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Wave transmission and reflection at low-crested structures: Design formulae, oblique wave attack and spectral change

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Abstract

A part of the DELOS research focused on wave transformation at low-crested structures, called LCS. This paper gives a summary of all results. Wave transmission on rubble mound structures has been subject for more flume tests in the DELOS programme and simultaneously an existing database has been increased extensively by receiving data from other researchers in the world. This new database consists of more than 2300 tests and has been used to come up with the best 2D wave transmission formula for rubble mound LCS, although not necessarily new as existing ones have been evaluated. Oblique wave attack on LCS was a second objective within DELOS. Results were analysed leading to new empirical transmission formulae for smooth LCS and to conclusions on 3D effects for both rubble mound and smooth LCS. The spectral shape changes due to wave transmission and this change has been subject of analysis for all new test data described above. Although analysis has not been finished completely, former assumptions on spectral change were more or less confirmed. Finally, some analysis was performed on reflection at LCS and a first formula was derived to take into account the effect that wave overtopping or transmission reduces reflection and must be dependent on the crest height of the structure.

1. Introduction

Waves coming from deep water may reach a structure after refraction, shoaling and breaking. As soon as waves reach a structure, such as an LCS, a lot of processes start. The waves may break on the structure, overtop it, generate waves behind the structure and reflect from the structure. Another effect may be wave penetration through openings between structures and diffraction around the head of structures. Both wave penetration and diffraction do not depend on the fact whether the structure is low-crested or not and, therefore, one is referred to handbooks for these items.

The main effect of an LCS is that energy can pass over the crest and generate waves behind the struc-

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ture. The description of this wave transmission is the main objective in this chapter. As wave reflection decreases for lower structures, also this item will be treated. More in detail the following subjects will be treated:

- 2D wave transmission at rubble mound LCS
- 3D effects on rubble mound LCS
- Spectral change due to wave transmission
- Wave transmission at smooth and impermeable LCS
- Reflection at LCS

2. Governing parameters of wave transmission

The main parameters describing wave transmission have been given in Fig. 1, here for a rubble mound structure. These are:

H_i= Incident significant wave height, preferably H_{m0i}, at the toe of the structure
H_t= Transmitted significant wave height, preferably H_{m0t}
T_p= Peak period
s_{op}= Wave steepness, $s_{op}=2\pi H_i/(gT_p^2)$
R_c= Crest freeboard
h_c= Structure height
B= Crest width
D_{n50}= Nominal diameter of armour rock (in case of rubble mound structure)
K_t= Transmission coefficient H_t/H_i
ξ_{op}= Breaker parameter $\xi_{op}=\tan\alpha/(s_{op})^{0.5}$
tan α= Seaward slope of structure

Other parameters, but probably less important, are friction/roughness of the armour layer and the porosity/permeability of the core. Finally, the angle of incidence, β, will probably show an influence if tests have been performed in a wave basin.

3. 2D wave transmission at rubble mound LCS

Wave transmission and overtopping are the two phenomena that allow wave energy to pass over or through LCS. The other part of the wave energy will be dissipated by wave breaking on and over the structure and some of the energy will be reflected. As these structures are commonly employed in coastal defence interventions, the prediction of the amount of energy transmitted behind them is a crucial point in design practice and research in the past has led to various design formulae for wave transmission that are now commonly used in engineering practice—but each with their own limitations. A first effort made within the EU-funded project DELOS has been both to perform new tests on LCS and to gather many existing datasets on wave transmission and build an extensive database. A second effort was to perform a review and an upgrading of the existing approaches by means of this extensive database.

The studies by Van der Meer and Daemen (1994) and d'Angremond et al. (1996) have been used as the starting point of the present work. They began to collect and reanalyse data from different sources, giving a description of the various phenomena, which led to two different formulae. Amongst the more recent investigations it is worth to mention the extensive experimental study performed by Seabrook and Hall (1998) on submerged rubble mound structures. The wide range of variables tested makes this study fundamental to extend the description of the phenomena to structures with very large crest widths. A similar extensive study on LCS with large crest widths has been performed by Hirose et al. (2002), testing structures armoured with the recently developed armour unit called Aquareef. Both studies, however, looked at submerged structures only and not emerged structures. These studies, together with other valuable investigations, have been used as the basis of the present work on the wave transmission coefficient.

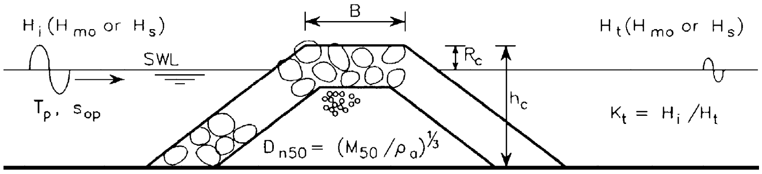

Fig. 1. Definitions of governing parameters involved in wave transmission.

3.1. Datasets used

A wide database concerning experiments on wave transmission at low-crested structures in wave flumes has been collected. The gathered database, made up of 2337 tests, includes the data previously described and analysed by Van der Meer and Daemen (1994) and by d'Angremond et al. (1996), that will be referred to as the "old database" here after. This database includes rubble mound rock structures as well as tetrapod and accropode armour layers. The range of the parameters tested is shown in Table 1.

Within the DELOS project series of 2D random wave tests have been carried out in 2001 at the University of Cantabria, Spain, (referred as UCA here after) and at the Polytechnic of Catalonia, Spain, (referred to as UPC), described in Gironella et al. (2002). See for the set-up of the tests Kramer et al. (2005—this issue) in this special issue. Both narrow and large crests have been tested, in particular in the UCA tests the parameter B/H_i ranged from 2.6 to 30, allowing a detailed analysis on the influence of this parameter. Large scale tests in the Large Wave Channel (GWK), of the Coastal Research Centre (FZK), in Hanover (Germany), have been performed and analysed by the University of Naples, Italy. A detailed description of the tests and results may be found in Calabrese et al. (2002). The main objective of these tests was to look at low-crested and submerged breakwaters in the presence of broken waves. The wave flume is $300 \times 5 \times 7$ m and a sloping 1 : 50 sandy foreshore was present, leading to heavily breaking waves in front of the structure. A narrow and a wide crest were tested. A total of 45 tests with irregular waves, driven by TMA spectra, have been analysed in that study.

