REFLECTION OF OBLIQUELY INCIDENT WAVES AT LOW-CRESTED STRUCTURES

Baoxing Wang[1], Jentsje W. van der Meer[2], Ashwini K. Otta[3] & Andrew J. Chadwick[4]

Abstract: The paper presents an experimental investigation of obliquely incident wave reflection at low-crested structures within the EU-funded project DELOS. The physical model tests were carried out with incident wave attack angles varying over a wide range from 0° to 60° at a multidirectional wave basin. Data comparisons suggest that long-crested and short-crested waves give similar reflection from low-crested structures. The reflection coefficient is noticeably dependent on the wave angle of incidence. On the basis of the test data, two wave reflection formulae including the influence of incident angles are proposed for the low-crested rubble mound structures and smooth structures respectively. Directional wave spectra analyses show that the incident and reflected spectra are similar in frequency domain, but different in spatial domain.

INTRODUCTION

Low-crested structures are typically built in shallow water for coastal protection purposes. The interference of waves by a low-crested structure dissipates part of the incident wave energy, while the rest is reflected or transmitted. Reflected waves may modify the wave field significantly in the structure neighbourhood. In view of its importance in the design and construction, coastal engineers have been long interested in the determination of the wave reflection.

It is common in engineering to use the reflection coefficient to characterize the magnitude of the wave reflection, which is defined as the ratio of the reflected wave height H_r to the incident wave height H_i. A considerable number of studies have been carried out to investigate wave reflection coefficients of normally incident wave attack on both smooth and rough slopes. These previous studies on determining wave reflection have been based on physical model tests in flumes for long-crested waves. An estimate for the reflection on smooth slopes was proposed by Battjes (1974) in terms of the surf-similarity parameter. Seelig (1983) proposed a formula with better performance over a wider range of the

[1] School of Engineering, University of Plymouth, Plymouth, PL4 8AA. Baoxing.wang@plymouth.ac.uk
[2] Infram, P.O.Box 81, 3890 AB Zeewolde, NL
[3, 4] School of Engineering, University of Plymouth, Plymouth, PL4 8AA

surf-similarity parameter for the rubble mound and smooth structures. Further tests and analysis of reflection on non-overtopped rock slopes similarity parameter for the rubble mound and were given by Postma (1989). For normal waves with some overtopping at low-crested structures, the recently finished EU-project DELOS (Environmental Design of Low Crested Coastal Defence Structures) proposed a further reduction factor by the decreasing crest height.

The assumption of normally incident waves is often violated in a natural coastal environment. Wave refraction over complex bathymetry may result in significantly oblique angles of incidence at the structure, particularly when the structure is not aligned with the surrounding depth contours. Until now little has been known about the reflection of obliquely incident short-crested waves. As a part of the DELOS research, which focussed on the three-dimensional wave performance at low-crested structures, physical model tests were carried out with incident wave attack angles varying over a wide range from 0° to 60° at the short-crested wave basin of Aalborg University, Denmark, in August 2002. The original aim of the tests concentrated on wave transmission over rubble mound structures and smooth structures, see van der Meer et al. (2003 and 2004). However, the recorded data of surface elevation in the foreside also enable us to quantify reflection for oblique incidence. By an in depth analysis of the experimental data, the paper presents the influence of wave directionality and directional spreading on reflection at low-crest structures. Data analyses in the paper lead to new formulations for oblique wave reflections at rubble mound structures and smooth structures.

PHYSICAL MODEL TESTS IN A MULTI-DIRECTIONAL BASIN

The three-dimensional wave transmission tests were conducted in the multidirectional wave basin (9.0 m×12.5 m×0.9 m) at Aalborg University. Two structures were tested, a rubble mound structure and a smooth structure made of plywood. A set of 84 tests was performed to identify the effect of different hydrodynamic conditions for each type of structure. The rubble mound structure was 25 cm high. It had a seaward slope of 1:2 and a leeward slope of 1:1.5. The crest width was 10 cm. The smooth structure had gentler slopes than the rubble mound structure, which is also the case in reality. The seaward slope was 1:3 and the leeward slope 1:2. The structure height was 0.30 m and the crest width 0.20 m.

