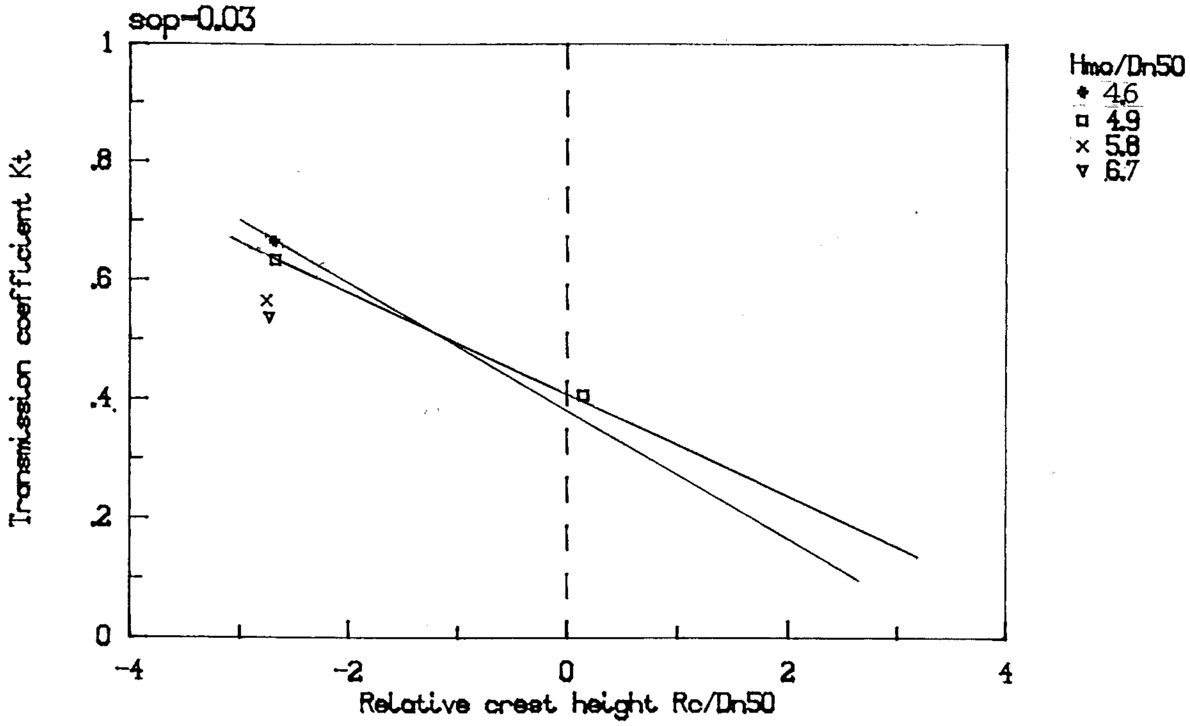


fig 17a. Influence of relative wave height for wave steepness 0.03, Data of Van der Meer (1988)

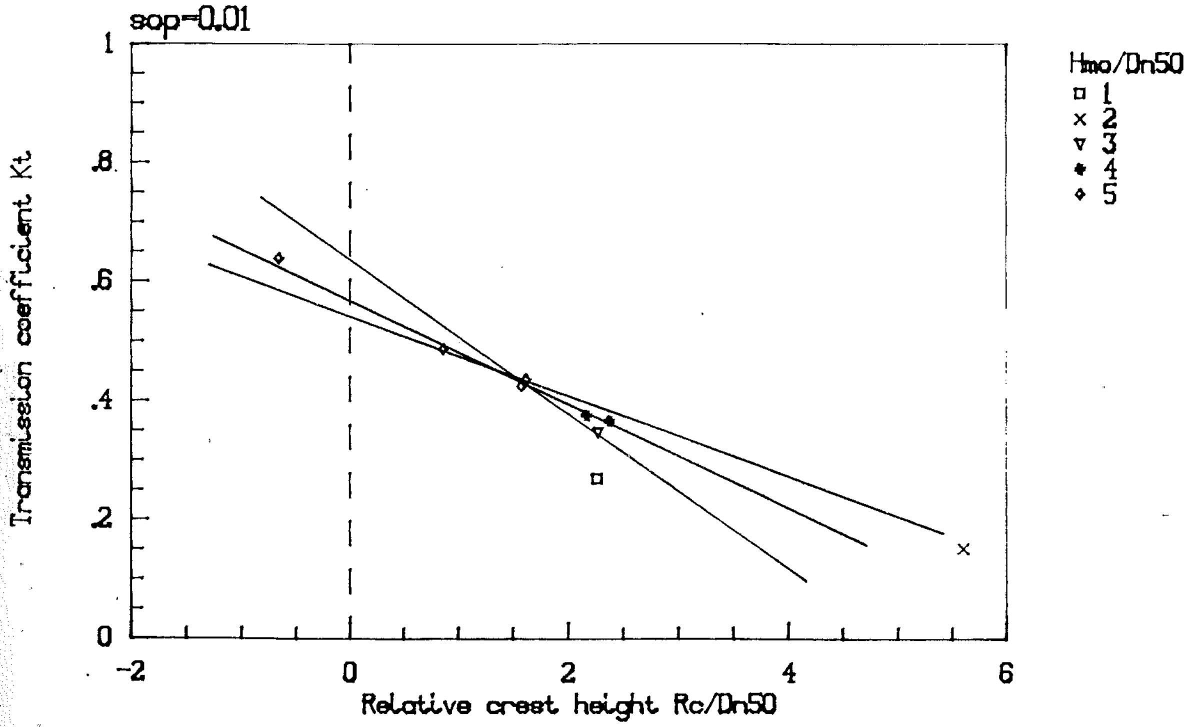


fig 17b. Influence of relative wave height for wave steepness 0.01, Data of Ahrens (1987)

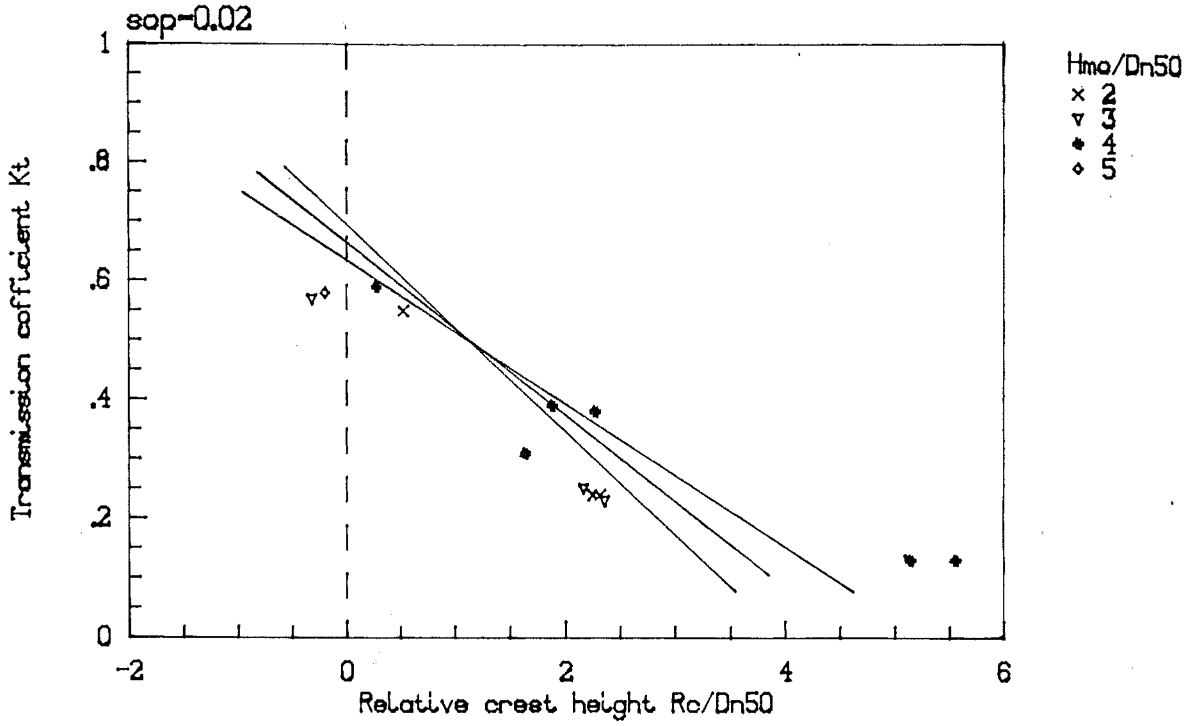


fig 18a. Influence of relative wave height for wave steepness 0.02, Data of Ahrens (1987)

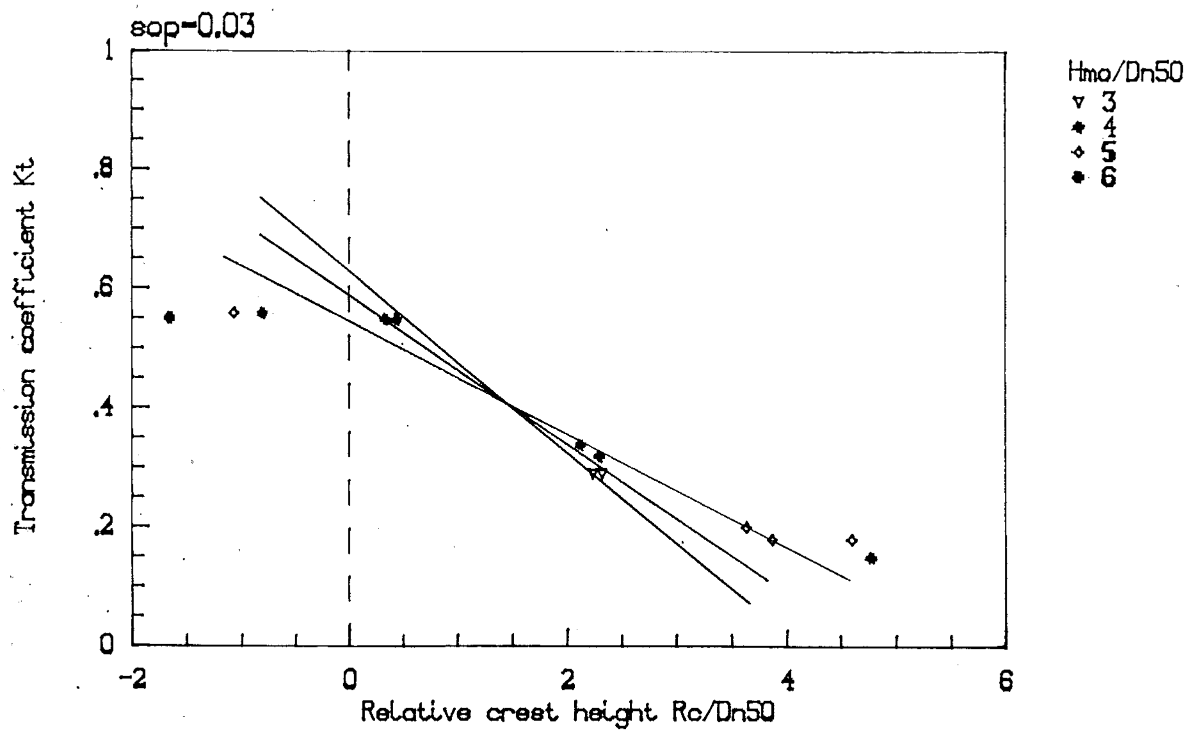


fig 18b. Influence of relative wave height for wave steepness 0.03, Data of Ahrens (1987)

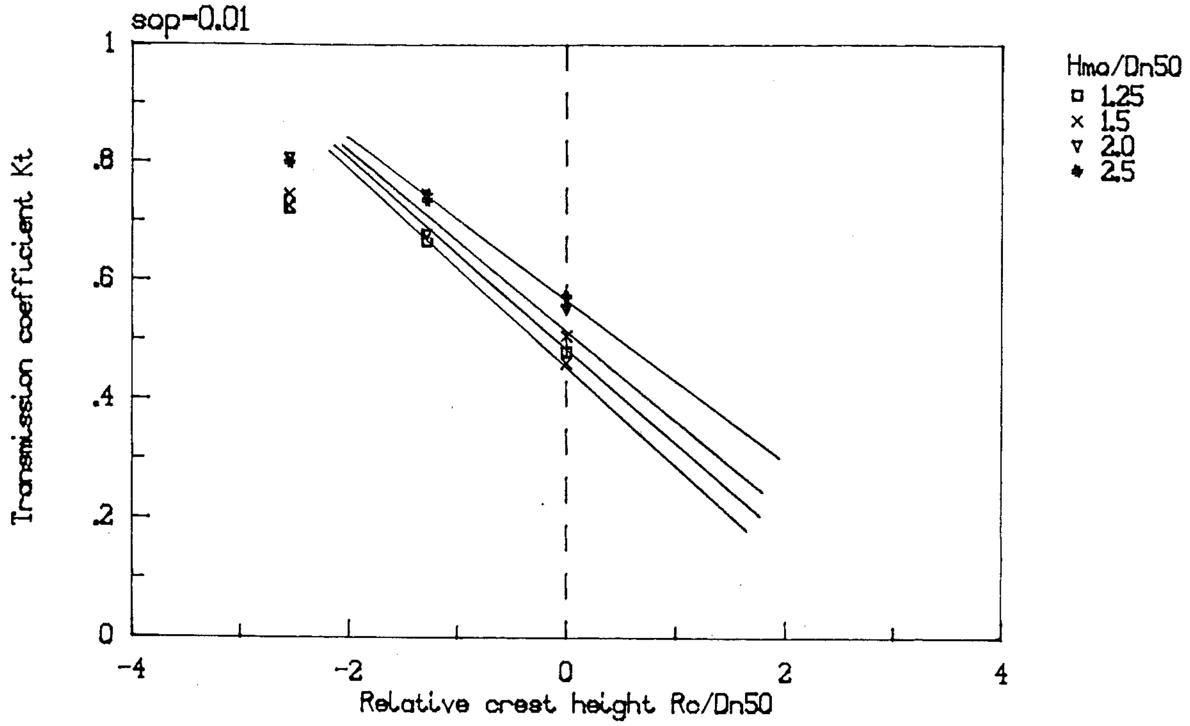


fig 19a. Influence of relative wave height for wave steepness 0.01, Data of Daemrich and Kahle (1985), B_c = 0.2 m