Furthermore, tests from Seabrook and Hall (1998) have been included in the database. Structures tested in this study are classical rubble mound submerged breakwaters. Both the relative freeboard and the relative crest width have been varied within a wide range. In particular B/H_i reaches values of 74. Also tests results from Hirose et al. (2002) concerning a new type of concrete armour units designed for submerged structures have been added to the dataset. Similar to the Seabrook and Hall (1998) tests, the relative crest width has been varied from very small values up to $B/H_i = 102$. Both datasets have submerged structures only and, therefore, do not cover the whole range of crest freeboards. Finally, experimental data coming from Melito and Melby's (2002) (M and M hereafter) investigation on hydraulic response of structures armoured with coreloc have been considered. These tests have been performed both on submerged and emerged structures with the relative freeboard varying in a wide range. An overall view of the extensive database is given in Table 1.

3.2. Analysis of database

Before starting any analysis it is worthwhile to take a look at Fig. 2, which shows the overall picture on transmission coefficient versus the relative freeboard. In these graphs the old database has been shown jointly

Table 1
Summary of the ranges of parameters involved in 2D wave transmission tests at LCS

Database	Armour type	R_c/H_i	B/H_i	B/L_{op}	ξ_{op}	H_i/D_{n50}	H_i/h	s_{op}	Tests #
Old database	Various	−8.7	0.37	0.009	0.7	0.3	0.03	$2*10^{-4}$	398
		4.0	43.48	0.51	8.26	6.62	0.62	0.06	
UCA	Rubble mound	−1.5	2.67	0.04	3.97	0.84	0.1	0.002	53
		1.53	30.66	0.4	12.98	2.42	0.37	0.02	
UPC	Rubble mound	−0.37	2.66	0.07	2.69	2.65	0.17	0.02	24
		0.88	8.38	0.24	3.56	4.36	0.33	0.034	
GWK	Rubble mound	−0.76	1.05	0.02	3	1.82	0.31	0.01	45
		0.66	8.13	0.21	5.21	3.84	0.61	0.03	
M & M	Core locks	−8.2	1.02	0.02	2.87	0.68	0.05	0.01	122
		8.9	7.21	0.13	6.29	4.84	0.5	0.054	
Seabrook	Rubble mound	−3.9	1.38	0.04	0.8	0.78	0.11	0.01	632
		0	74.47	1.66	8.32	3.2	0.58	0.06	
Aquareef	Aquareef	−4.77	1.24	0.02	1.78	0.59	0.1	0.01	1063
		−0.09	102.12	2.1	5.8	4.09	0.87	0.08	

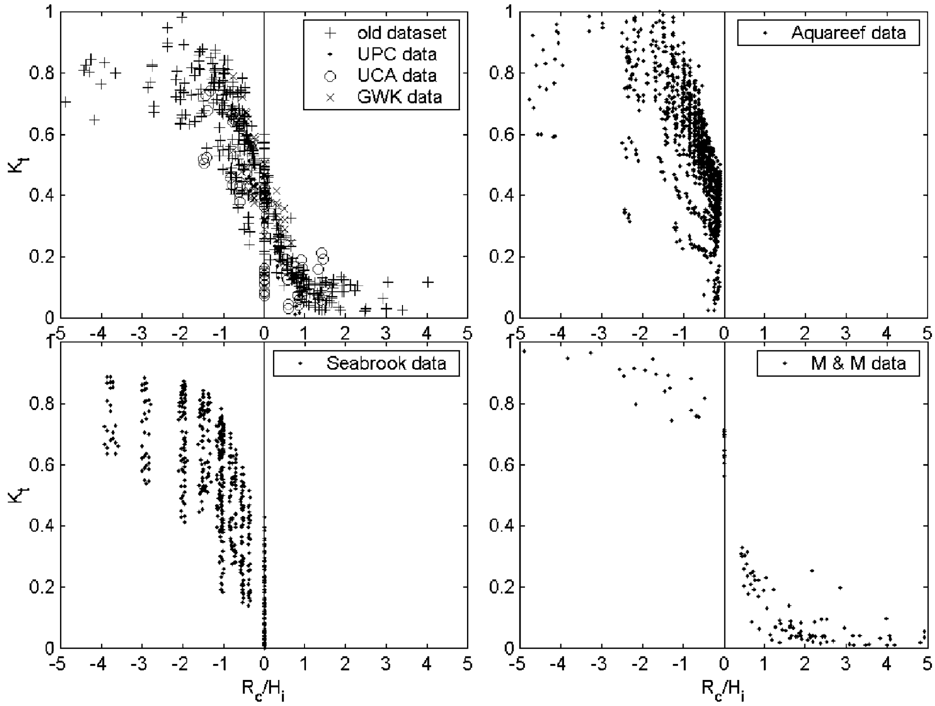

Fig. 2. Wave transmission coefficient versus relative freeboard for the four sub-datasets used in this study.

with UPC, UCA and GWK data, while the other three datasets have been shown separately. The range of R_c/H_i plotted is limited to $-5 < R_c/H_i < 5$. It is clear that structures armoured with Aquareef show higher maximum values of K_t compared to the other structures, probably due to the high permeability of the armour layer or due to the definition of the crest height (top of the Aquareef unit). Moreover, these large values are reached at relatively large values of R_c/H_i.

Some restrictions on the parameters in the database involved in wave transmission have been applied. Waves with $s_{op} > 0.07$ are not stable and will break due to their steepness. Therefore, tests with s_{op} exceeding this value have been discarded. Also a very low wave steepness of $s_{op} < 0.002$ is difficult to be generated in a flume and tests showing a wave steepness smaller than this value are considered less reliable and thus discarded. Some tests in the datasets have been performed with breaking waves in front of the structure, but the reflection analysis was still based on two or three wave gauges in front of the structure. Such an analysis is less reliable and may lead to a wrong incident wave height. Very often tests without a structure in the flume are then required to establish the right incident wave height. If these calibration tests were not performed the tests were considered as less reliable and some of them were discarded. Moreover, in Van der Meer and Daemen (1994) it has been pointed out with reason that for emerged structures with $H_i/D_{n50} < 1$ the K_t shows a wide scatter. In this study tests with $R_c/H_i > 1$ have been taken into account only if $H_i/D_{n50} > 1$. Also tests with $H_i/D_{n50} > 6$ have not been used in this study as these values will cause instability of the structure.