The target irregular 3-D waves were generated using the parameterised Jonswap spectrum and a directional spreading function of cosine distribution with spreading parameter s=50. The test program included different water levels, yielding data for different freeboard heights. Wave steepness values were either 0.02 or 0.04. Incident angles varied from 0° to 60° with repect to the structure normal. In each test, the water surface elevations were measured in front of the structure using an array of five wave gagues. Test set-up and test conditions were described in further detail in van der Meer et al. (2003).

DATA ANALYSIS

Directional spectra describe the distribution of the wave energy in both the spatial and frequency domains. Time series of surface elevation in front of the structure recorded by the five-wave gauge array were used to estimate incoming and reflected wave spectra for each wave condition. The Bayesian directional spectrum estimation method was proposed for the analysis of directional wave spectrum. Having estimated the complete directional wave spectrum as shown in figure 1, it is possible to extract information on the incident and reflected waves respectively. Based on their spectra, the reflection performances of the structure exposed to short crested waves can be assessed. For the orientation of the gauge system, the incident waves are in the range of -90° and 90°, and waves propagating between 90° and 270° are reflected waves. This will form the basis for estimating reflection coefficients. An average reflection coefficient C_r in term of their spectra can be defined as $C_r = \sqrt{m_{o,r} / m_{o,i}}$, where $m_{o,i}$ and $m_{o,r}$ = zeroth moments of the incident and reflected wave energy density spectra.

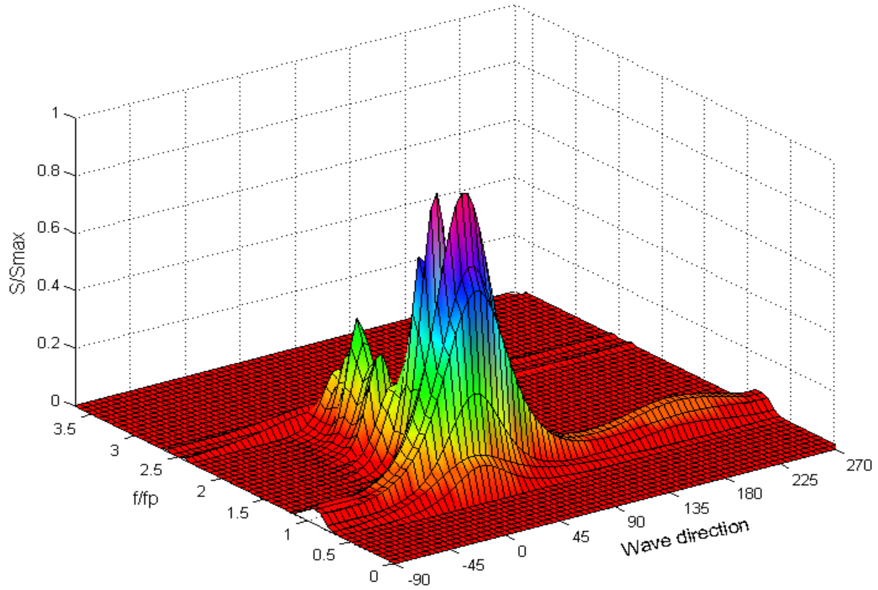

Figure 1 Directional wave spectra

In general, the measured reflection coefficients ranged from 0.1 to 0.40 for wave conditions tested at low-crested structures. The reflection coefficients were found to decrease with decreasing crest height of structure and increasing angle of incidence. The influences of crest height and incident wave angle will be fully investigated in the following sections.

Long-crested versus short-crested waves

Contrary to the long-crested waves, the direction of a single short-crested wave can be different from the main wave direction due to the energy spreading. For those diverted waves, some of them can attack the structure even perpendicularly; others may approach the structure more obliquely. Theoretically the reflection of a short-crested wave should be similar to that of a long-crested wave for perpendicular wave attack ($\beta = 0^\circ$). But, the question to consider here is whether similar reflection results still can be found for the waves with oblique incident angles.

To investigate the influence, ten long-crested wave tests with grouped set-ups were performed for each type of structure with a freeboard of zero. The analysis is carried out by comparing the reflection coefficients between the short-crested waves and the long-crested waves with the similar measured wave conditions.