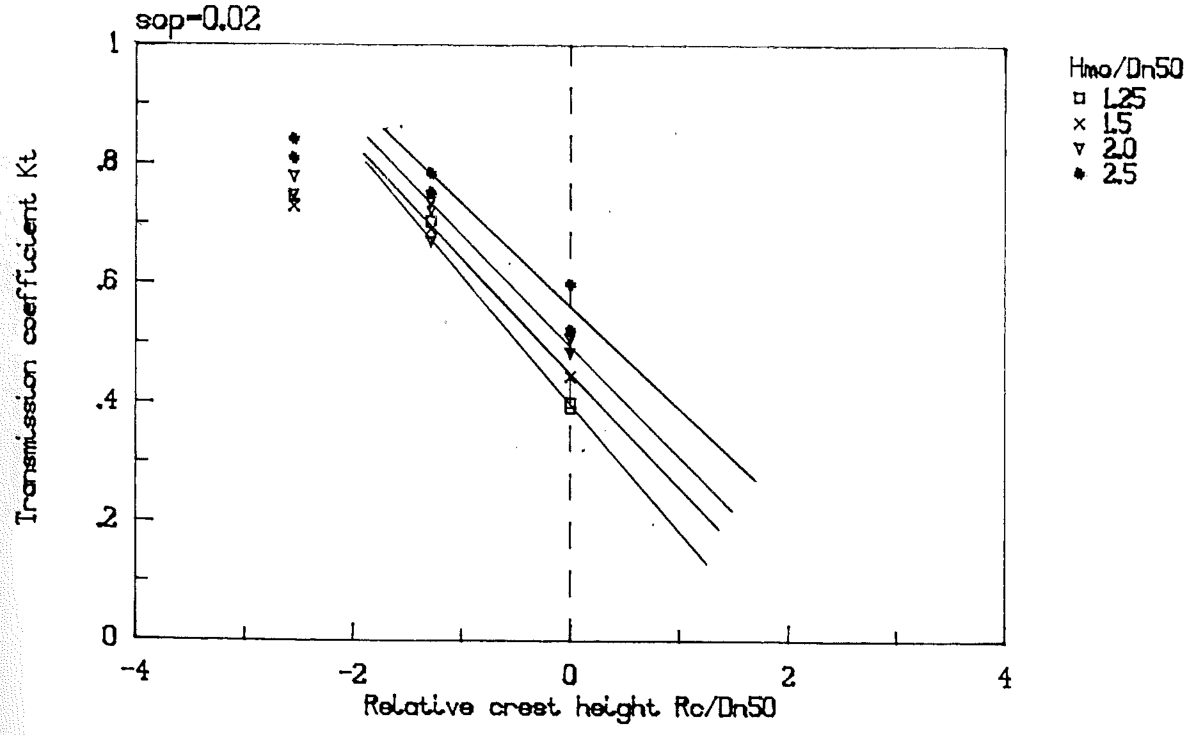


fig 19b. Influence of relative wave height for wave steepness 0.02, Data of Daemrich and Kahle (1985), B_c = 0.2 m

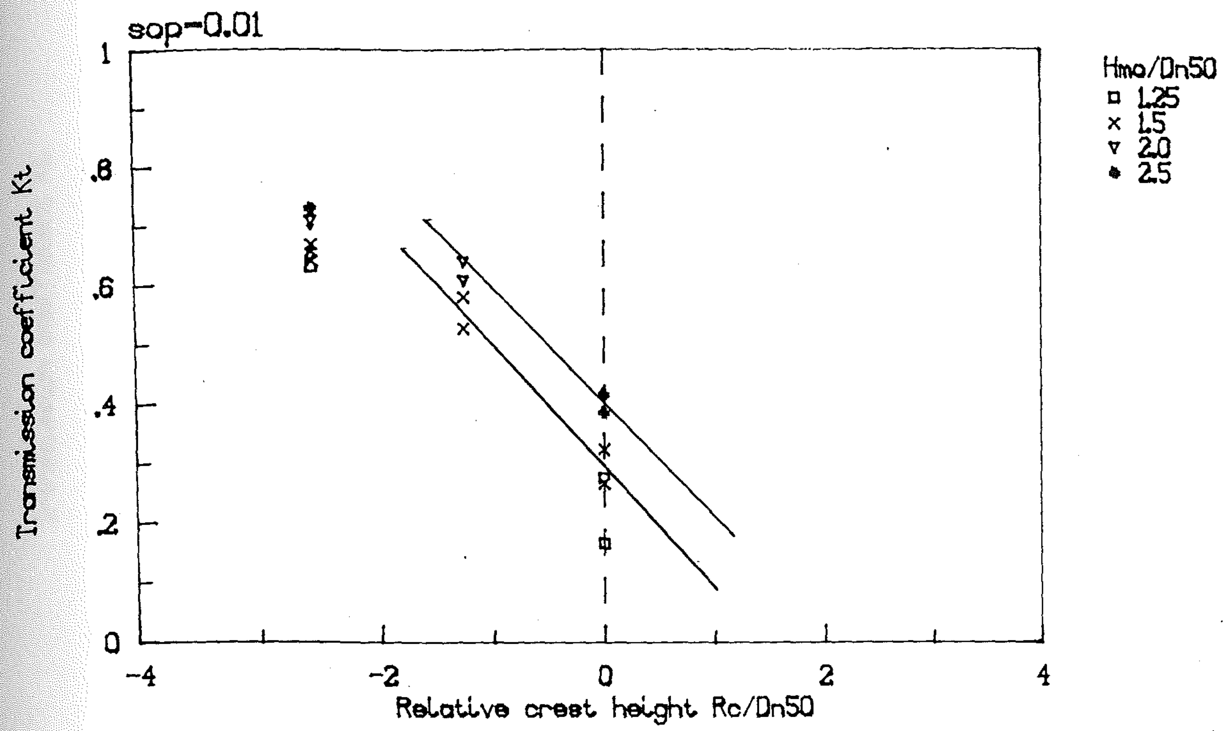


fig 20a. Influence of relative wave height for wave steepness 0.01, Data of Daemrich and Kahle (1985), B_c = 1.0 m

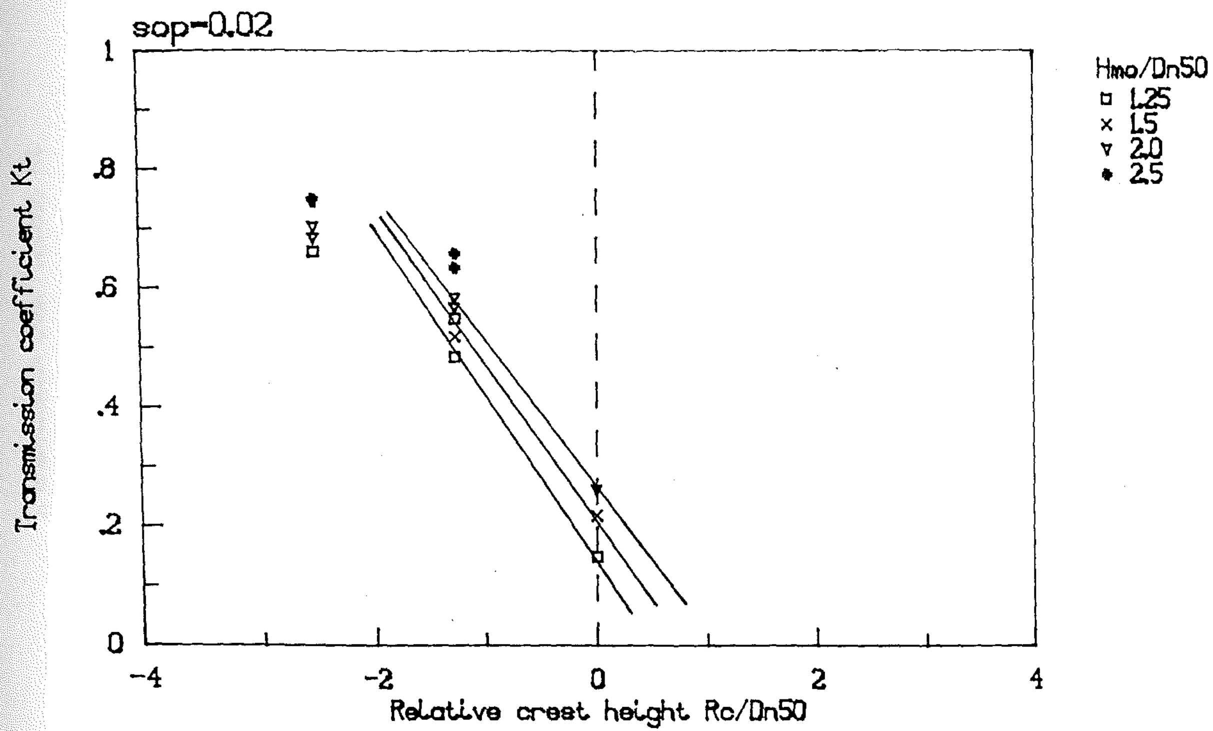


fig 20a. Influence of relative wave height for wave steepness 0.02, Data of Daemrich and Kahle (1985), B_c = 1.0 m

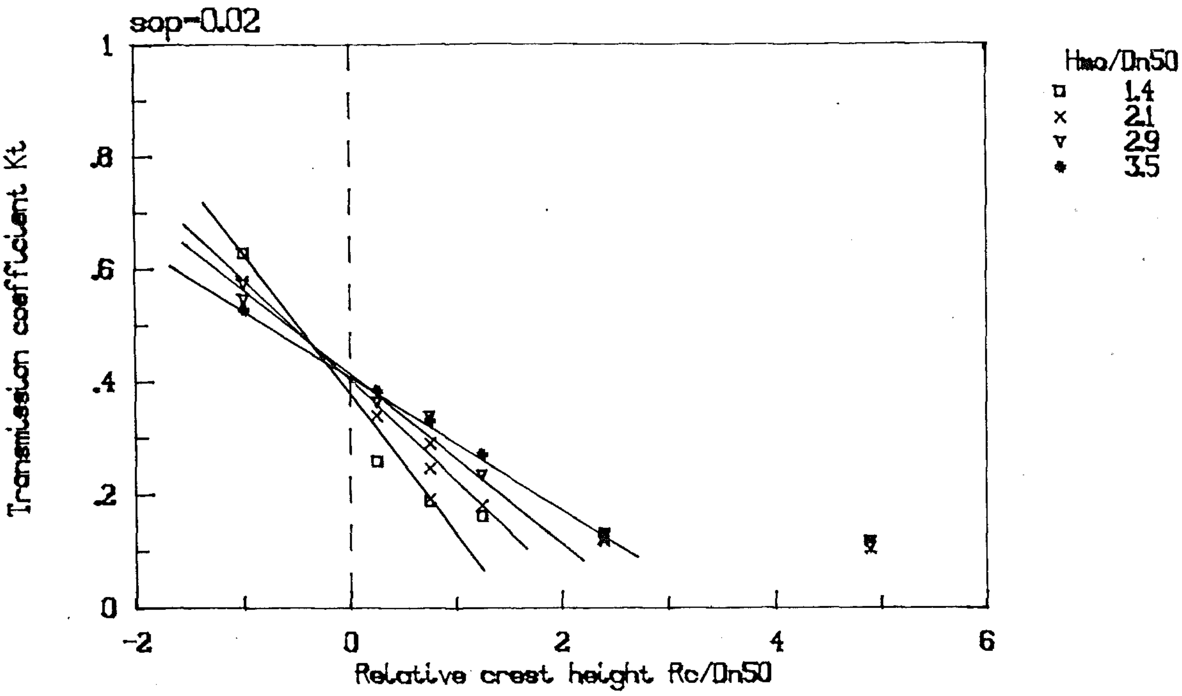


fig 21a. Influence of relative wave height for wave steepness 0.02, Present data

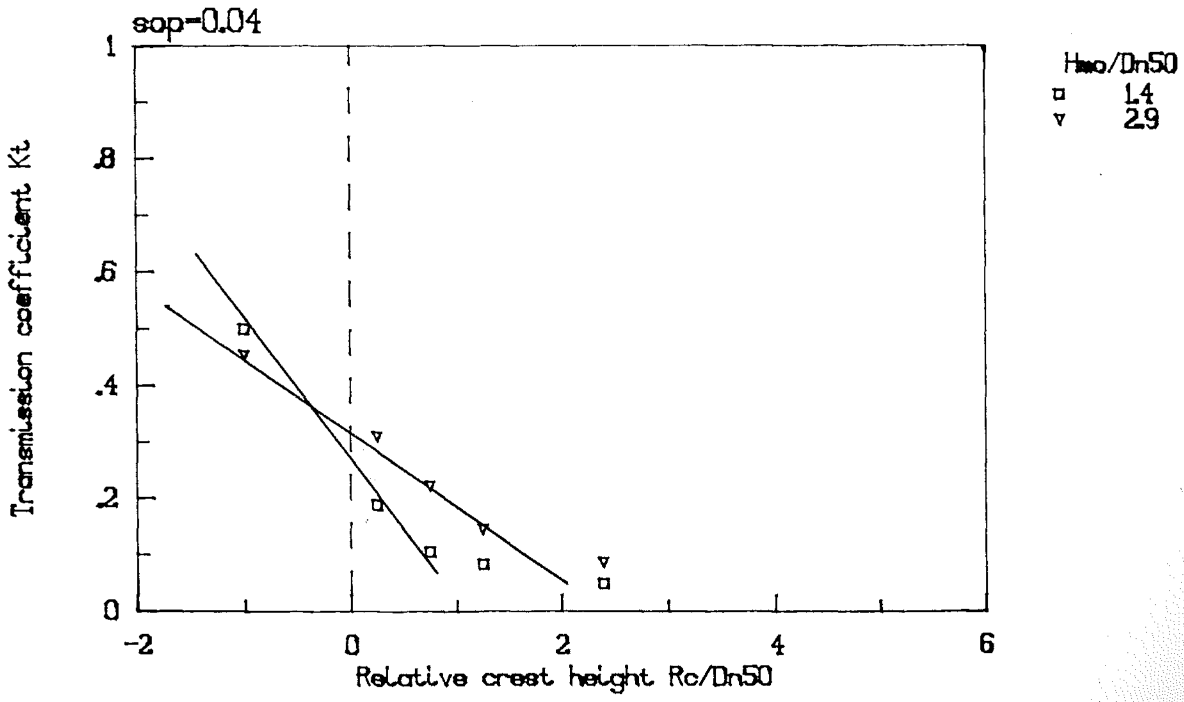


fig 21b. Influence of relative wave height for wave steepness 0.04, Present data

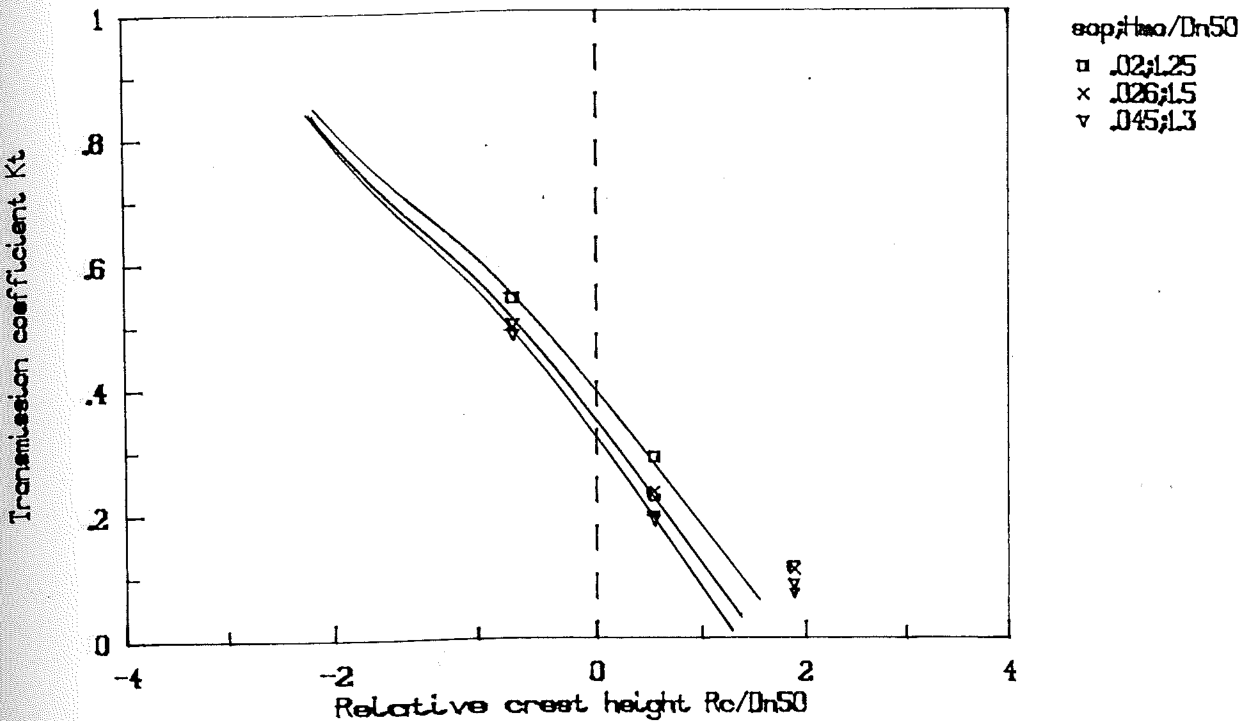


fig 22a.Influence of relative wave height and wave steepness,
Data of Seelig BW4 (1980)