3.3. Re-analysis of existing formulae and possible improvement

Many formulae on wave transmission exist, most of them developed on limited data sets. Van der Meer and Daemen (1994) and d'Angremond et al. (1996) proposed two different design formulae for K_t, which gives the starting point of the present analysis. The formulae were developed on data sets from various authors and not only on a limited data set. As many formulae exist the goal of this study is not to come up with a new formula, but mainly to check the formulae against the present large database and only improve if omissions are noted. Also a complete theoretical analysis of wave transmission is not given here. One is referred to the many existing references on this subject.

Van der Meer and Daemen (1994) consider the use of the nominal diameter D_{n50} in order to describe the influence of crest height on wave transmission; d'Angremond et al. (1996) relate the crest freeboard directly to the incident wave height. This enables a description of impermeable smooth structures too and not only rubble mound structures. Both formulae of above references include the influence of non-dimensional crest freeboard, R_c/D_{n50} or R_c/H_s, the wavelength L_{op} (or steepness, s_{op}) and the crest width B. In both formulae a linear dependency of K_t on the relative freeboard is assumed in the sharply varying region for K_t. The influence of crest width is included to explain the behaviour of K_t if $R_c=0$. See for more background both references. The Van der Meer and Daemen formula for traditional breakwaters reads:

$$K_t = a\frac{R_c}{D_{n50}} + b \qquad (1)$$

where: $a = 0.031\frac{H_i}{D_{n50}} - 0.024$ and

$$b = -5.42s_{op} + 0.0323\frac{H_i}{D_{n50}} - 0.017\left(\frac{B}{D_{n50}}\right)^{1.84} + 0.51$$

The d'Angremond et al. (1996) formula reads:

$$K_t = -0.4\frac{R_c}{H_i} + 0.64\left(\frac{B}{H_i}\right)^{-0.31}\left(1 - e^{-0.5\xi}\right) \qquad (2)$$

Both formulae have been limited with two values for K_t, which are $K_t=0.75$ and $K_t=0.075$ in Van der Meer and Daemen (1994) and $K_t=0.8$ and $K_t=0.075$ in the formula of d'Angremond et al. Of course it is obvious that for very large crest freeboards the transmission coefficient should become 0 and for a very small structure (very large negative freeboard) 1. But this is very often outside the range of practical applicability, as even for a very high structure small wave transmission may occur due to transmission through and not over the structure. The main area is of course were the wave transmission varies fairly quickly from small to large with decreasing freeboard.

Eqs. (1) and (2) have been applied to the present database, keeping in mind that the parameter ranges are sometimes different from the ones investigated in the two original studies. It is obvious that if any formula is used outside the range in which it has been inferred, the accuracy of the estimate will decrease. In particular the influence of crest width described in Eqs. (1) and (2) relies on a limited number of data, so it was expected that this variable might be crucial for the accuracy of the formula. Fig. 3 shows the K_t calculated with the two formulae versus the measured K_t. Data have been subdivided in classes of B/H_i. For Eq. (2) (see the right panel of Fig. 3) it is quite evident that the error in predicting K_t increases with B/H_i. Moreover, for structures with $B/H_i>10$, Eq. (2) overestimates the transmission coefficient. The analysis of the comparison with Eq. (1) in Fig. 3 is complex as the influence of the crest width is not very clear. In the following only Eq. (2) will be taken into account.

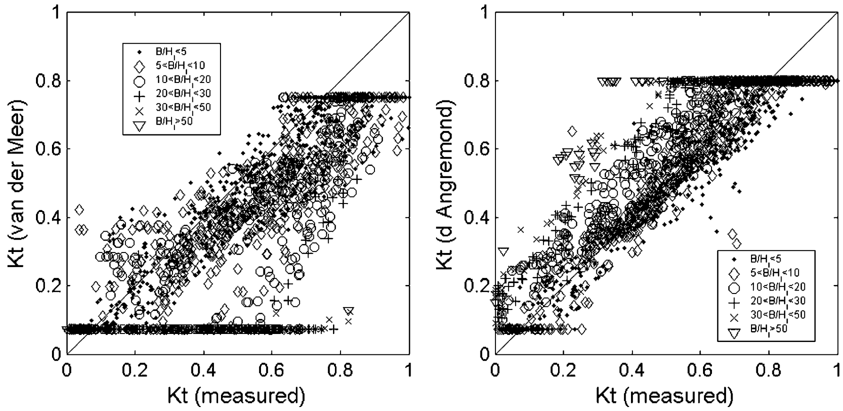

Fig. 3. Performance of two existing wave transmission formulae on the present database.

To investigate the reason of the deviation for high values of B/H_i it is necessary to remind that in Eq. (2) the function that represents the influence of this parameter has been retrieved by analysing tests with zero freeboard in the old database. The analogous graph for the present dataset (see Fig. 4) shows large scatter for $0<B/H_i<10$, but also a large influence of this parameter. If the relative crest width is larger than 10, the scatter seems to decrease; only some tests with $H_i/D_{n50}<1$ show higher values of K_t, as seen in the left panel of Fig. 4. Furthermore the right panel of the same figure shows the influence of the surf similarity parameter (ξ_{op}). It has to be pointed out that for $\xi_{op}<3$ the experimental values are disposed towards the lower edge of the cloud. Also the curve used in d'Angremond et al. (1996) to describe the influence of the relative crest width has been shown in the two graphs of Fig. 4. It is evident that this curve fits only the data with $B/H_i<10$ pretty well, hence it is necessary to improve the prediction for larger values.

