WAVE TRANSMISSION AT LOW-CRESTED STRUCTURES, INCLUDING OBLIQUE WAVE ATTACK

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A part of the DELOS research focused on wave transformation at low-crested structure and is summarised in this paper. Several flume tests have been carried out within the project to analyse wave transmission on rubble mound structures and simultaneously an existing database has been extensively increased 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. Oblique wave attack on LCS was a second objective within DELOS. Small scale model results were produced and analysed leading to new transmission formulae for smooth LCS and to conclusions on 3D effects for both rubble mound and smooth LCS.

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 a low-crested structure – (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 process of wave transmission over and through a structure, permeable and impermeable, in 2D and 3D conditions, is subject of this paper.

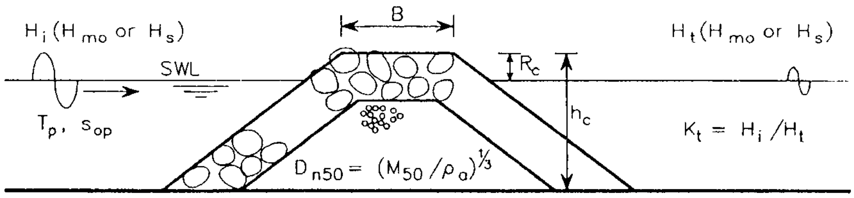

Figure 1. Definitions of governing parameters involved in wave transmission

The main parameters describing wave transmission have been given in Figure 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
K_t =transmission coefficient H_t/H_i
ξ_{op} = breaker parameter $\xi_{op} = \tan\alpha/(s_{op})^{0.5}$; α = slope angle of structure

2. 2D wave transmission at rubble mound LCS

2.1. *Database*

Wave transmission and overtopping are the two phenomena that allow wave energy to pass over or through LCS. 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. Research in the past has led to various design formulae for wave transmission that are now commonly used in engineering practice, but each contain 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. More details are given in Briganti et al. (2003).

A wide database concerning experiments on wave transmission at low-crested structures in wave flumes has been collected. Earlier work by Van der Meer and Daemen (1994) and d'Angremond et al. (1996) has 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. 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 tested parameters is shown in Table 1.

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

Database	Armour type	Rc/Hi	B/Hi	B/Lop	ξop	Hi/Dn50	Hi/h	sop	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	

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). 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, Calabrese et al. (2002). The main objective of these tests was to look at low-crested and submerged breakwaters in presence of broken waves on a beach.

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. (2000) concerning a new type of concrete armour units, Aquareef, 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. Finally, experimental data coming from Melito and Melby's (2000) (M & 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.

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

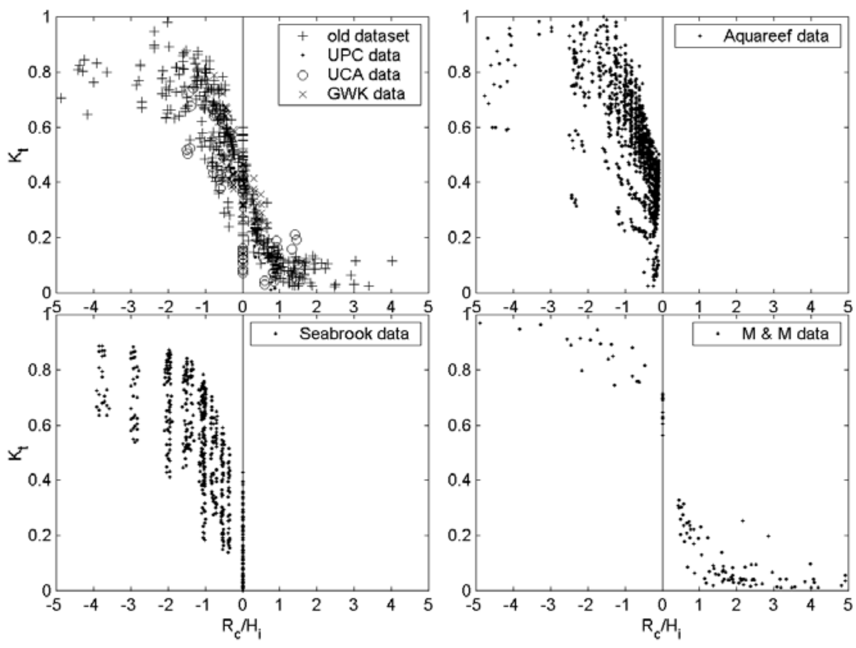

Figure 2. Wave transmission coefficient versus relative freeboard for the four sub-datasets used in this study.

