WAVE TRANSMISSION BEHIND LOW-CRESTED STRUCTURES

Riccardo Briganti[1], Jentsje van der Meer[2], Mariano Buccino[3], Mario Calabrese[4]

Abstract

Within the European Union funded research project DELOS, a wide database containing more than 2000 2D laboratory tests on wave transmission behind low crested structures has been collected. The data has been reanalysed in order to test and improve the reliability of the existing design formulae by improving the description of the dependency of wave transmission on structural and hydraulic parameters. Also the change of wave energy spectra has been analysed and related to governing parametetrs.

Introduction

Wave transmission and overtopping are the two phenomena that allow wave energy to pass over or through low-crested structures (LCS here after). 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. This consideration led to a number of experimental studies aiming to derive practical design formulae for wave transmission that are now commonly used in engineering practice. As a result of this, a considerable amount of data is now available and it is possible to perform a review and an upgrading of the existing approaches.

The effort made within the EU-funded project DELOS has been to both perform new tests on LCS and to gather many existing datasets on wave transmission and build a very wide 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 deep description of the phenomenon, which led to two different formulae. Amongst the more recent investigations it is worth to mention the extensive experimental study carried out by Seabrook and Hall (1998) on submerged rubble mound structures. The wide range of variables tested make this study fundamental to extend the description of the phenomenon to structures with large crest widths. Also an extensive study on LCS with large crest widths has been performed by Hirose *et al.* (2000), testing structures

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[1] PhD Student, DSIC, Univ. of Rome III, Rome, Italy e-mail: briganti@uniroma3.it

[2] Dr, Infram, PO Box 81, 3890 AB Zeewolde, NL. e-mail: jentsje.vandermeer@infram.nl

[3] PhD Student, Università degli studi di Napoli, Federico II, Naples, Italy, e-mail: buccino@unina.it

[4] Professor, Università degli studi di Napoli, Federico II, Naples, Italy, email: calabres@unina.it

armoured with the recently developed armour unit called Aquareef. These studies, together with other valuable investigations, have been used as the basis of the present work on the wave transmission coefficient.

The effect of LCS on wave attack is not only the reduction of the wave energy in the lee of the structures, but also a modification of the spectral shape due to wave breaking on and dissipation in the structure. This aspect covers an important role in the prediction of the shoreline changes induced by the structures and in the prediction of the wave reforming in cases in which large fetches are present in the lee of the structures, as pointed out in Van der Meer *et al.* (2000). The attention to the modelling of the spectral changes for design purposes is relatively new in the studies on wave transmission. Van der Meer *et al.* (2000) proposed a simple representation of the energy shift due to the presence of LCS.

Within this study an analysis of the spectral shape is also carried out. Notwithstanding that this analysis is still underway, some results can be presented and discussed.

Governing parameters of wave transmission

The most important variables with respect to wave transmission are summarized in this section and explained in figure 1. As shown in previous studies, the transmission coefficient K_t is defined as the ratio between the transmitted and the incident significant wave heights H_t/H_i. In datasets considered in the present study, H_i and H_t were indifferently defined using the zero crossing technique ($H_{1/3i}$ and $H_{1/3t}$) or the spectral analysis (H_{moi} and H_{mot}). Where possible, the spectral measures of the wave heights have been used. The K_t dependence on structural and hydraulic parameters is illustrated in figure 1. R_c is the structure crest freeboard from still water level (SWL), B is the crest width, α is the breakwater seaward slope angle, D_{n50} is the nominal diameter of the armour units defined as $(M_{50}/\rho_r)^{1/3}$, being M_{50} the median mass of unit given by 50% on mass distribution curve and ρ_r the mass density of the rock. As far as the hydraulic parameters are concerned, L_{op} is the offshore wave length associated to the peak period T_p, and h is the water depth at the toe of the structure.