In this study an attempt to improve the formula has been done by using two different relations, one for structures with $B/H_i<10$ (Eq. (2)) and one for structures with larger relative crest width. The relationship for $B/H_i>10$ has been obtained by simply refitting the structure of Eq. (2) on data with relative crest widths belonging to this class. The result is:

$$K_t = -0.35\frac{R_c}{H_i} + 0.51\left(\frac{B}{H_i}\right)^{-0.65}\left(1 - e^{-0.41\xi}\right) \qquad (3)$$

For structures with $B/H_i<10$, Eq. (2) has been considered still accurate. The two formulae, however, give a discontinuity at $B/H_i=10$. For practical application it is better to use Eq. (2) for $B/H_i<8$, Eqs. (3) and (4) for $B/H_i>12$ and to linearly interpolate in the range $8<B/H_i<12$.

Another problem to solve was the description of the limits of the formulae. The presence in the database of tests concerning submerged structures with large values of B/H_i, allows us to study the limit as a function of the adopted non-dimensional parameters. Fig. 5 shows that there is a dependency of the maximum reached by the transmission coefficient on the relative crest width B/H_i. The larger the relative crest width, the lower the wave transmission coefficient. Moreover, the range in which K_t sharply varies increases with increasing B/H_i. For $B/H_i>40$ the relative freeboard still influences the transmission coefficient if $R_c/H_i<-3$, see Fig. 5.

It is useful to limit the maximum value in Eq. (3) in analogy with the two aforementioned studies. The definition of a maximum independent from B/H_i would lead to an inaccurate estimation of K_t. Therefore, a maximum function has been derived instead of a constant value. The average values of K_t corresponding to $R_c/H_i<-2$ have been considered for the six classes of B/H_i analysed in Fig. 5 and the influence of the relative crest width has been studied, see Fig. 6. The upper limit can be described by

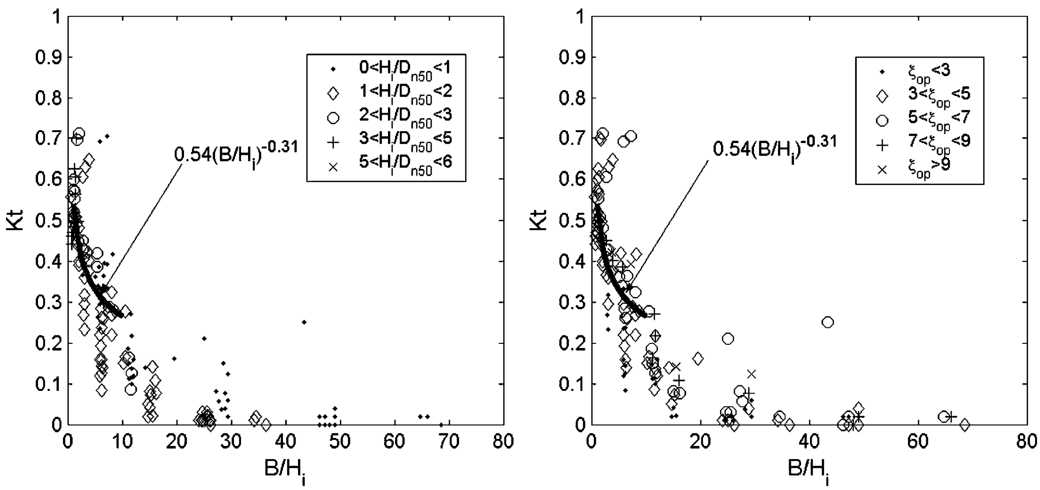

Fig. 4. Influence of B/H_i on K_t for structures with zero freeboard and all data sets.

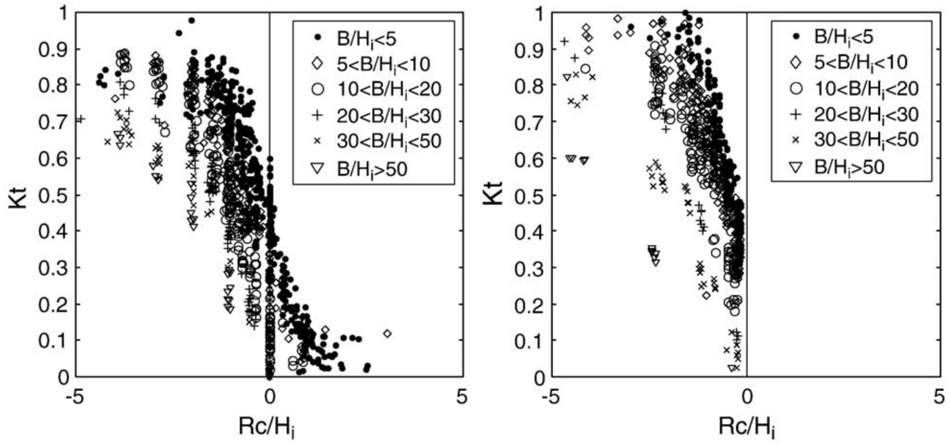

Fig. 5. Influence of the relative freeboard on K_t for various classes of B/H_i. Right panel, Aquareef data; left panel shows the results from all other tests.

assuming a linear dependency from the relative crest width:

$$K_{tu} = -0.006\frac{B}{H_i} + 0.93 \tag{4}$$

The lower limit of the formula has been kept constant and equal to $K_{tl}=0.05$. The measured values of K_t have been compared with the ones predicted with Eqs. (2) and (3), making use of the proposed limiting relationship (4). The results have been shown in Fig. 7. The performances of Eqs. (1)–(4) may be evaluated in terms of round mean square error (RMSE) and R^2. Eqs. (1) and (2) show a RMSE of 0.112 and 0.072 and R^2 equal to 0.81 and 0.91, respectively for $B/H_i<10$, hence the formula of d'Angremond et al. may be considered more accurate in this range. Eq. (4) shows a RMSE equal to 0.082 and R^2 equal to 0.90 for $B/H_i>10$ which represents its range of application. The standard deviation is 0.05 for Eq. (2) and 0.06 for Eqs. (3) and (4).

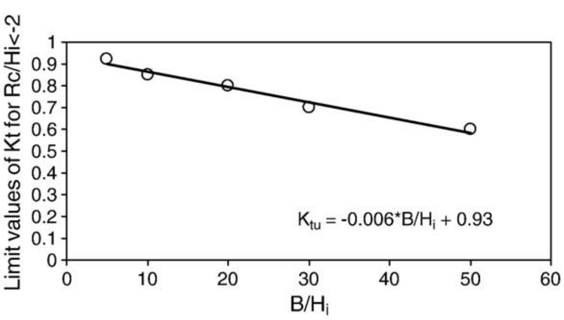

Fig. 6. Determination of an upper limit for K_t for very wide crests.

