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Analysis of orthogonal wave reflection by a caisson with open front chamber filled with sloping rubble mound

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ABSTRACT

A new combined caisson, including an open window on the front wall and an internal rubble mound with a slope, has been proposed and used in Italy. This study presents a semi-analytical solution to estimate the wave absorbing performance of the new combined caisson with regard to orthogonal wave attack. The internal slope of the rubble mound is assumed to be a series of horizontal steps. Then the matched eigenfunction expansions are used to develop the semi-analytical solution. The square-root singularity of fluid velocity at the upper tip of the front submerged wall is incorporated into the solution to enhance the convergence of calculated results. The new semi-analytical solution is confirmed by an independently developed multi-domain boundary element method solution. Also the predictions of the semi-analytical solution agree reasonably well with experimental data. Based on both the calculations and the experimental data, some useful results are presented for practical engineering.

1. Introduction

The development of global trade and ship transportation often requires that the existing docks must be upgraded, consolidated or enlarged, in order to face effectively the increasing demand of people and freight traffic.

To this aim, quay over piles, having an absorbing slope below the structure, or perforated wall-caissons can be used to enlarge or restructure existing quays or to build new ones. As regards the wave energy dissipation within the harbor basin: (i) the absorbing slope behaves generally better (see for example Postma, 1989; Sunamura and Okazaki, 1996), but the overall structure requires a large horizontal space, which is not always available, due to construction problems or to other specific limitations; (ii) the perforated caissons are characterized by higher reflection coefficients if compared to absorbing slopes (see for example the experimental studies of Jarlan, 1961; Suh et al., 2001; Brossard et al., 2003 or the analytical–numerical investigations performed by Fugazza and Natale, 1992; Suh et al., 2001; Takashi et al., 2002), but may perform better in terms of total costs, construction time and maintenance, as well as space-saving. After the pioneeristic work of Jarlan (1961), several non-conventional structures have been proposed aiming at reducing reflection of incident waves. Examples are single or multiple vertical barriers or screens (Allsop, 1995), Jarlan-type structures filled with large diameter rocks (Isaacson et al., 2000), precast concrete units, consisting of a concrete base and piles placed on site and then filled with rocks (Requejo et al., 2002), or caissons with an absorbing porous structure replacing the perforated front wall (Zhu and Chwang, 2001). It is worth pointing out that all these studies including porous structures do not take into account the presence of a slope to absorb the incident waves.

A combination of quays over piles and Jarlan-type structures consists of a concrete caisson with large gaps and a porous slope inside. Indeed such a caisson joins the good performances of both the aforementioned structures as it does not require too much horizontal space and, due to its internal rubble mound, should reduce wave reflection. This caisson, hereinafter referred to as combined caisson, boasts some applications for harbor enlargements. For example, the Port of Siracusa (Italy), originally built by the ancient Greeks in the VIII century B.C., was recently interested by a growth plan in order to increase the touristic traffic. The harbor is located in a very large and shallow natural embayment, with a narrow inlet where, due to the extension and the orientation of the basin, the waves generated by the wind within the bay can be substantial and may affect the operations within the port. Moreover, the harbor basin is extremely important from an archeological point of view, thus not only the caissons to be used have to be suitable for reducing wave reflection, but also their width has to be limited, due to the constraints imposed in order to preserve the archeological findings onto the sea bottom. For these reasons the combined caissons seemed to be the most appropriate solution, joining the advantages of wave reflection control to a limited space (see Fig. 1). A similar application was recently designed to build a new harbor basin of the port of Piraeus, Greece. It consists of an innovative wave absorbing quay-wall made of a single

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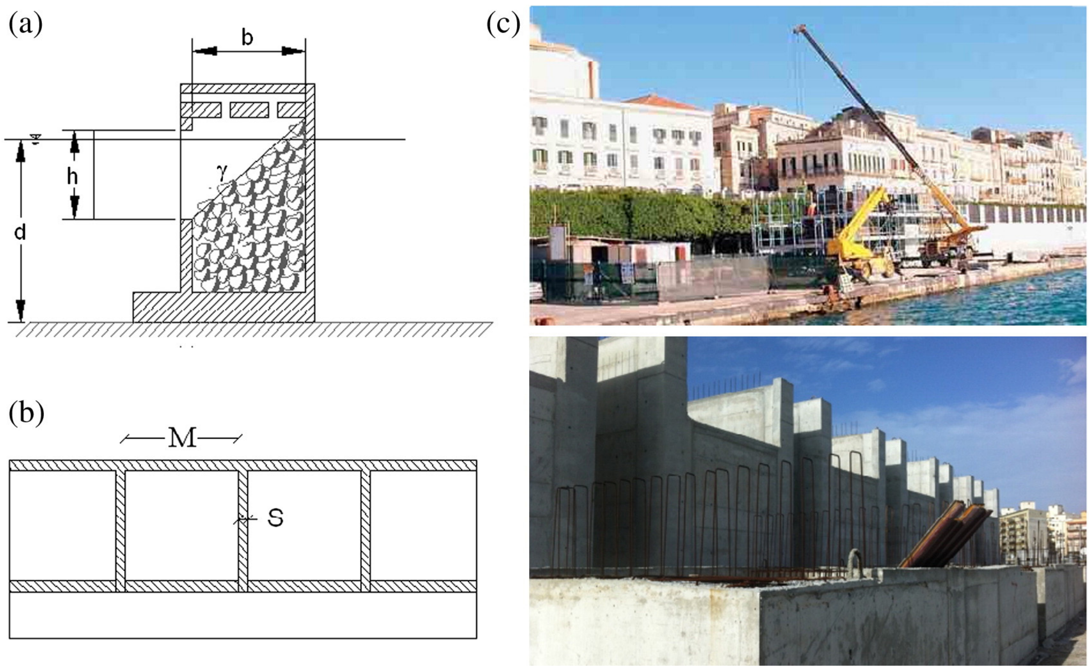

