Spectral analysis of water surface elevations near submerged breakwaters

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Abstract

Submerged breakwaters are one solution to prevent coastal erosion problems, achieving a greater protection to the coastline, decreasing the risk of erosion and helping sand accretion. Due to their lower crest height, they do not eliminate landward transport and can be successfully used in some cases. Their efficiency depends on the relation between the incident wave height and the correspondent reflected and transmitted one.

Understanding of wave energy transmission is also an important aspect in the design of these structures. Several studies were conducted in order to understand with more accuracy the behaviour of submerged breakwaters and this article intends to analyse the performance of these structures when submitted to the action of incident irregular waves, in respect of the transmission of the wave energy.

The wave transmission can be analysed through the incident and the transmitted significant wave heights calculated through the measured free surface elevation. However, focussing the analysis on the shape of the registered wave spectra, it is also possible to verify some other characteristics related to the transfer of energy between wave frequencies.

1 Introduction

Submerged breakwaters are becoming a popular solution to prevent coastal erosion as, from the sustainability, the environmental and the aesthetical points of view (one of the major engineering priorities at the moment) they do not have so many disadvantages as the called “hard structures” like groins, detached breakwaters, revetments, seawalls, etc. These structures are designed to attenuate
the wave action and, as they are constructed below a specified design water level
some overtopping is allowed, as well as the circulation along the shoreline zone.
Moreover, once they are less submitted to wave action (due to their lower
height), the required quantity of material necessary for their construction is
smaller than in similar emerged structures.

Nevertheless, they can still act as an active measure to decrease the waves
before they reach the shore and it is their capability for retaining or permitting
sediment accumulation (if there is shore sediment transport) at their backward
side that is responsible for their important role in beach protection. The
attenuation of the wave height is caused by the energy dissipation and by the
formation of diffraction currents at the ends of the structure.

Research has been done to better understand the variables and processes
involved in the wave-structure interaction but there are still some outstanding
questions, namely in the transmission of the wave energy process.

In the incidence of the wave in a porous submerged breakwater, the wave is
partially reflected, partially transmitted and partially absorbed by the structure
and, it is the knowledge of the corresponding wave heights (incident, reflected
and transmitted) that will permit to evaluate their efficiency. The transmission
coefficient is the ratio between transmitted and incident significant wave heights,
\( H_t \) and \( H_i \), and is expressed by:

\[
K_t = \frac{H_t}{H_i} = \frac{H_{t,m_0}}{H_{i,m_0}} \quad (1)
\]

Once the significant wave height can be achieved by the zero order moment of
the spectrum \( m_0 \) by \( H_{m_0} = 4\sqrt{m_0} \), one can expressed \( K_t \) as a relation between
the energy of the wave spectrum seawards \( (E_i) \) and landwards \( (E_t) \) the
submerged breakwater, as follows:

\[
K_t = \frac{H_{t,m_0}}{H_{i,m_0}} = \sqrt{\frac{m_{0,t}}{m_{0,i}}} = \sqrt{\frac{E_t}{E_i}} \quad (2)
\]

This approach will take into account all the wave components in the record of
the wave surface, including the higher harmonics.

The energy distribution within the spectrum is often suggested as helpful for
understanding the hydraulic performance of the submerged breakwater. Bleck
and Oumeraci [1] have carried out model tests with smooth and impermeable
rectangular (vertical slopes on the seaward and landward sides of the structure)
submerged breakwater in order to investigate its influence in the spectral
evolution leeward the structure.

The authors referred some of the detected effects occurring at these structures,
namely: local effects like shoaling, flow separation, wave breaking, non-linear
interactions, vortex shedding, etc and global ones, like energy loss and energy
transfer within the spectrum, that are the result of the previous ones. They also
point out that waves behind the submerged breakwater have shorter periods and
smaller heights than in front of the structure, which implies a decrease in the
total energy density spectrum (significant wave height reduction) and a
deformation of the spectrum (change in the wave form/period) while passing the submerged breakwater. In addition, the spectrum behind the submerged breakwater becomes multi peaked, as the wave period decreases.

The generation of secondary wave crests while waves passed the submerged breakwater was also clearly showed. Besides that, it was observed a decrease of the total wave energy, as well as a broadening of the spectrum behind the submerged breakwater. No change of the peak period was observed before and behind the submerged breakwater, indicating that the highest energy remains at the same frequency.