Reflection comparisons between long-crested and short-crested waves for rubble mound and smooth structures, respectively, are plotted in figures 2.1 and 2.2. In the figures the wave reflection coefficient has been given as a function of the incident wave angle. Similar symbol shapes are used for the same wave conditions and they should be compared with each other. Open symbols represent long-crested waves and solid symbols give short-crested waves. The figure show a clear influence of the angle of wave attack on reflection, but this aspect will be treated later. At the present stage, instead of being interested in the trends of the data points along the incident wave directions, we will directly compare the open and solid symbols for the same angle of wave attack. The conclusion from the measured data is that the long-crested and short-crested waves give similar reflection for the rubble mound and smooth structures. Their difference is only marginal and in the range of measured errors.

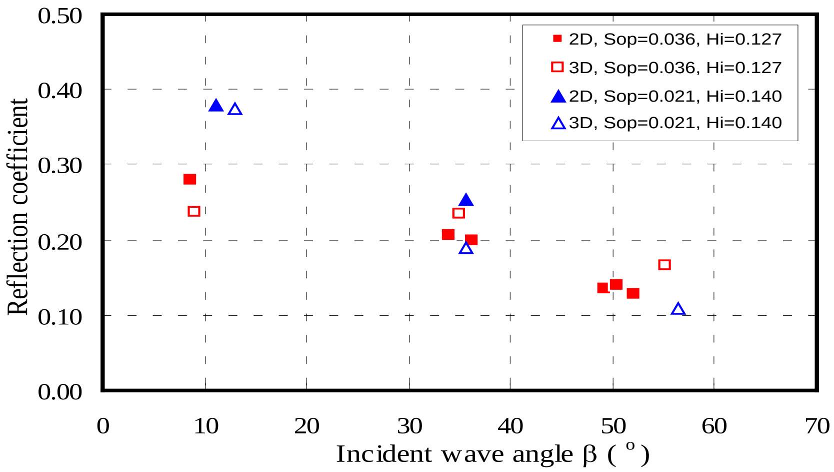

Figure 2 Comparison of long-crested and short-crested waves for rubble mound structures

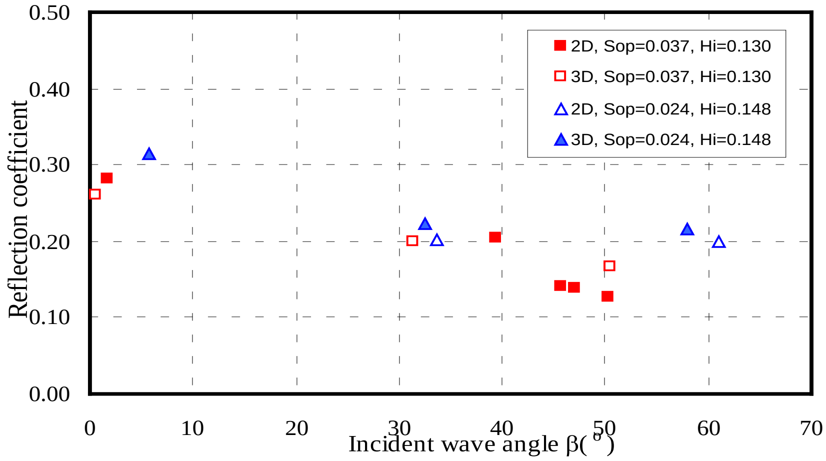

Figure 3 Comparison of long-crested and short-crested waves for smooth structures

Normal wave reflection at non-overtopped structures

There have been many attempts to find expressions that will accurately predict the reflection coefficient at non-overtopped structures. First, a brief review is given of the equations currently available to the coastal engineer for the prediction of wave reflection at smooth and rubble mound structures.