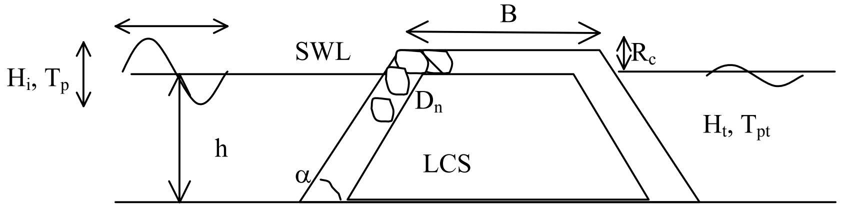

Figure 1. Definitions of the parameters involved in wave transmission

Datasets used

A wide database concerning experiments on wave transmission behind 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 "old database" here after. This included rubble mound rock structures as well as tetrapod and accropode ones. The range of the parameters tested is shown in Table 1 and the graph showing the influence of R_c/H_i on K_t is reported in figure 2. It has to be stressed that only a few data amongst the ones considered in the afore mentioned studies, coming from an investigation performed by Daemrich and Kahle (1985), show B/H_i greater than 10.

Within the DELOS project a series of 2D random wave tests has 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). The UCA tests have been carried out in a flume 24x0.58x0.80 m considering both emerged and submerged LCSs. In total 53 tests have been performed with random waves driven by TMA-spectra. The UPC tests have been carried out in a large 87x3.0x5.0 m flume. In total 24 tests with random waves are available. A Jonswap spectrum has been generated in the tests. Both narrow and large crests have been tested, in particular in the UCA tests the parameter B/Hi ranged from 2.67 to 30.66, 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 presence of broken waves,. The wave flume is 300x5x7 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 this study.

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	

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

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 74.47.

Also tests results from Hirose e*t al.* (2000) concerning a new type of concrete armour units designed for submerged structures have been added to the dataset. Similarly to the Seabrook and Hall (1998) tests, the relative crest width has been varied from very small values up to $B/H_i = 102.12$. Both datasets have submerged structures only.

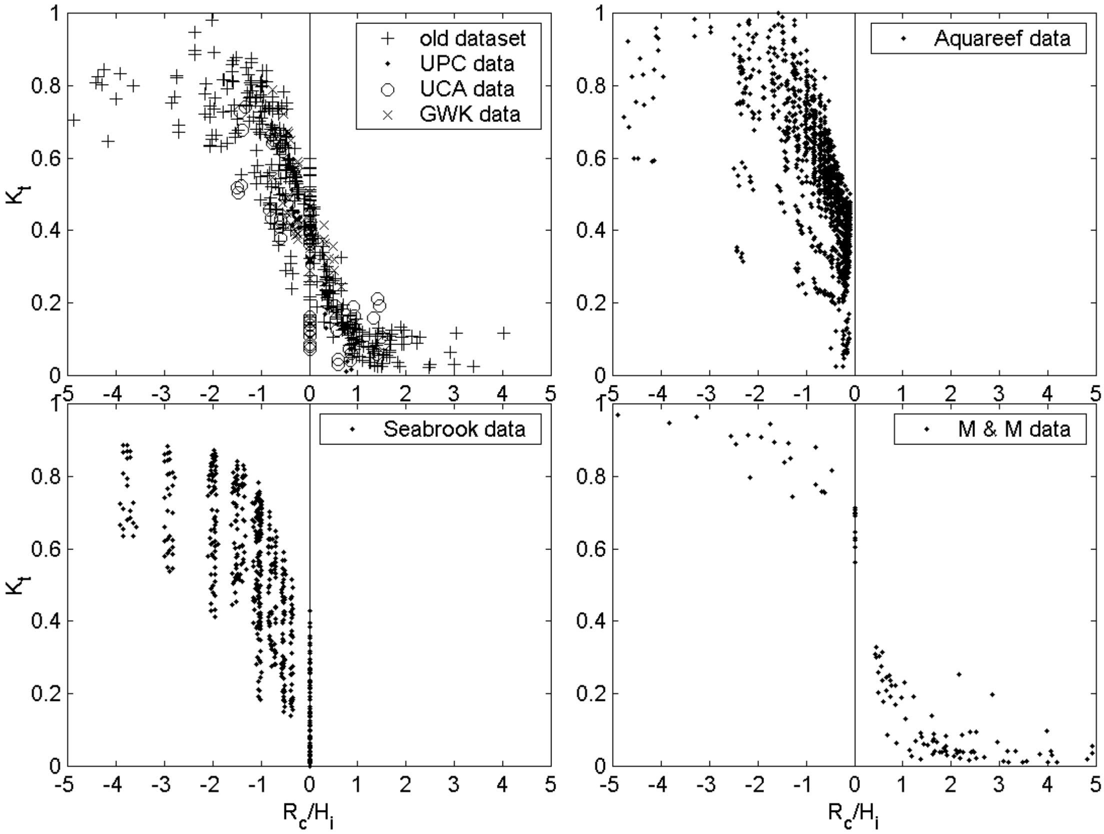

Figure 2. Wave transmission coefficient versus relative freeboard for the four sub-datasets used in this study.