Based on their own experimental data, the authors proposed a predictive formula for the calculation of the transmission coefficient,

\[
K_t = \left[ 1.0 - 0.83 \exp\left( -0.72 \frac{d_r}{H_i} \right) \right] \tag{3}
\]

being \(d_r/H_i\) the relative submergence depth (where \(d_r\) represents the submergence depth or the difference between the water depth and the height of the structure and \(H_i\) the incident wave height). This expression is valid for \(d_r/H_i\) values between 0.5 and 12 and for theoretical single peak spectra.

The results of other similar experimental studies with impermeable submerged breakwaters of rectangular shape, Bleck and Oumeraci [2], clearly show the shift of the wave energy towards the higher frequency range within the wave spectrum behind the submerged breakwater, which means that not only the height of the waves, but also their periods change, suggesting that it is important to consider this shift in the design process, in addition to the transmitted significant wave height. The shift of the wave period was proved to vary with the relative submergence depth, the wave steepness (\(H_i/L_i\)) and the relative submerged breakwater length (\(B/L_i\)), being the first parameter the most influential one. In fact, the transmitted peak wave period could be equally important to describe the hydraulic efficiency of the structure, as the wave period affects the transmitted wave energy flux, relevant for both the wave loading (forces, run up, overtopping) and sediment transport behind the submerged breakwater.

The authors suggested that the transmission coefficient could be expressed by,

\[
K_t = \left[ 1.0 - 0.92 \exp\left( -0.83 \frac{d_r}{H_i} \right) \right] \tag{4}
\]

for \(d_r/H_i\) values between 0.5 and 12.

The similarity of equations (3) and (4) suggests a re-analysis of the data.

Yamashiro et al. [3] pointed out for the importance of the transmitted wave field of a submerged breakwater analysis, as it is in the transmitted wave region that non-linear wave-structure interactions, local scour and bottom topography changes take place. To fully understand the phenomena wave tank experiments using several waves and breakwater models with 1:1 slopes were carried out.

The incident and the transmitted wave spectra were plotted and the total power of the transmitted wave, \(P_A\), and the total power of the incident wave, \(P_1\)
were calculated, allowing the evaluation (through their ratio) of the efficiency of the structure. The results proved that $P_A/P_1$ decreased exponentially with the increase of the non-linear parameter proposed by Goda, 1983, $\Pi$, due to the wave reflection and the energy dissipation caused by the vortices and the wave breaking. The non-linear parameter $\Pi$ is given by,

$$\Pi = \left(\frac{H_i}{L_q}\right) \coth^3 k_q h_q$$  \hspace{1cm} (5)

where $L_q$ represents the wavelength on the crown, $k_q$ the wave number on the crown and $h_q$ the crown depth. In the experiments with random waves, $L_q$ and $k_q$ were chosen as the significant wavelength and the significant wave number of the incident random wave and $H_i$ as $H_s/1.42$.

The experiences of Yamashiro et al. [3] were conducted with different wave heights ($H_s$ equal to 2, 4, 6 and 8cm), different periods ($T_p$ equal to 1.2, 1.43 and 1.79s) and different crown widths ($B$ equal to 2.0h and 4.0h) and depths of crown (equal to 0.1h, 0.2h and 0.3h) of the model. The water depth $h$ was fixed to 0.38m. Some of the results are shown in Table 1, where some expressions relating $P_A/P_1$ and $\Pi$ (for $\Pi$ ranging from 0.1 to 10) are proposed:

<table>
<thead>
<tr>
<th>B/h</th>
<th>$T_{\text{model (s)}}$</th>
<th>Regular Waves</th>
<th>Irregular Waves</th>
<th>Equation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>1.79</td>
<td>$P_A/P_1 = 0.42\Pi^{(-0.90)}$</td>
<td>$P_A/P_1 = 0.40\Pi^{(-0.60)}$</td>
<td>(6)</td>
</tr>
<tr>
<td></td>
<td>1.43</td>
<td>$P_A/P_1 = 0.25\Pi^{(-0.86)}$</td>
<td>$P_A/P_1 = 0.27\Pi^{(-0.77)}$</td>
<td>(7)</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>$P_A/P_1 = 0.18\Pi^{(-1.06)}$</td>
<td>$P_A/P_1 = 0.20\Pi^{(-0.82)}$</td>
<td>(8)</td>
</tr>
<tr>
<td>4.0</td>
<td>1.79</td>
<td>$P_A/P_1 = 0.25\Pi^{(-1.11)}$</td>
<td>$P_A/P_1 = 0.33\Pi^{(-0.69)}$</td>
<td>(9)</td>
</tr>
<tr>
<td></td>
<td>1.43</td>
<td>$P_A/P_1 = 0.15\Pi^{(-1.17)}$</td>
<td>$P_A/P_1 = 0.22\Pi^{(-0.74)}$</td>
<td>(10)</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>$P_A/P_1 = 0.10\Pi^{(-1.22)}$</td>
<td>$P_A/P_1 = 0.16\Pi^{(-0.87)}$</td>
<td>(11)</td>
</tr>
</tbody>
</table>