Finally, it should be stated that existing formulae derived by Seabrook and Hall (1998) and Hirose et al. (2002) were not used as they were based on submerged structures only. They are not able to predict wave transmission over the full range of crest freeboards and have therefore not been considered further. They will be of course applicable for submerged structures, certainly with a wide crest.

Another remark is that in this analysis only existing formulae were used and checked and that a complete new analysis, starting from fresh and including more parameters, was not performed. This could be done in the future, however, to reduce the scatter which is still present in the formulae, but this was not part of the DELOS work.

4. 3D effects on rubble mound LCS

In 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 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? Here's more in detail:

- Are the prediction formulae for K_t still valid?
- Is there any influence of short-crestedness of waves?

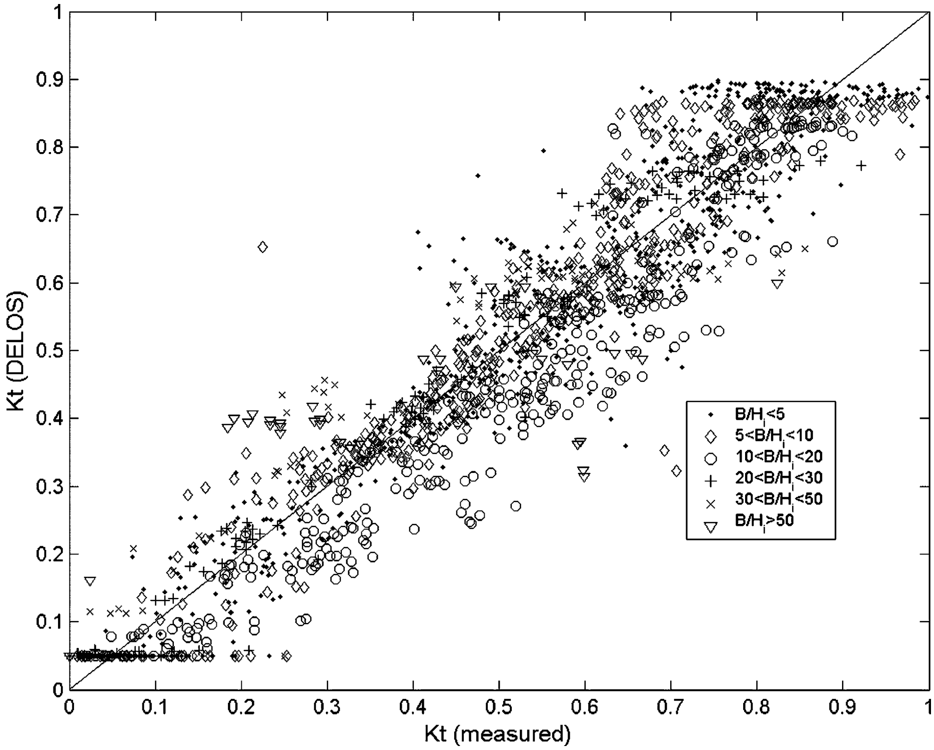

Fig. 7. Comparison between calculated and measured values of the transmission coefficient using the proposed Eqs. (2)–(4).

- Are wave directions similar in front of the structure and after transmission?
- Is the spectral change (more energy to high frequencies) similar to perpendicular wave attack?

Three-dimensional tests on wave transmission were performed under DELOS in the short-crested wave basin at Aalborg University, Denmark to answer these questions. See Kramer et al., 2005—this issue for a set-up of the tests, the test programme and analysis of wave records. A detailed analysis of the tests has been given in Wang (2003) and a summary in Van der Meer et al. (2003).

4.1. 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 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). Fig. 8 gives a comparison for the rubble mound structure. Tests were selected which were similar in both cases. This resulted in wave steepnesses of $s_{op}=0.036$ and 0.021 with wave heights of respectively $H_{mo}=0.127$ and 0.140 m. In the graph the wave transmission coefficient has been given as a function of the incident wave angle. Similar shape

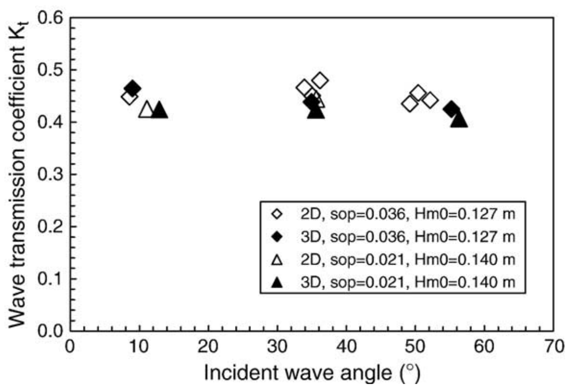

Fig. 8. Comparison of long- and short-crested waves for rubble structures.

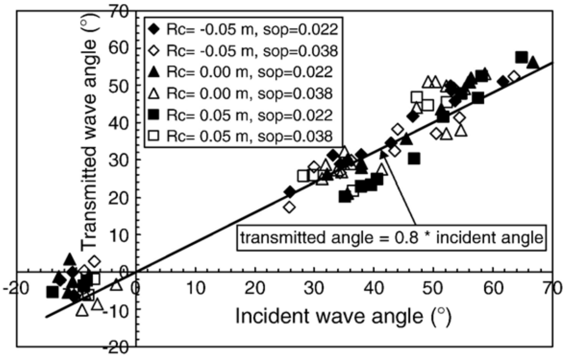

Fig. 9. Transmitted wave angle versus incident angle. Rubble mound structure.

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 is. The conclusion from Fig. 8 is that long- and short-crested waves give similar overtopping for rubble mound structures, although in average the short-crested waves give 1–2% lower values.

