Wave reflection, transmission and spectral changes at permeable low-crested structures

J.P. Sierra†‡, D.D. Dowding†, V. Persetto†, T.A.C. Oliveira†, X. Gironella†‡, C. Mösso†‡ and M. Mestres†‡

†Laboratori d'Enginyeria Marítima
Universitat Politècnica de Catalunya, Barcelona
08034, Spain
joan.pau.sierra@upc.edu
dddowding@gmail.com
vito.persetto@upc.edu
tiago.oliveira@upc.edu

‡ Centre Internacional d'Investigació dels
Recursos Costaners
Barcelona
08034, Spain
xavi.gironella@upc.edu
cesar.mosso@upc.edu
marc.mestres@upc.edu

ABSTRACT

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Physical model tests were carried out in order to improve the understanding about the hydrodynamic processes that take place around a LCS when it is under wave attack. In particular, the wave transmission and reflection coefficients as well as the spectrum transformation were analysed for both emerged and submerged structures. The results of the experiments indicated that there is a clear inverse proportionality between the transmission (K_t) and reflection (K_r) coefficients and the wave steepness s_{op}. This trend is much more noticeable for emerged than for submerged structures. A comparison with some widely employed formulae was also made; in most of the cases these expressions underpredicted K_t and overpredicted K_r. Moreover, the spectral changes in the waves transmitted through the structure were analyzed, showing a shift of energy to higher frequency bands greater than that observed in previous works. It was also noted that the higher the s_{op}, the more likely it is for the transmitted energy to be retained in the lower frequency bands.

ADDITIONAL INDEX WORDS: *Low-crested structures, Wave transmission, Wave reflection*

INTRODUCTION

Due to the increasing pressure on the coastal zone and the multitude of problems currently being faced by the coastal areas, more and more coastal defence mechanisms have to be used. Detached breakwaters are often employed to protect beaches against erosion. When these structures are frequently overtopped they are named Low-Crested Structures (LCS). The functional design of LCS is extremely difficult due to the large number of processes contributing to the resulting water and sediment fluxes (Sanchez-Arcilla et al., 2006) and beach morphodynamics. These difficulties increase when the structure is permeable, allowing the flow of water and sediment through it. Beside these drawbacks, they show significant advantages over other forms of coastal protection and as such, low-crested permeable structures are being increasingly employed

Many laboratory and field experiments have been conducted in relation to LCS. Recently, the European community has become more interested in LCS as an area of scientific study because of increased, and in some cases incorrect, use of these structures. Major research projects such as DELOS have been launched in an attempt to understand the effect of LCS.

To date, the LCS research has been chiefly concentrated into three primary efforts: (1) the morphological effect of the structures on the sediment beaches which they are aimed to protect; (2) the hydrodynamics of the waves inciding on these structure types; and (3) the optimization of modelling approaches in order to capture better the behaviour associated with LCS.

These research efforts are all inter-related and heavily dependent on a basic knowledge of the hydrodynamics of the structure. The final morphological response will result from the time-averaged transmissivity of the structure (Pilarczyk, 2003). Thus, the transmission of the structure must be known in order to gauge the corresponding sediment morphology. In order to best simulate the shoreline response in the designing process, in a numerical simulation for example, it is necessary to know the variation in the transmission coefficient for various submergence conditions. It is therefore apparent that an understanding of the hydrodynamics related to LCS is essential to predict the beach response to such structures.

For low crested structures (LCS), Van der Meer et al. (2000, 2005) developed two different formulae for predicting the transmission coefficient in a wide range of incident wave conditions and structure geometry. These formulae were developed from a collection and reanalysis of data originated from different sources, including previous studies of Van der Meer and Daemen (1994) and D'Angremond et al. (1996). Other research into the hydrodynamic behaviour related to LCS include the work of Seabrook and Hall (1998), who conducted tests with so varied parameters that they allowed for a description extended to include structures with very large widths. Hirose et al. (2002) also performed tests on structures with large widths and special

armouring. Although both studies focused solely on emerged and not on submerged structures, they were still able to contribute, along with other investigations, to the database upon which Van der Meer et al. (2005) supported their work on the wave transmission coefficient. Within this study, the formulae developed by Van der Meer and Daemen (1994) and D'Angremond et al. (1996) were analysed in detail to ascertain their validity in relation to the experiments conducted.