Finally experimental data coming from Melito and Melby's (2000) (M & M hereafter) investigation on hydraulic response of structures armoured with CORE LOC® 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 limiting values of K_t compared to the other structures, probably due to the high permeability of the armour layer. Moreover these limits are reached at relatively high values of R_c/H_i.

Some restrictions on the parameters 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 $s_{op} < 0.002$ is difficult to be generated in a flume and tests showing wave steepness smaller than this value are considered less reliable and thus discarded.

Some tests in the datasets have been performed with highly nonlinear and breaking waves before the structure, but not specifically designed for investigating the effect of these hydraulic conditions. In particular, reflection analysis is performed with methods valid for linear waves that might be inaccurate in this conditions. According to this consideration, a threshold value of the parameter H_i/h, above which wave are considered breaking, has been introduced. Following Kamphuis (1991) this value has been assumed equal to 0.56. Therefore, tests in which the incident and transmitted waves have been estimated with classical separation methods in presence of breaking waves according to this criterion, are considered less reliable and discarded. Moreover, in Van der Meer and Daemen (1994) it has been pointed out that, for emerged structures, in tests 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 in account only if $H_i/D_{n50} > 1$. Also tests with $H_i/D_{n50} > 6$ have not been used in the study as this values will cause instability of the structures.

Improvement of the 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 non-dimensional crest freeboard, R_c/D_{n50} or R_c/H_s, 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:

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

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

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

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

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

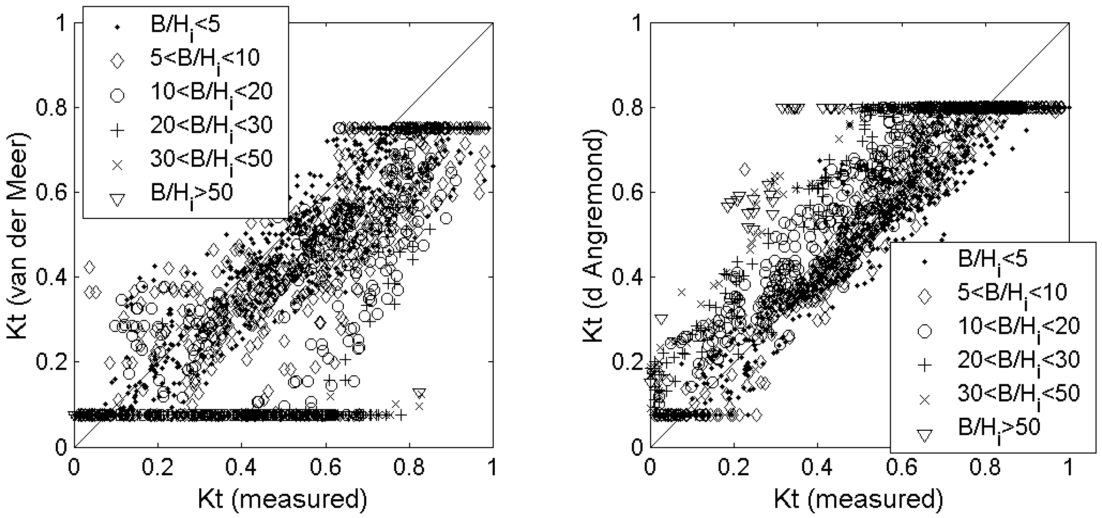

Figure 3. Performances of the two previous formulae on the present database.

Both formulae have been limited with two values for K_t that 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' s formula.

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 (1) and (2) relies on a few data, so it was expected that this variable may be crucial for the accuracy of the formula. Figure 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 formula (2) (see the right panel of figure 3) it is quite evident that the error in predicting K_t increases with B/H_i. Moreover, for structures with $B/H_i > 10$ the K_t-estimate is biased, i.e. equation (2) overestimates the transmission coefficient. The analysis of the results of the (1) from Figure 3 is more difficult as the influence of the crest width is not very clear. In the following only the relation (2) will be taken into account.

