Oblique wave transmission over low-crested structures

Jentsje W. van der Meer[1], Baoxing Wang[2], Ard Wolters[3], Barbara Zanuttigh[4] and Morten Kramer[5]

Introduction

Wave transmission over low-crested structures has often been subject for research, as the wave field behind these structures determines what will happen in this area. Detached low-crested structures are often parallel to the coastline and in most cases wave attack will be perpendicular to this coastline and therefore, perpendicular to the structure. This situation can be simulated by small scale physical modeling in a wave flume. Results have been given by Van der Meer and Daemen (1994) and d'Angremond, van der Meer and de Jong (1996). Recent research, including all data of the above given references and new extensive data sets, has enlarged the insight on the topic, see Briganti et al. (2003). The results from 2D tests are:

- prediction formulae for the wave transmission coefficient K_t
- a description of change of spectral shape due to wave transmission

In quite some situations low-crested structures are not parallel to the coast. T-shaped groynes are an example, but also breakwaters for a harbour where only under very extreme storm surge the structure can be considered as low-crested. In these situations wave attack is very often not perpendicular to the alignment of the structure and in many situations even quite oblique wave attack and transmission occurs. But what will be the difference with perpendicular attack? More in detail:

- Are the prediction formulae for K_t still valid?
- Is the spectral change (more energy to high frequencies) similar to perpendicular wave attack?
- Is there any influence of short-crestedness of waves?
- Are wave directions similar in front of the structure and after transmission?

Only a three-dimensional investigation in a short-crested wave basin can give answer to these questions. Within the EU-project DELOS these tests have been performed and are the subject of this paper.

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[1]Infram, POBox 81, 3890 AB Zeewolde, NL, jentsje.vandermeer@infram.nl
[2]UNESCO-IHE, Institute for Water Education; former MSc-student, Westvest 7, 2611 AX Delft, NL [3]Ministry of Transport, Public Works and Water Management; Road and Hydraulic Engineering Division, POBox 5044, 2600 GA Delft, NL
[4]Università di Bologna, DISTART Idraulica, viale Risorgimento 2, 40136 Bologna, IT
[5]Aalborg University, Sohngaardsholmvej 57, 9000 Aalborg, DK

Test set-up and programme

Basin and layout. The three-dimensional wave transmission tests were carried out in the short-crested wave basin (9.0 m × 12.5 m × 0.9 m) at Aalborg University, Denmark. Two structures were tested, a rubble mound structure and a smooth structure made out of plywood. The rubble mound structure had an armour layer of rock. In reality smooth structures have a cover layer of asphalt or placed block revetments, a type of structure quite common in the Netherlands.

The structures were placed on a horizontal plateau, which was 0.16 m higher than the bottom of the basin. This created a larger depth in front of the wave generator and made it easier to generate the required waves. Three layouts were constructed for each structure: 0° (perpendicular wave attack, structure parallel with the wave generator), 30° and 50°. Figure 1 shows the layout of the smooth structure, which was constructed under an angle of 30° with the wave generator and Figure 2 shows the layout for the rubble mound structure under 50°. The two lowest horizontal lines in both figures give the area between the deeper water in front of the wave generator and the 0.16 cm higher plateau.

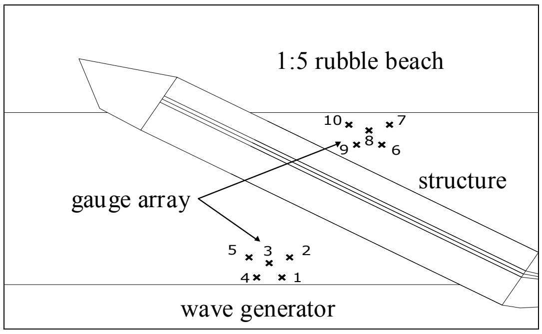

Figure 1. Smooth structure under 30° angle

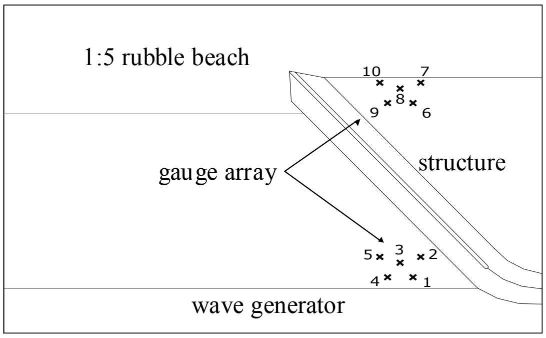

Figure 2. Rubble mound structure under 50° angle

Cross-sections. The rubble mound structure was 25 cm high. It had a seaward slope of 1:2 and a leeward slope of 1:1.5, see Figure 3. The crest width was 10 cm. The core consisted of B-rock with D_{n50} = 0.031 m and the bottom layer of C-rock with D_{n50} = 0.016 m. The armour layer consisted of A-rock with W_{50} = 0.269 kg, D_{n50} = 0.0466 m and a grading of D_{85}/D_{15} = 1.25. The shape of the armour rock can be described by L/H and the blockiness coefficient; where L = the largest dimension of the rock, H = the smallest dimension, B = the third dimension, V = the volume of the rock and the blockiness coefficient is defined as V/(LxBxH). The shape can be described by two values: the percentages of rock exceeding 2L/H and 3L/H. These values were 50% and 4%, respectively. The blockiness coefficient was 0.42 (see also Stewart et al. 2002).