Research was conducted into the reflection against smooth, impermeable slopes (Seelig and Ahrens, 1981), as well as the reflection against various armour layers (Allsop and Channel, 1989). Seelig and Ahrens (1981) theorized that the wave reflection from porous structures is a function of the toe depth, the offshore seabed slope, the armour characteristics and the number of armour layers on the structure. Postma's (1989) analysis on rock slopes revealed a strong dependence of the reflection coefficient on the Iribarren number, ξ, and negligible correlations with spectral form and toe depth. Van der Meer (1992) used multiple regression to differentiate the effects of wave height and period, structure permeability and slope. Davidson et al. (1996) introduced the use of a non-dimensional parameter that weights the contributions of wave length, wave height, toe water depth, structure slope and armour diameter, to the prediction scheme for the reflection coefficients.

The DELOS EU-project generated large sets of tests on various structure types, for most of which the reflection coefficient is available. An extensive and homogeneous database on wave reflection was prepared based mostly on this research (Zanuttigh and Van der Meer, 2006). Using this database, the reflection behaviour for various types of structures was analysed by Zanuttigh and Van der Meer (2008), and a formula for the reflection coefficient was developed.

As mentioned, most of the studies pertaining to wave transmission were done in order to develop formulae for the prediction of the transmission coefficient (among others: Van der Meer, 1988; Van der Meer and Daemen, 1994; D'Angremond et al., 1996) instead of performing an analysis of the transmitted wave energy spectrum. Zanuttigh and Martinelli (2008) created a model for the prediction of energy transmission in the presence of permeable low crested structures through the reconstruction of the transmitted wave by filtration and overtopping leeward of the structure. That work was preceded by Lamberti et al. (2006) and the development of a physical model for the prediction of spectral changes, which unfortunately only involved emerged permeable LCS. Buccino et al. (2009) investigated the spatial distribution of the transmitted wave energy due to both wave overtopping and diffraction and the corresponding change of the power spectrum functions, although this work was however limited to impermeable LCS. Therefore, the wave energy distribution at permeable LCS was really only examined in great detail by Zanuttigh and Martinelli (2008).

Numerous laboratory experiments have been performed on LCS and described in excellent detail (Vidal et al., 2002; Kramer et al., 2005; Clementi et al., 2006). However, these works are either aimed at the physical modelling techniques and the flaws therein (Clementi et al., 2006), or are focused on parameters which were not studied in the flume, such as wave obliquity (Kramer et al., 2005). Additionally, a significant portion of the research done on LCS was related to impermeable LCS (Cáceres et al., 2008), or to LCS with a low permeability (Vidal et al., 2002), as these structures were more frequently employed than highly permeable structures. There is thus a shortfall in the number of physical modelling experiments conducted on LCS with high permeability

and, as a consequence, some gaps in the knowledge of the behaviour and impact of permeable LCS still persist.

The goal of this paper is to analyze data from experiments carried out with permeable LCS, obtaining transmission and reflection coefficients and comparing the results to state-of-art predictive formulae, in order to verify their performance in the case of permeable structures. Another objective is to determine the energy distribution among frequencies of transmitted waves comparing it to the results of other authors to check if the permeability introduces changes in the observed patterns of wave energy transfer among frequencies

METHODS

The experiments were carried out at the CIEM flume, located at the Maritime Engineering Laboratory from the Universitat Politècnica de Catalunya in Barcelona, Spain. This is a large-scale experimental facility 100 m long, 3 m wide and 5 m deep. It is equipped with a wedge-type paddle to generate waves up to 1.6 m in height with a frequency range between 0.125 and 1 Hz.

The 2D experiments (Sierra et al., 2009) consisted of the measurement of waves, orbital velocities, currents, water levels and bottom evolution around a permeable LCS located on a sloping beach (1/15) with a mobile bed of sediment with a 200 μm mean size. The tests were performed with two different structures built with concrete blocks: one submerged, with a 0.25 m freeboard, and one emerged with a crest height of 0.15 m, featuring a porosity of 0.5.

In order to gather information about wave parameters, 24 wave gauges (15 resistive and 9 acoustic) were deployed along the flume and, in particular, in the vicinity of the structure. Nine irregular wave conditions were tested for each structure, corresponding to three wave heights and three different wave steepnesses. Table 1 summarizes the parameters of the performed tests. Due to a failure in the gauge recording system data were lost in one of the tests for the emerged structure.