4.2. Change of wave direction

Another important question is whether transmitted waves have the same direction as the incident waves. Fig. 9 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° (the cloud of data points in the lower left corner of Fig. 9.) This was caused by a slightly different layout with a roundhead at one of the ends of the structure. The figure shows clearly that 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 that the 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:

$$\beta_t = 0.80\beta_i \qquad \text{for rubble mound structures} \qquad (5)$$

4.3. 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 are the coefficients still valid if the angle of wave attack is oblique? Fig. 10 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 Fig. 10, 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, in 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°.

Seabrook and Hall (1998) also performed some 3D-tests with 30° wave incidence and came to the same conclusion that the angle of incidence did not show substantial influence. 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 prediction formulae for transmission at rubble mound structures, such as Eqs. (2)–(4) are valid for oblique wave attack

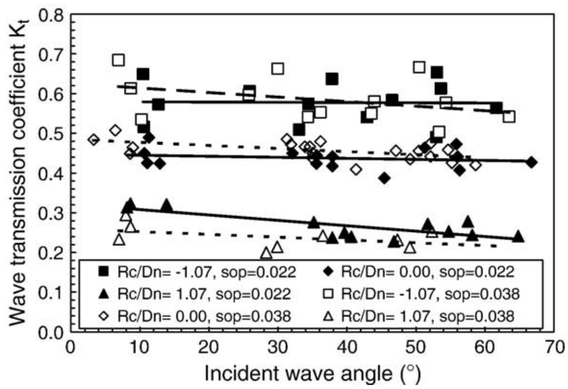

Fig. 10. Influence of wave angle on wave transmission coefficient K_t for rubble mound structures.

as well. One restriction may be that it is only valid for rubble structures with a small crest width.

5. 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. If the reduction of wave energy is mainly led by the dissipations due to the flow *through* the armour layer, however, higher frequencies may be cut. A first analysis on this topic, and giving base for above statements, 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.

Fig. 11 shows an example of a transmitted spectrum for a smooth structure and gives clearly the picture that energy is present more or less at 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 Fig. 12. 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 $3.5f_p$. These assumptions of division of energy in 60%/40% parts and the frequency of

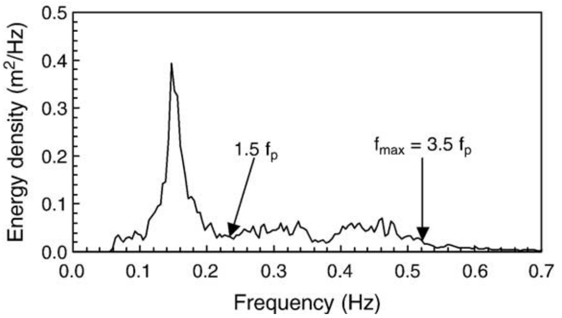

Fig. 11. Example of transmitted spectrum with energy at high frequencies.

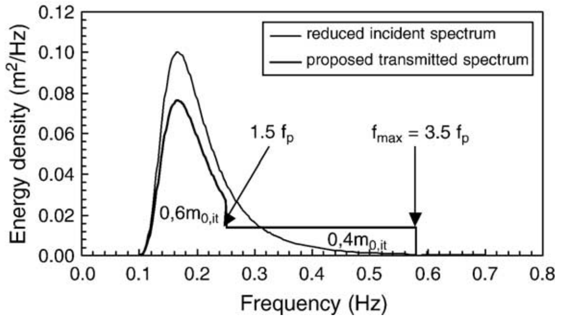

Fig. 12. Proposed method by Van der Meer et al. (2000) for transmitted spectrum.

$f_{max}=3.5f_p$, only based on a limited number of tests, which were more elaborated with new data of the DELOS project.

The conclusion from the new 2D tests was that overall results were similar to the proposed method in Fig. 12. However, rubble mound and smooth structures do not give a similar behaviour. The method is applicable for submerged rubble mound structures, but not for emerged ones (these ones were not tested in Van der Meer et al. (2000)). In the case of emerged structures 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. The results of the 3D research on both rubble mound and smooth structures are given in Table 2. In general rubble mound structures gave a little smaller values than smooth structures. There was no effect of obliquity of the waves.

6. Wave transmission at smooth and impermeable LCS

Not all low-crested structures are of the rubble mound type. Sometimes smooth and impermeable structures exist, for example low-crested structures covered with asphalt or armoured with a block revet-

Table 2
Average results on spectral shape in 3D tests compared with Van der Meer et al. (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)
$E_{1.5f_p}–f_{max}/E_{total}$	40%	34% (20–51%)	42% (30–60%)

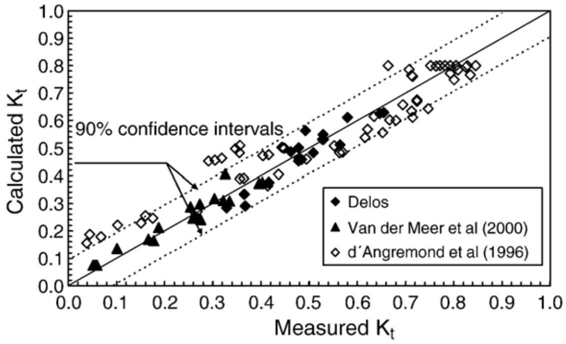

Fig. 13. All 2D-data on smooth structures compared with new Eq. (6).

ment. Often the slope angles of the structure are gentler (1 : 3 or 1 : 4) than for rubble mound structures, mainly for construction reasons. Wave transmission over smooth low-crested structures is completely different from rubble mound structures. First of all, the wave transmission is larger for the same crest height, simply because there is no energy dissipation by friction and porosity of the structure. Furthermore, the crest width has less or even no influence on transmission, also, on the crest there is no energy dissipation, which is completely different from rubble mound structures. For only very wide (submerged) structures there could be some influence on the crest width, but this is not a case that will often be present in reality as asphalt and block revetments are mainly constructed in the dry and not under water. The presence of tide makes it possible to construct these kind of structures above water.

Eq. (2) in this paper, given by d'Angremond et al., 1996, appeared to be a good formula for rubble mound structures. An almost identical formula was given for smooth structures, but now with a coefficient of 0.80 instead of 0.64. At that time it was assumed on limited data, that rubble mound and smooth structures perform more or less the same. The opposite is true as already stated above and therefore, smooth structures are treated independently from rubble mound structures. A re-analysis was done on all smooth structure data available and this led to the following equation to be used for 2D wave transmission at smooth LCS:

$$K_t = -0.3R_c/H_i + 0.75\left[1-\exp\left(-0.5\xi_{op}\right)\right] \quad \text{for } \xi_{op}<3 \quad (6)$$

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

Fig. 13 shows all data compared with Eq. (6). 3D effects were investigated in the same way as for rubble mound structures. The main conclusions are given here.