The smooth structure had gentler slopes than the rubble mound structure, which is also the case in reality. The seaward slope was 1:3 and the leeward slope 1:2. The structure height was 0.30 m and the crest width 0.20 m.

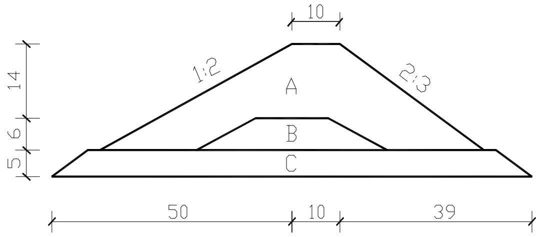

Figure 3. Rubble mound structure

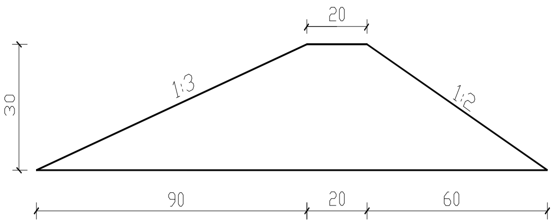

Figure 4. Smooth structure

Test programme. For both the rubble mound structure as well as for the smooth structure 84 tests were performed. Table 1 gives an overall view. Three crest freeboards were tested with two wave steepnesses and for each wave steepness three wave heights. The main angles of attack were 0°, 30° and 50°, but as the multi-directional wave generator could also generate waves under an angle, a limited number of tests were performed with 20°, 40° and 60°. Only 10 of the 84 tests were performed with long-crested waves.

Table 1 Overall view of test programme

Tests per structure	84 (10 long-crested, 74 short-crested)
Crest freeboard	+0.05 m; 0.0 m; -0.05 m
Dimensionless freeboard R_c/H_s	-0.7 to +0.8
Wave height H_s	0.07 m to 0.14 m
Wave steepness s_{op}	0.02 and 0.04
Angles of wave attack β	**0°**, 20°, **30°**, 40°, **50°** and 60°

Data processing. A Jonswap spectrum with γ=3.3 was used for the tests. The short-crested tests were performed with a $\cos^{2s}$ spreading function, where s=50. In fact the testing was quite simple, as only incident and transmitted wave conditions were required. A wave gauge array of 5 gauges was placed in front of the structure to measure the incident waves and a similar array behind the structure to measure the transmitted waves, see also Figures 1 and 2.

The PADIWA package for directional wave analysis, as available at Aalborg University, was used to analyze the measured wave signals. The Bayesian Directional Spectrum Estimation Method (BDM) was used to estimate the directional wave spectrum. Also analysis on individual wave gauges was performed, both in time and frequency domain. The processing resulted in: incident and transmitted wave heights H_{m0i}, excluding reflection from structure or 1:5 spending beach; wave periods like the peak period T_p, the mean period T_m and the spectral period $T_{m-1,0}$, wave directions β and spectral shapes. Finally, the ratio of transmitted wave height to incident wave height resulted in the transmission coefficient $K_t = H_t/H_i$.

Data analysis

Long-crested versus short-crested waves. The first question to consider is whether similar results are found for long-crested and short-crested waves. In theory it should

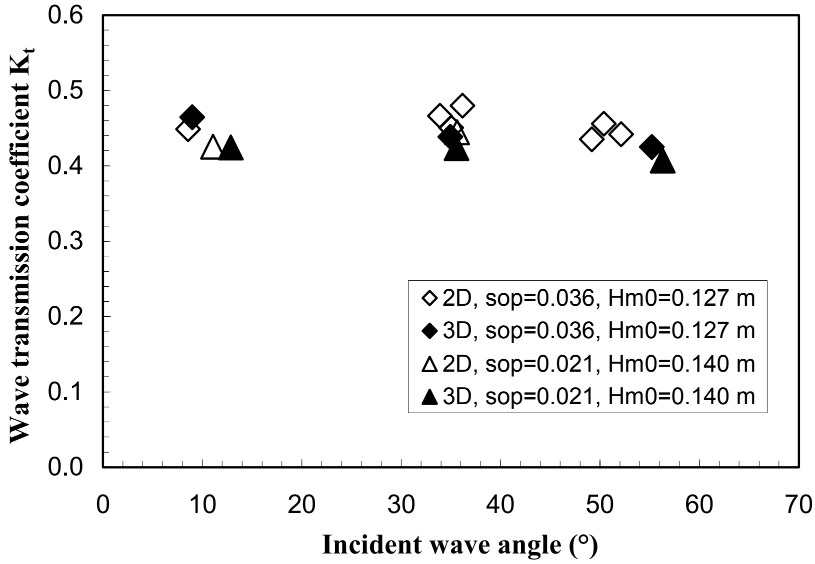

Figure 5. Comparison of long-crested and short-crested waves for rubble structures

be similar for perpendicular wave attack ($\beta = 0°$), but differences may occur for angled wave attack. For wave run-up and overtopping on dikes, for example, short-crested waves gave less reduction for larger wave angles than long-crested waves, see Van der Meer et al. (1998).