The most common parameter to predict the reflection is the surf-similarity parameter ξ_p, which embodies both the effects of slope angle and incident wave steepness. It is defined as $\xi_p = \tan\alpha / \sqrt{s_{op}}$, where $\tan\alpha$ = structure slope; wave steepness $s_{op} = H_i / L_0$; H_i = incident wave height; $L_0 = g/(2\pi f_p^2)$ = deep-water wave length computed at the peak frequency f_p of the spectrum. Examples of this kind of research include Battjes (1974) and Seelig (1983). An estimate for reflection coefficient on smooth slopes was proposed by Battjes (1974), which is

$$C_r = 0.1\xi_p^2 \qquad (1)$$

Laboratory tests with random waves (Ahrens 1980) indicated that equation 1 overestimated reflection coefficient C_r for higher values of ξ_p. Seelig (1983) proposed equation 2 with better performance over a wider range ξ_p for smooth structures.

$$C_r = a\zeta_p^2 / \left(\zeta_p^2 + b\right), \qquad (2)$$

where a and b are empirical coefficients with values of 1.0 and 5.5 respectively.

Based on the available data for rough and permeable slopes, Seelig(1983) proposed equation 2 with $a = 0.6$ and $b = 6.6$ for design purpose of rubble mound breakwaters. Davidson, et al. (1996) pointed out the equation provides a conservative estimation for wave reflection, and 95% of the available data are below the predicted values.

Postma(1989) analysed 300 random-wave flume tests on rock slopes (tests by Van der Meer, 1988) and analysed this data together with those of Allsop and Channell(1988) to derive an empirical equation similar in form to Battjes(1974). Postma gave:

$$C_r = 0.14\xi_p^{0.73} \quad \text{for } \xi_p < 10 \quad (3)$$

Postma conluded too that the surf-similarity parameter ξ_p does not accurately describe the combined effect of slope and wave steepness. Wave reflection from permeable structures is also a function of porosity and permeability. A more elaborated expression, equation 4, was developed by separating the structure slope $\tan\alpha$, wave steepness s_{op} and permeability factor P.

$$C_r = 0.071P^{-0.082}(\tan\alpha)^{0.62} s_{op}^{-0.46} \qquad (4)$$

The permeability factor P was given in van der Meer (1988) and defined between 0.1 for a rock revetment with an impermeable core and 0.6 for a homogeneous rock structure without filter layer and core.

The performances of equations in term of ξ_p are displayed in figure 2 together with the measurements for those emerged cases with $R_c / H_i \geq 0.5$ (nearly non-overtopping). For smooth structures, Battjes (1974) and Seelig (1983) systematically overestimate the reflection compared with the measurements. Seelig (1983) gives a better prediction for higher values of ξ_p. Postma(1989) presents a better estimation than Seelig (1983) for rubble mound structures.

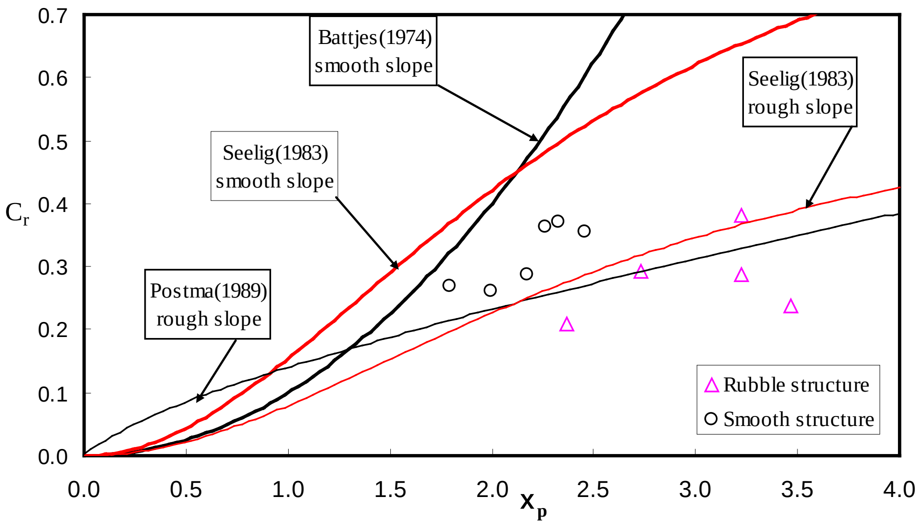

Figure 4 Comparisons of the measurements and predictions

Normal wave reflection at low-crest structures

All above reflection formulae are only valid for non-overtopped structures. It is expected that low-crested structures will have smaller reflection than non-overtopped due to the fact that more energy will pass over the structure. Within the DELOS project, data analysis assumed that the relative crest height R_c/H_i has the main influence on a possible reduction of the reflection coefficient. R_c is the freeboard defined as the distance between the still water level and crest level of the structures; a negative value of freeboard represents a submerged structure case. A simple reduction factor f_r was proposed for low-crested structures

$$f_r = 0.2R_c / H + 0.9 \qquad \text{for } R_c / H_i < 0.5 \qquad (5)$$
$$f_r = 1.0 \qquad \text{for } R_c / H_i \geq 0.5$$

