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An experimental study on scale effects in wave reflection of low-reflective quay walls with internal rubble mound for regular and random waves

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ABSTRACT

Physical model tests at small and large scales have been carried out to assess the influence of the model scale on the wave reflection of low-reflective quay walls consisting in prefabricated caissons with frontal openings and internal rubble mounds. Both monochromatic and random waves have been modeled. The experiments have been carried out in the small and large scale facilities at Laboratori d'Enginyeria Maritima of the Universitat Politècnica de Catalunya, in Barcelona. The approach described in Burcharth et al. (1999) for the treatment of scale effects for porous flows has been applied to scale down the nominal diameter of the grain material at small scale (1:33). The results with and without correction of scale effects have been compared with large scale ones (1:4). However, there is not plenty of literature on wave reflection of such kind of structure: Matteotti (1991) and Faraci et al. (2012) carried out physical model tests for configurations similar to the one analyzed in the present work. Altomare et al. (2013a) applied an innovative data-driven modeling technique to analyze the relationship between wave reflection and hydraulic-geometrical parameter for random waves, basing the analysis on the results from small scale tests. A discussion on similarity or differences with the mentioned studies has been conducted confirming that the approach proposed by Burcharth et al. (1999) led to more accurate results. The main aim of the present work is to provide a reliable description of the behavior of such structure exposed to the wave actions, considered remarkable since a similar quay can be implemented as berthing structure inside the harbors. The paper underlines the importance of the treatment of the scale effects in such kind of modeling and the choice of a proper model scale. Finally a new equation to evaluate the reflection coefficient of such kind of structures is proposed.

1. Introduction

Physical modeling plays an important role in hydraulics engineering to insight into phenomena not yet or properly described and understood. Despite the continuous developments in numerical models, laboratory tests still present several advantages, strengthened by the latest improvements in the measurement techniques. Physical models allow obtaining measures for complicated phenomenon and extreme storm conditions otherwise difficult to obtain in the field, provide an immediate feedback on the physical processes studied, and represent the governing physical processes without simplifications or assumptions proper of theoretical and numerical approach. The results of laboratory tests can be used to verify theoretical results and to validate numerical and analytical models that will be used afterwards as predictive models for future scenarios. However physical models present some disadvantages or also drawbacks especially related to model and scale effects. In fact it can be demonstrated that a fully dynamic similarity cannot be achieved in scaled models. When a Froude law is applied, other forces, like the viscous ones, cannot be properly scaled. This leads in general to an overestimation of such forces that is higher as the model scale is smaller. Since physical models are often used to give response to practical problems, it becomes significant to remove the scale effects a priori (e.g. choosing a large enough model scale) or a posteriori (e.g. applying correction factors to the results). For all the aforementioned reasons, combining scale modeling in different facilities can provide important insights of the analyzed phenomenon and the influence of the model scale on the laboratory results.

The present work aims to give a contribution in the understanding of the influence of choice of the laboratory facility and consequent model scale focusing the attention on the wave reflection exerted by a particular type of low-reflective quay walls.

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1.1. Vertical low-reflective dike and quay walls

Quays over piles with absorbing rubble mound slopes can be used to enlarge or rebuild structures in the existing docks. This is becoming important since there is an increasing demand for big merchant ships with high tonnage capabilities and high draft. Generally the rubble mound assures low reflection in the port basins, very important for mooring and maneuvering but they lead to the construction of very wide superstructures that are not always possible due to the available spaces. The use of vertical walls as berthing structures is an alternative quite used in port areas: in fact this kind of solution represents a compromise between the simplicity of construction and the small covered area. Nevertheless vertical quay walls present the drawback of undesirable high wave reflection into the port areas.

A vertical solution cannot absorb or attenuate the wave incident energy and reflects almost the all amount of incident wave energy increasing the agitation within the dock that unfavorably can lead to increased efforts on the structures and difficult operating conditions. Low-reflecting quays sort out the reflection in port areas by means of porous or open structures that dissipate a part of the incident wave energy. Thereby several different vertical dissipative solutions have been proposed during the last decades as result of research studies from all over the world. Jarlan (1961) was the first to investigate the main factors governing the wave reflection of perforated walls which consist in breakwaters with an internal dissipative chamber and a solid back wall; Marks and Jarlan (1968) analyzed the effectiveness of a perforated breakwater for different sea states; Ijima et al. (1976) studied permeable seawalls where WAROCK elements are used; Shiraishi et al. (1976) studied the efficiency of quay walls with wave absorber IGLOO blocks; Suh et al. (2001) analyzed the effects of the chamber width on the wave reflection for irregular waves; Berenguer (2003) presented the BARA blocks as alternative to realize vertical absorbing dikes; Li et al. (2003) carried out experiments on reflection due to obliquely incident waves on perforated walls; Huang (2007) investigated the wave reflection and transmission of regular waves at surface-pitching slotted barriers both physically and analytically; Garrido et al. (2010) and Gonzalez-Escriva and Medina (2012) present a new low reflective quay wall based on a multi-cell circuit scheme as described in Medina et al. (2010); Taveira Pinto et al. (2011) investigated the wave reflection of quay walls whose structure consists in NOREF blocks adjusted in a way to allow a good hydraulic or structural efficiency.