Figure 5 gives a comparison for the rubble mound structure. Tests were selected which were similar in both cases. This resulted in wave steepnessess of s_{op} = 0.036 and 0.021 with wave heights of respectively H_{mo} = 0.127 m and 0.140 m. In the graph the wave transmission coefficient has been given as a function of the incident wave angle. Similar shape of symbols give similar wave conditions and these should be compared with each other. Open symbols give long-crested waves and solid symbols give short-crested waves. The trend of the data points is not important at this stage, only the direct comparison of similar open and solid symbols for the same angle of wave attack.

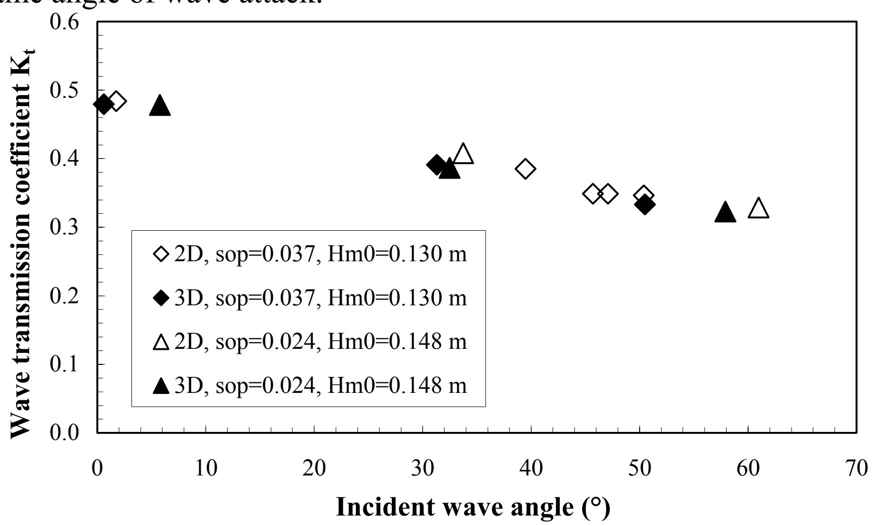

Figure 6. Comparison of long-crested and short-crested waves for smooth structures

The conclusion from Figure 5 is that long-crested and short-crested waves give similar overtopping for rubble mound structures, although in average the short-crested waves give 1%–2% lower values.

Figure 6 gives similar results for the smooth structure. The graph shows a clear influence of the angle of wave attack on transmission, but this aspect will be treated later. Direct comparison of similar symbols give the same conclusion as for rubble mound structures: there is no or only a marginal difference between long-crested and short-crested waves.

Change of wave direction. Another important question is whether transmitted waves have the same direction as the incident waves. Figure 7 gives the results for the rubble mound structure. First of all this graph shows that perpendicular generated waves did in fact not reach the structure completely perpendicular, but in average under an angle of about -10°. This was caused by a slightly different layout with a roundhead at one of the ends of the structure.

The figure shows clearly that for rubble mound structures the transmitted wave direction is smaller than the incident one. The reason for this could be that roughness and porosity of the structure cause dissipation of energy in such a way thatthe waves do not go on in the same direction. A simple straight line fits all data points quite well and leads to the conclusion that the transmitted wave angle is about 80% of the incident wave angle, or:

$\beta_t = 0.80\ \beta_i$ for rubble mound structures

Figure 8 shows the results for the smooth structure. The conclusions now are quite different from the one for rubble mound structures. Up to 45° transmitted and incident waves have similar directions. For larger incident angles than 45° this