RESULTS

The analysis of the transmitted waves revealed that the transmission coefficient K_t was dependent on both the incident wave height (H_{m0}) and steepness (s_{0p}). This dependence was much more noticeable for the emerged structure than for the submerged one, as it can be clearly seen in Figure 1. There, for the emerged structure, the transmitted wave heights are plotted for $H_{m0} = 0.25$ m. This graph reveals the most important trend observed for the transmission coefficient of the emerged structure, in the sense that the K_t value was inversely proportional to the wave steepness, that is, higher K_t values were related to lower wave steepness.

Table 1. Wave parameters of the laboratory tests. H_s is the significant wave height, T_p is the peak period, L_0 is the wave length at deep water and s_{op} is the wave steepness at deep water

Test	H_s (m)	T_p (s)	L_0	s_{0p}
1	0.20	2.25	7.86	0.025
2	0.25	2.51	9.83	0.025
3	0.30	2.75	11.80	0.025
4	0.20	1.63	4.16	0.048
5	0.25	1.83	5.20	0.048
6	0.30	2.00	6.24	0.048
7	0.20	2.86	12.74	0.016
8	0.25	3.20	15.92	0.016
9	0.30	3.50	19.11	0.016
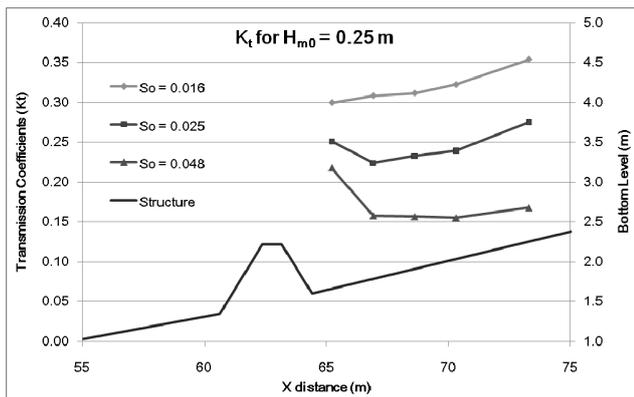
Figure 1. Transmission wave heights in the case of emerged structure

This trend was significantly less noticeable for the submerged structure, for which the gauge data recorded for the transmitted waves revealed that the K_t value was slightly dependent on H_{m0} and very slightly dependent on wave steepness.

Although the largest wave steepnesses gave the lowest K_t values, the differences were less important, as it is shown in figure 2.

The measured transmission coefficients were compared to one of the most widely employed expressions, that from D'Angremond et al. (1996). This expression states that the transmission coefficient is a function of the non-dimensional freeboard and crest width and the Iribarren parameter (which is a function of the wave steepness and the structure slope). In figure 3 a plot with this comparison is shown. It can be observed that K_t is lower for emerged structures (measured values between 0.29 and 0.33) than for submerged ones (values between 0.79 and 0.86). From this figure it can be concluded that the expression of D'Angremond et al. (1996) underpredicts, in all the cases except one, the measured transmission coefficients.

Another analyzed parameter is the reflection coefficient K_r. In figure 4, K_r vs B/L (where B is the structure crest width and L the wave length) is represented for both cases. As it can be seen in this figure, larger L (smaller B/L ratios) resulted in larger reflection coefficients, although K_r remained almost constant for values of B/L exceeding a given threshold. This value of B/L was 0.07 in the case of emerged structures (with K_r around 0.17) and 0.08 for submerged structures (with K_r about 0.10). Obviously, reflection coefficients were larger in the case of emerged structures (ranging
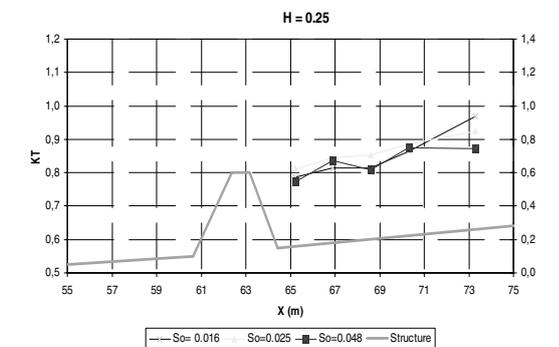
Figure 2. Transmission wave heights in the case of submerged structure
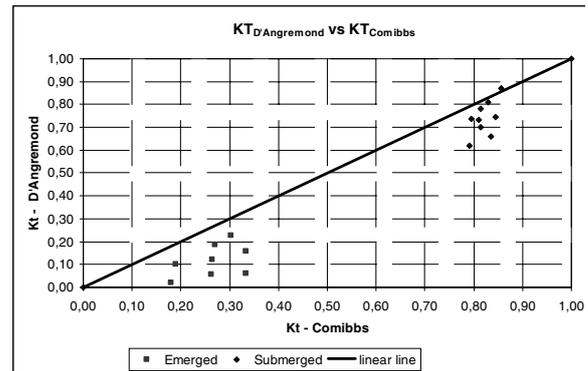
Figure 3. Comparison of the measured K_t values with the D'Angremond et al. (1966) expression.

