Wave Reflection: Small and Large Scale Experiments on Wave Absorbing Quay Walls

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Summary
The paper reports on small and large scale experiments carried out to assess the response of prefabricated caissons with internal rubble mound in terms of wave reflection. The research was conducted to analyse the effect of the model scale on the structural response and the treatment of the scale effects. Physical model tests were carried out in the small and large scale facilities at Universitat Politècnica de Catalunya, in Barcelona. The authors applied the Burcharth et al (1999) approach to treat scale effects and compared the results with the Matteotti’s ones (1991).

Introduction
Vertical quay walls are a widespread solution as berthing structures because they allow an optimized use of the port area with small occupancy. Notwithstanding, they reflect almost all the incident wave energy, thus their use is not advisable in port basins exposed to re-reflected waves. A solution based on less reflective structures would be advantageous. Non-conventional vertical structures can represent an alternative. Anti-reflection quays and dikes have been experimentally studied over the years (Jarlan 1961, 1965; Hattori 1972; Ijima et al. 1976; Matteotti 1991; Fugazza and Natale 1992; Tanimoto and Takahasi 1994; Chegini 1997; Suh et al. 2006; Huang 2007; Garrido et al. 2010, Taveira Pinto et al. 2011; Faraci et al. 2012).

Figure 1. Scheme of the quay as in Matteotti (1991)

This paper describes the reflection response of low-reflection vertical quays, whose upper wall, exposed to the incoming waves, is replaced by dissipative cells with rubble mound inside (Figure 1). The study aimed to characterize the influence of model scale and nominal diameter of the rubble
mound on the wave reflection for regular waves. An exhaustive literature is not yet available for such kind of structure: Matteotti (1991) carried out physical model tests with monochromatic waves; Faraci et al. (2012) studied how the changes in rubble mound inside the chamber can affect the reflection coefficient. In both cases the experiments have been carried out in small scale facilities. Large and small scale tests were conducted in the Maritime Engineering Laboratory (LIM/CIIRC-UPC) of the Universitat Politècnica de Catalunya, in Barcelona (Spain) to study the response of the quay in a wide range of wave heights and periods. Results of small and large scale tests have been compared to analyze the influence of scale effects.

Scale Effects in Wave Reflection
The wave reflection is expressed by the bulk reflection coefficient, defined as follows:

$$C_r = \frac{H_r}{H_i} = \sqrt{\frac{E_r}{E_i}}$$

where $H_r$ and $H_i$ are the wave height of reflected and incident waves, respectively, and $E_r$ and $E_i$ are the reflected and incident wave energy. The reflection coefficient can vary between 0 and 1, where 1 defines total wave reflection. Wave reflection has studied by several authors such as Allsop & Hettiarachchi (1988), Allsop (1990, 1995), Seelig and Ahrens (1981) and Seelig (1983) (literature not fully exhaustive).

Generally vertical dikes or jetties present values close to 1, breakwaters or rubble mounds can show $C_r$ around 0.3, but it should be properly assessed for each structure by means of physical model tests. The reflection coefficient depends on several parameters such as hydraulic conditions, geometrical layout and structural properties but, if assessed by physical model tests, it can be affected by model or scale effects.

Porous structures dissipate wave energy within the structure’s voids, where turbulent flows are triggered. As higher is the dissipation inside the structure, as lower is the reflected wave energy. The geometric scaling of grain materials in the physical models follows the Froude’s law and can cause an incorrect scaling of viscosity, leading to low Reynolds numbers and large viscous forces (Burcharth et al, 1999). As consequence the flows can be laminar instead of being fully turbulent within the structure’s void and the model reflects more energy than the equivalent prototype due to the reduced relative wave energy dissipation (Wilson and Cross 1972, Hughes 1993).