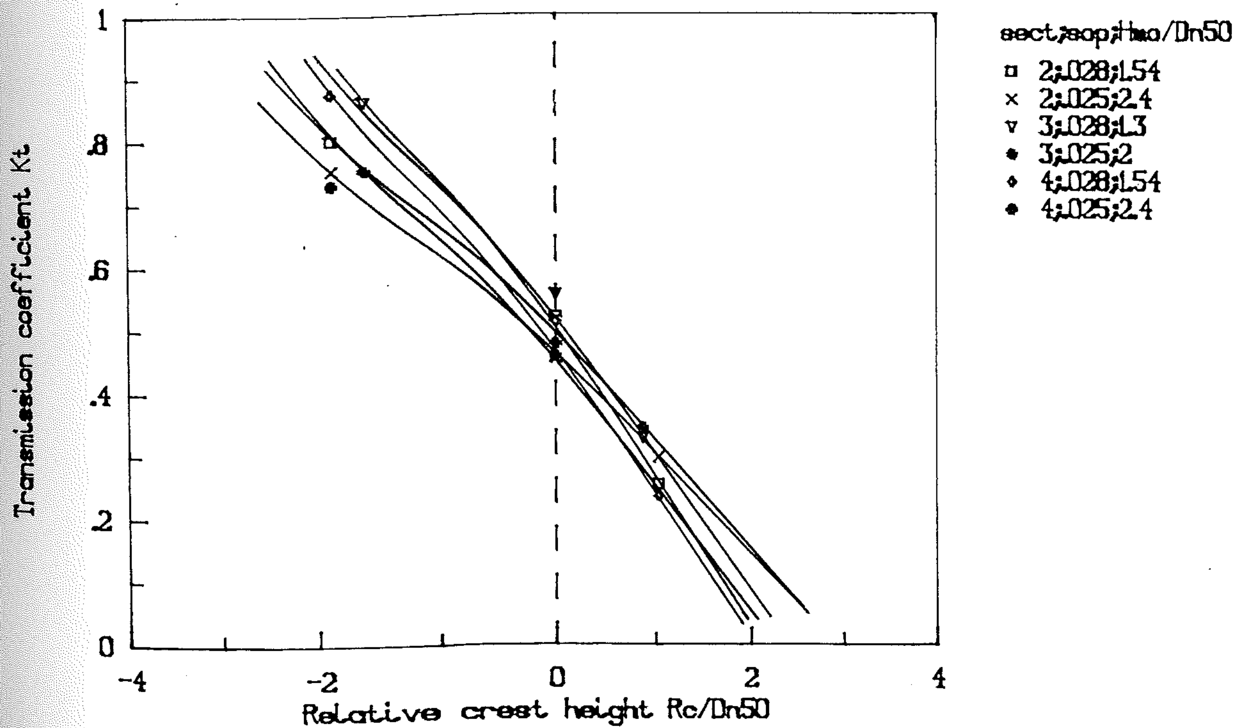


fig 22b.Influence of relative wave height and wave steepness,
Data of Powell and Allsop (1985), sections 2 to 4

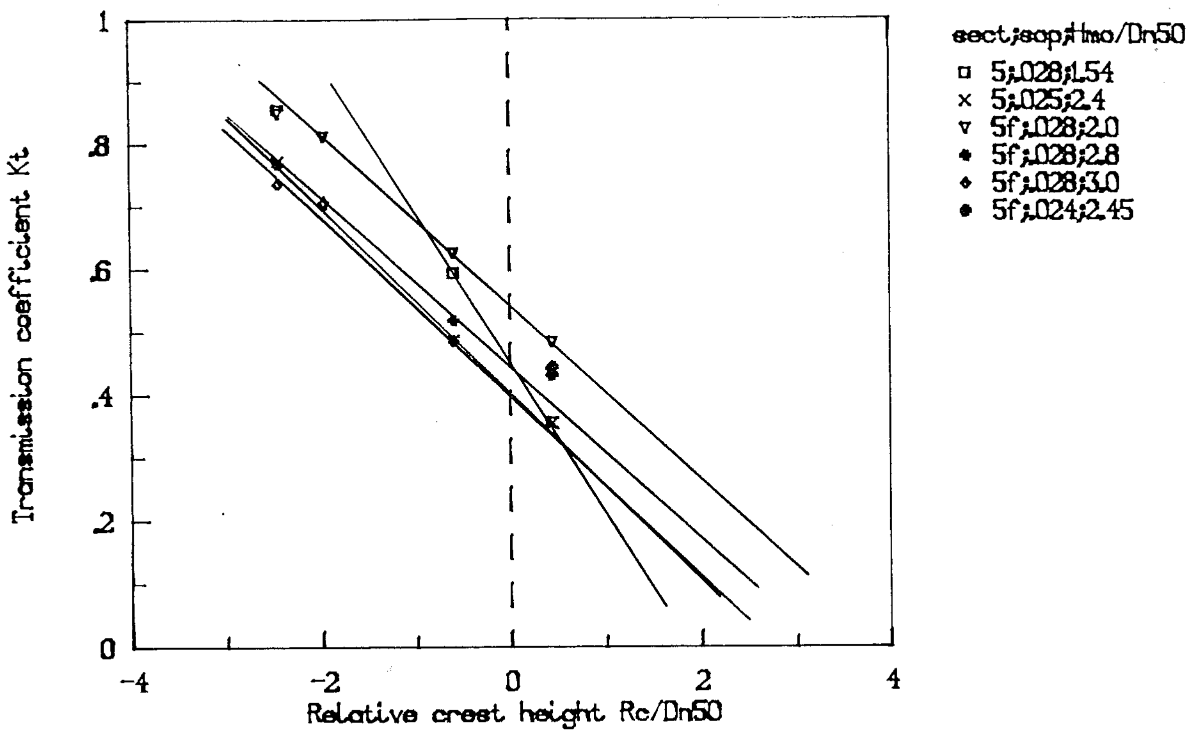


fig 23a. Influence of relative wave height and wave steepness, Data of Powell and Allsop (1985), section 5

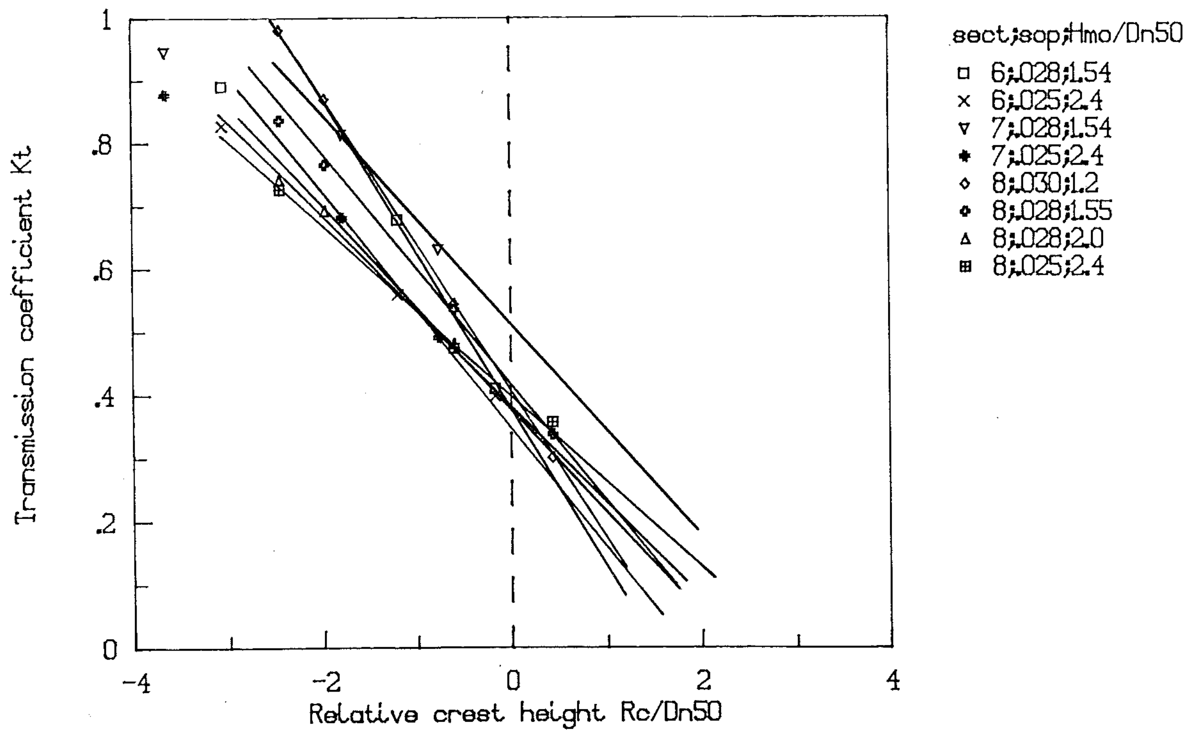


fig 23b. Influence of relative wave height and wave steepness, Data of Powell and Allsop (1985), sections 6 to 8