It was also shown that the crown width hardly influences $P_A/P_1$, at least for the experimental conditions used in the study. The authors concluded that the contribution of the higher order waves to the wave motion was bigger for higher crown widths, fact that could affect the sediment transport in the lee region of the submerged breakwater. They also found that although the shape of the transmitted spectrum changed considerably with the crown width, the total power of the transmitted wave was not so much dependent on this parameter.

Van der Meer and Veldam [4] have noticed differences in the wave height transmission values between tests performed at different model scales. Generally, the wave transmission was superior in the tests performed at higher scale, which could be explained by the differences in the wave flow characteristics (wave flow in the tests with bigger scale was more turbulent).
The present paper aims to analyse, through the spectral analysis of the free surface elevation, some of the phenomena occurring during the wave incidence on a 2:1 slope of a rough impermeable submerged breakwater, namely in the transmission process. The results presented cover $d/H_i$ ranging from 0 to 1.67, leading to different formulae when compared with eq. (3) and (4).

2 Experimental set-up

The experiments were carried out in the old wave tank of the Faculty of Engineering of the University of Porto, that was 4.8m wide, 24.5m long and 0.6m deep in the measuring section. A thin diving wall was used to isolate the measuring section from the rest of the tank, avoiding tri-dimensional and diffraction effects during the tests. A dissipating beach was constructed in the extremity of the tank in order to reduce wave reflections from the tank wall.

The tests were conducted with a rough and impermeable model of a submerged breakwater model, with 2:1 slopes, as Figure 1 illustrates.

Figure 1: Location of wave probes and cross section of the submerged breakwater model.

The location of the six wave probes that registered the water surface elevation is also schematised in Figure 1. Three of them were located in front of the model (wave probes No. 0, 2 and 3) for the reflection analysis and one behind it (wave probe No. 5) for the transmission analysis. The values registered in wave probes 9 and 10 (located outside the channel) allowed the analysis of the mean incident wave height, $H_{smi}$, Taveira-Pinto [5].
The tests were performed with two distinct prototype water depths ranges, allowing the definition of significant short (\(H/L \leq 0.03\)) and long wave regimes. Random waves according to the JONSWAP spectra were generated, considering different prototype parameters: peak periods of 8, 10, 12.5 and 15 s; theoretical incident significant wave heights of 4, 6 and 8 m and water depths of 10, 11.5, 13, 14, 20, 21.5, 23, 24 and 28 m.

3 Results and discussion

The spectral analysis of the free surface elevation recorded by each wave probe for the different test conditions allowed the analysis of the behaviour of the submerged breakwater, that could be useful to obtain the reflected and transmitted coefficients. For the present analysis we only considered the values registered in probes No. 5, 9 and 10, since no reflection analysis will be presented.

Figure 2 is one example, in prototype values, of this analysis and as it can be observed, there are significant differences between the wave field in the seaward side of the structures and the transmitted one.

The values registered in probes No. 9 and 10 were very similar, indicating some uniformity of the incident wave field characteristics.
As expected, comparison of the spectra in front and behind the submerged breakwater shows that the presence of this structure affects the wave field, as it is clearly seen a change in the spectral shape for waves passing the structure. Besides that, a decrease in the total wave energy, a broadening of the spectrum (a shift of the wave energy towards the higher frequency range) behind the structure is also observed. The generation of higher harmonics (higher order waves by non linear interactions) is another relevant aspect that can be observed over the
higher frequencies and under the lower frequencies (with lower power). No change of the peak period was observed before and behind the submerged breakwater, indicating that the highest energy remained at the same frequency, as predicted by Bleck and Oumeraci [1].