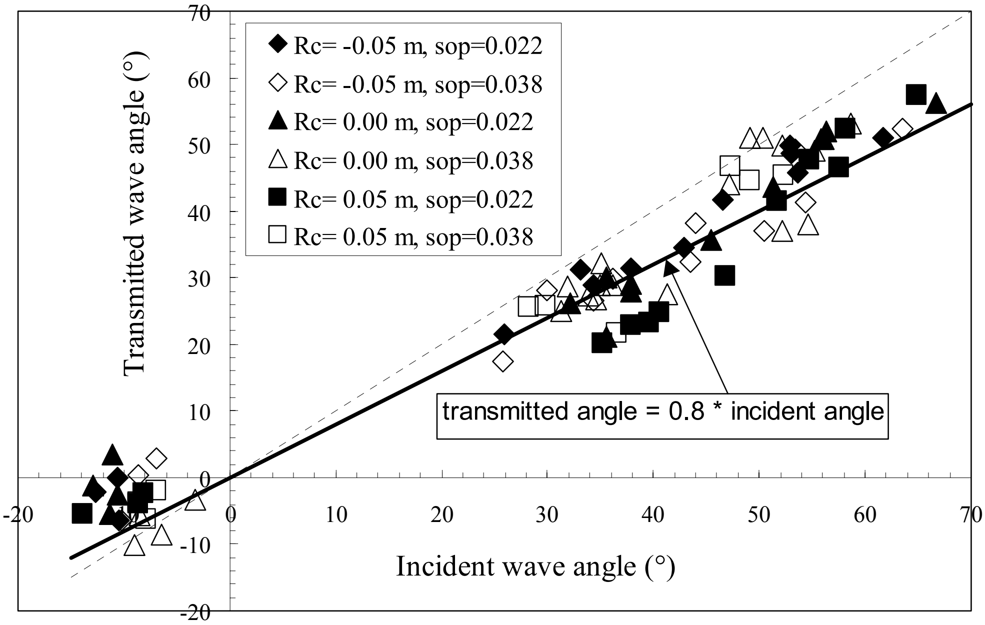

Figure 7. Transmitted wave angle versus incident angle. Rubble mound structure

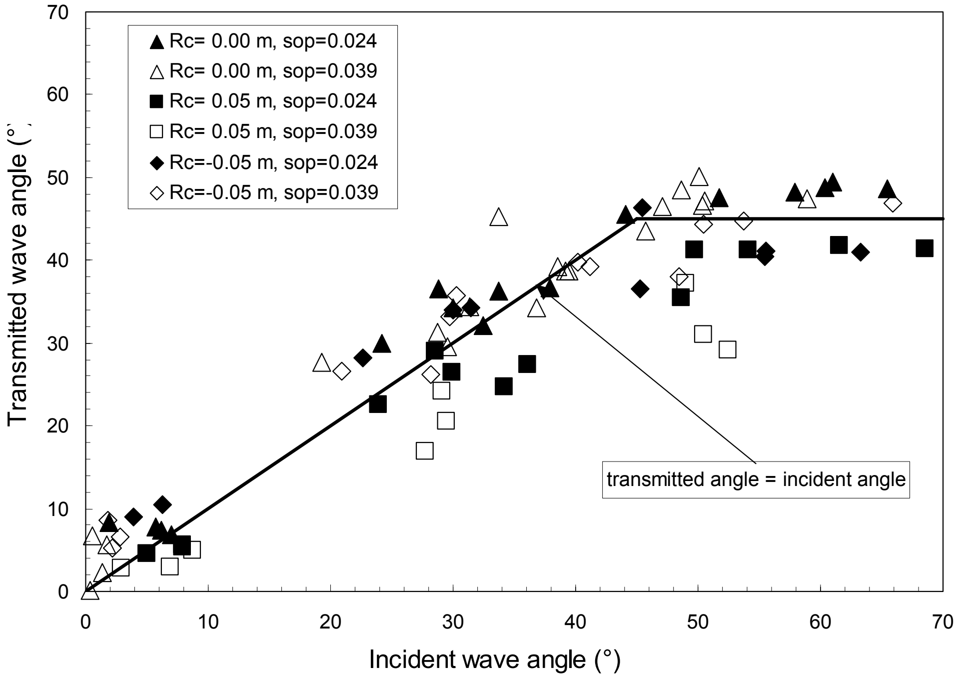

Figure 8. Transmitted wave angle versus incident wave angle. Smooth structure

changes: the transmitted wave angle remains 45°. Probably the smooth structure works in such a way that for larger angles the waves run along the crest of the structure and generate always a transmitted angle of 45°. There is also a tendency that for lower wave transmission (the data points for $R_c = 0.05$ m) the transmitted wave angle is a little smaller than the incident one. For smooth structures the behaviour can be described by:

$\beta_t = \beta_i$ for $\beta_i \leq 45°$
$\beta_t = 45°$ for $\beta_i > 45°$ for smooth structures

Influence of angle of wave attack on transmission coefficient. Transmission coefficients are mostly obtained by 2D flume testing where the angle of wave attack is always perpendicular to the structure. But is this still true if the angle of wave attack is oblique? Figure 9 gives the answer for rubble mound structures. The transmission coefficients are given for 3 groups of data points (the 3 different crest levels) and within each group a distinction has been made for the wave steepness. Of course a lower crest level gives larger transmission, which is according to 2D research.

The main objective in Figure 9, however, is to look at the trend within each group of data points with respect to the incident wave angle. For the two lowest crest heights, the upper part of the graph, there is a very small tendency that the transmission coefficient decreases with increasing angle of wave attack. But within the scatter of the data it is only marginal. For the highest crest height the trend seems a little more pronounced, but even there no influence is found for incident wave angles between 30° and 60°.