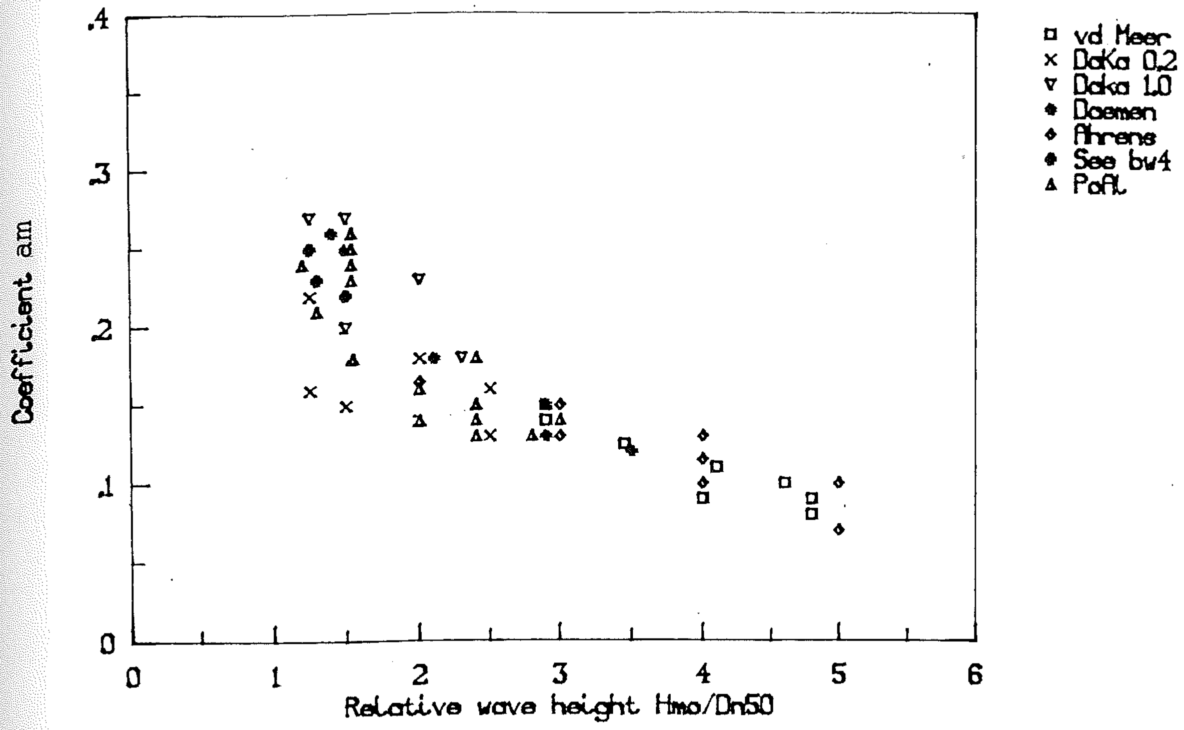


fig 24a.Coefficient "a" as a function of relative wave height

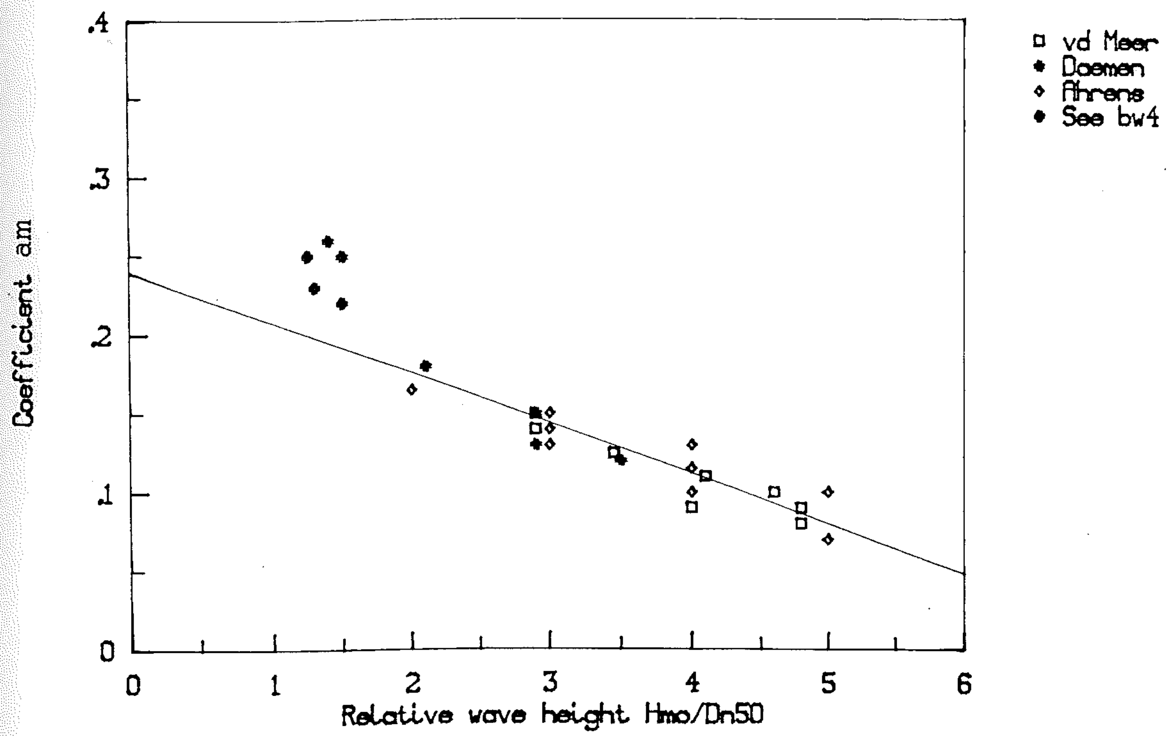


fig 24b.Coefficient "a" as a function of relative wave height
with equation 4.4

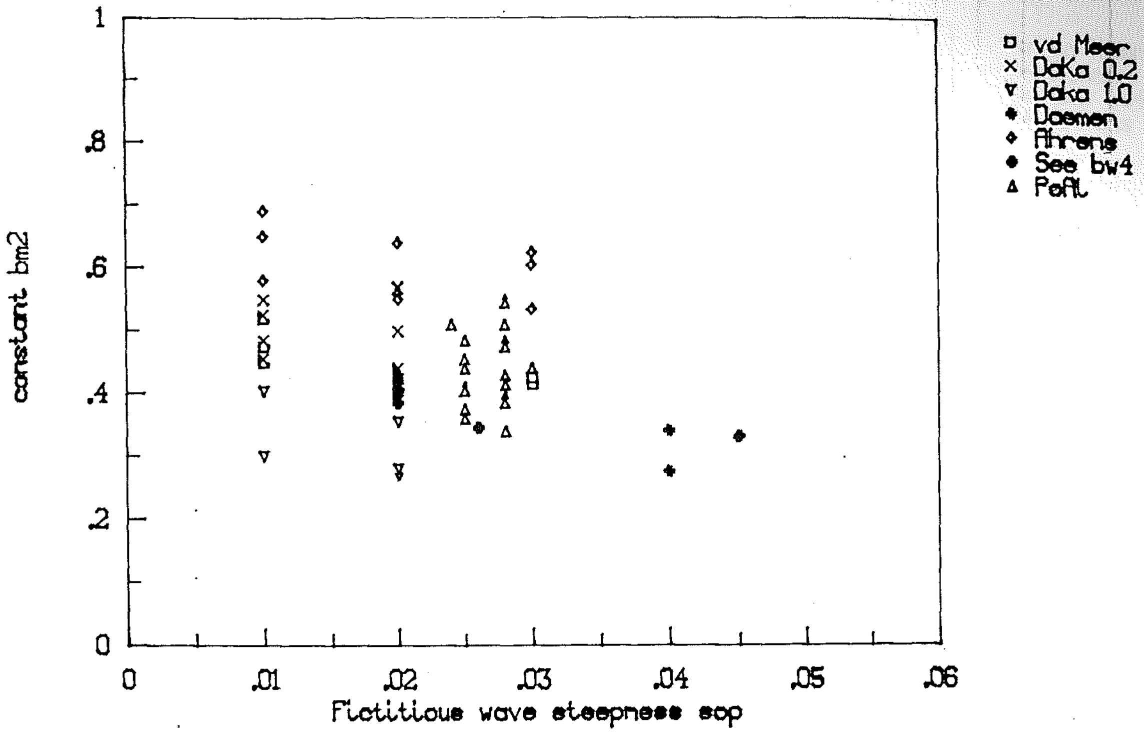


fig 25a.Constant "bm2" as a function of wave steepness

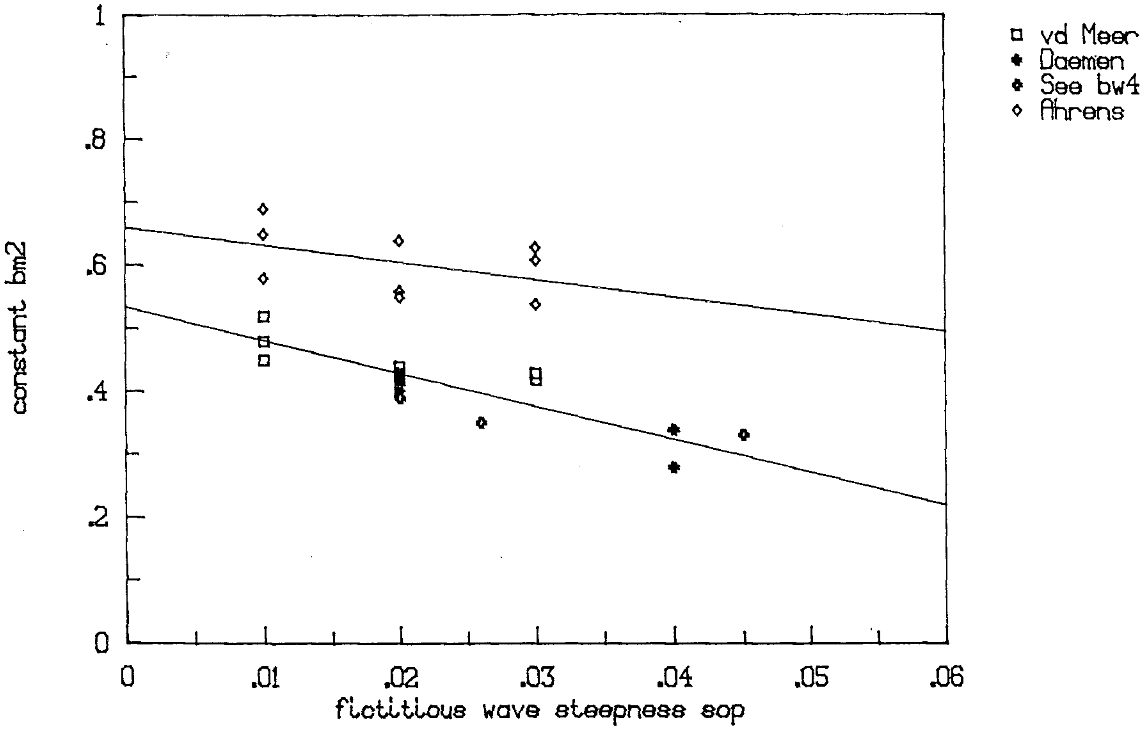


fig 25b.Constant "bm2" as a function of wave steepness with equations 4.6 (lower line) and 4.12 (upper line)

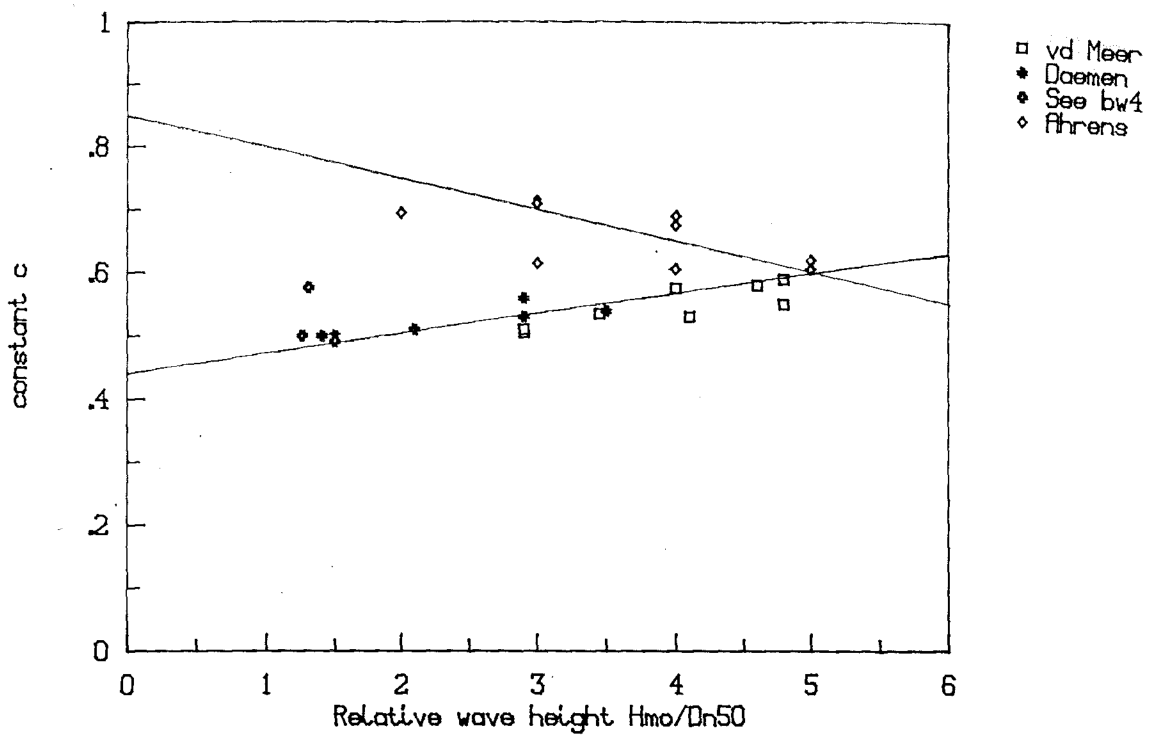


fig 26a. Constant "c" as a function of relative wave height with equations 4.9 (rising line) and 4.13 (descending line)

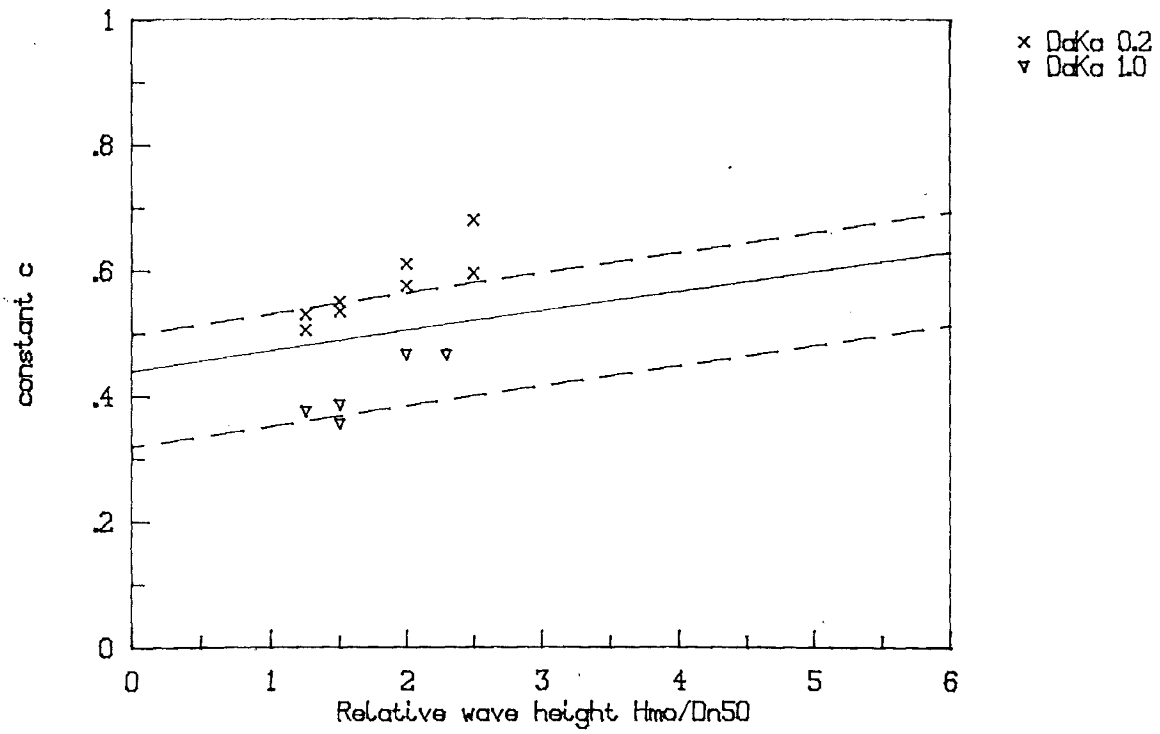


fig 26b. Constant "c" as a function of relative wave height with equation 4.9 (solid line) and adaptions (dash lines)

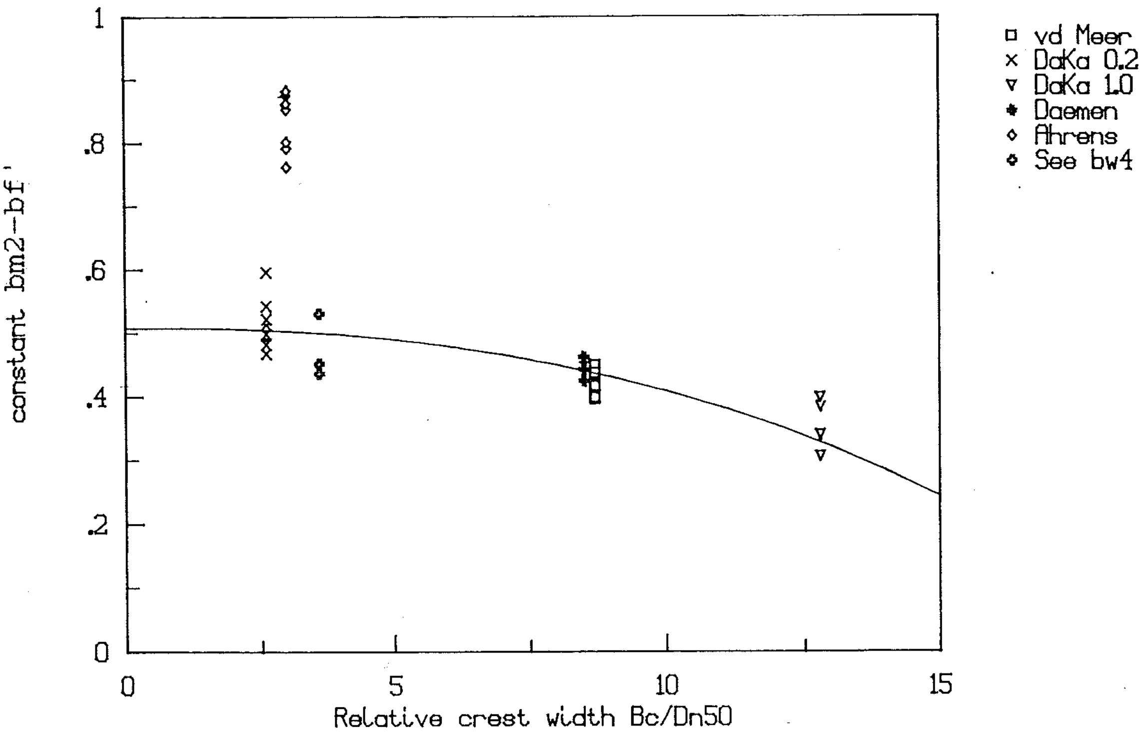


fig 27a.Constant "bm2-bf'" as a function of relative crest width with equation 4.19