To estimate the reflection at low-crested structures, it was suggested that the reduction factor f_r in equation (5) can be applied to reflection coefficients determined by equations (3) or (4), or by other existing equations for normal wave reflection. For the structures with $R_c / H \geq 0.5$, the influence on the reflection would be very small or not existing; the reduction factor was assumed to be 1.0.

Data analyses indicate that equation 4 also give good reflection predictions to the tested cases with $R_c / H_i \geq 0.5$ at the rubble mound structure. However, the combination of equations 4 and 5 underestimates the reflection coefficient about 15% for those cases with $R_c / H_i < 0.5$. It may be caused by the approximate expression of reduction factor f_r. Postma(1989) multiplied by equation 5 was found to generally fit well to the current experimental results of the normal waves. Therefore, equations 3 and 5 are combined here to compute the reflection coefficient C_{rn} for normal waves at low-crested rubble mound structures, which reads

$$C_{rn} = 0.14\xi_p^{0.73}(0.2R_c / H + 0.9) \qquad \text{for } R_c / H < 0.5 \qquad (6)$$
$$C_{rn} = 0.14\xi_p^{0.73} \qquad \text{for } R_c / H \geq 0.5$$

There is no method available for smooth structures other than using also equation 5 as an approximate estimation in present investigation. The average ratio of the measured reflections to the predictions from Seelig (1983) and Battjes (1974) coupled with equation 5 is 0.7 for the normal tested cases. Two reasons may contribute the discrepancies between the measurements and the predictions. Firstly, Battjes (1974) and Seelig (1983) give conservative estimations for non-overtopped structures as stated in the above section. Secondly, equation 5 could not properly describe the influence of crest height at smooth structures. For those wave conditions with $R_c / H \geq 0.5$, the overtopping was still observed and the measured wave transmission coefficient was up to 0.37. Due to the overtopping over the structure, the reflection may reduce, and the assumption that the reduction factor is 1.0 for $R_c / H \geq 0.5$ become unreasonable. To build a basis for the further the investigations of wave obliquity, we propose equation 7 which fits the current measured dataset well at low-crested smooth structures.

$$C_{rn} = 0.7\frac{a\zeta_p^2}{\zeta_p^2 + b}(0.2R_c / H + 0.9) \qquad \text{for } R_c / H < 0.5 \qquad (7)$$
$$C_{rn} = 0.7\frac{a\zeta_p^2}{\zeta_p^2 + b} \qquad \text{for } 0.5 \leq R_c / H \leq 0.8$$

where $a = 0.6$ and $b = 6.6$. The upper boundary is set as $R_c / H \leq 0.8$, which is the maximum value measured in the test.

Oblique wave reflection at low-crest structures

Equation 6 includes the reduction factor which solely relies on the relative crest height R_c/H_i and is still only valid for perpendicular wave attack. It must be realized that the increasing obliqueness results in an increasing energy flux in parallel direction and decreasing energy flux in perpendicular direction to the structure. Consequently, reflection will be reduced with increasing obliquities. A further reduction should be added to the reflection coefficient due to the oblique incidence.

Taking into account the influence of wave obliquity, reflection coefficients can be generally expressed as $C_r = C_{rn} f(\beta)$, where C_{rn} is the normal wave reflection coefficient from equation (6), $f(\beta)$ is the reduction function of wave obliquity, and β is the wave propagation direction with respect to the structure normal. To derive the reduction function $f(\beta)$, we write it in terms of the measured reflection coefficient C_{rm} and the predicted normal reflection coefficient C_{rn} from equation (6), i.e. $f(\beta) = C_{rm} / C_{rn}$. Figure 5 shows the relation $f(\beta)$ and incident wave angles at rubble mound structures. Dependence of the reflection R on the angle of incident is clear despite some scatter. The reduction trend from the figure can be approximately represented by cosine function, i.e. $f(\beta) = \cos\beta$. The final reflection expression for rubble mound structures is proposed as:

$$C_r = 0.14\xi_p^{0.73}(0.2R_c / H + 0.9)\cos\beta \quad \text{for } R_c / H < 0.5 \qquad (7)$$
$$C_r = 0.14\xi_p^{0.73}\cos\beta \quad \text{for } R_c / H \geq 0.5$$