2.2. *Improvement of existing formulae*

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 first reference considers the use of the nominal diameter D_{n50} in order to describe the influence of crest height on wave transmission; the second reference relates 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 the non-dimensional crest freeboard, R_c/D_{n50} or R_c/H_i, the wave length 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 $R_c = 0$.

The Van der Meer and Daemen formula for traditional breakwaters reads:

$$K_t = a\, R_c/D_{n50} + b \tag{1}$$

where:
$a = 0.031H_i/D_{n50} - 0.024$ and
$b = -5.42s_{op} + 0.0323H_i/D_{n50} - 0.017(B/D_{n50})^{1.84} + 0.51$

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

$$K_t = -0.4R_c/H_i + 0.64(B/H_i)^{-0.31} * (1 - \exp(-0.5\xi_{op})) \tag{2}$$

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 d'Angremond et al.'s formula.

Equations 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 equations 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.

In this study an attempt to improve the formulae has been done by using two different relations, one for structures with B/H_i<10 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 equation 2 on data with relative crest width belonging to this class. The result is:

$$K_t = -0.35R_c/H_i + 0.51(B/H_i)^{-0.65} * (1 - \exp(-0.41\xi_{op})) \tag{3}$$

For structures with B/H_i <10 equation 2 has been considered still accurate.

It is useful to limit the maximum value in equation 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 Figure 2 and the influence of the relative crest width has been studied. The upper limit, K_{tu}, can be described by assuming a linear dependency from the relative crest width:

$$K_{tu} = -0.006B/H_i + 0.93 \qquad (4)$$

The lower limit, K_{tl}, 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 equations 2 and 3, making use of the proposed limiting relationship 4, see Figure 3. The performances of the equations 1 - 4 may be evaluated in terms of round mean square error (RMSE) and R^2. Equations 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 d'Angremond et al's formula may be considered more accurate in this range. Eqaution 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 equation 2 and 0.06 for equations 3 and 4.

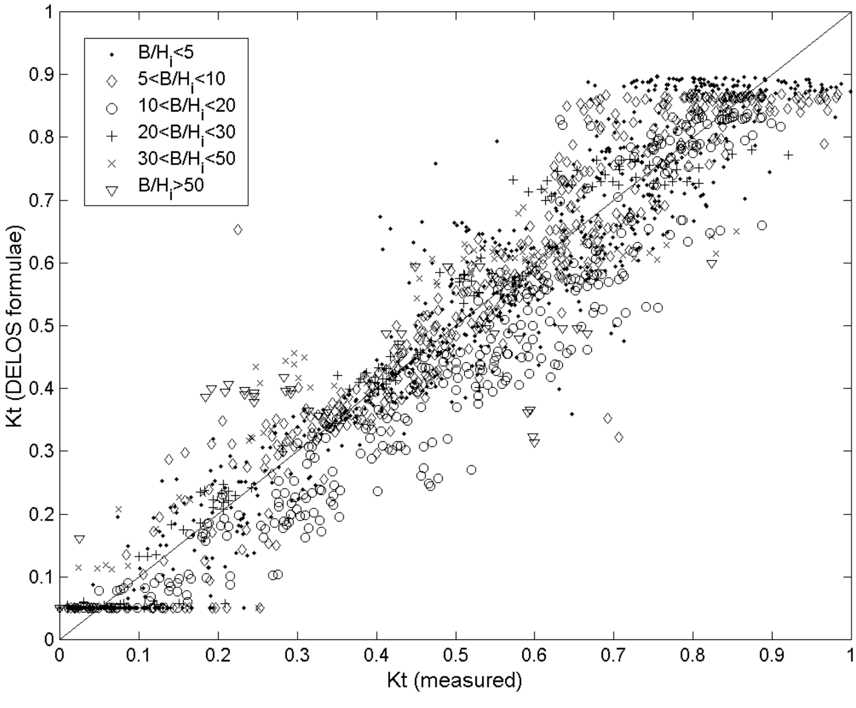

Figure 3. Comparison between calculated and measured values of the transmission coefficient using the proposed equations 2 – 4.

3. 3D effects on rubble mound LCS

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 there any influence of short-crestedness of waves?
- 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 Van der Meer et al. (2003).

3.1. *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). The conclusion from the present research, however, 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. For more details see Van der Meer et al. (2003).

3.2. *Change of wave direction*

Another important question is whether transmitted waves have the same direction as the incident waves. Figure 4 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. 4).