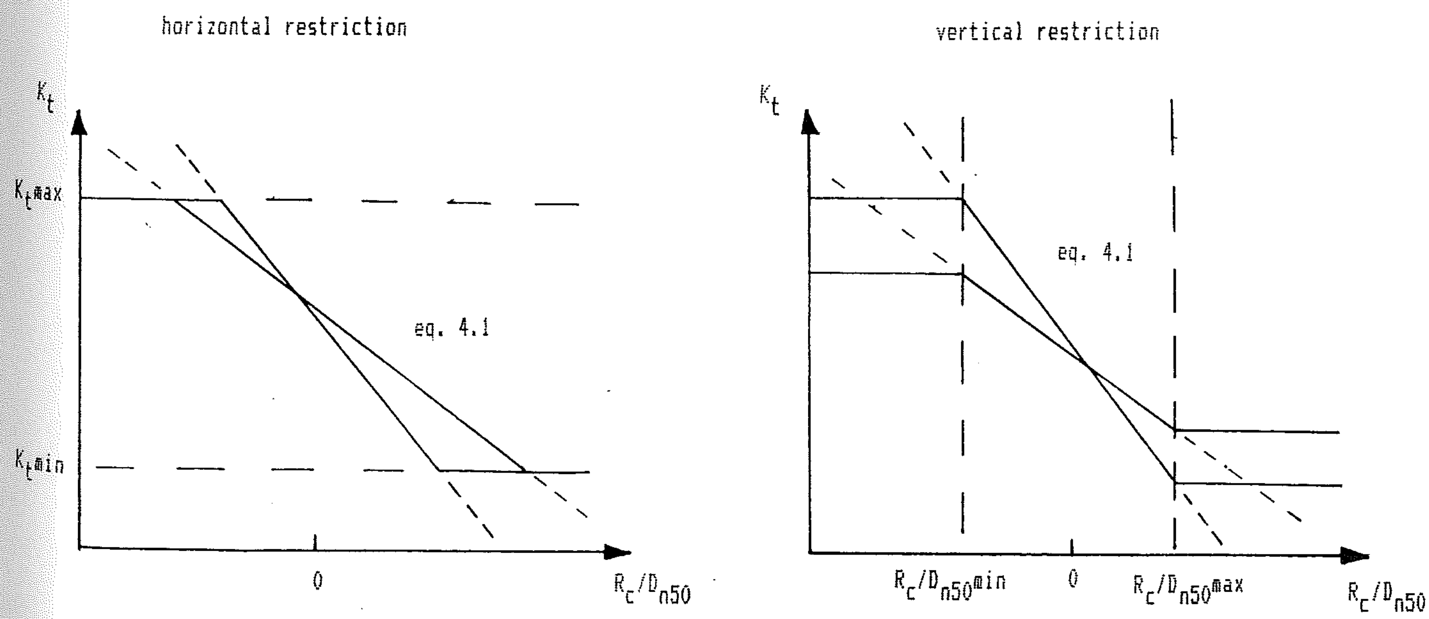


fig 27b.Examples of horizontal and vertical restriction

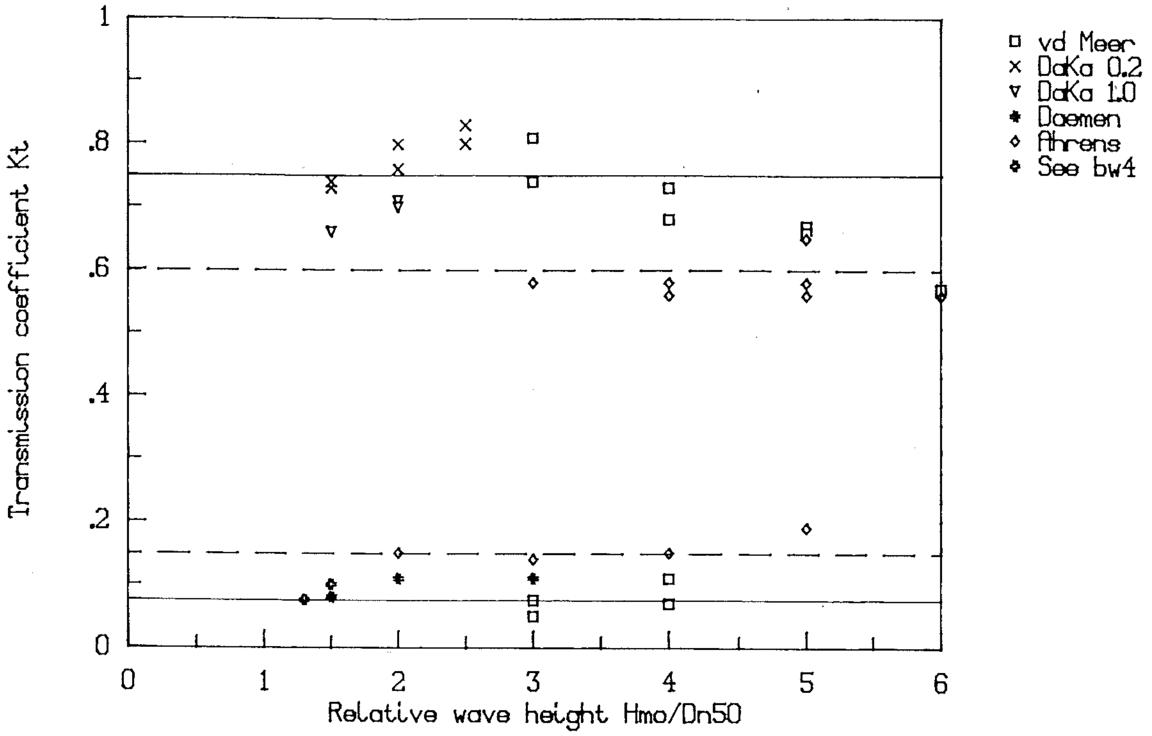


fig 28a. Minimum and maximum transmission coefficient as a function of relative wave height with equations 4.22 (solid line) and 4.23 (dash line)

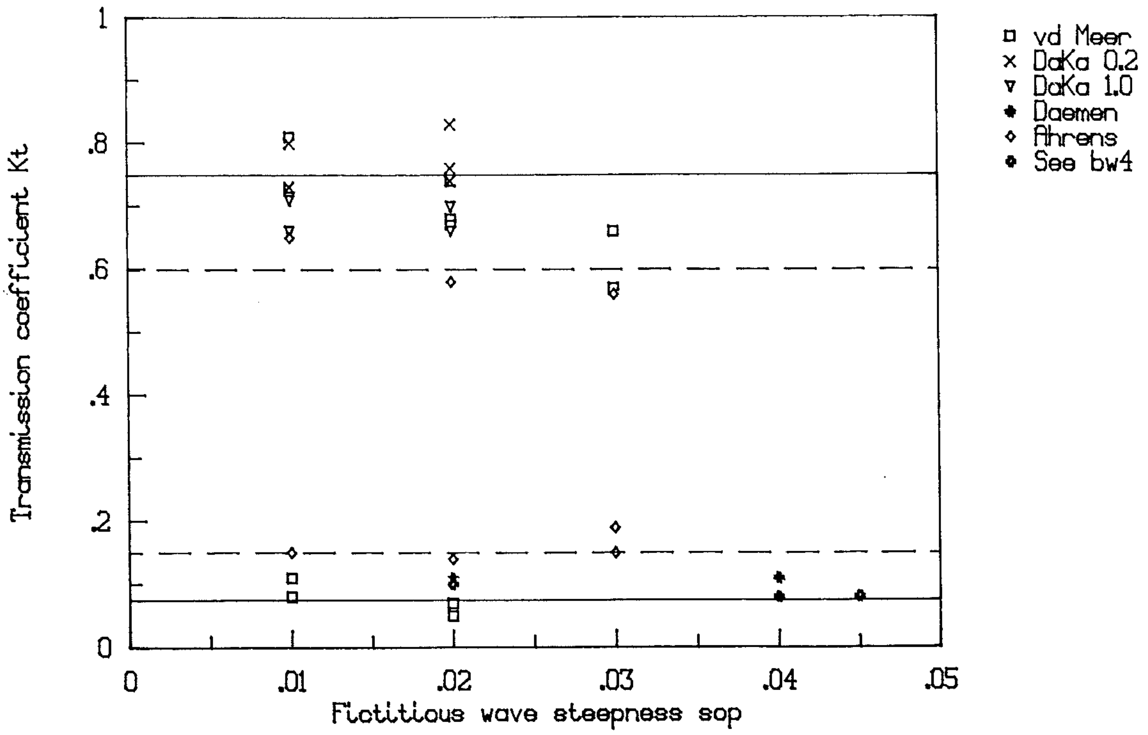


fig 28b. Minimum and maximum transmission coefficient as a function of wave steepness with equations 4.22 (solid line) and 4.23 (dash line)

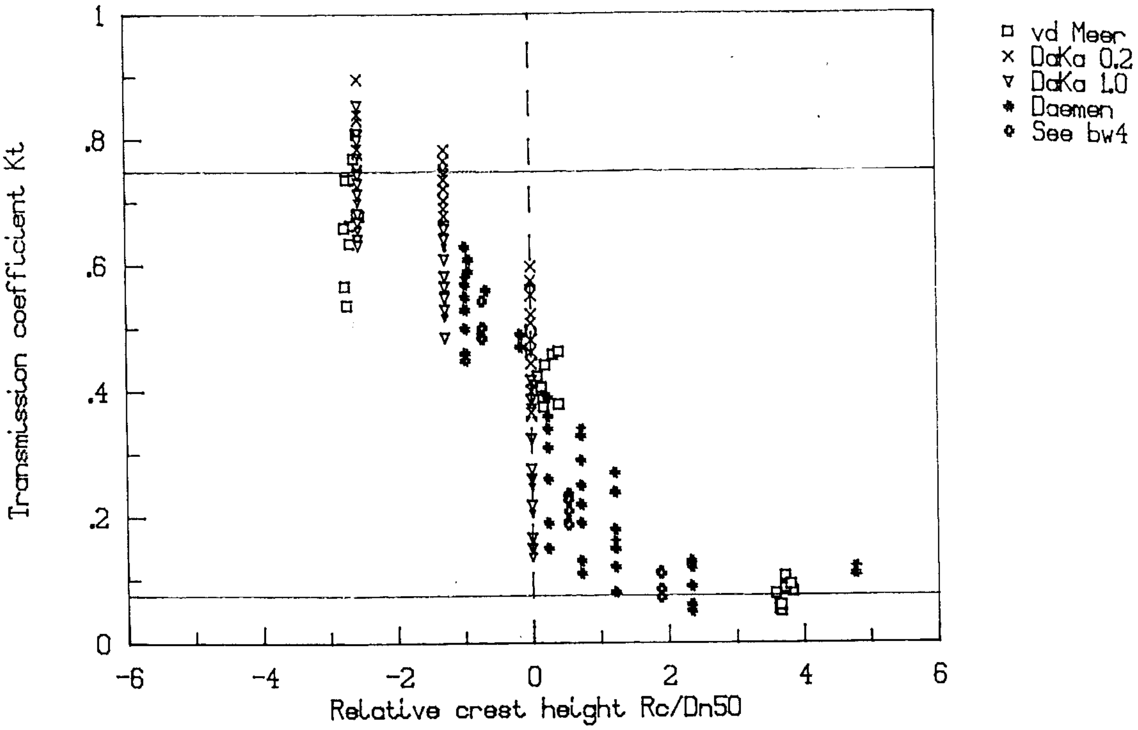


fig 29. Transmission coefficient as a function of relative crest height with equation 4.22

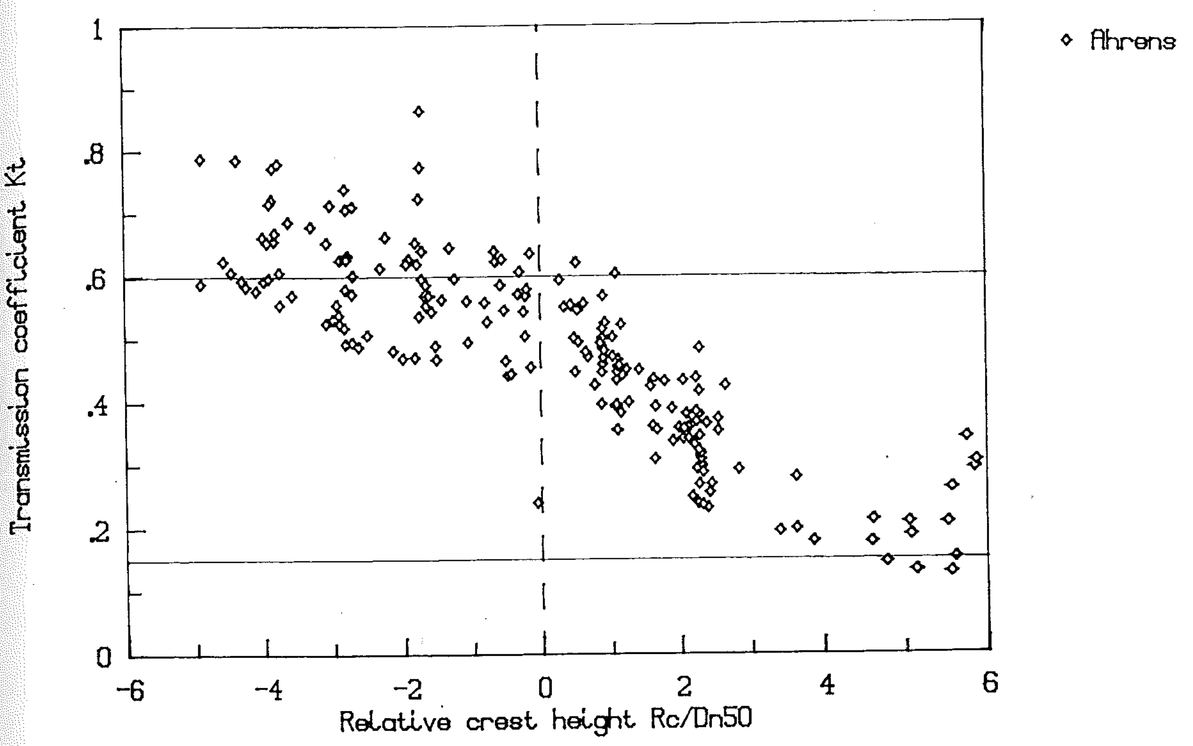


fig 30a. Transmission coefficient as a function of relative crest height with equation 4.23

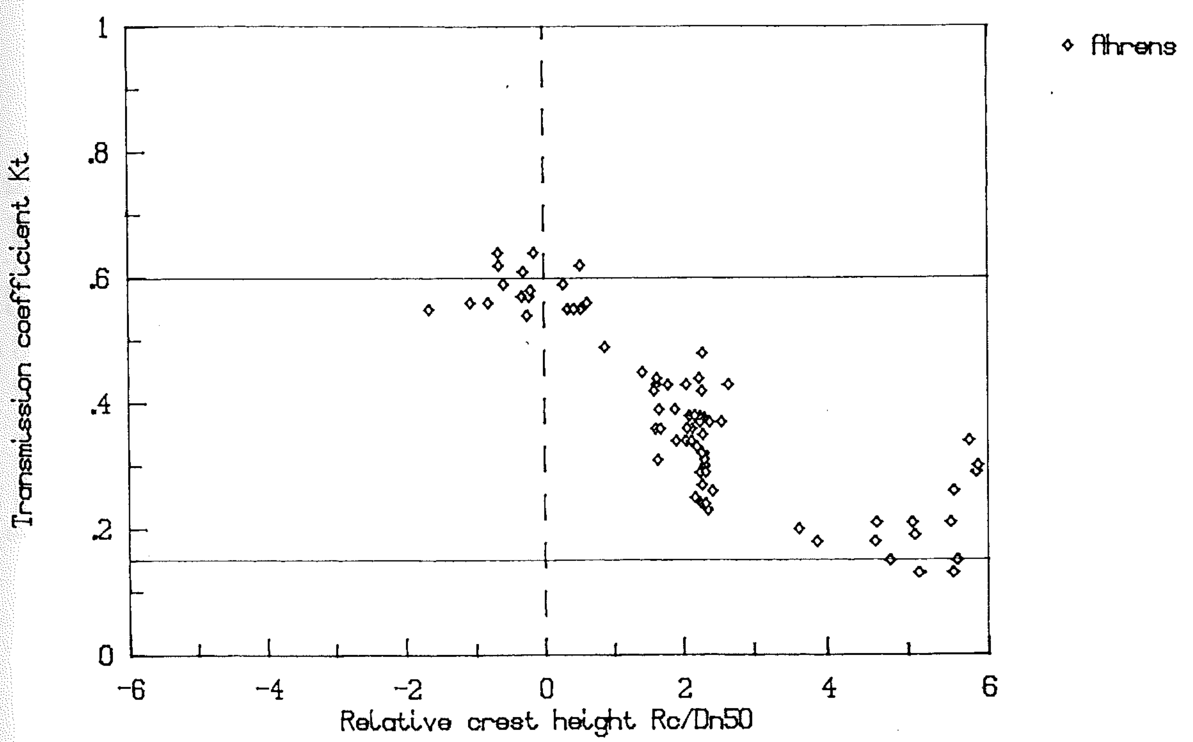


fig 30b. Transmission coefficient as a function of relative crest height with equation 4.23, Data with lowering of crest height < 10%