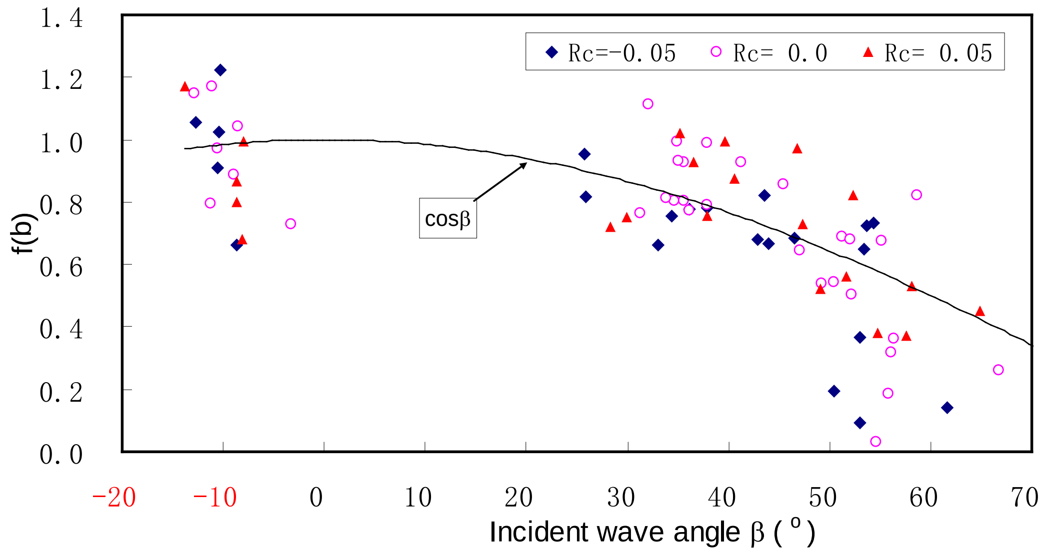

Figure 5 *f(β)* at rubble mound structures

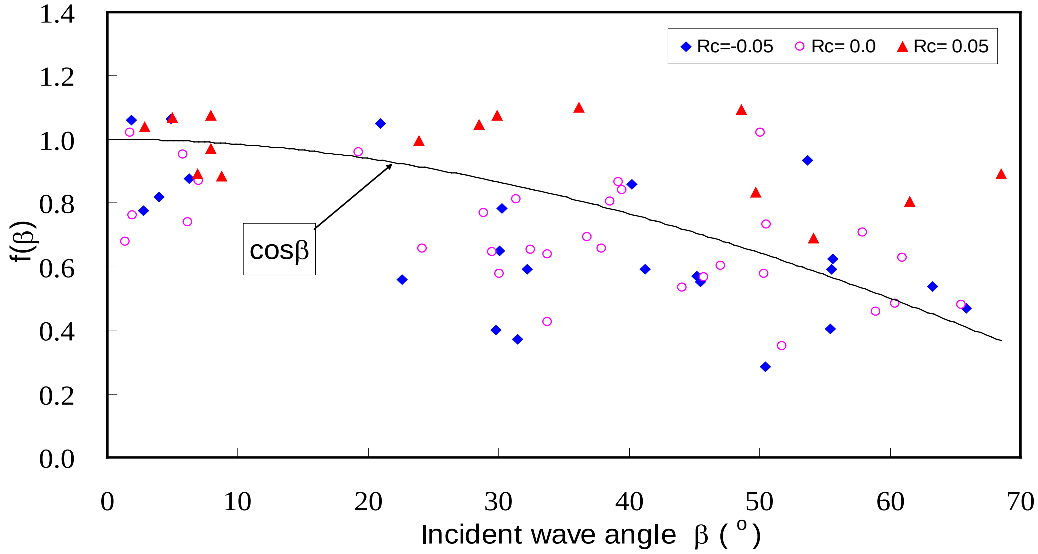

Figure 6 *f(β)* at smooth structures

In figure 6, it can be seen that the influence of the incident wave angle is obvious at smooth structures. The general trend can also be approximately described as a cosine reduction function, therefore, we suggest the following equation:

$$C_r = 0.7\frac{a\zeta_p^2}{\zeta_p^2 + b}(0.2R_c / H + 0.9)\cos\beta \qquad \text{for } R_c / H < 0.5 \qquad (8)$$

$$C_r = 0.7\frac{a\zeta_p^2}{\zeta_p^2 + b}\cos\beta \qquad \text{for } 0.5 \le R_c / H \le 0.8$$

where *a* and *b* are empirical coefficients with values of $a = 0.6$ and $b = 6.6$ respectively. It should be stressed that the good formulation of oblique wave reflection at smooth structures is subject to a more accurate expression for normal waves, which is beyond the current research.

REFLECTED WAVE SPECTRA

The reflection coefficient only contains information about the reflected wave heights in front of the structure. The directional wave spectrum contains wave period and direction information, which is often required to predict the wave conditions for use in structural design. Directional spectral density is commonly expressed as a product of the unidirectional wave spectrum $S(f)$ and a spreading function $D(\theta, f)$. $S(f)$ is the one-side frequency spectrum which is determined from the free surface elevation. $D(\theta, f)$ is the spreading function that characterises the distribution of wave energy in wave propagation directions. Figures 7 and 8 display the typical incident and reflected wave spectra in frequency and spatial domains respectively, where $S_{max}(f)$ is the maximum wave energy density in frequency domain, f_p is peak frequency, $S_{max}(\theta)$ is the maximum wave energy density in spatial domain and θ is the wave propagation direction with respect to the structure normal.

The studies show that the reflected spectra are similar to the incident spectra in frequency domain. In general the reflected peak period is quite close to the incident peak period. The most energy is present around the peak frequency; more energy is reflected for low frequency waves than for high frequency waves. In the spatial domain, one important feature is that the reflected waves show more spreading than the incident waves. The incident waves possess a main wave propagation direction with limited energy spreading around it. However, the reflected energy density widely distribute over the spatial domain. This may be caused by the wave refraction on the slope of structure. The incident waves with a main direction will be continuously refracted and reflected on the slope. Reflected wave directions will spread over a larger spatial domain due to wave refraction.

