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Hybrid modeling of pore pressure damping in rubble mound breakwaters

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ABSTRACT

Rubble mound breakwaters dissipate the incident energy of waves using friction through different layers of porous media. The porosity of these layers decreases from the external slope to the core. The flow through the breakwater induces high internal pore pressures, which might cause breakwater failures. Indeed, high pressure in the core can provoke failure of the armor layer and geotechnical instability. The experimental study of the pressure evolution inside a breakwater is tough and the existing semi-empirical approximations diverge. Consequently, the analysis of pore pressure damping through a porous media is still an open task. However, nowadays there are powerful numerical models that can be used with that aim. Therefore, pressure evolution inside the breakwaters is analyzed in this work by means of a combination of experimental, numerical and previously existing semi-empirical formulations. Hence, a hybrid modeling of pore pressure damping in rubble mound breakwaters is presented here, taking advantage of the strengths of each approach. After a validation of the numerical modeling using the experimental data, the numerical model is used to analyze the pressure field inside the breakwater. Numerical and physical model results are also compared with existing semi-empirical formulae.

1. Introduction

The main objective of rubble mound breakwaters is to protect the coastal area from wave loads by dissipating part of the energy of the incident waves. The analysis of the pore pressure inside a rubble mound is highly important because it affects the processes acting on the interaction of the porous structure with waves, such as reflection, transmission, dissipation, overtopping and run-up (de Groot et al., 1994). The current breakwater design methods do not consider the pressure field inside the structure body. Harlow (1980) studied a series of rubble mound breakwater failures and concluded that most of them occurred due to enormous pressures inside the breakwater core, for instance, the Sines breakwater in Portugal (Zwamborn, 1979). Harlow (1980) stated that the evaluation of the pressure inside the breakwater is necessary for a stable, safe breakwater design.

One of the most important processes to be considered when studying pressure inside a breakwater is the flow attenuation caused by the friction through the porous media. The free surface elevation and the pressure oscillation amplitude inside a breakwater are tightly related. Biesel (1950) developed a theoretical linear relationship between the wave height and the pressure oscillation at a determined level below the still water level (SWL). Many authors have studied the pressure field inside a rubble mound breakwater and observed the influence of different variables on that pressure field. According to Hall (1991) and Muttray et al. (1995), free surface elevation and pressure oscillation amplitude decrease exponentially inside the porous media in the direction of wave propagation. Moreover, free surface elevation, pressure oscillation inside the breakwater and set-up increase with wave height, wave period and breakwater slope (Hall, 1991; Oumeraci and Partenscky, 1990). However, they decrease when increasing core permeability and thickness of the filter layer (Hall, 1991).

The damping rate of the pressure oscillation through the porous media has also been studied. Burger et al. (1988) and Troch et al. (1996) hold that it increases with wave steepness, and Oumeraci and Partenscky (1990) and Troch et al. (1996) state that it decreases as the distance to the SWL increases. Vanneste and Troch (2012) considered the influence of the wave height and the wave length on the pressure damping separately and they concluded that the damping rate increased by increasing the wave length (for a constant wave height) and also by increasing the wave height (for a constant wave period). Oumeraci and Partenscky (1990) proposed an approach for the damping of the pressure oscillation amplitude in a horizontal direction inside the breakwater, which has been validated against field data. Vanneste and Troch (2012) experimentally defined two different zones for this pressure damping under non-breaking and non-overtopping conditions. The pore pressure experimental analysis is essential, but it faces the usual limitations of physical modeling, such as scale effects, reduced sea state selection and constructive problems in reproducing complex geometries, as well as the difficulty of installing pressure gauges in the breakwater core. In addition, physical modeling has high economic and time costs, which makes numerical modeling a very important tool in coastal

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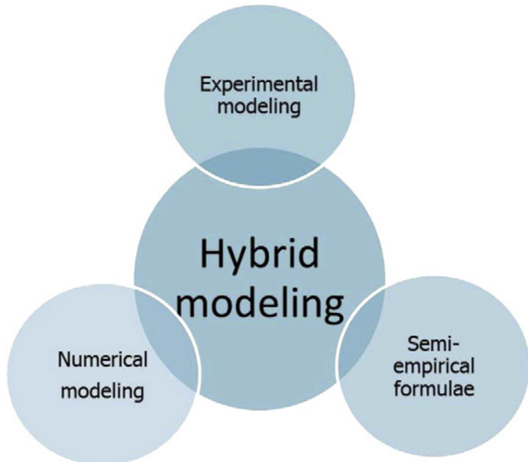

Fig. 1. Hybrid modeling scheme.

engineering. Recently, attempts have been done to analyze the detailed hydrodynamics of block mound structures by means of numerical models, such as Cavallaro et al. (2012), Dentale et al. (2014) or Latham et al. (2013). However, numerical models need to be experimentally calibrated and validated to become reliable tools. In addition, experimental testing can provide physical parameters to feed numerical models, such as accurate geometric information, that significantly improve the numerical modeling. In this paper, an example of hybrid modeling retrofitting between experimental, semi-empirical and numerical modeling is shown to predict pore pressure damping inside a rubble mound breakwater; see Fig. 1.