Fig. 1. Sketch of the combined caisson: (a) cross section; (b) plane view; (c) building of combined caissons in the Siracusa harbor.

partial wave chamber with limited height and depth above and below the water level containing a rock armored slope (Theocharis et al., 2011).

However, in spite of their breaking through importance, an exhaustive literature about such caissons and their reflection characteristics is not yet available. On the experimental point of view, recently Faraci et al. (2012) and Faraci et al. (accepted for publication) performed two laboratory campaigns focused on the acquisition of the reflection coefficients of combined caissons whose front opening and chamber width could be adjusted. They found that the reflection coefficient increases as the wave period increases, while a small reduction of the reflection coefficient occurs as the wave height increases. Theocharis et al. (2011) experimentally compared an antireflective wave chamber filled with a rock armored slope with alternative absorbing systems as well as with a conventional quay-wall with a solid front wall. They found that this caisson allows for a reduction of wave reflection of 20–30% with respect to other solutions. Altomare et al. (2012) studied the wave reflection of a low reflective vertical quay proposed by Matteotti (1991), where the upper part, exposed to the waves, is replaced by an open chamber with sloping rubble mound inside, paying attention to the slope porosity and the scale effects.

From the theoretical point of view, however, it must be stressed that most of the existing analytical solutions have been developed for perforated or slotted caissons with or without back walls (see Huang et al., 2011 for a detailed review), while to the authors' knowledge, combined caisson seems to be ignored. Wave interaction with permeable breakwaters has been tackled originally by Sollitt and Cross (1972) who considered a potential flow problem satisfied by an eigen series solution for a rectangular shaped breakwater. In the same wake, Madsen (1983) developed a theoretical solution for the reflection of linear shallow-water waves from a vertical porous wave absorber on a horizontal bottom. More recently, Liu and Li (2006) analyzed a Jarlan type breakwater filled with large diameter rock from the bottom to some distance under the still water level by means of the matched eigenfunction expansion method. However such analytical solutions can be useful only in the presence of rectangular shaped breakwaters. In the present work, limiting to the case of orthogonal wave attack, this approach will be adapted to the case of combined caisson, where the internal rubble mound has a sloping face. In particular a step approximation theory will be applied, based on the idea to discretize the domain into a finite number of strips of constant width where the boundary value problem has constant boundary conditions on its boundaries (Evans and Linton, 1994). Moreover, the solution will be compared with the multi-domain boundary element method (BEM) solution for wave reflection by porous structures developed by Liu et al. (2012), and with the experimental data of Faraci et al. (2012, accepted for publication). The paper is organized as follows: in Section 2 a dimensional analysis of the problem is proposed; in Section 3 the semi-analytical solution is derived; in Section 4 the experiments on combined caissons are summarized, in Section 5 the solution is validated through both multi-domain BEM approach and experimental data. Discussion and conclusions then end the paper.

2. Dimensional analysis

The wave reflection problem is held up on the following quantities:

- d water depth at the structure toe;
- H wave height;
- L wavelength (or equivalently T, wave period, or wavenumber $k_0 = 2\pi/L$);
- h caisson frontal opening;
- b chamber width;
- h_{swl} submerged depth of the front wall;
- b_{swl} width of the surface piercing rubble mound at the still water level;
- θ wave incidence angle;
- D characteristic linear dimension of an armor unit;
- g gravity acceleration;
- μ dynamic viscosity of water;
- ρ water density;
- ρ_a armor unit density.

Both the simulations and the experiments all used wave heights well within the armor stability threshold to avoid introducing damage to the rubble mound. Thus, in the present work the loss of performance of the caisson due to eventual fall of some armor units outside of the chamber has not been taken into account.