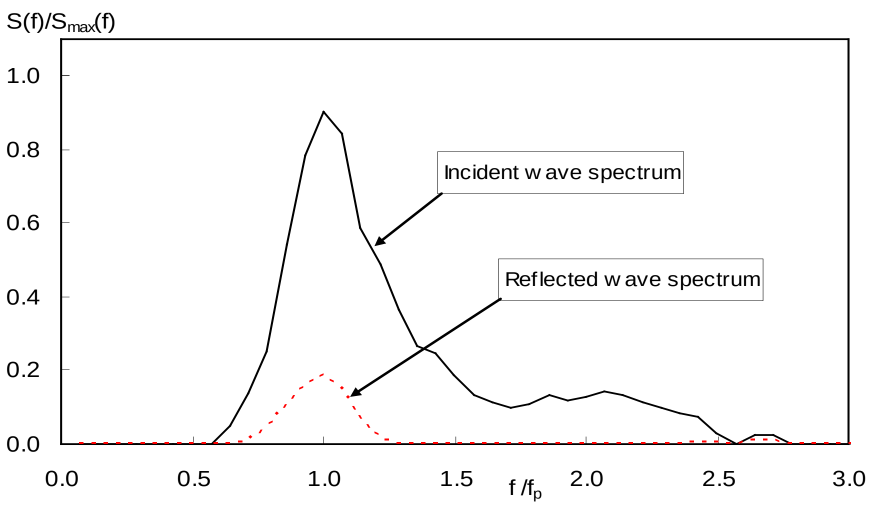

Figure 7 Incident and reflected wave spectra in frequency domain

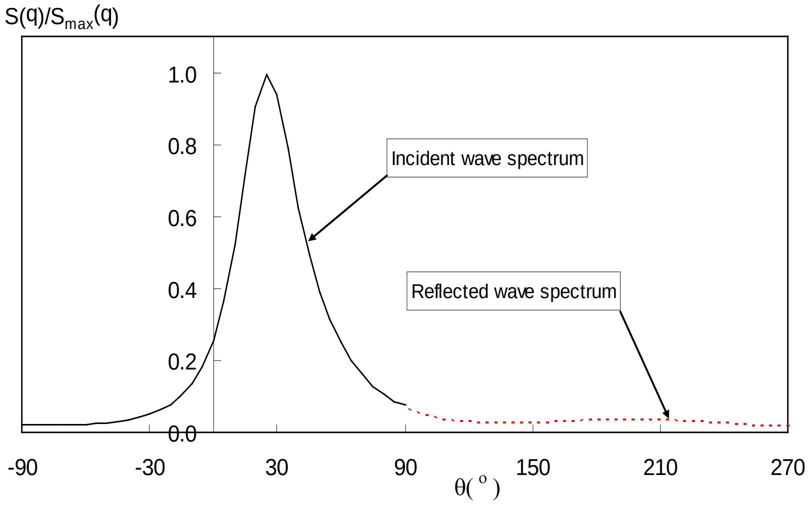

Figure 8 Incident and reflected wave spectra in spatial domain

CONCLUSIONS

Physical model tests were conducted to measure oblique wave reflection characteristics of low-crested structures. Results from tests indicate that long-crested and short-crested waves give similar wave reflection. The measured reflection coefficients ranged from 0.1 to 0.4 for the range of wave conditions tested. In addition to the fact that the reflection reduces if the crest height decreases, wave obliquities contribute a further reduction. Oblique wave reflection is noticeably dependent on the angle of incidence for both rubble mound and smooth structures.

The reduction factor due to the oblique incidence can be approximately estimated as a cosine function in terms of the main wave propagation direction for the two types of structure investigated. Equation 7 is proposed as a reflection expression for low-crested rubble mound structures. Wave reflection from low-crested smooth structures can be estimated using equation 8.

The present studies show that the reflected spectra are similar to the incident spectra in frequency domain. In general the reflected peak period is quite close to the incident peak period. In the spatial domain, the reflected waves from the low-crested structures gain more spreading than the incident waves.

ACKNOWLEDGEMENT

The studies are based on the data within the EU-funded projects DELOS (EVK3-2000-00038). The authors would like to extend their thanks to the research group for the valuable datasets.

REFERENCES

Ahrens, J. P. (1980) Irregular wave reflection data. U.S. Army Corps of Engineeris, Coastal Engineering Resear Centre, Fort Belvoir, VA.

Allsop, N.W.H & Channell, A.R. (1988) Wave reflections in harbours: The reflection performance of wave screens, Hydraulic Research Report OD 102.

Battjes, J.A., (1974) Surf similarity. Proccedings of 14th Coastal Engineering Conference Copenhagen, Denmark, ASCE, New York, pp466-477.

Davidson, M., A. Bird, P.A.D., Bullock, G.N. & Huntely, D.A. (1996) A new non-dimensional number for the analysis of wave reflection from rubble mound breakwaters. Coastal Engineering 28(1966) pp93-120.

Seelig, W.N.(1983) Wave reflection from coastal structures, Proceedings of coastal structures' 83 Conference, Arlington, USA, ASCE, New York, pp.961-973.

Postma, G.M. (1989) Wave reflection from rock slopes under random wave attack. MSc. Thesis, Delft University of Technology.

Van der Meer, J.W. (1988). Rock slopes and gravel beaches under random wave attack. PhD-thesis Delft University of Technology, the Netherlands.

Van der Meer, J.W., Wang, B., Wolters, A., Zanuttigh, B. & Kramer, M.. (2003) Oblique wave transmission over low-crested structures. Coastal Structures 2003, Portland, Oregon, USA.

Van der Meer, J.W., R. Briganti, B. Wang and B. Zanuttigh, (2004). Wave transmission at low-crested structures, including oblique wave attack. ASCE, Proc. 29th ICCE, Lisbon, Portugal.