In the present work both methodologies proposed by Jensen and Klinting (1983) and Burcharth et al. (1999) are applied and compared. Jensen and Klinting (1983) started from the assumption that the hydraulic gradient, expressed by Forchheimer equation and function of the Reynolds number, has to be identical between the model and prototype to assure a correct similitude. This can be obtained by using larger stones in the laboratory model than those whose diameter has been calculated according to the Froude’s law. This approach presents a large uncertainty related to the assessment of the velocity field in breakwater. In fact the variation in flow velocity into the structure is not taken into account.

Burcharth et al. (1999) outlined the drawbacks of the methodology proposed by Jensen and Klinting (1983) and started from the knowledge of the wave induced pore pressure distribution. This let to estimate the flow field that is necessary to choose realistic flow velocities to be used in the scaling procedure. Finally the characteristic pore velocity is calculated as the average value in the most affected area of the rubble mound slope.

Experimental Setup
The structure object of study is a caisson with an internal rubble mound and can be regarded as a trade-off between a completely impermeable vertical quay and a rock sloping structure. This kind of quay was proposed to be built in the new commercial harbour in Molfetta, Italy, so the geometry used in the physical experiments reproduced the prototype conditions delivered by the designers of the Molfetta harbour. Figure 2 shows the cross section of the tested quay (dimensions in prototype scale units of m).
The so-called CIEMito and CIEM facilities at LIM/CIIRC-UPC were used to carry out the experiments at small and large scale respectively. Regular and irregular waves are tested. The present work describes the results for the regular wave experiments to be compared with Matteotti’s experiments. The CIEMito flume is 18 m long, 0.38 m wide and 0.56 m high and is equipped with a piston paddle capable to generate waves up to 0.28m wave heights and wave periods up to 2 sec (Figure 3). The scale used for the test was 1:33.

The CIEM flume (Canal d’Investigació i Experimentació Marítima) is 100 m long, 3 m wide and 5 m high (Figure 4) and has a wedge type paddle, that allows waves to be generated up to 1.5 m wave heights. The scale used for the test was 1:4.
Physical model experiments with regular waves were carried out in both facilities. Each incident regular wave train was 20 wave periods long. Wave motions were measured in both flumes by means of resistive wave gauges, with accuracy of 1 mm: an array of three sensors has been positioned in front of the caisson in order to compute incident and reflected wave components; two wave gauges more have been also displaced closed to the wave paddle to measure and check the wave generation. Depending on the scale, more sensors have been installed along flumes for further controls. Figure 5 shows a snapshot of the models in both flumes.

Two different values for the nominal diameter, $D_{n50}$, of the bulk-placed material were tested at each model scale, to investigate its influence on the wave reflection. For each scale, one value of $D_{n50}$ corresponds to the prototype one that has been geometrically scaled following the Froude’s law; the other one has been used to investigate the effects of the nominal diameter on the reflection at the same model scale.

The methodology contained in the Rock Manual (2007) has been used to assess the size and mass distribution of the armour stone grading in prototype, following the European standard EN 13383. Starting from the design condition of this structure that foresees the use of armour stones in the prototype with weight between 50 kg and 1000 kg, the value of $M_{50}$ has been assessed, where $M_{50}$ is the mass of the theoretical block for which half of the mass of the sample is lighter. The nominal diameter, $D_{n50}$, has been calculated from $M_{50}$ resulting equal to 61.90 cm. The final armour grading width, $D_{n85}/D_{n15}$, was about 1.6 (wide gradation).
In the present work the methodology proposed by Burcharth et al. (1999) has been applied to calculate a corrected value for the stone nominal diameter in small scale (1:33). It has been also verified applying the procedure of Jensen and Klinting, giving results of the same order of magnitude. Starting from the design value of $D_{n50}$ equal to 61.9 cm in prototype scale, the corrected nominal diameter for the small scale has been calculated, resulting equal to 80.5 cm (dimensions in prototype scale). Thus 80.5 cm (2.4 cm at 1:33 geometrical scale) represents the nominal diameter of the rubble mound when the scale effects have been already treated following the methodology presented by Burcharth et al. (1999). The value of $D_{n50}=1.9$ cm at small scale corresponds to the diameter scaled geometrically following the Froude’s law and not applying any correction for the scale effects. Furthermore the value of 58.4 cm (14.6 cm at 1:4 model scale) for diameter of the rubble mound at large scale was modelled in order to analyse the influence of the diameter of the bulk-placed material for large scale model tests as well as for the small scale tests. The choice of such value for $D_{n50}$ depended on the material available for the experiments at that time.