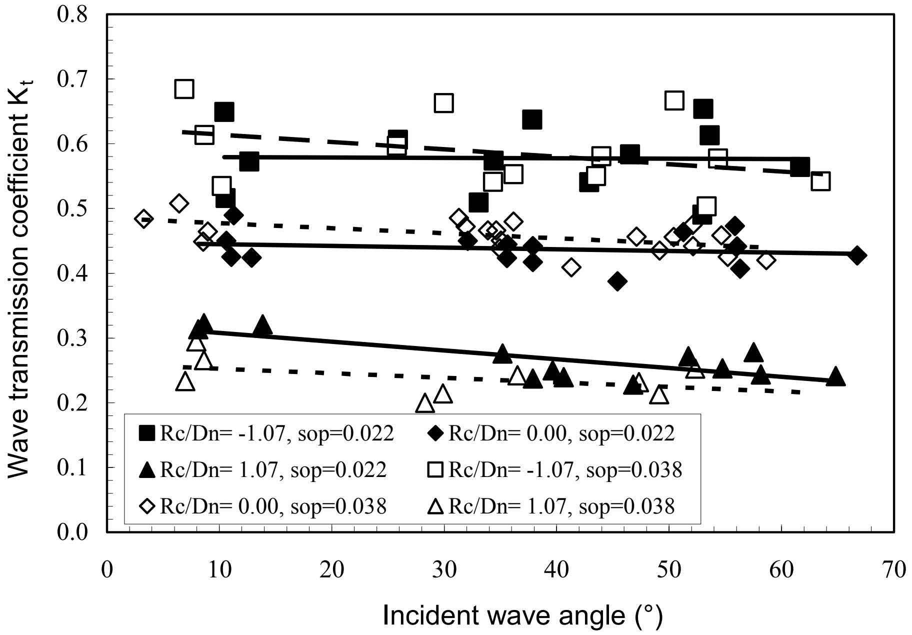

Figure 9. Influence of wave angle on wave transmission coefficient K_t for rubble mound structures

For rubble mound structures it can be concluded that the angle of wave attack has no or only marginal influence on the wave transmission coefficient. This leads also to the conclusion that earlier 2D research, resulting in prediction formulae for transmission at rubble mound structures, is valid for oblique wave attack. One restriction may be that it is only valid for rubble structures with a small crest width.

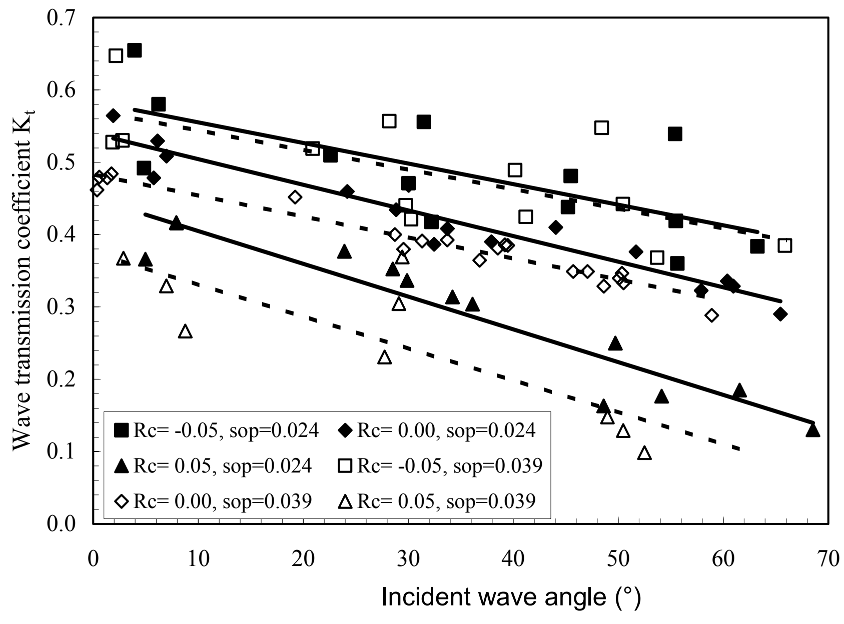

Figure 10. Influence of wave angle on wave transmission coefficient K_t for smooth structures

Figure 10 shows a similar graph as Figure 9, but now for the smooth structure. The conclusions, however, are completely different! It is very clear that for smooth structures the wave transmission coefficient decreases significantly with increasing angle of wave attack. It means also that if 2D prediction formulae for smooth structures are used for oblique wave attack, the predicted wave transmission is quite conservative. Further analysis is required to come up with a prediction formula on the influence of the angle of wave attack on transmission, see the next section.