6.1. Influence of angle of wave attack on transmission coefficient

In contrast to rubble mound structures, smooth LCS showed a strong dependency between transmission coefficient and angle of wave attack. With a good formula for 2D wave transmission on smooth structures (Eq. (6)) it is possible to make a straight forward analysis on the effect of oblique waves. Eq. (6) 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 Fig. 14. Although Fig. 14 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 Eq. (6). This leads to the final prediction formula for smooth structures, including obliquity:

$$K_t = \left[-0.3R_c/H_i + 0.75\left[1-\exp\left(-0.5\xi_{op}\right)\right]\right]\cos^{2/3}\beta \quad (7)$$

with as minimum K_t=0.075 and maximum K_t=0.8. and limitations: $1<\xi_{op}<3$; $0°\leq\beta\leq70°$; $1<B/H_i<4$.

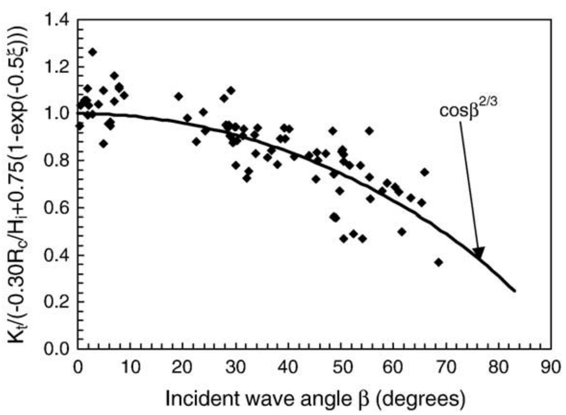

Fig. 14. Influence of oblique wave attack on smooth structures.

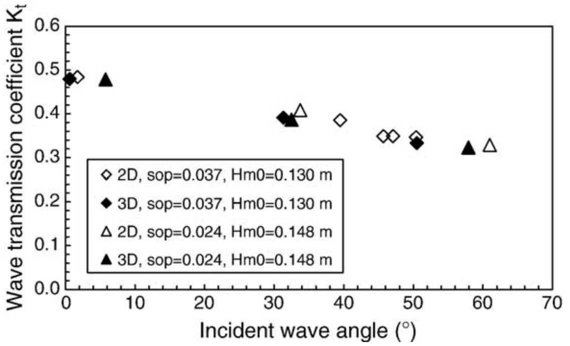

Fig. 15. Comparison of long- and short-crested waves for smooth structure.

6.2. Long-crested versus short-crested waves

Fig. 15 gives similar results for the smooth structure as in Fig. 8 for the rubble mound structure. The graph shows a clear influence of the angle of wave attack on transmission, as described above by Eq. (7). Direct comparison of similar symbols gives the same conclusion as for rubble mound structures: there is no or only a marginal difference between long- and short-crested waves.

6.3. Change of wave direction

Fig. 16 shows the results of change of wave direction for the smooth structure in a comparable way as in Fig. 9 for the rubble mound LCS. 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 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°. Recently more theoretical research has been performed on this aspect, see Wang et al. (2005), giving a more detailed explanation.

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:

$$\beta_t = \beta_i \quad \text{for } \beta_i \leq 45^\circ$$

$$\beta_t = 45^\circ \quad \text{for } \beta_i > 45^\circ \quad \text{for smooth structures} \qquad (8)$$

7. Reflection

As far as wave transformation over low-crested structures is concerned, the DELOS project was focused on wave transmission only. Wave reflection was not considered to be an important aspect and was only treated at the end of the project. Preliminary results are given here. Wave reflection at non-overtopped structures is described in the Rock Manual (CUR/CIRIA, 1991). For rock structures there are data of Van der Meer (1988) and of Allsop and Channel (1989). The most simple prediction formula given in the Rock Manual is:

$$K_r = 0.14\xi_{op}^{0.73} \qquad \text{for } \xi_{op} < 10 \qquad (9)$$

A more elaborated formula for rock slopes in the Rock Manual is:

$$K_r = 0.071P^{-0.82}\cot\alpha^{-0.62}s_{op}^{-0.46} \qquad (10)$$

In this formula the slope angle has a little larger influence than the steepness, compared to the relationship in the breaker parameter ξ_{op}. Also the notional permeability factor (see Van der Meer (1988) has an influence. In the case of overtopped structures, the P-value will often be close to P=0.4 – 0.6 and the influence of the slope angle will reduce if the structure becomes more submerged. Therefore the simple formula (9) was taken for comparison. It is expected that (very) submerged structures will have smaller reflection than non-overtopped, due to the fact that more energy will go over the structure. It is also expected

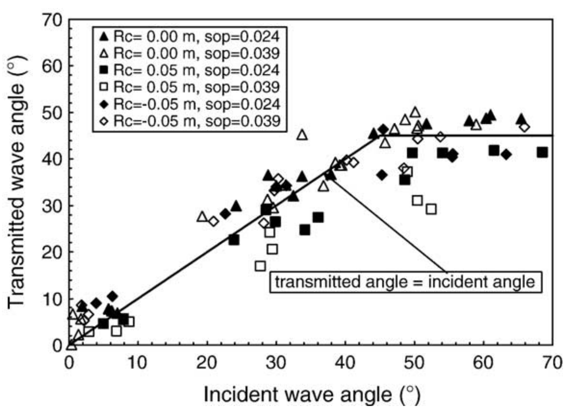

Fig. 16. Transmitted wave angle versus incident angle. Smooth structure.