from 0.17 to 0.27) than for submerged ones (K_r between 0.10 and 0.20).

In figure 5, measured K_r are compared to those given by Ahrens's (1984) expression. In almost all the cases, the measured K_r were lower than the theoretical ones for both structures.

Concerning the wave spectrum, it is well known that it changes due to the wave transmission through LCS. Zanuttigh and Martinelli (2008) indicate that there is a shift of energy to higher frequencies. Thus, these authors found that the transmitted wave energy E_t is distributed (relative to the peak frequency of the incident wave f_{pi}) as follows:

- 70% of E_t is in the range $f \leq 1.5\ f_{pi}$.
- 17% of E_t is for $1.5\ f_{pi} < f \leq 2.5\ f_{pi}$.
- 8% of E_t is for $2.5\ f_{pi} < f \leq 3.5\ f_{pi}$.
- E_t tends to zero for $f > f_{max} = 4.36\ f_{pi}$.

Figure 6 shows the transmitted wave energy distribution for the submerged structure at a wave gauge located just behind it. The general theory that the energy distribution shifts to higher frequencies after interacting with the structure is validated by this figure. After the structure's influence, the energy distribution of the waves changed as follows:

- The percentage of energy in the range $f \leq 1.5\ f_{pi}$ varied between 51 % and 65%.
- In the range $1.5\ f_{pi} < f \leq 2.5\ f_{pi}$, it varied from 29 % to 38 %.
- In the range of $2.5\ f_{pi} < f \leq 3.5\ f_{pi}$ the values were from 5 % to 15 %.

Figure 7 shows the transmitted wave energy distribution for the emerged structure at a wave gauge located just behind it. The distribution of wave energy after the structure's influence changed as follows:
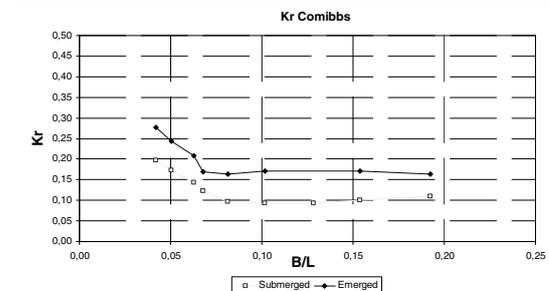
Figure 4. Reflection coefficients as a function of B/L for both structures.
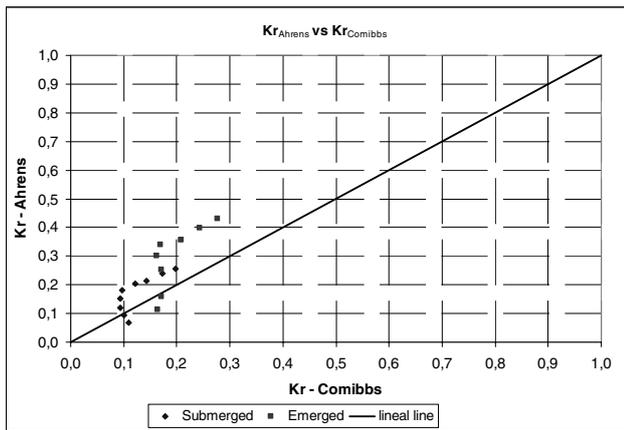
Figure 5. Comparison of K_r measured and those given by Ahrens's (1984) expression.

- In the range $f \leq 1.5 \, f_{pi}$, the percentage of energy varied from 63 % to 81%.

- In the range $1.5 \, f_{pi} < f \leq 2.5 \, f_{pi}$, the percentage of energy varied from 12 % to 29 %.