The objective of this paper is to analyze pore pressure attenuation inside a rubble mound breakwater combining different approaches. In Section 2, the experimental setup is described, and in Section 3, the numerical model used and its setup are described; numerical model validation is shown in Section 4. In Section 5, breakwater bottom pressure is analyzed, and in Section 6, pressure in vertical sections and at interfaces between layers is analyzed. Section 7 compares the numerical and experimental results with semi-empirical formulae, and finally, in Section 8, some conclusions are presented.

2. Experimental setup

Following the hybrid methodology introduced and to gain a better understanding of the processes under investigation, a set of experiments on wave pressure attenuation in breakwaters was used, described in Cantelmo et al. (2010). The objectives of the experimental work were the in depth analysis of the pore pressure inside the core, the improvement of numerical models using a high quality data set for their validation and the comparison of the physical results with existing semi-empirical formulae. The laboratory experiments were performed in the wave flume of HR Wallingford; see Fig. 2. The flume is 45 m long (41 m from the paddle to the end of the flume), 1.2 m wide and 1.7 m high. The flume bed slope in the inclined portion was 1:30. The sidewalls of the testing area are made of glass and concrete. A piston-type wave maker with active absorption was used for wave generation. At the rear end of the wave flume, a dissipative beach made of foam was placed to absorb the transmitted waves.

The modeled rubble mound breakwater consisted of a core, an underlayer and an armor layer, scaled at 1:25; see Fig. 3. The slope of the landward and seaward sides of the breakwater was 2:1.

The toe of the breakwater is located 35.097 m from the beginning of the flume, and the breakwater ends 38.487 m from the beginning of the flume. The breakwater was composed of natural rocks placed in two layers over a core. A summary of the characteristics of the breakwater can be seen in Table 1. The unusually large size of the rocks in the armor layer makes the breakwater a singular structure.

Ten wave gauges were placed along the wave flume. The location of the wave gauges is described in Table 2 and Fig. 2. These gauges were used to verify the capability of the numerical model to simulate the sea states tested in the physical model. The first three wave gauges were used to calculate the incident and reflected waves following Mansard and Funke (1980). For that reason the position of these gauges was variable as a function of the period of each wave case.

Twenty pressure gauges were installed along the wave flume for the measurement of the pressure induced by the wave action. The relative measurement error of the pressure gauges is of 0.1%, which means a total error of 0.00035 bars. Three of them were located on the flume bottom in front of the breakwater and the others below and inside the structure body (see Fig. 4 and Table 3), enabling a detailed analysis of the pressure field inside the breakwater. The measurements of both free surface elevation and pressure were performed at a sampling frequency of 60 Hz. Additionally, some tests were sampled with a 1000 Hz frequency.

Although a wider range of water depths and sea states was experimentally tested, only the cases that are numerically reproduced within the scope of this study are herein described. Hence, the numerically reproduced tests were irregular wave trains at a water depth of 1.12 m. The range of significant wave heights varied between 0.10 m and 0.21 m, and the peak periods between 1.5 s and 4 s. These sea states are described in Table 4. Each test was a thousand times its peak period in length. Two independent sets of experiments were performed for the sea states in Table 4, with and without the breakwater. The objective of the tests carried out in absence of the structure was to create a database to afterwards verify the correct wave generation and propagation along the flume with the numerical model, without the influence of the breakwater in the problem.

3. Numerical model setup

To complete the investigation, the physical model tests were simulated numerically. In this study, the numerical modeling was performed using IH-2VOF (Lara et al., 2011), which is based in the model COBRAS-UC (Losada et al., 2008). See Liu et al. (1999) and Hsu et al. (2002) for

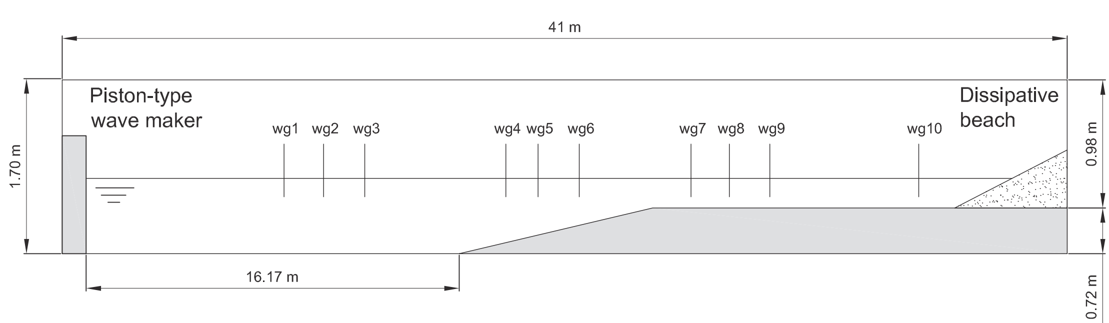

Fig. 2. Experimental wave flume geometry and wave gauges.