To investigate the reason of the bias for high values of B/H_i it is necessary to remind that, in equation (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 figure 4) shows large scatter for $0 < B/H_i < 10$, but also a large influence of this parameter. If the relative crest is greater 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 the figure 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.

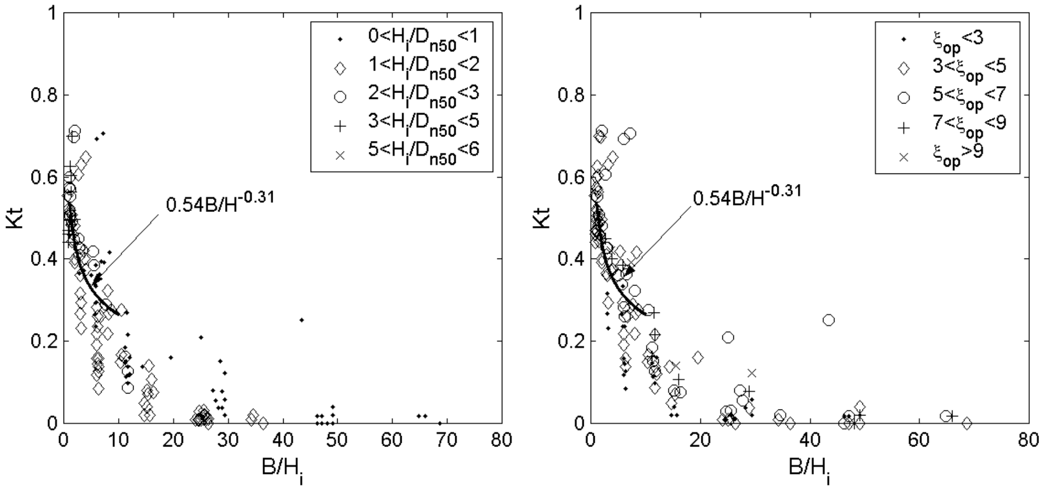

Figure 4. Influence of B/H$_i$ on K$_t$ for structures with zero freeboard

Also the curve used in d' Angremond *et al.* (1996) to describe the influence of the relative crest width has been reported in the two panels of figure 4. It is evident that this curve fits pretty well only the data with B/H$_i$<10, hence it is necessary to improve the prediction for larger values.

In this study a first attempt to do that has been done by using two different relations, one for the structures with B/H$_i$ <10 and one for the structures with larger relative berm width. The relationship for B/H$_i$ >10 has been obtained by simply refitting the (2) on data with relative width belonging to this class. The result is:

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

For structures with B/H$_i$ <10, eq. (2) has been considered still accurate.

Another problem to solve was the description of the limits of the formulae. The presence in the database of tests concerning submerged structures with high values of B/H$_i$ allow to study the limit as a function of the adopted non-dimensional parameters. Figure 5 shows that there is a strict dependency of the limit reached by the transmission coefficient on the relative crest width B/H$_i$. 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 Figure 5).

It seems useful to limit the formula results horizontally in analogy with the two aforementioned studies. The definition of a limit independent from B/H$_i$ would lead to an inaccurate estimation of K$_t$. Therefore, a limit 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 5 and the influence of the relative crest width has been studied (see figure 6).

