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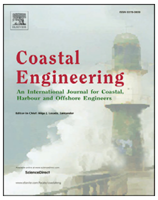

Experimental study of the hydraulic efficiency of a novel perforated-wall caisson concept, the LOWREB

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ABSTRACT

A novel perforated-wall caisson concept, the so-called LOW REflection Breakwater (LOWREB), based on a three-chamber perforated-wall and inner weirs, is under development in the University of Porto – Faculty of Engineering, Portugal. Physical model tests, carried out in the wave basin of the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division, Civil Engineering Department, have been used to study the hydraulic processes related to wave reflection. The physical model was built to a Froude scale of 1:50. Test conditions covered two water levels and irregular waves at three significant wave heights (3.0, 4.0 and 5.0 m) and three peak wave periods (10, 14 and 18s). Three models of varying porosity, and vertical slots' arrangements were tested under the same hydrodynamic conditions to study how these affect the LOWREB performance, namely how these affect the wave reflection from the structure, as compared to a plain caisson tested under the same conditions. The experimental study demonstrates that the LOWREB caisson is a valid concept for marine structures, namely harbour breakwaters, because of its wave energy dissipation capacity, for which the inner weirs were found to play a major role. Results indicate that the hydraulic efficiency of the LOWREB caisson increases with wave height for the lower water level, and decreases with it for the highest. Greater efficiency with respect to wave reflection was accomplished with the highest water level.

1. Introduction

The efficiency of port operations is often related to the wave conditions inside the harbour basin. The harbour layout and the characteristics of the breakwaters and berthing structures with regard to wave reflection have an important influence on those conditions. This explains why vertical perforated/slotted structures are becoming more popular, not only as external caisson breakwaters (see, e.g., Sankarbabu et al., 2008; Liu et al., 2012), but also as lower reflective quay walls (see, e.g., Taveira-Pinto et al., 2011; Altomare and Gironella, 2014), when the use of rubble-mound breakwaters and gentle slopes within the harbour basin are unfeasible due to space limitations or physical, economical or technical constraints. Among the advantages of the partially perforated-wall caissons is their capability to absorb part of the wave energy within the chambers or openings in the exposed wall, partly overcoming specific limitations of vertical-wall caissons (see, e.g., Oumeraci et al., 2001): large reflections, forces, overtopping and toe scour.

In fact, the main purpose of a breakwater is to reduce wave action at the shore and to protect harbour facilities and infrastructures, whilst improving the conditions for ships' manoeuvring and the safety of ships inside the port. To that extend, those structures shall ensure that reflection is minimized in the vicinity and within the harbour basin, and that the amount of offshore wave energy that reaches the inner harbour areas is minimal. On the other hand, low reflection quay walls prevent multi-reflections inside the harbour basin that could otherwise locally increase wave agitation levels and negatively affect the efficiency of port terminals. Hence, one important challenge is to find ways to limit the (large) wave reflection of vertical impermeable structures and to design structures able to absorb or dissipate a significant amount of the incident wave energy with a favourable construction- and cost-wise compromise, and still maintaining low spatial requirements (small footprint).

Jarlan (1961) proposed the first concept of a perforated caisson breakwater with energy dissipating chambers. The so-called Jarlan-type (Jarlan, 1961) breakwater caisson had its first application in 1966 in Comeau Bay, Canada. In the coming years, several theoretical and experimental research studies have been carried out in order to analyse

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the hydraulic behaviour of this type of structures, namely with regards to wave reflection or wave energy dissipation, and the stability increase by the reduction of the wave forces acting on the structure. Over the years, many have been built (see, e.g., Taveira-Pinto et al., 2011; Theocharis et al., 2011; Huang et al., 2011).

Proof of concept was accomplished by the experimental research of Jarlan (1961) and Marks and Jarlan (1968). In their studies, the authors showed that the wave reflection is effectively reduced by using a perforated-wall on the exposed side of a marine structure.

Kondo (1979) developed an analytical model to estimate the reflection coefficient of a perforated caisson with one or two wave chambers, based on shallow water linear wave theory and concluded that the two chambered caisson has a better hydraulic efficiency with regard to wave reflection. Fugazza and Natale (1992), concluded otherwise, i.e. concluded that having a single wave chamber could provide the largest reduction of wave reflection in the range of practical applications, by using their analytical model based on potential flow theory and experimental data. Also relevant is the apparent link between the wave reflection coefficient and the relative chamber width. In that instance, it is found that the reflection coefficient reaches its minimum value as the chamber width is about a quarter of the incident wavelength (see, e.g., Zhu and Chwang, 2001). Huang et al. (2011) concluded that small wave reflection coefficients can be obtained for multiple perforated-walls over a wide range of wave frequencies.

Using the Galerkin-eigen function technique, Suh and Park (1995) developed an analytical model able to predict the reflection coefficient from a perforated-wall caisson mounted on a rubble mound foundation (composite breakwater) for obliquely incident regular waves, which showed a reasonable agreement with available experimental data. Suh and Park (1995) have also verified that for obliquely incident waves, the minimum reflection coefficient occurs for a relationship between the chamber width and the incident wavelength that depends on the wave approach angle. In order to predict the reflection of irregular waves normally incident upon a perforated-wall caisson breakwaters, Suh et al. (2001) extended the model from Suh and Park (1995) using a frequency-averaged method. More recent work by Suh et al. (2006) further extended the application of the model to partially perforated-wall caissons with one wave chamber and verified it with 2D experimental results.