2D wave transmission on smooth structures. d´Angremond et al. (1996) with as basis De Jong (1996) came up with a formula for wave transmission on smooth structures. The formula is as follows:

$$K_t = -0.4R_c/H_i + [B/H_i]^{-0.31} * [1 - \exp(-0.5\xi)] * 0.80 \quad (1)$$

with as minimum $K_t = 0.075$ and maximum $K_t = 0.8$.

This formula has a similar shape as the one for rubble mound structures, only one coefficient is different, ie 0.80 is 0.64 for rubble mound structures. The formula for smooth structures at that time was only based on a limited data set. Now new data are available: Van der Meer et al. (2000) and the data within the present project with perpendicular wave attack.

The comparison of all data on smooth structures with the formula of d´Angremond et al. (1996), equation 1, is given in Figure 11. The total picture gives data well distributed around the line, but in detail the conclusion is different. The original data (open symbols) are in average located above the line, where the new data (solid symbols) are below the line. Therefore a new analysis was performed on the data in order to come up with an improved method for smooth structures.

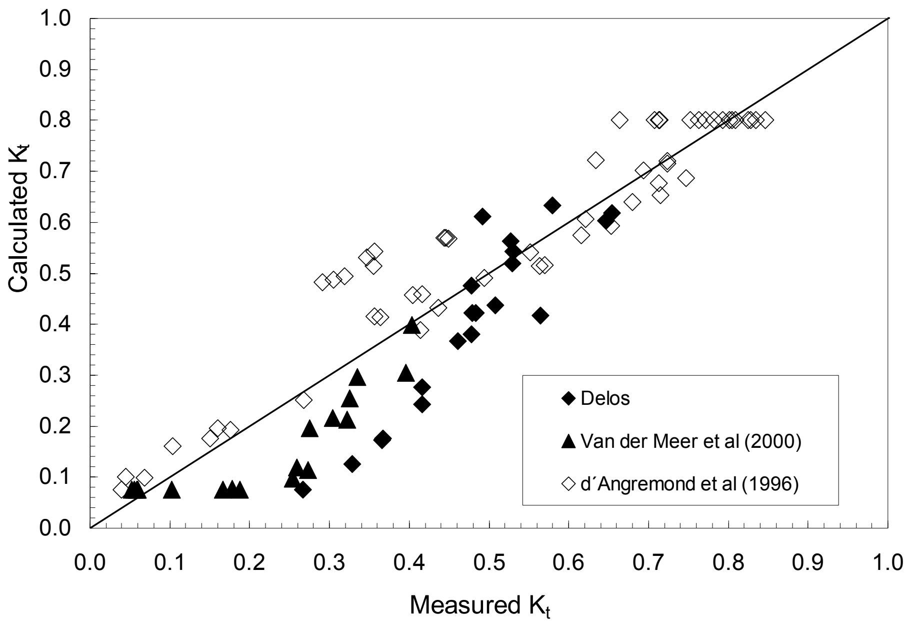

Figure 11. All data on smooth structures compared with equation (1)

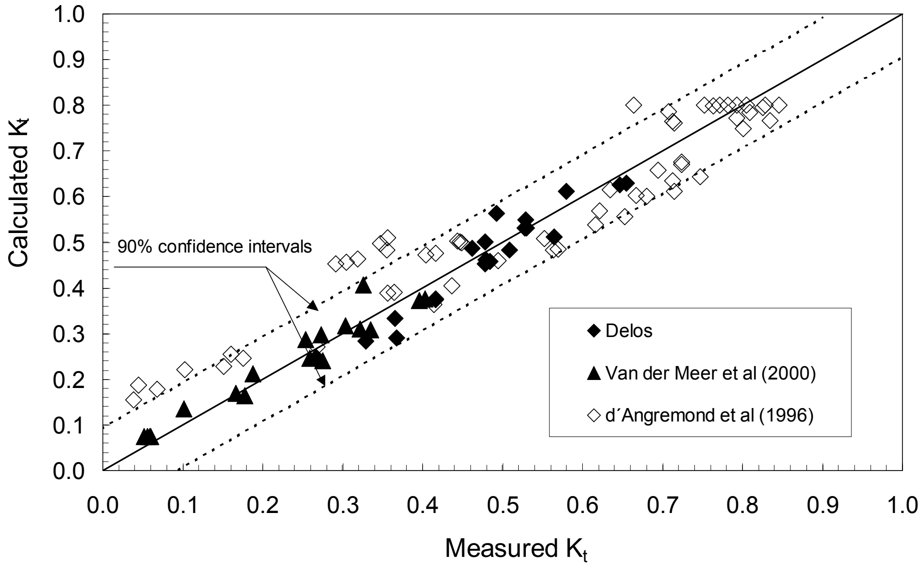

Figure 12. All data on smooth structures compared with new equation (2)

In equation (1) there is quite a strong influence of the crest width on wave transmission. This expression in (1) was based on rubble mound structures, where indeed a permeable and rough crest with a large width has a tremendous effect on transmission. Van der Meer et al. (2000) tested smooth structures with different crest widths and it was very clear that for smooth structures there was hardly any influence of crest width, if the seaward slope was quite gentle. The waves broke on the seaward slope and jumped over the smooth crest without any energy dissipation on the crest. The first conclusion for a new analysis is that the crest width B has no or hardly influence on transmission. This could be different for non-breaking waves (large ξ-values) and structures with very wide submerged crests.