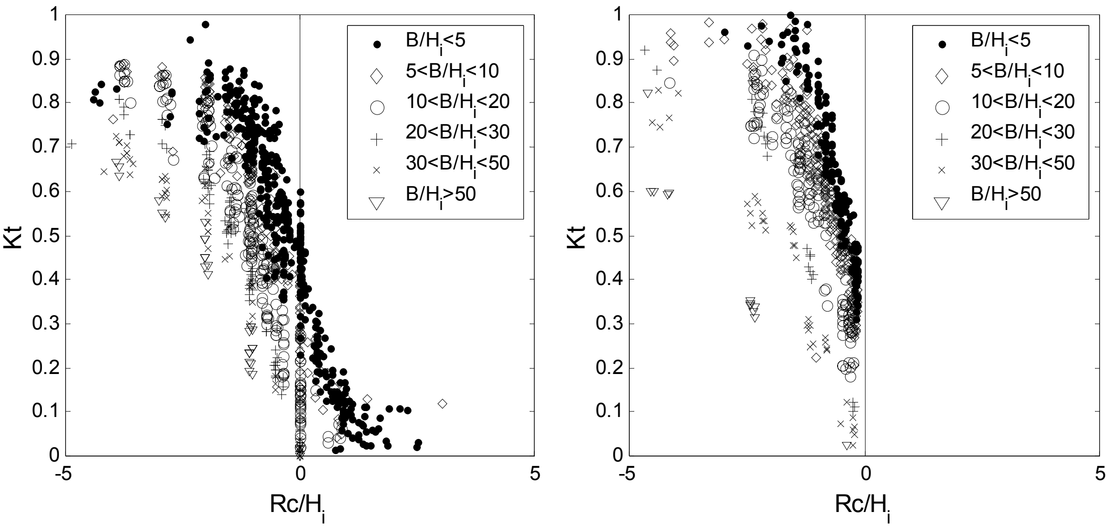

Figure 5. Influence of the relative freeboard on K_t at various classes of B/H_i. Right panel, Aquareef data, left panel shows the results from all other tests

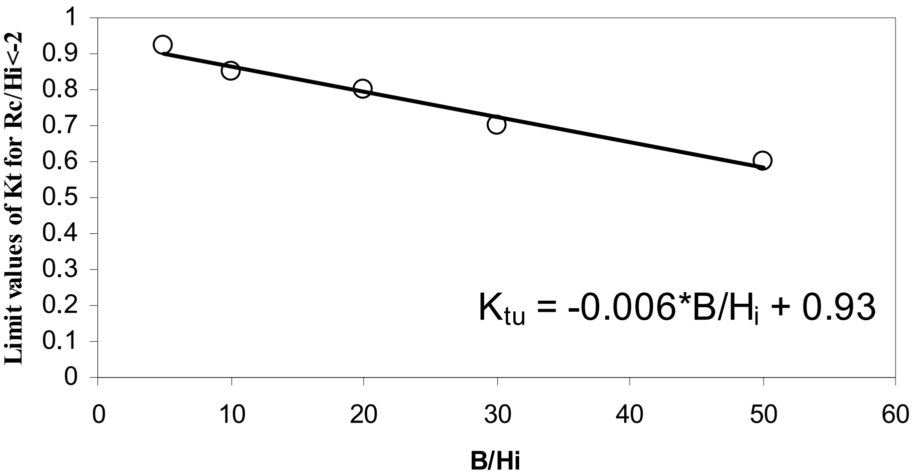

Figure 6: Determination of an upper limit for K_t

The upper limit can be described by 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 the (2) and the (3) making use of the proposed limiting relationship (4), the results have been shown in figure 7.

The performances of the cited formulae may been evaluated in terms of round mean square error (RMSE) and R^2. The (1) and (2) show an RMSE of 0.112 and 0.072 and R^2 equal to 0.81 and 0.91 respectively for $B/H_i<10$, hence d'Angremond's formula may be considered more accurate in this range. The relationship (4) shows an 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 s is 0.05 for eq. (2) and 0.06 for eq. (4).