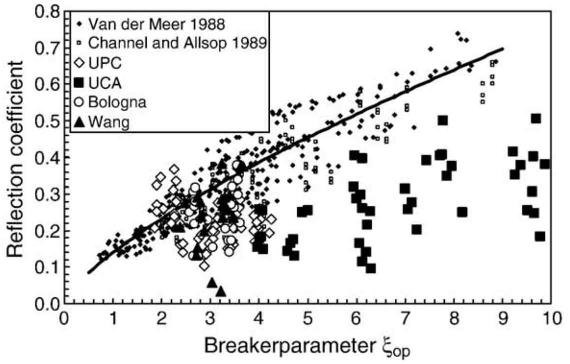

Fig. 17. Reflection from LCS compared with non-overtopped structures.

that the relative crest height R_c/H_i has the main influence on a possible reduction of the reflection coefficient. The crest width will have no influence as waves reflect from the seaward side only.

Within the DELOS project there are 4 data sets with low-crested structures, with the set-up of the tests described in Kramer et al., 2005—this issue:

– UPC—large scale 2D tests; in total 63 tests
– UCA—small scale 2D tests; in total 53 tests
– UB—3D tests in Aalborg by University of Bologna; random waves; lay-out 1; in total 28 tests
– INF—3D tests in Aalborg by Infram; rubble mound structure; perpendicular attack; in total 19 tests.

A comparison of reflection coefficients for non-overtopped and low-crested structures is given in Fig. 17. The original data for non-overtopped structures have smaller symbols than the LCS data. Fig. 17 shows, for various reasons, some scatter. But it is clear from the figure that lower structures give indeed lower reflection. One of the reasons for scatter could be the influence of the foreshore. Also the foreshore gives reflection and if the reflection coefficient is measured in front of the foreshore, it does also include this reflection. If a foreshore is present, some wave conditions may give wave breaking on this foreshore. Under these conditions the traditional "three-point method" to establish incident and reflected waves does not work properly, leading to large scatter in reflection coefficients. A first idea of the influence of the crest height on wave transmission is achieved by comparing the measured reflection with the one expected from formula (9) as a function of this relative crest height. Fig. 18 gives the results and again shows a lot of scatter. The only trend from this figure is that the reflection coefficient reduces for submerged structures, but a further analysis is required to say something more conclusive.

In order to reduce the scatter and to come to a first and very preliminary conclusion about the reduction in reflection by low-crested structures two assumptions were made:

- In most cases hydraulic conditions were repeated for different crest heights. Therefore, the averages of groups of similar data points were taken, i.e. the average of R_c/H_i and the average of the reflection coefficient.
- For the highest structures tested ($R_c/H_i>0.5$), the influence on the reflection would be very small or not existing. These tests were considered as reference for the other test conditions in the same test programme and for these relatively high structures the reduction factor was determined to be 1.

Based on these assumptions a reduction in average reflection coefficients was determined for data groups of the four mentioned projects. Fig. 19 gives the final graph, which still must be considered as a preliminary result. The most simple relationship for low-crested structures becomes:

Reduction factor f_r on K_r:

$$f_r = 0.2R_c/H_s + 0.9 \qquad \text{for } R_c/H_s < 0.5$$

$$f_r = 1 \qquad \text{for } R_c/H_s \geq 0.5 \qquad (11)$$

The reduction factor f_r in Eq. (11) can be applied to reflection coefficients determined by Eqs. (9) or (10),

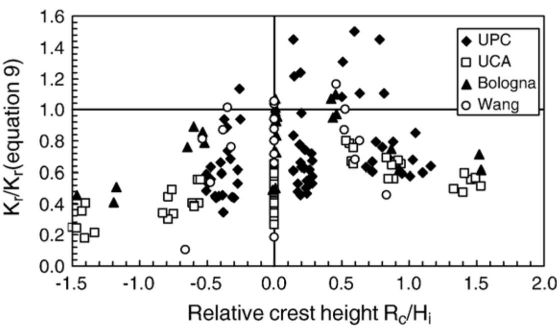

Fig. 18. Influence of relative crest height on reflection, all data.

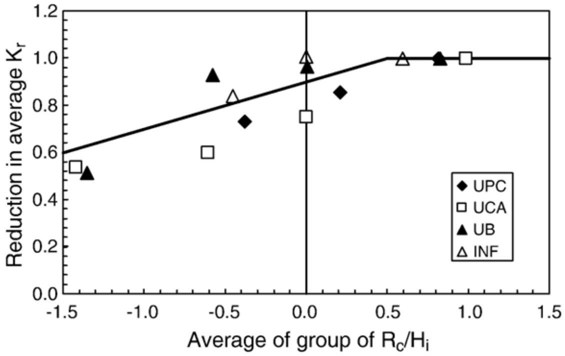

Fig. 19. Reduction in reflection coefficient for low-crested rubble mound structures.

or by other existing equations for wave reflection. The above results are valid for rubble mound structures, but are still tentative without further detailed research. There is no method for smooth structures other than using also Eq. (11), but now applied to a prediction of reflection for smooth non-overtopped structures. Such prediction formulae can be found in the mentioned Rock Manual.

8. Conclusions

Within the EU funded project DELOS an extensive database of 2D random wave tests of wave transmission at LCS has been collected. It includes more than 2300 tests. The gathered results have been reanalysed and used to check existing prediction formulae and where required, improve the prediction of the transmission coefficient. The outcome of this analysis is the design formulae of d'Angremond et al. (1996) for relatively small crest widths ($B/H_i<8$), a new one for large to very large crest widths (Eq. (3) for $B/H_i>12$) and interpolation for $8<B/H_i<12$.

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 there is a lot of energy dissipation through the permeability and roughness of the structure. A new design formula for the transmission coefficient was developed for smooth structures.

Incident and transmitted wave angles are not always similar: for rubble mound structures, the transmitted wave angle is about 80% of the incident one, whereas for smooth structures the transmitted wave angle is equal to the incident one for incident wave angles less than 45° and is equal to 45° for incident wave angles larger than 45°.

The influence of the wave angle on the transmission coefficient is none to marginal for rubble mound structures. This means that Eqs. (2)–(4) can be taken for 3D situations. Smooth structures, however, show a clear influence on the wave angle which can be described by a cosine function, see Eq. (7).

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.

Reflection from low-crested structures decreases if the crest height decreases. A first estimation of this reduction in reflection has been developed and has been given by Eq. (11). This is only a first and tentative formulae and much more research is needed to be more conclusive.

Acknowledgement

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