The measured significant wave heights were obtained through integration of the respective spectral diagram. Figures 3 and 4 show the variation of the transmission coefficient, $K_t$, with the relative water depth, $d_r/H_i$ ($H_i$ is the incident significant wave height that corresponds to the mean of the values registered in probes No. 9 and 10) for the short wave and long wave regimes, respectively. The measured results were compared with expressions (3) and (4) and are also presented. Following Bleck and Oumeraci approaches, [3, 4], an expression for the transmission coefficient is suggested for each wave regime.

As it can be seen, the proposed relationships show a reasonable correlation with the measured values with a coefficient of correlation of 0.89 and 0.82 in model tests performed with short and long wave regimes, respectively. Differences between equations (3) and (4) and the proposed ones could be mainly explained by the different geometry and roughness of the models. The first tests were based in experiments with submerged breakwaters with vertical slopes and the present tests with models with 2:1 rough slopes, leading to different cross sections. The range of tested $d_r/H_i$ values considered herein is also much smaller and closer to zero than the used in the other experiences.

Figure 5: Ratio of total power of the transmitted wave to the total power of the incident wave versus the non-linear parameter $\Pi$.

The total power of the transmitted wave, $P_1$ and the total power of the incident wave, $P_A$ were also calculated (through integration of the respective wave spectra over the corresponding frequency ranges) and its variation with the non-linear
parameter, eq. (5), is illustrated in Figure 5. It is also shown the comparison between the measured and the corresponding values calculated through the expressions presented in Table 1. The wave periods are in model values.

For the data of the 2:1 slope rough model, the authors propose the following relations between \( P_A/P_1 \) and the non linear parameter:

\[
\begin{align*}
\text{Long wave regime} & : \frac{P_A}{P_1} = 0.31 \Pi^{-0.57} & R^2 &= 0.97 \\
1.76 & \text{Long wave regime} & \frac{P_A}{P_1} = 0.28 \Pi^{-0.42} & R^2 &= 0.84 \\
1.50 & \text{Short wave regime} & \frac{P_A}{P_1} = 0.19 \Pi^{-0.37} & R^2 &= 0.74 \\
1.41 & \text{Long wave regime} & \frac{P_A}{P_1} = 0.2425x-0.3997 & R^2 &= 0.76 \\
1.25 & \text{Short wave regime} & \frac{P_A}{P_1} = 0.13 \Pi^{-0.43} & R^2 &= 0.64 \\
1.13 & \text{Long wave regime} & \frac{P_A}{P_1} = 0.1954x-0.453 & R^2 &= 0.80
\end{align*}
\]

Table 2: Ratio of total power of the transmitted wave to the total power of the incident wave versus nonlinear parameter \( \Pi \).

Note that no expressions are suggested for the wave periods equal to 1.0 and 0.8s due to the lack of data. It is also interesting to note that in the long wave regime tests, the \( P_A/P_1 \) measured values show a better correlation than in the tests with short waves, being closer to those predicted by Yamashiro et al. [3]. The measured values are smaller than those proposed by those authors, fact that could be partially explained by the different geometries of the models (crown width and slopes) or by the differences in the roughness of the models. No separation of \( B/h \) values was considered, as it was not detected a significant effect.

4 Conclusions

The wave transmission process was analysed through experimental tests, carried out with a 2:1 slope of a rough impermeable submerged breakwater. The test conditions were related with low \( d_\ell \) and/or high \( H_i \), leading to low values of \( d_\ell/H_i \).

Spectral analysis of the free surface elevation showed a decrease in the total wave energy and a broadening of the spectrum behind the structure, although no change of the peak period was observed (the highest energy remained at the same frequency).
Two expressions, depending on the wave regime tested, were proposed for the variation of the transmission coefficient with the relative water depth, $d_r/H_i$. The measured values indicate a relatively good correlation and the comparison with other expressions show some differences that could be explained by the different $d_r/H_i$ values covered or by the different geometry and roughness of the models.

Expressions for the variation of the ratio $P_\lambda/P_1$ with the nonlinear parameter of Goda were suggested and compared with the corresponding values suggested by other authors. The measured values were smaller than those, fact that could be partially explained by the different crown width and slopes of the models or by the different roughness.

It is clear with these experiments that there is some obvious influence of the slope angle and roughness in the wave transmission characteristics.

References