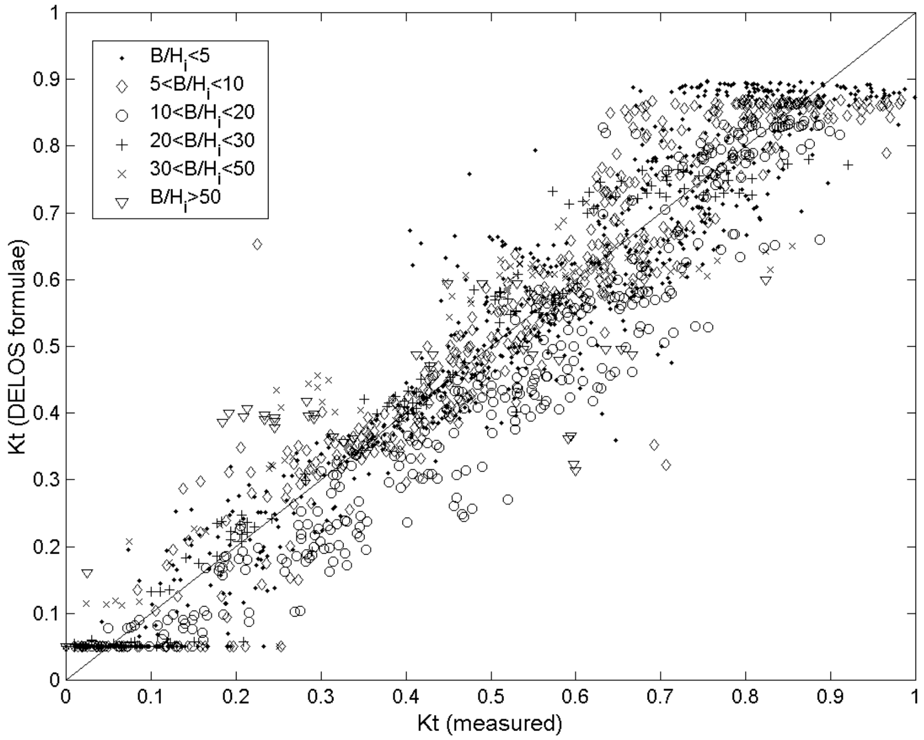

Figure 7. Comparison between calculated and measured values of the transmission coefficient using the proposed relationships (2) and (3).

Spectral shape change due to wave transmission

Transmitted wave energy spectra past low crested structures are very different from incident ones. For submerged structures, due to wave breaking, the wave energy is reduced and shifted towards higher frequencies. In case of positive freeboard, on the other hand, overtopping and flow through the armour layer are responsible for wave transmission; the relative importance of the two phenomena determines the energy shift towards high frequencies. If the reduction of wave energy is mainly led by the dissipations due to the flow through the armour layer, higher frequencies may be cut.

For design purposes it is useful to quantify this energy shift by relating it to structural and hydraulic parameters involved in wave transmission. An attempt at this has been shown in Van der Meer *et al.* (2000). Before introducing the analyses carried out in the present investigation it is useful to summarise some definitions. Figure 8 show an example of normalised incident and transmitted spectra from UPC tests. Here f_p is the peak frequency of the energy density spectra, and f_t is a frequency which represents the limit at which the transmitted energy density is considered significant. It has been seen from experimental results that usually the value $1.5f_p$ represent a frequency after which the shape of the spectra is significantly changed by wave transmission.

E_i is the incident wave energy, i.e. the area of the incident spectra, E_t is the same for the transmitted spectra. E_{t15} is the area of the transmitted spectra for $1.5f_p < f < f_t$ (represented by the shaded area in figure 8). Van der Meer *et al.* (2000) have pointed out that the transmitted spectral energy density is distributed almost uniformly in the frequency domain in the range $1.5f_p < f < 3.5f_p$. For higher frequencies the spectral energy density is negligible. That study considered only results from an investigation on asphalt covered LCSs. In the next analysis also the results of UPC and UCA tests concerning rubble mound structures have been added. Two aspects have been analysed, the energy shifting and the spectral decay, both necessary to describe the shape of the transmitted energy density distribution.

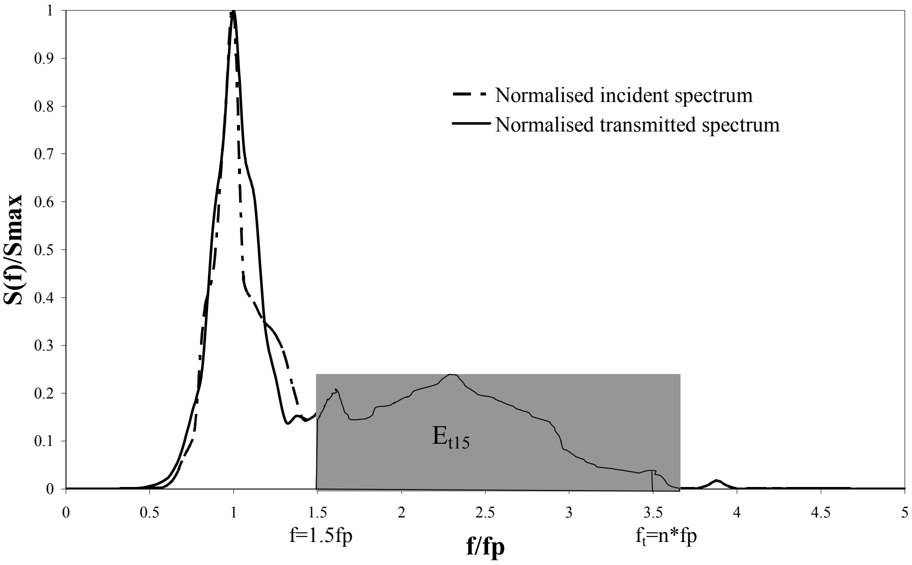

Figure 8: Definitions used in the analysis of spectral changes.