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:

$\beta_t = 0.80\ \beta_i$ for rubble mound structures (5)

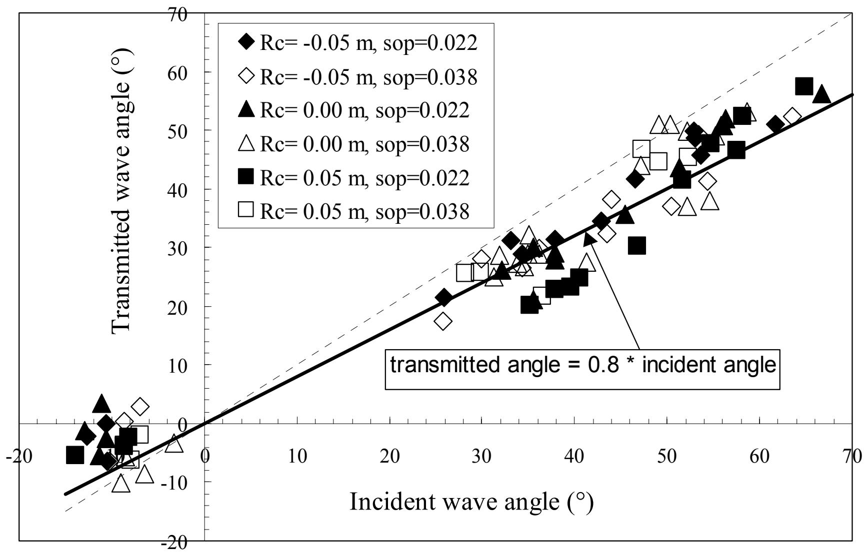

Figure 4. Transmitted wave angle versus incident angle. Rubble mound structure.

3.3. *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? Figure 5 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 5, 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°.

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 equations 2-4, are valid for oblique wave attack as well. One restriction may be that it is only valid for rubble structures with a small crest width and up to an angle of about 60°.

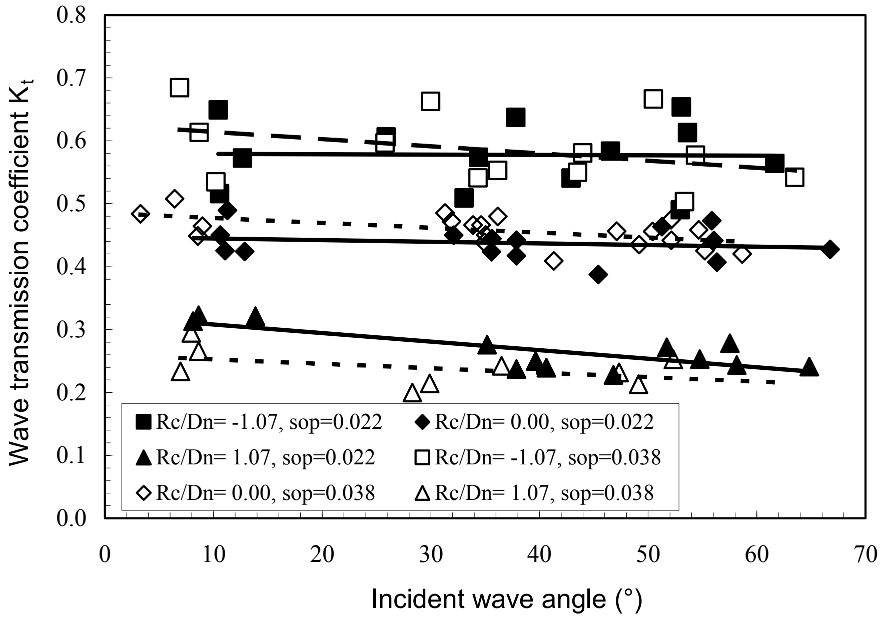

Figure 5. Influence of wave angle on wave transmission coefficient K_t for rubble mound structures

4. Wave transmission at smooth and impermeable LCS

4.1. *Normal wave attack*

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 revetment. 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, as also on the crest there is no energy dissipation, which is completely different from rubble mound structures. Only for 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.

Equation 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 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:

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

$$K_t = -0.3R_c/H_i + [B/H_i]^{-0.31} * [1 - \exp(-0.5\xi_{op})] * 0.75 \qquad \text{for } \xi_{op} \geq 3 \qquad (6)$$

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

4.2. *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 (equation 6) it is possible to make a straight forward analysis on the effect of oblique waves. Equation 6 was used as a reference and for each test condition the K_t for perpendicular wave attack was calculated. The measured to calculated K_t ratio for $\beta = 0°$ was then plotted versus the incident wave angle β, see Figure 6.