Once the nominal diameters were defined, the mass distribution for standard grading as reported in the Rock Manual (2007) for quarry rock stones has been used to select the stone size respecting the grading for both model scales. Table 1 reports the experimental hydraulic boundary conditions, wave height $H_{\text{regular}}$ and wave mean period $T_m$ expressed in prototype scale, the values of nominal diameter $D_{n50}$ that have been considered and the number of test for each model scale.

Table 1. Experimental test setup.

<table>
<thead>
<tr>
<th>Conditions in prototype scale</th>
<th>Model scale</th>
</tr>
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<tbody>
<tr>
<td>Scale</td>
<td># tests</td>
</tr>
<tr>
<td>1:33</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>1.35</td>
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<tr>
<td></td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>1.80</td>
</tr>
<tr>
<td>1:4</td>
<td>24</td>
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<td>24</td>
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<td>1.35</td>
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*corresponding to the design conditions in prototype.

As already mentioned above, the results of the physical model campaign described in the present work have been compared with those from Matteotti (1991). Matteotti carried out experiments with regular waves at 1:20 model scale. Table 2 reports a comparison between the model scale, stone weight, wave steepness ($H_{\text{regular}}/L$) and relative chamber size ($I/L$) between with Matteotti, where $I$ is the chamber width and $L$ is the wave length calculated in deep water conditions. It can be noticed that the physical tests conducted at LIM-CIIRC/UPC present hydraulic conditions and structural properties similar or in the same range of the Matteotti’s ones.

Table 2. Comparison between Matteotti’s and LIM-CIIRC/UPC test conditions.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Model scale</td>
<td>1:20</td>
<td>1:4, 1:33</td>
</tr>
<tr>
<td>Stone weight (kg)</td>
<td>500</td>
<td>50-1000</td>
</tr>
<tr>
<td>$H_{\text{regular}}/L$ (-)</td>
<td>0.006±0.06</td>
<td>0.007±0.043</td>
</tr>
<tr>
<td>$I/L$ (-)</td>
<td>0.05±0.25</td>
<td>0.033±0.14</td>
</tr>
</tbody>
</table>

Results

The spectral Mansard & Funke method (1980) can produce unreliable results for monochromatic wave trains. Therefore both Mansard & Funke (1980) and Goda & Suzuki (1976) methods to calculate the reflection coefficient $C_r$ have been used and an average values using both methods have been calculated. Figure 6 shows the variability of $C_r$ with the wave period $T$. 
Both small and large scale test results are plotted in comparison with those given in the Matteotti’s work. The trend of the variation of the reflection coefficient is in agreement with Matteotti. The reflection is governed mainly by the wave period, as expected. The greatest values of $C_r$ are obtained for the highest wave periods, in agreement with the results from Faraci et al. (2012). The highest reflection coefficient can be up to 40% larger than the smallest one for the same wave height but varying the wave periods.

![Figure 6. Reflection coefficient vs wave period](image)

The large scale tests led in general to smaller values of wave reflection than Matteotti’s ones. The small scale experiments give results larger than Matteotti’s ones. This appears consistent if considering that the scale used by Matteotti (1:20) is between the CIEMito and CIEM scale.