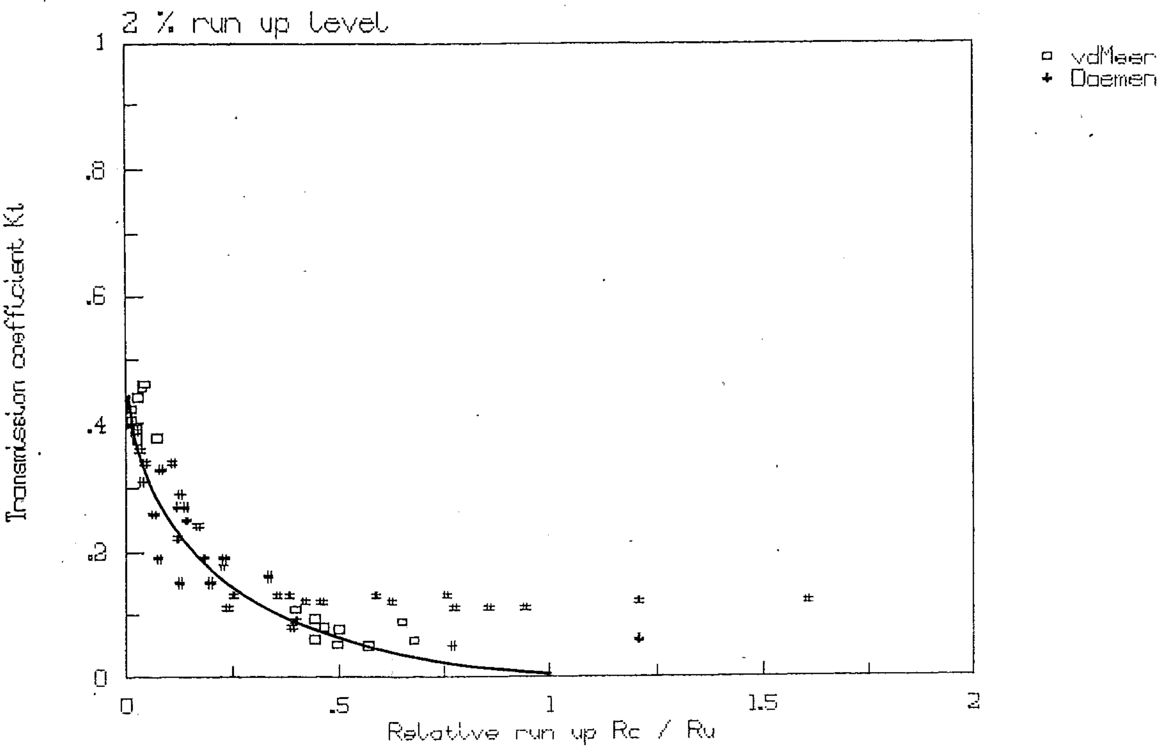


fig 31a.Transmission coefficient as a function of relative run-up R_c/Ru

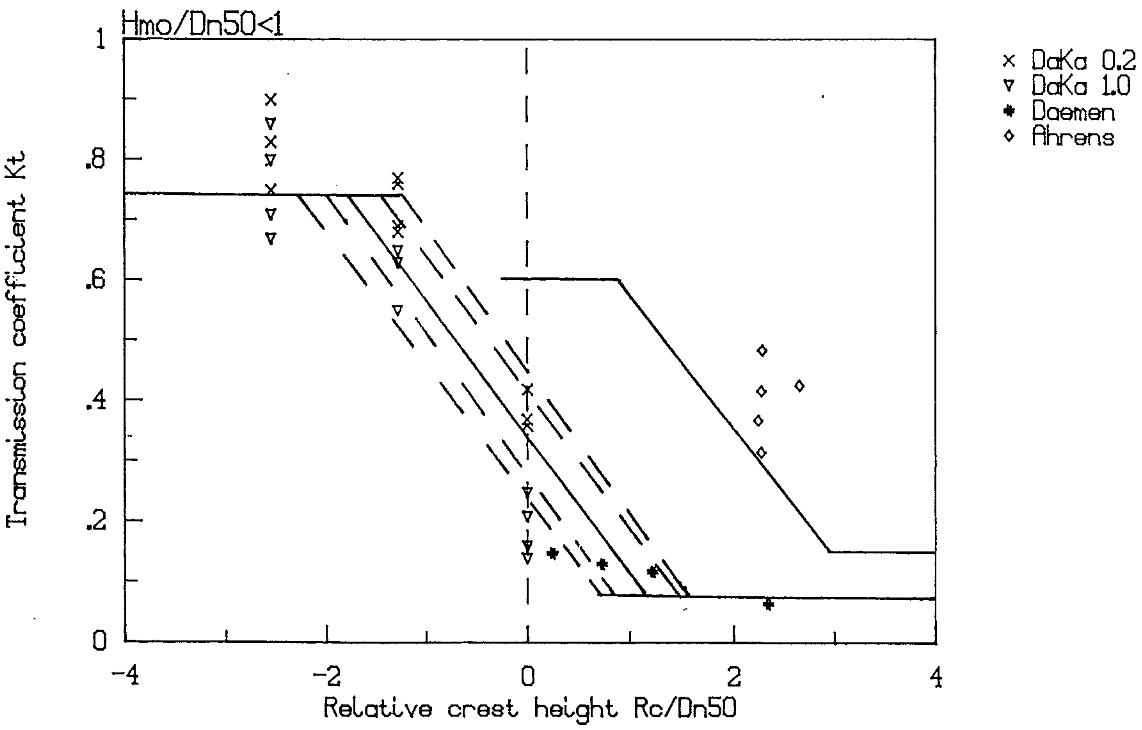


fig 31b.Transmission coefficient as a function of relative crest height, Data with relative wave height smaller then 1

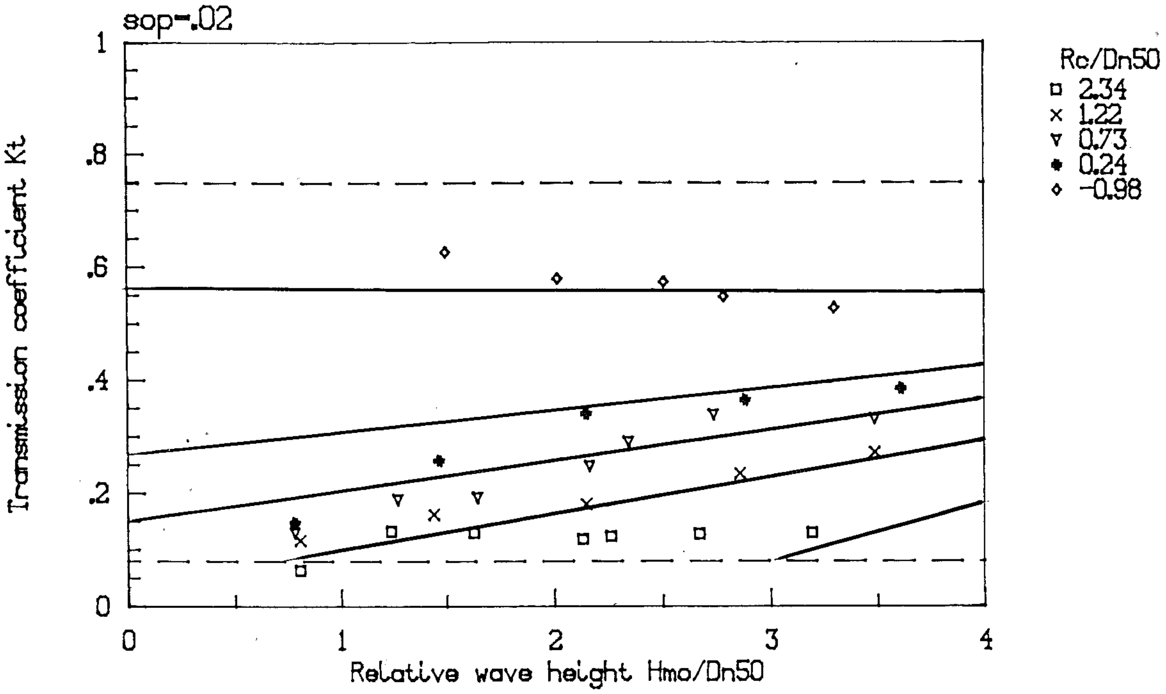


fig 32a.Transmission coefficient as a function of relative wave height and relative crest height for wave steepness 0.02, Present data

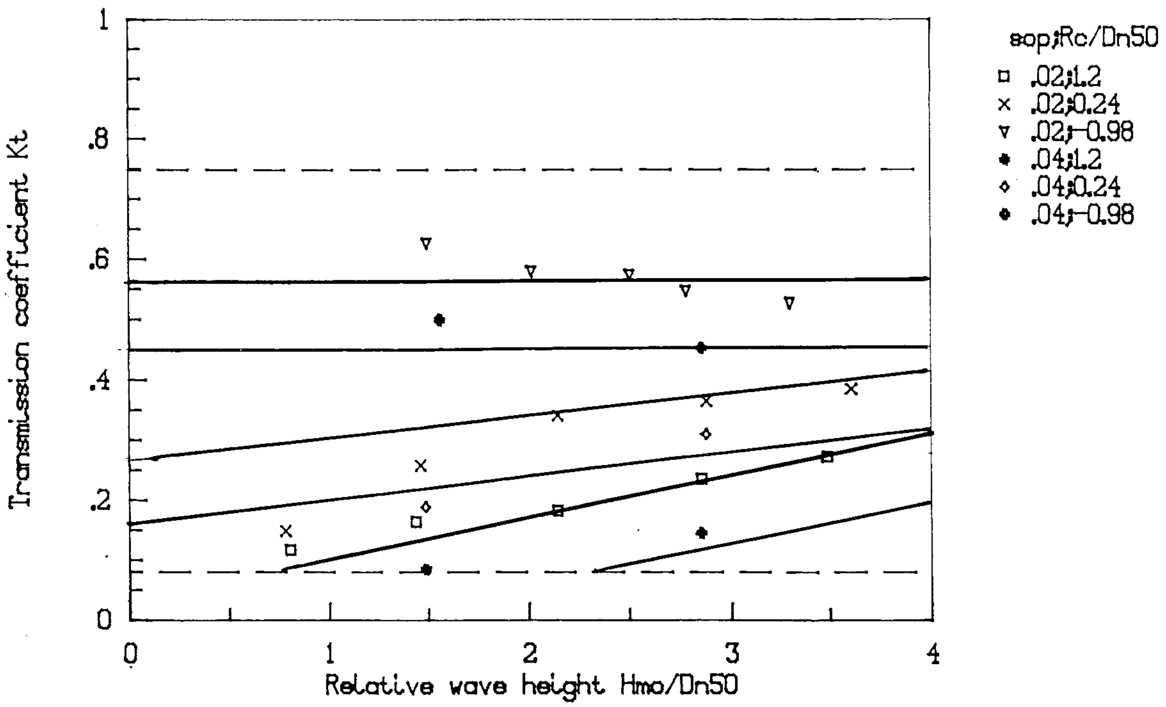


fig 32b.Transmission coefficient as a function of relative wave height, relative crest height and wave steepness, Present data

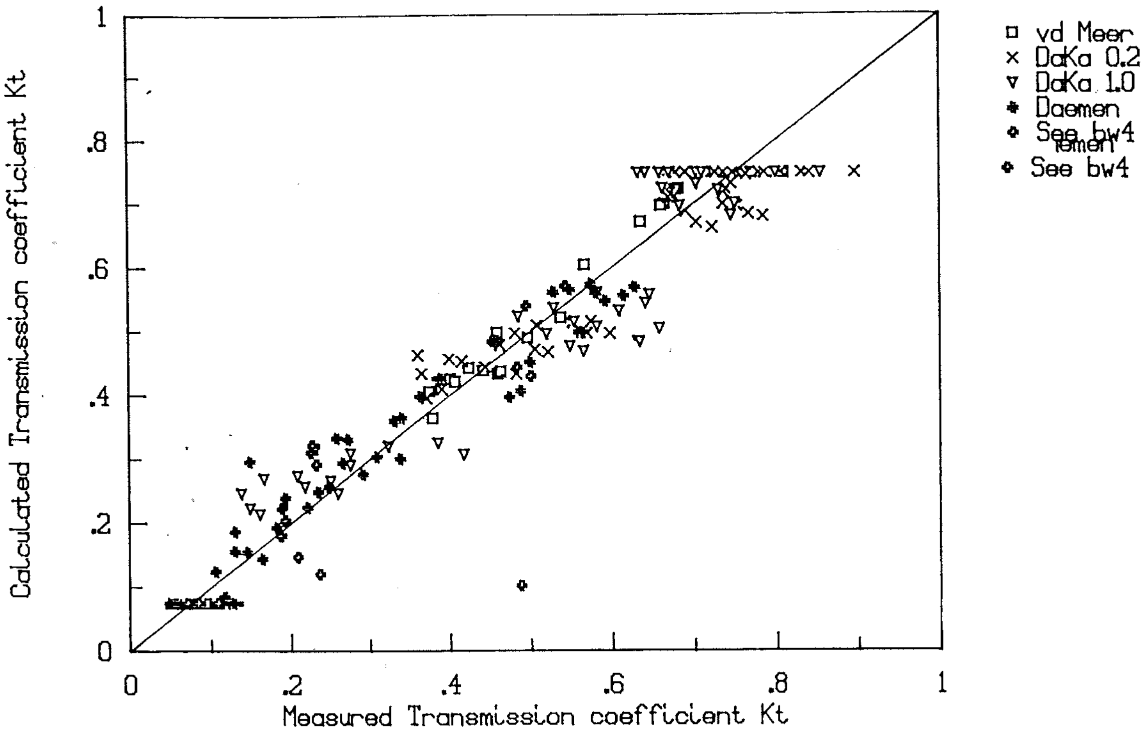


fig 33a.Calculated versus measured transmission coefficient

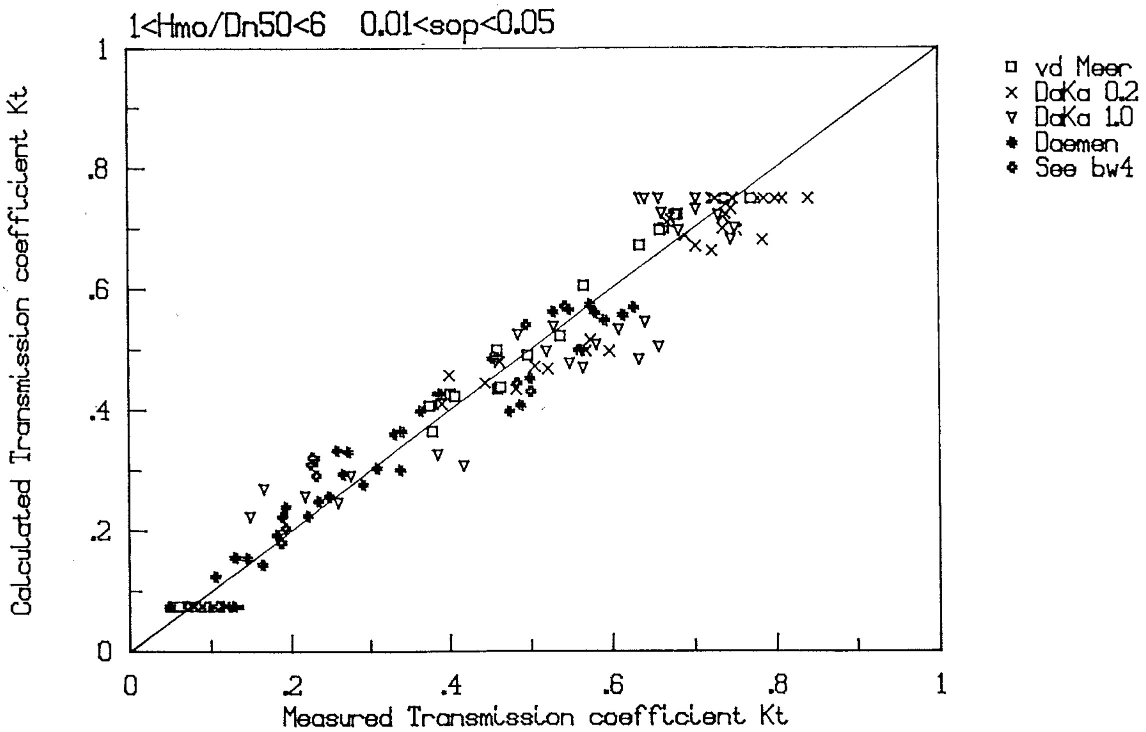


fig 33b.Calculated versus measured transmission coefficient, Data in the range of application