- In the range of $2.5 \, f_{pi} < f \leq 3.5 \, f_{pi}$, it varied from 5 % to 9 %.

DISCUSSION AND CONCLUSIONS

From the analysis of the results it is clear that in the performed experiments the wave transmission was greater than expected and the wave reflection less than the predicted by widely used expressions. Although the porosity of both structures was 0.5, which is usual in this type of structures (when they do not have core, as in this case), it appears that they were very permeable, allowing the transmission of more energy and, therefore, reflecting less than expected.

On the other hand and similarly to other authors, a clear inverse relationship has been found between K_t and the wave steepness, in particular for emerged structures. For submerged LCS this correlation is not as strong.

In the same way, K_r is proportional to the wave length to some extent, after which it remains almost constant.

Focusing on the energy of the transmitted waves, the peak period is similar to that of the incident wave. Another remarkable
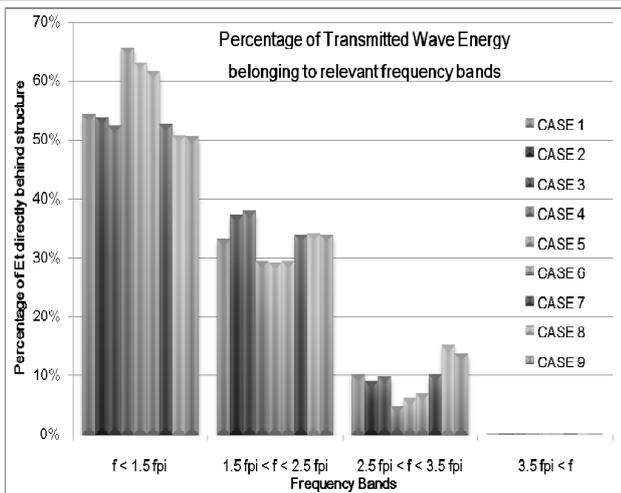
Figure 6. Percentage of transmitted wave energy categorized in frequency bands from a wave gauge located just behind the submerged structure (case 1 on the left and case 9 on the right).
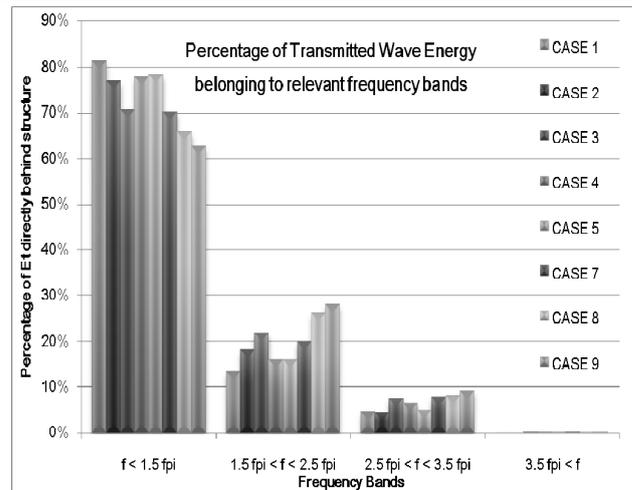
Figure 7. Percentage of transmitted wave energy categorized in frequency bands from a wave gauge located just behind the emerged structure (case 1 on the left and case 9 on the right).

feature (not shown here due to the lack of space) is that longer transmitted waves have a more irregular spectrum than shorter ones.

Furthermore, transmission through and over permeable LCS produces a shift of energy to higher frequencies. The shift observed during the experiments carried out in this work is larger than that obtained by other authors in previous works.

One of the main drawbacks of this work that prevents extracting more conclusions is that structure permeability was not measured and it could only be observed qualitatively during the experiments, evidencing the high permeability of both structures. This apparent higher permeability is also suggested by the different hydrodynamic behaviour observed around the structures, with more transmitted energy (and as a consequence less reflection) and more shifting of energy to higher frequencies than that observed in previous works.

In summary, it seems like structure permeability plays an important role in the wave pattern around LCS, including wave transmission, reflection and changes in the wave spectrum. Nevertheless, this parameter is not taken into account in the existing formulations to predict transmission and reflection coefficients.

Although the number of experiments performed in this work is limited, the study of the importance of structure permeability in these processes should be contemplated by considering a greater amount of data. Therefore, the research of the hydrodynamic patterns around permeable LCS is a subject that deserves a substantial amount of work in the near future.

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