With above conclusion a new analysis was done on the total data set, keeping the structure of the original formula similar. The formula was divided in two parts, one for breaking waves ($\xi_{op} < 3$), where the influence of the crest width was not present and one for non-breaking waves with the same structure as equation (1). The same lower and upper boundaries for K_t were used. The result is given as equation (2). The comparison between measured and calculated K_t is shown in Figure 12.

Modified formula for smooth structures:

$$K_t = -0.3R_c/H_i + 0.75[1 - \exp(-0.5\xi)] \qquad \text{for } \xi_{op} < 3$$

$$K_t = -0.3R_c/H_i + [B/H_i]^{-0.31} * [1 - \exp(-0.5\xi)] * 0.75 \text{ for } \xi_{op} \geq 3 \qquad (2)$$

with as minimum $K_t = 0.075$ and maximum $K_t = 0.8$.

3D wave transmission on smooth structures. With a good formula for 2D wave transmission on smooth structures it is possible to make a straight forward analysis on the effect of oblique waves. Equation (2) was used as a reference and for each test condition the K_t for perpendicular wave attack was calculated. The ratio measured K_t over calculated K_t for $\beta = 0°$ was then plotted versus the incident wave angle β. This graph is shown in Figure 13.

Although Figure 13 shows some scatter, the trend is very clear that wave transmission decreases with increasing incident wave angle. An easy way to include the effect of oblique waves is to add a $\cos^{2/3}\beta$ function to the 2D equation (2). This leads to the final prediction formula for smooth structures:

$$K_t = [-0.3R_c/H_i + 0.75[1 - \exp(-0.5\xi)]] \cos^{2/3}\beta \quad (3)$$

with as minimum $K_t = 0.075$ and maximum $K_t = 0.8$.

and limitations: $1 < \xi_{op} < 3$ $0° \leq \beta \leq 70°$ $1 < B/H_i < 4$

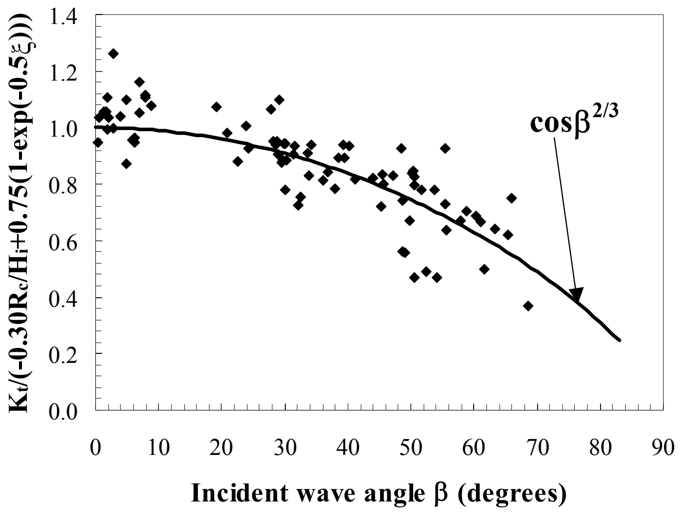

Figure 13. Influence of oblique wave attack on smooth structures

Spectral change due to wave transmission.

Transmitted spectra are often different from incident spectra. Waves breaking over a low-crested structure may generate two or more transmitted waves on the lee side. The effect is that more energy is present at higher frequencies than for the incident spectrum. In general the peak period is quite close to the incident peak period, but the mean period may decrease considerably. A first analysis on this topic can be found in Van der Meer et al. (2000).

The wave transmission coefficient only contains information about the wave heights behind the structure. It is the spectrum which contains wave period information. Very often information is required on both wave heights and periods, for example for wave run-up or overtopping at structures behind a low-crested structure, or for calculation of morphological changes.

Figure 14 shows an example of a transmitted spectrum for a smooth structure and gives clearly the picture that energy is present more or less a similar level up to high frequencies. Based on this a simple and rude model was developed by Van der Meer et al. (2000), which is shown in Figure 15. In average 60% of the transmitted energy is present in the area of < $1.5f_p$ and the other 40% of the energy is evenly distributed between $1.5f_p$ and $3.5f_p$.

It are these assumptions of division of energy in 60%/40% parts and the frequency of $f_{max} = 3.5f_p$, which were only based on a limited number of tests, that can be more elaborated with new data. Analysis showed that there was no clear dependency on wave direction, so all data were taken together. The results are given in Table 2.