For most of the available studies, the water depths inside and outside the perforated structure are the same; however, it is found that the use of partially perforated wall caissons (see, e.g., Suh et al., 2006) or perforated structures with a rock filled core (e.g., Isaacson et al., 2000; Liu et al., 2007) results in an improvement of their structural stability as compared to fully perforated ones, due to the extra weight added to the lower part of the caisson. For a partially perforated-wall, single-chambered caisson breakwater, Tanimoto and Yoshimoto (1982) concluded that the wave reflection coefficient reached a minimum with a chamber width to internal wave length ratio ranging from 0.15 to 0.20 for a slot depth to water depth ratio in the range of 0.83 to 0.33.

Lee and Shin (2014) investigated the wave reflection from single- and double-chambered partially perforated-wall caissons in a wave flume, with varying chamber width, number of slots, and porosity of the vertical wall. The authors concluded that for the same chamber width, the double-chambered model with a porosity of the middle wall smaller than of the front wall, leads to a larger wave reflection drop, as compared to the single-chambered model. On the other hand, when the front wall porosity was lower than the middle wall porosity, the reflection coefficient in the double chamber cases was not improved. In addition, for a single chambered model, the reflection coefficient reduced with the reduction of the front wall porosity if it were between 20 and 60%.

It is usual to place a cover plate on top of the perforated caisson breakwater so to enable other uses. Huang et al. (2011) reviewed previous experimental and numerical studies on this topic, to conclude that the reflection coefficient of a perforated structure increases when this cover plate is placed on top of the structure, and that it gradually decreases with increasing spacing between the top cover plate and the still water level. In addition, the reflection coefficient from a perforated structure with a cover plate is about 1.0–1.3 times the one without a cover plate under regular waves with $S_c/H = 0.33–2.0$, and 1.0–1.2 times under irregular waves with $S_c/H_s = 0.5–2.0$, where S_c is the spacing between the top cover and the still water level and H_s is the significant wave height (no slamming impact forces were observed on the top cover plate). Further conclusions by Huang et al. (2011) indicate that the reflection coefficients are generally larger under irregular waves than regular ones for equivalent conditions, and that oblique waves could result in larger wave reflection than normally incident waves.

Many of the researches on perforated marine structures focused on the impact on wave reflection reduction; nonetheless, part of it also demonstrates that the wave (pressure) forces may also be reduced through the perforated-walls and wave chambers. Liu et al. (2007) studied the wave-structure interaction on a caisson breakwater with a perforated front wall, a solid back wall and an intermediate wave absorbing chamber with a two-layer rock-filled core, to conclude that the rock fill reduces wave loads on the structure but may increase the reflection coefficient, as compared to the original Jarlan-type breakwater without rock fill. Özgür Kirca and Sedat Kabdaşli (2009) carried out an experiment on a new type of partially perforated-wall caisson with a chamber divided by a horizontal impermeable plate. The authors found that the dimensionless wave forces and wave moments can be reduced by up to 35–40% under both regular and irregular waves and that the structure performance increases with decreasing wave length.

Most of the research available on the performance of perforated-wall caisson breakwaters is based on physical model testing results or analytical models based results, for instance, based on the potential flow theory or the Galerkin-eigen function. Semi-empirical models based on neural networks (multi-parametric nonlinear regression methods) were also developed and successfully validated with experimental data (see, e.g., Garrido and Medina, 2012). In recent decades, there was a remarkable evolution in the application of advanced numerical models to an extensive range of complex hydrodynamic phenomena in the field of coastal engineering, which makes the study of, for example, the interaction of waves with perforated and permeable structures possible to a reasonable level of detail and accuracy. The models based on the Navier–Stokes equations, either Eulerian (see, e.g., Higuera et al., 2014a, 2014b; and Vanneste and Troch, 2015) or Lagrangean (see, e.g., Meringolo et al., 2015), have only a few simplifications (*e.g.* treatment of aerated turbulent flow) in the translation of the problem physics. Main limitations that prevent their wider use in practical/engineering applications relate with the computational time and, very often, the lack of readily available data for model calibration and validation.

The present paper presents the proof of concept of a novel perforated structure, the LOW REflection Breakwater (LOWREB). This concept was initially presented by Pinto (2012), but hydraulic testing was only conducted at a later time. The results of that testing presented herein focus on the analysis of the hydraulic performance of LOWREB with respect to wave reflection, for different hydrodynamic conditions (i.e. water levels, wave-heights, and wave periods) and different structural configurations based on physical model testing. Its use is justified in this early stage of concept development, given that the nature of the hydrodynamic interaction between the incident waves and the perforated-walls and internal weirs of the LOWREB caisson breakwater is complex and non-linear, involving wave breaking, flow separation, intense turbulence and flow aeration, and wave overtopping.

2. The LOW REflection Breakwater (LOWREB)

2.1. *The LOWREB concept*

Jarlan-type (Jarlan, 1961) breakwater caisson consists of one or more dissipative wave chambers having an exposed perforated-wall(s) and a rear impervious wall. The incident wave energy is partly reflected at the front perforated-wall and partly transmitted through the openings into