![Figure 7. Reflection coefficient vs wave steepness](image)
Furthermore, a smaller nominal diameter leads to a higher reflection. This is confirmed by Altomare et al (2013, in press) where the authors find out a relationship between the main variables responsible of the phenomena and the reflection coefficient. But the same nominal diameter gives different results between small and large scale, with higher values of \( C_r \) at small scale than at large scale.

Figure 7 plots the variation of the reflection coefficient depending on the deep water wave steepness, defined as the ratio between the incident wave height \( H_{\text{regular}} \) and the wave length \( L \) in deep water conditions (calculated using the mean wave period \( T_m \)). Higher wave steepness causes larger wave energy dissipations and less reflection in agreement with Suh et al (2006) that found that increasing wave steepness leads to less reflection and Faraci et al (2012) who confirmed those results.

The dependence on the wave height does not seem very important if compared with the wave period, in agreement with the Faraci et al. (2012) and Altomare et al (2013) results. The differences in the wave height affect slightly the response for the same wave period, leading to variations of \( C_r \) of about 8-10%. Figure 8 shows the variation of the reflection coefficient with the wave period for different wave height values (prototype scale). Noteworthy differences appear only for the highest value of \( H_{\text{regular}} \), 1.80m in prototype.

![Figure 8. Reflection coefficient vs wave period for different wave height values](image)

**Conclusions**

Vertical walls are largely used as berthing structures or quays in harbor basins. Such kind of structure is generally preferred because of its relatively small footprint but their use can lead to very high wave oscillations inside the harbor. Therefore the research of the last decades has been focused on finding a compromise between vertical structures and less reflective solutions.

The present work has described the reflection analysis for a particular type of low-reflection vertical quay where the upper part of the wall that is exposed to the waves is replaced by an open chamber with rubble mound inside.

The reflection of this structure is mainly related with the energy dissipation of the waves breaking on the rubble mound. The energy dissipation is governed by the turbulent flows into the voids among the rubble mound units; if the Froude’s law is followed to scale the material, the viscosity is not proper treated and scale effects can influence the response of the structure especially at small model scales. Therefore the stone size has to be chosen properly to eliminate any laminar (viscous-dominant) flows in the voids, since the flows are fully turbulent in prototype scale.

Physical model tests were conducted in the Maritime Engineering Laboratory (LIM/CiIRC-UPC) of the Universitat Politècnica de Catalunya, in Barcelona (Spain) to study the response of the quay in a wide range of wave heights and periods. The experiments were carried out at both small and large scale to assess the presence of scale effects.

The work is mainly focused on the effects due to the model scale, the nominal diameter of the rubble mound and the hydraulic boundary conditions. The approach proposed by Burcharoth et al (1999) has
been used to treat the scale effects calculating a corrected stone nominal diameter. Finally two diameters have been used for each scale.

The analysis of the results shows that scaling the nominal diameter just following the Froude’s law lead to significant differences in the results between large and small scaled models. The results have been compared with the experiments carried out by Matteotti (1991). The results of the large scale tests show a different behaviour, leading in general to smaller values of the reflection coefficient than in Matteotti. The small scale tests show results closer to Matteotti ones, especially when no correction for the stone diameter has applied. Using the Burcharth et al. (1999) method, the results at small scale approach the ones at the large model scale, even though they are still far from the large scale values. This can be due on the drawbacks of the methodology itself, since the calculation strongly depends on the pore velocity and this characteristic pore velocity is calculated as just the average value in the most affected area of the rubble mound slope.

The experimental campaign underlines that the model scale affects the response of the structure because scaling by following the Froude’s law leads to the introduction of viscous forces not present at prototype scale. Thus small scales generally overestimate the wave reflection of porous structures. Physical experiments in large model facilities help to estimate the magnitude of the scale effects, because at large scales the response of the structure can be assumed close to the prototype one. The paper represents a preliminary analysis of such effects on wave reflections. Further analysis should be done, for example characterizing the rubble mound permeability for different scales and the response of the structure to irregular wave trains.

**Acknowledgements**

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**References**