The first step in this analysis is to define a value of f_t for each spectrum taken in account. It was found that $f_t=3.5*f_p$ is indeed a good approximation, but only for submerged rubble mound structures or emerged smooth and impermeable structures. Tests from UCA on emerged structures reveal that f_t can be also equal to $2.0*f_p$, due to the effect of energy dissipation in the armour layer. This difference is consistent with the conclusions of the analysis of the energy shift.

In the aforementioned study the ratio between E_{t15} and E_t has been used as a measure of the energy content associated to the high frequencies in the transmitted spectra. In this study asphalt covered LCS have been considered and it has been found that E_{t15}/E_{t15} tends to a constant value of 0.4 when $K_t > 0.3$. In the present study we tried to quantify also the shift of the energy induced by the transmission process. In order to do that is necessary to preserve some information of the shape of the incident spectra. We found that it is useful to introduce a parameter named energy distribution parameter (edp hereafter), defined as follows:

$$edp = \left(\frac{E_{t15}}{E_t}\right) - \left(\frac{E_{i15}}{E_i}\right) \Bigg/ \left(\frac{E_{i15}}{E_i}\right) \qquad (5)$$

In this parameter the energy associated to $f > 1.5*f_p$ in the incident spectra (E_{i15}) is taken in account. Hence the edp describes the variation of the amount of energy associated to f>1.5f_p between the incident and the transmitted spectra. The edp is positive if energy is shifted towards $f > 1.5f_p$ and negative in case the energy related to these frequencies is cut.

It has been found that the edp is well correlated with K_t, whereas it is difficult to distinguish among the contributions of the single parameters involved in wave transmission. The only parameter with a plain correlation with it is the relative freeboard, which is the leading parameter in the phenomena. Figure 9 shows the correlations between edp and K_t (left panel) and the correlation between e.d.p. and the relative freeboard for UCA, UPC and the dataset considered in Van der Meer *et al.* (VDM here after). These two plots clearly show the different behaviour of smooth and impermeable structures from rough and permeable ones in the modification of spectral shape. For the former class of structures there is no effect of permeability in wave transmission and the energy is always shifted towards high frequency.

For submerged structures (both belonging to UCA and UPC datasets) the edp is positive and an average value of 0.4 can be found in the range -1.5 > R_c/H_i <0.
As far as the spectral decay is concerned, this has been studied by assuming that $S_t(f) \propto f^b$ for $f > 1.5f_p$, hence the dependency of the exponent b has been studied as a function of the K_t and the relative freeboard (see figure 10). For a JONSWAP incident spectrum, b =-5. Consistently with the considerations made so far, b is lower than -5 for submerged structures and emerged smooth ones; for them an average constant value with R_c/H_i in the range -1.5 < R_c/H_i < 1.5 of b = -1 can be assumed. For emerged structures higher values of b are reached as a consequence of the cut-off of the energy related to higher frequencies.