Table 2. Average results on spectral shape compared with Van der Meer etal (2000)

	proposed method	rubble mound	smooth structure
f_{max}/f_p	3.5	3.2 (2.1-4.3)	3.8 (2.9-5.6)
$E_{1.5fp-fmax}/E_{total}$	40%	34% (20%-51%)	42% (30%-60%)

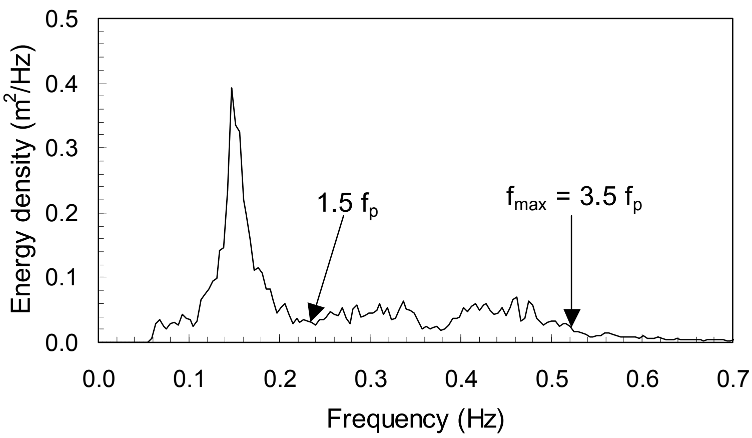

Figure 14. Example of transmitted spectrum with energy at high frequencies

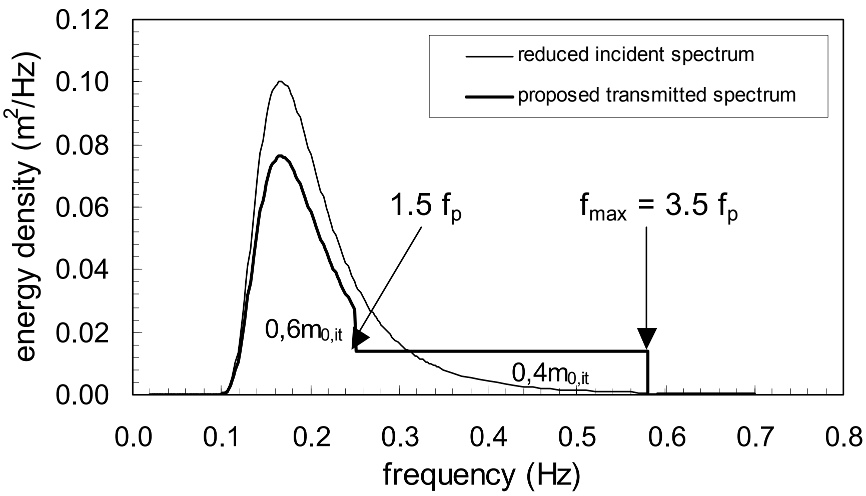

Figure 15. Proposed method by Van der Meer et al. (2000) for transmitted spectrum

The overall results are similar to the proposed method, although rubble mound structures give a little smaller values than smooth structures. Briganti et al. (2003) have taken this a little further and come to the conclusion that rubble mound and smooth structures do not give a similar behaviour. The method is also applicable for submerged rubble mound structures, but not for emerged ones. In the latter case much less energy goes to the higher frequencies and f_{max} may become close to 2.0. More research is needed to improve the method as described above.

Conclusions

General **conclusions**. The first conclusion is that rubble mound structures have a completely different behaviour than smooth structures. The structures are of course also quite different. Gentle smooth slopes cause the waves to break, where steep rubble mound slopes give no breaking, but a lot of energy dissipation through the permeability and roughness of the structure. Although d´Angremond et al. (1996) developed a similar wave transmission prediction formula for rubble mound and smooth structures, it is better to treat both structures independently.

Another general conclusion is that long-crested and short-crested waves give similar wave transmission.

Transmitted wave angle. Incident and transmitted wave angles are not always similar. The conclusions are:

$\beta_t = 0.80\ \beta_i$		for rubble mound structures
$\beta_t = \beta_i$	for $\beta_i \leq 45°$	for smooth structures
$\beta_t = 45°$	for $\beta_i > 45°$	

Transmission coefficient. The influence of the wave angle on the transmission coefficient is non to marginal for rubble mound structures. This means that the most recent and well calibrated formulae of Briganti et al. (2003) can be taken for 3D situations. A new formula was developed for smooth structures, where the angle of wave attack has large influence on the transmission coefficient:

$$K_t = [-0.3R_c/H_i + 0.75[1 - \exp(-0.5\xi)]] \cos^{2/3}\beta \qquad (3)$$

with as minimum $K_t = 0.075$ and maximum $K_t = 0.8$.
and limitations: $1 < \xi_{op} < 3$ $0° \leq \beta \leq 70°$ $1 < B/H_i < 4$

Spectral change. Results on spectral change were not conclusive, but in general results were according to an earlier proposed method (Van der Meer et al. (2000)). Emerged rubble mound structures show a different behaviour and more research is required on this aspect.

Acknowledgements
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