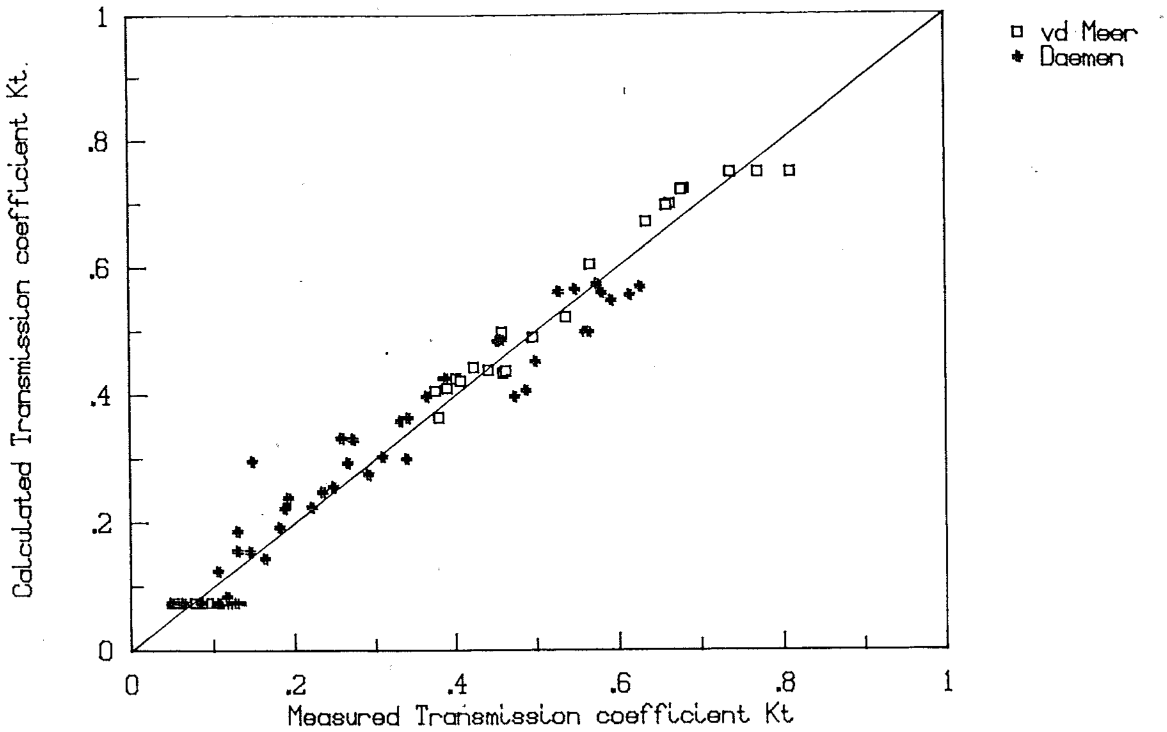


fig 34a.Calculated versus measured transmission coefficient

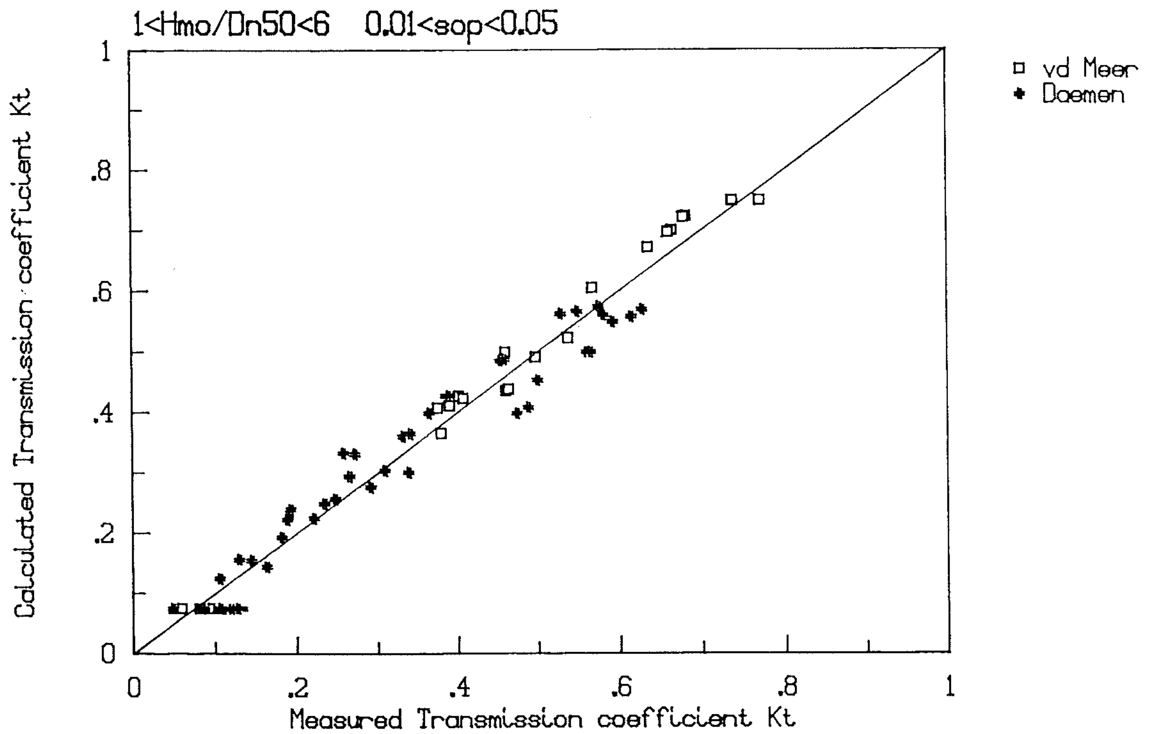


fig 34b.Calculated versus measured transmission coefficient, Data in the range of application

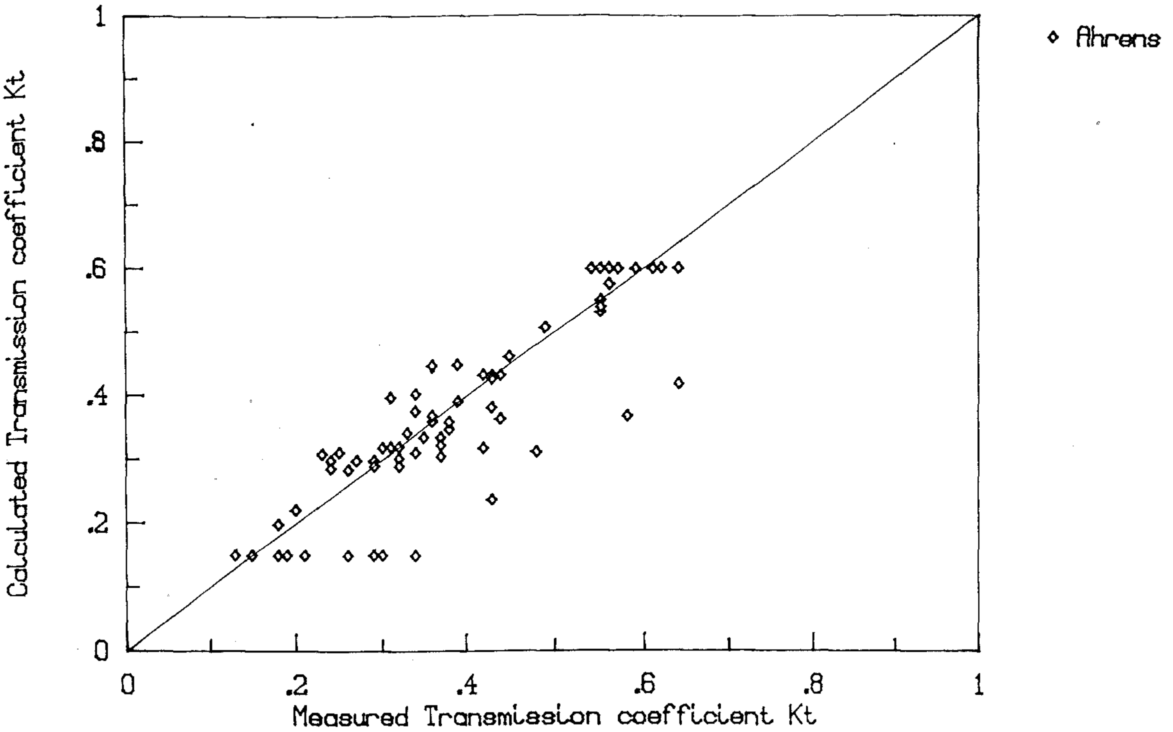


fig 35a. Calculated versus measured transmission coefficient, Data with lowering of crest height < 10%

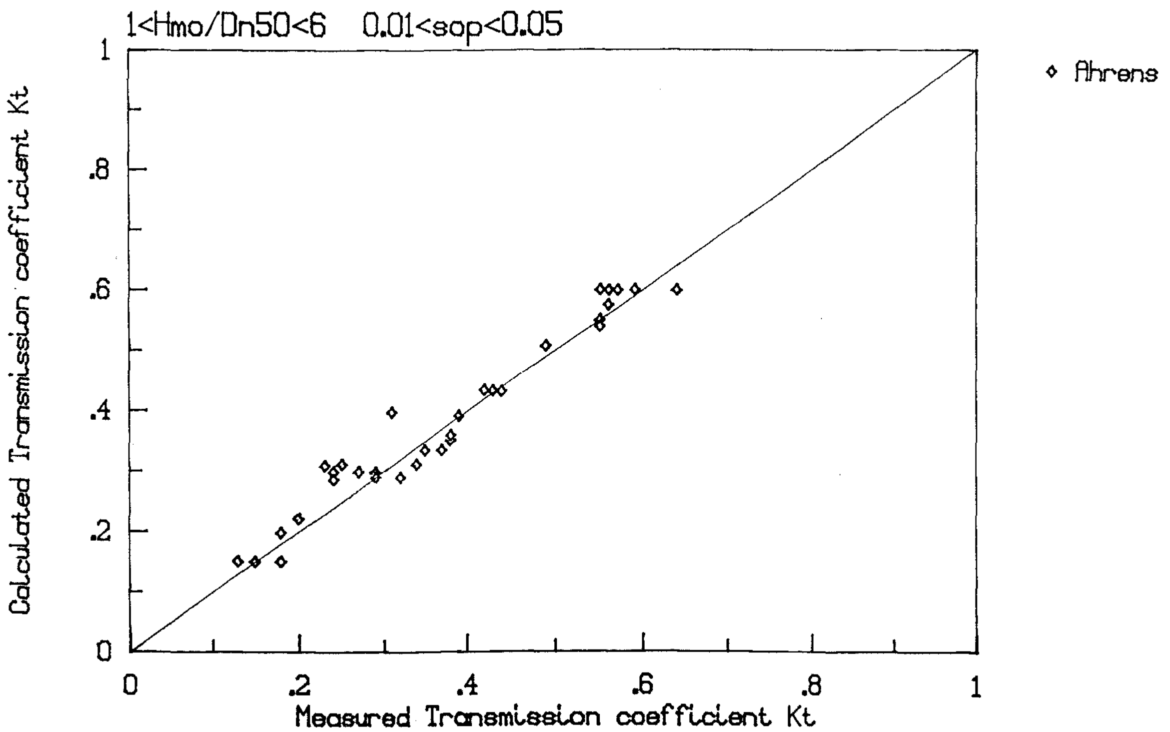


fig 35b. Calculated versus measured transmission coefficient, Data in the range of application, with lowering of the crest height < 10%

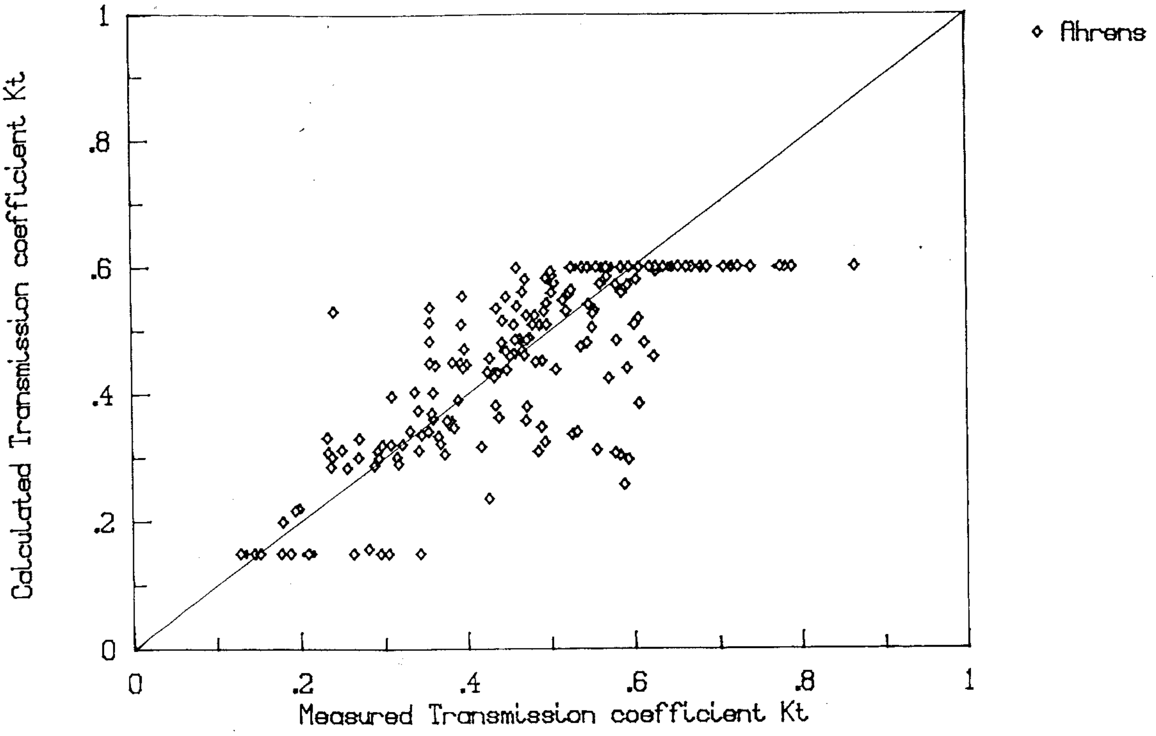


fig 36a.Calculated versus measured transmission coefficient

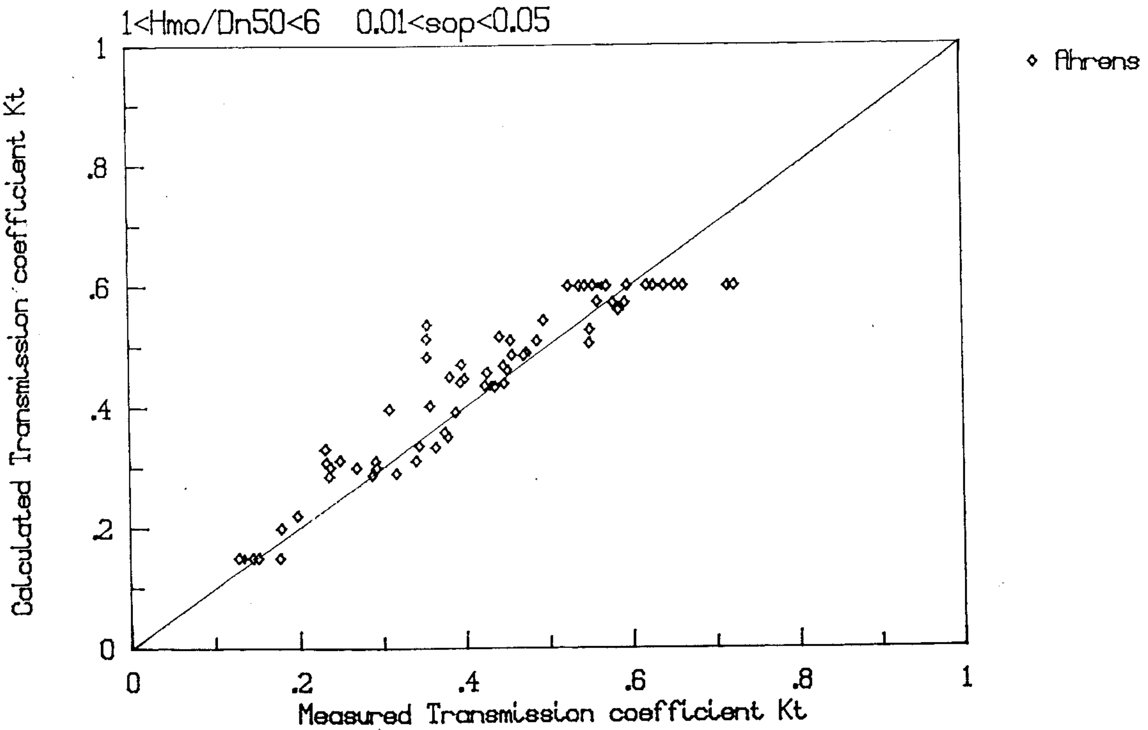


fig 36b.Calculated versus measured transmission coefficient
Data in the range of application