Although Figure 6 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 $(\cos\beta)^{2/3}$ function to the 2D-equation 6. This leads to the final prediction formula for smooth structures, including obliquity:

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

with as minimum $K_t = 0.075$ and maximum $K_t = 0.8$, and limitations:

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

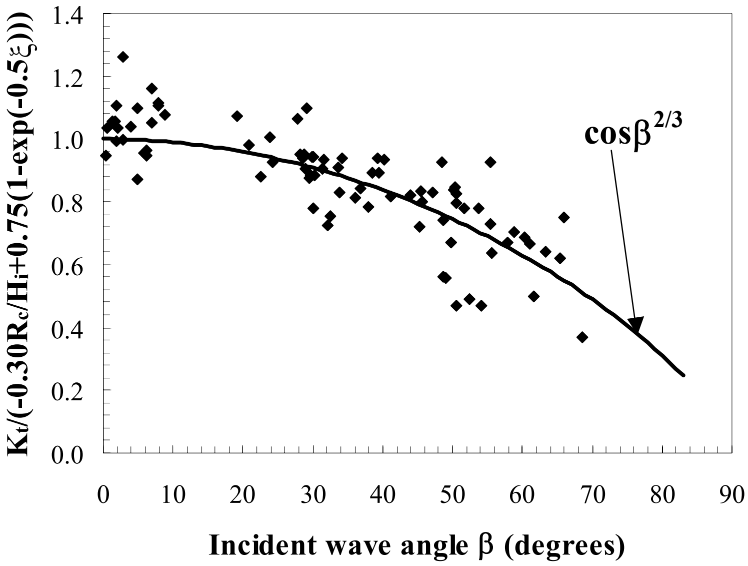

Figure 6. Influence of oblique wave attack on smooth structures.

4.3. *Long-crested versus short-crested waves*

Comparsion of long-crested and short-crested results on smooth slopes gave the same conclusion as for rubble mound structures: there is no or only a marginal difference between long-crested and short-crested waves. See for more details Van der Meer et al. (2003).

4.4. *Change of wave direction*

Figure 7 shows the results of change of wave direction for the smooth structure in a comparable way as in Figure 4 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°. 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 (8)

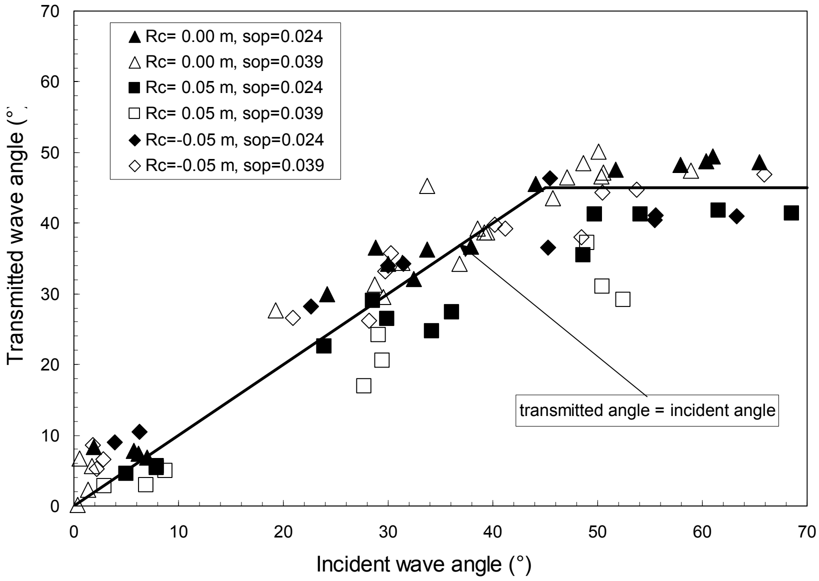

Figure 7. Transmitted wave angle versus incident angle. Smooth structure

Conclusions

Within the EU funded project DELOS 2D and 3D experiments at permeable and impermeable LCS have been carried out and an extensive database of 2D wave transmission at LCS has been collected. The gathered results have been reanalysed and used to improve the prediction of the transmission coefficient.

The outcome of this analysis consists in two new design formulae: for rubble-mound structures, eqs. (3)-(4), which are respectively d'Angremond et al. (1996) formula for relatively small crest widths ($B/H_i < 10$) and a new formula for large to very large crest widths; for smooth structures, eq. (6) gives different expression depending on the breaking parameter.

Incident and transmitted wave angles are not always similar: for rubble mound structures, the transmitted wave angle is about the 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 small for rubble mound structures, whereas smooth structures show a clear influence on the wave angle which can be described by a cosine function, see eq. (7).

Acknowledgments

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