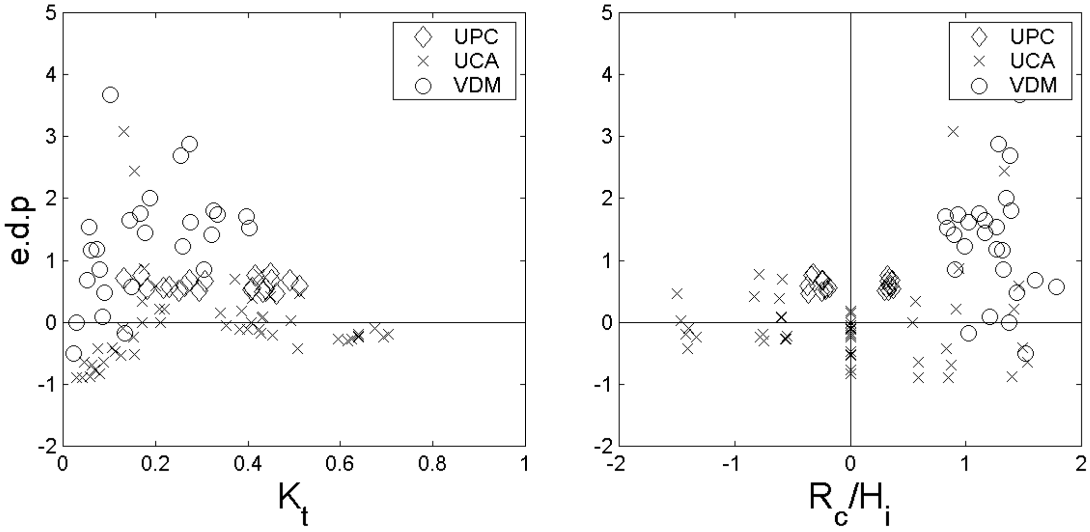

Figure 9: Correlation of the edp with the K_t and the relative freeboard for the three datasets considered.

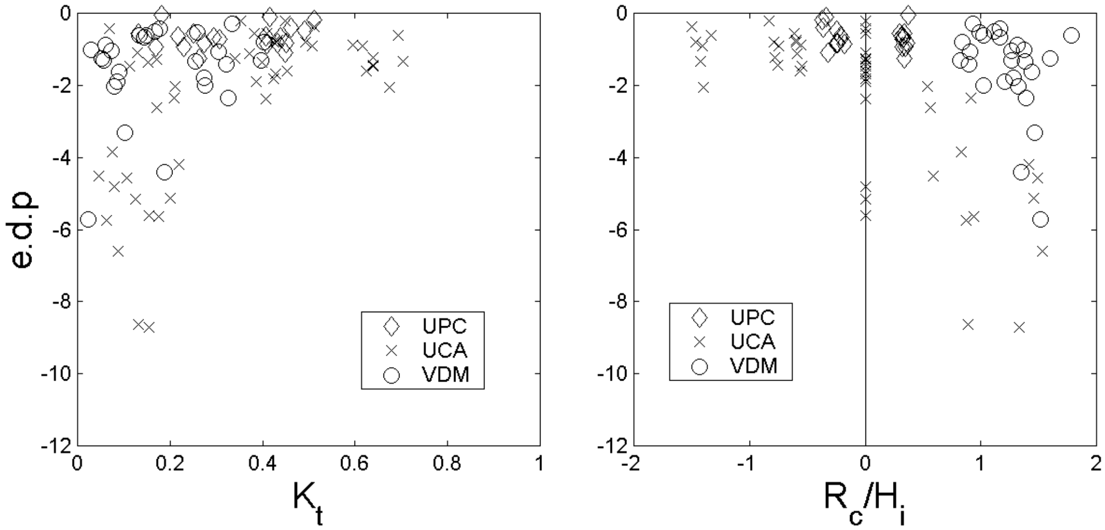

Figure 10: Correlation of the parameter b that describes the spectral decay with the K_t and the relative freeboard for the three datasets considered.

Conclusions

Within the EU funded project DELOS an extensive database of 2D random wave tests of wave transmission behind LCSs has been collected. The gathered results have been reanalysed and used to improve the prediction of the transmission coefficient starting from two existing design formulae (Van der Meer and Daemen 1994 and d' Angremond *et al.* 1996). The same set of parameters was used as the governing ones for wave transmission in the aforementioned papers.

The outcome of this analysis is the calibration of two design formulae based on the d'Angremond *et al.*(1996) relationship. The analysis highlighted the need of a supplementary formula allowing a reliable estimate of the transmission coefficient at wide crested breakwater ($B/H_i > 10$). This has been given in equation (3). Despite it introduces a discontinuity in the prediction formula, which is in principle undesirable, it could be of course useful in design practice. Work is still in progress in order to face this problem.

Furthermore, a preliminary analysis of the spectral shape changes has been performed on the new tests carried within DELOS project. This analysis is based on the correlation of the energy shift induced by the LCS and the same parameters used in estimating the wave transmission coefficient.

A parameter useful to quantify the shift has been defined, also the spectral decay of the transmitted spectra has been studied. It has been shown that these two variables are well correlated with K_t as a whole and it is difficult to have plain information on the dependency of single parameters. The definition of a straightforward parameterisation of the transmitted spectral shape, useful for design purpouses, is the aim of an ongoing research on this topic.

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