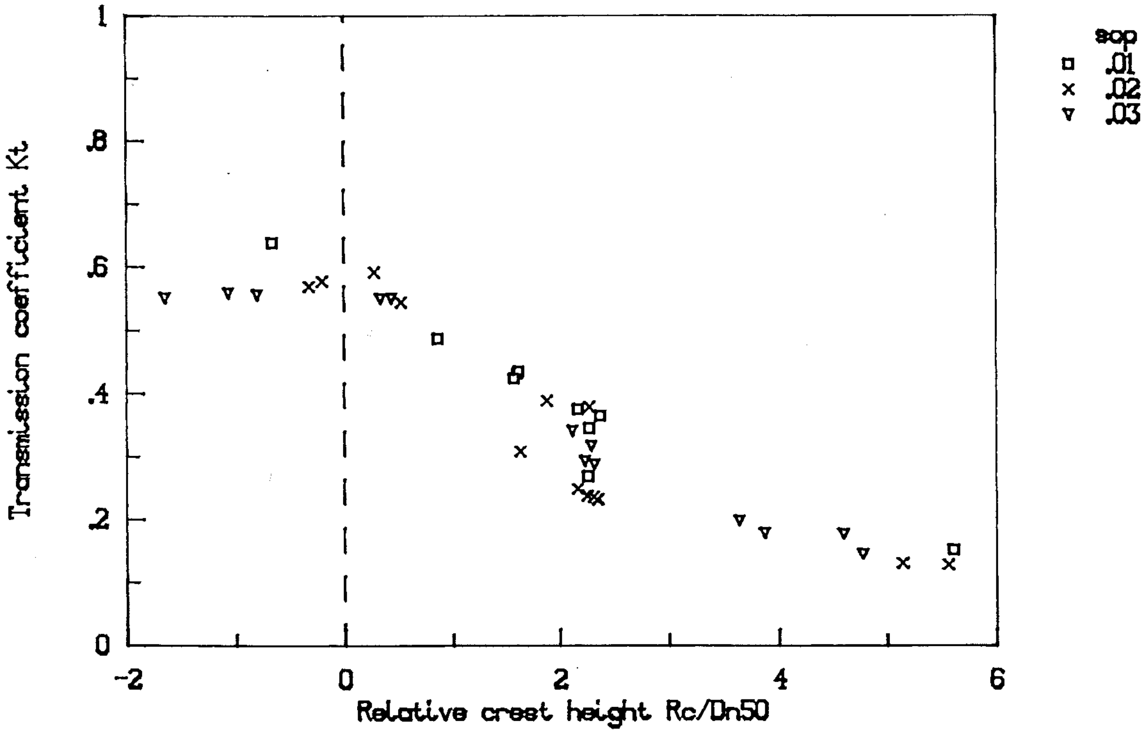


fig 37 .Influence of wave steepness. Data of Ahrens (1987)

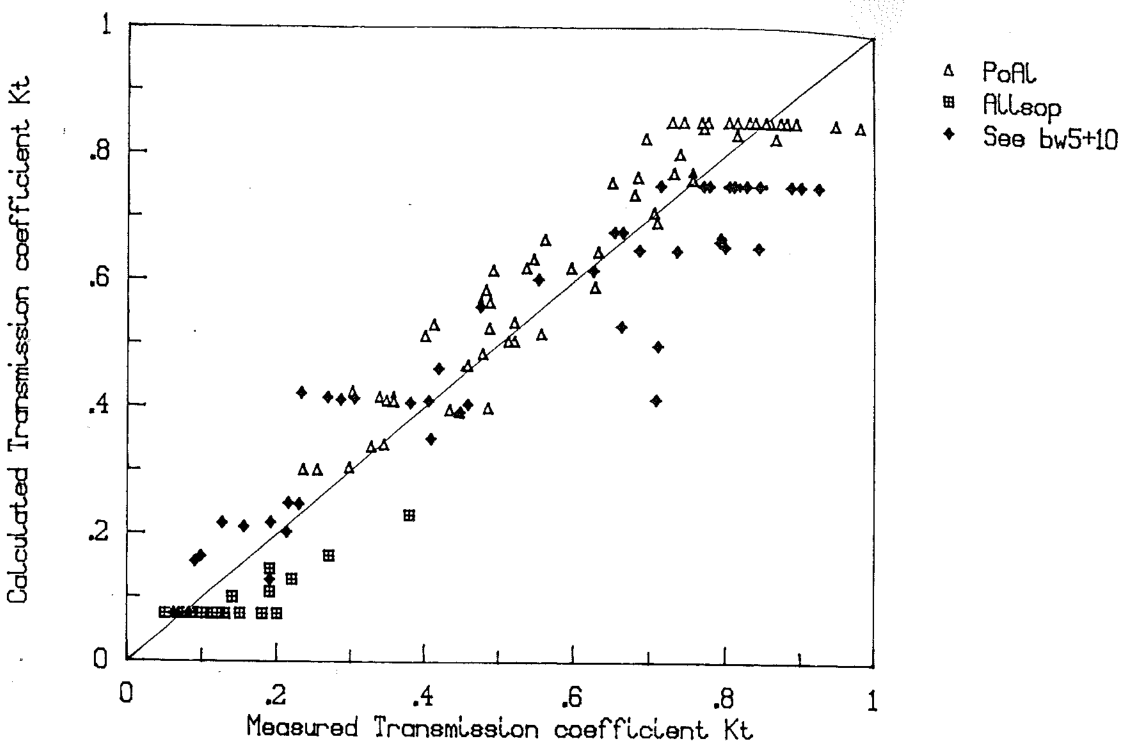


fig 38a.Calculated versus measured transmission coefficient

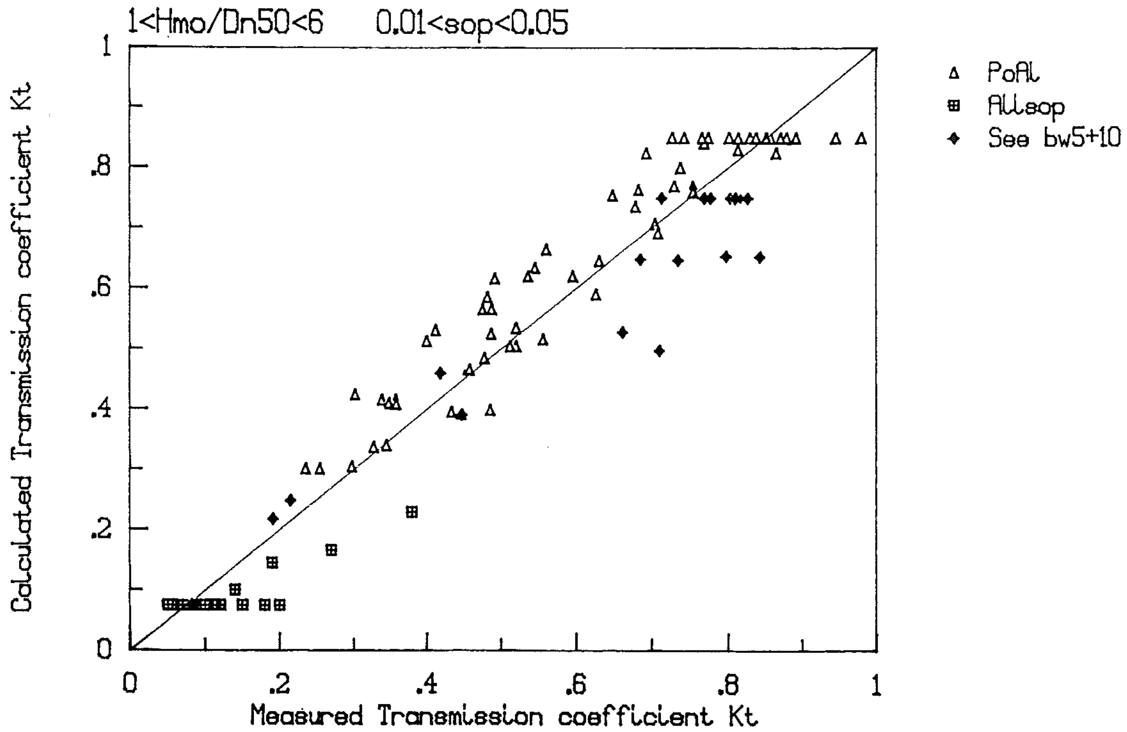
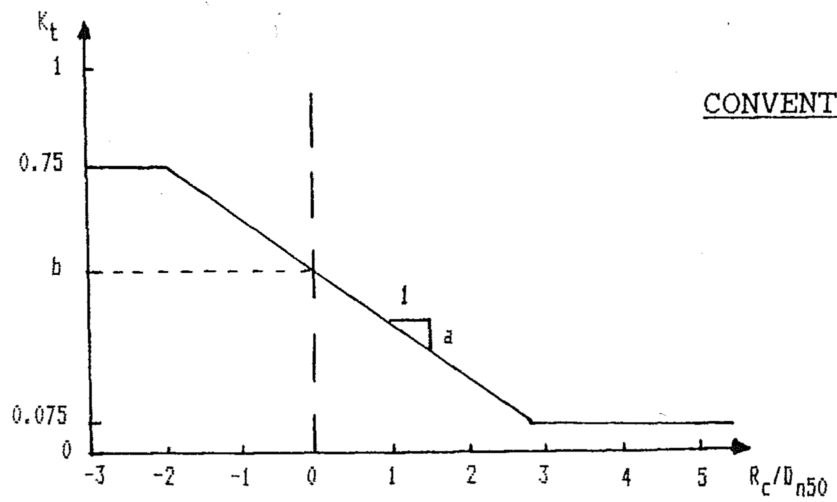


fig 38b.Calculated versus measured transmission coefficient, data in the range of application



CONVENTIONAL BREAKWATERS

$$K_t = a * R_c/D_{n50} + b \quad \text{(eq. 4.1)}$$

$$a = 0.031\ H_{mo}/D_{n50} - 0.24 \quad \text{(eq. 4.4)}$$

$$b = -5.42\ s_{op} + 0.0323\ H_{mo}/D_{n50} + 0.51 - 0.0017\ B_c/D_{n50}^{1.84} \quad \text{(eq. 4.20)}$$

minimum: $K_t = 0.075$ (eq. 4.22a)

maximum: $K_t = 0.75$ (eq. 4.22b)

Range of investigation:

$-3 < R_c/D_{n50} < +5$ (eq. 4.24a)

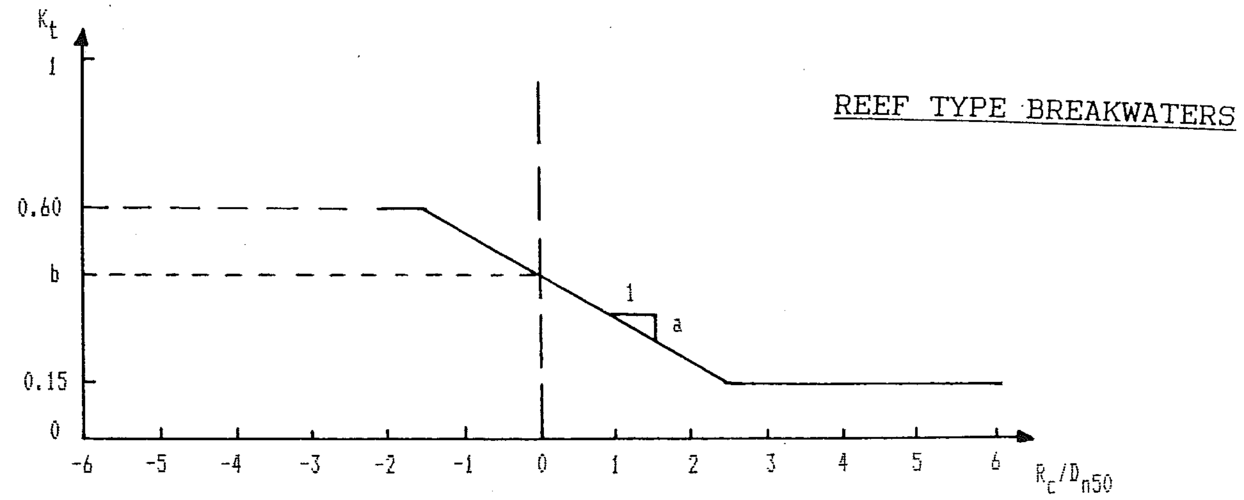
Range of application:

$1 < H_{mo}/D_{n50} < 6$ (eq. 4.29)

$0.01 < s_{op} < 0.05$ (eq. 4.30)

Reliability: $\sigma(K_t) = 0.048$
90% confidence levels: $K_t \pm 0.08$

fig 39. Overall view of formula for wave transmission at conventional breakwaters



$$K_t = a * R_c/D_{n50} + b \qquad \text{(eq. 4.1)}$$

$$a = 0.031\ H_{mo}/D_{n50} - 0.24 \qquad \text{(eq. 4.4)}$$

$$b = -2.6\ s_{op} - 0.05\ H_{mo}/D_{n50} + 0.85 \qquad \text{(eq. 4.14)}$$

minimum: $K_t = 0.15$ (eq. 4.23a)

maximum: $K_t = 0.60$ (eq. 4.23b)

Range of application:

$1 < H_{mo}/D_{n50} < 6$ (eq. 4.29)

$0.01 < s_{op} < 0.05$ (eq. 4.30)

Tests only at which the crest height, during a test, lowered less then 10% of the initial height:

Range of investigation:

$-2 < R_c/D_{n50} < +6$ (eq. 4.24b)

Reliability: $\sigma = 0.031$
90% confidence levels: $K_t \pm 0.05$

All tests:

Range of investigation:

$-6 < R_c/D_{n50} < +6$ (eq. 4.24c)

Reliability: $\sigma = 0.054$
90% confidence levels: $K_t \pm 0.09$

fig 40. Overall view of formula for wave transmission at reef type breakwaters