Several efforts have also been made in analytical investigation and numerical modeling for predicting the wave reflection coefficient: Kondo (1979) developed an analytical model to predict the reflection of perforated caisson breakwater based on shallow water theory; Kakuno et al. (1992) studied mechanics of the interactions of waves with slit-type breakwaters; Bennett et al. (1992) calculated the reflection properties of wave-screen breakwaters; Fugazza and Natale (1992) proposed design formulas to be used for the optimized hydraulic design of Jarlan-type breakwaters; Suh et al. (2001) extended, using an average-frequency method, the model of Suh and Park (1995) that was developed to predict the reflection coefficients of perforated caissons on rubble mound foundations and oblique wave attack; Takahashi et al. (2002) described the application of VOF numerical techniques to assess the reflection performance of perforate wall caissons; Suh et al. (2006) compared the experimental data of Park et al. (1993) with Suh and Park's (1995) numerical model results; Chen et al. (2006) reported on numerical solutions for the wave reflection of submerged porous structures in front of the impermeable vertical breakwaters; Garrido (2011) proposed new formulas to estimate the reflection coefficient for single- and double-perforated chambers in Jarlan-type breakwaters valid for regular and random waves; and Castro et al. (2011) investigated the reflection process at submerged breakwaters by means of an artificial neural network (ANN) model, proposing that as virtual laboratory able to evaluate the reflection coefficient without the need to carry out physical model tests.

The present work deals with physical model experiments on wave reflection of a low-reflective vertical quay at large and small model scale. The quay consists in a prefabricated caisson with internal rubble mound. The rubble mound is exposed to the wave action because the upper part of the caisson presents a frontal opening. The turbulent flows triggered into the rubble mound are the main responsible of the dissipation of the incident wave energy. A scheme of the structure is depicted in Fig. 1.

Despite this kind of solution could guarantee the desirable wave condition in the harbor basin and reduce the footprint of the mooring structures, an exhaustive literature is not available yet. Matteotti (1991) carried out physical tests with monochromatic waves, showing the performance of this kind of solution in reducing wave reflection. Faraci et al. (2012) studied how the changes in rubble mound slope can affect the reflection coefficients and compared the experimental results with analytical model ones available in literature.

Both works of Matteotti (1991) and Faraci et al. (2012) consist in small scale physical model tests. The main concern is that in general there is more reflection than in large scale models or prototype for geometrically scaled physical models of porous structures, due to the low armor unit Reynolds number as described by Burcharth et al. (1999). In fact the dissipation of wave energy and the consequent reduction of wave reflection are mainly due to the turbulent flows that are triggered into the voids of the rubble mound, but these flows can be laminar instead of turbulent at small scales, thus leading to smaller dissipation than in large scale model and so in the prototype. The treatment of scale effects deserves further investigation for such kind of low-reflective quay walls.

Large and small scale tests have been carried out in the Laboratori d'Enginyieria Maritima of the Universitat Politecnica de Catalunya (LIM/CIIRC-UPC), in Barcelona, Spain. The structure that was modeled is representative of a real solution proposed for a Mediterranean harbor. The main objective of the experimental campaign was to study the response of the quay in a range of wave heights and periods and to compare the results of small and large tests, analyzing the influence of scale effects. Altomare et al. (2013a) applied the hybrid evolutionary modeling technique described in Giustolisi and Savic (2006) to find a simple and easily interpretable mathematical model that expresses the reflection coefficient variation for irregular waves as function of the main hydraulic and geometrical parameters, starting from the results of small scale model experiments. For regular waves, the effects of the rubble mound and scale effects on the structural response are reported in Altomare et al. (2013b).

The present work aims to extend the latest mentioned study to random waves, to analyze the influence of scale effects and the applicability of the Burcharth et al. (1999) size material modification and to study the differences in wave reflection between irregular and regular waves, comparing the results with ones from Matteotti (1991) and Faraci et al. (2012).

2. Wave reflection

The wave reflection induced by a coastal structure is generally quantified by the reflection coefficient, defined as follows:

$$C_r = \sqrt{\frac{E_r}{E_i}} = \frac{H_r}{Hi} \quad (1)$$

where H_r and H_i are the reflected and incident wave heights, respectively, and E_r and E_i are the related wave energies. The reflection coefficient can vary between 0 and 1, where 1 defines total wave reflection, and depends on the sea state, the structural properties and the geometrical layout of the quay, sea dike or breakwater. For example, sloping dikes behave differently than vertical structures, and the structural response changes if the structure is overtopped or not.