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Estimation of friction coefficient for double walled permeable vertical breakwater

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ABSTRACT

The present study deals with the derivation of an empirical formula for determining the friction coefficient of a double walled permeable vertical breakwater. The formulation is achieved in terms of variables representing the porosities of seaward side and shoreward side vertical walls, gap between the walls and depth of water. This formula is derived based on the results of experimental and theoretical studies carried out on a structure consisting of two vertical porous walls separated by some space. The theoretical model is developed by employing the method of eigenfunction expansion, which aids the prediction of such hydrodynamic coefficients as transmission, reflection, and energy dissipation coefficients. The values of friction coefficient are calculated by means of a best fit between the predicted and experimental values of hydrodynamic coefficients. The validity of the proposed formula is evaluated by conducting experiments and by comparing with published results. The results indicate that the proposed empirical formula can be effectively applied for the direct estimation of the friction coefficient of a double walled permeable vertical breakwater within the specified range.

1. Introduction

Permeable and slender coastal protection systems are emerging due to their relative economy and easy constructability over conventional type breakwaters like rubble mound and gravity breakwaters. Traditional breakwaters prevent water circulation, resulting in deterioration in the quality of water near the coast and hinder fishes and bottom-dwelling organisms from passing across (Rageh and Koraim, 2010). The width and the weight of the traditional type breakwaters increase with water depth, requiring a considerable amount of construction material (Rageh and Koraim, 2010). On the other hand, permeable breakwaters allow excellent circulation of water, thereby improving water quality in harbours and minimizing obstruction to aquatic life. Compared to conventional rubble-mound breakwaters, the operative inner harbour space for mooring of vessels can be increased by using vertical permeable breakwaters. Moreover, the use of vertical permeable structures tends to reduce the construction costs for increased water depths. The main advantage of these permeable structures is that they considerably reduce disturbances of the coastal environment (Huang et al., 2011).

Researchers have developed different theoretical models to study the hydrodynamic characteristics of permeable breakwaters (Huang and Ghidaoui, 2007; Koutandos and Prinos, 2011; Losada et al., 1993). The theory of wave energy transmission for an immersed rigid vertical thin barrier was proposed by Wiegel (1960). The approximate solution assumed that the transmitted wave power (average wave energy per unit time) is equal to the wave power below the vertical breakwater. Wiegel's theory was validated through experiments by Reddy and Neelamani (1992). Hayashi and Kano (1966) theoretically and experimentally investigated the hydraulic properties of closely spaced pile breakwaters. They presented a theory for the thrust and bending moment exerted on each pile by the waves and for the transmitted waves as well. The higher harmonic component effects generated by a barrier on fundamental wave scattering was studied by Mei et al. (1974), by performing a numerical analysis based on nonlinear matching conditions. Mei (1989) examined rectangular obstacles to propose a method to solve wave transmission and reflection coefficients theoretically as a function of relative obstacle length and height. Koley et al. (2015) investigated the oblique surface wave scattering by a submerged vertical flexible porous plate in both the cases of water of finite and infinite depths using Green's function technique. They concluded that the porous-effect parameter has small influence on the motion of a highly flexible plate and membrane barriers acting under the influence of higher tensile force.

The design formulae for the hydraulic design and prediction of response of Jarlan-type breakwaters were proposed from studies

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conducted by Fugazza and Natale (1992) on the wave reduction produced by a perforated vertical barrier with multiple chambers. Baquerizo et al. (2002) analyzed scattering of an edge wave propagating on an infinitely long, straight coastline, impinging on a permeable coastal structure perpendicular to the coastline. The edge wave interaction problem was solved by a mode matching method including a head loss at the structure by assuming that the width of the structure is considerably smaller than the wavelength. They established that the hydrodynamic coefficients of the structure depend on a friction coefficient f, which should be determined experimentally. Avila et al. (2008) improved the model of Baquerizo et al. (2002) to deal with the edge wave problem for an arbitrary beach profile. The studies on linear waves impinging obliquely on rigid vertical thin barriers by applying linear wave theory were performed by Losada et al. (1992). They used eigenfunction expansion method to determine the hydrodynamic coefficients theoretically. The amplitude of the reflected wave reduced with an increase in the angle of incident waves. Isaacson et al. (1999) performed laboratory tests to investigate the wave interactions with double walled vertical permeable structures. A numerical model based on an eigenfunction expansion method was developed to validate and compare the results. The experimental investigations on the hydrodynamic characteristics of a double vertical wall with impermeable upper part and permeable lower part were conducted by Koraim et al. (2011). The authors also developed a theoretical model based on an eigenfunction method to study the hydrodynamic characteristics of the structure. Somervell et al. (2017) experimentally and theoretically studied hydrodynamic characteristics of a vertical cellular breakwater with double wall and different upper and lower part porosities. Eigenfunction expansion method was used to develop a theoretical model to study the hydrodynamic performance of the breakwater. Sahoo et al. (2000a) discussed the scattering problem of surface waves which were obliquely incident on a vertical permeable barrier in finite depth of water for varying barrier configurations with the help of eigenfunction expansion method. They observed that the incident wave angle and porosity of the barriers had reduced the reflection of waves, amplitude, and the hydrodynamic pressure exerted on the barriers. Sahoo et al. (2000b) analyzed the wave trapping phenomena by vertical permeable barriers with varying configurations. In this case, the wave trapping was found to be very sensitive to the position of barrier and porous effect parameter.

The scattering of oblique waves was studied by Behera et al. (2016) for a permeable barrier with stepped bottom topography. They developed a semi-analytic model for the study and established that the model and methodology could be employed to analyze similar problems. Liu and Faraci (2014) developed a semi-analytical solution to examine the horizontal wave forces acting on combined caissons breakwater having an inner rubble mound slope. The calculated results of the wave forces were validated using the results of multi-domain boundary element method. They found that the total horizontal wave force was insensitive to the depth of submergence of the front barrier. The wave energy dissipation effectiveness of combined caissons breakwaters was investigated by Faraci et al. (2015) with the help of experiments. They established that when the ratio of the depth of water to wavelength increased, the reflection coefficient calculated decreased.

The eigenfunction expansion method is a widely used and acceptable theoretical method to estimate the hydrodynamic characteristics of single and double wall vertical permeable breakwaters (Ahmed and Schlenkhoff, 2014; Huang, 2007; Isaacson et al., 1999; Koraim et al., 2011; Nallayarasu et al., 1995; Rageh and Koraim, 2010; Teh and Venugopal, 2013; Usha and Gayathri, 2005; Wang et al., 2016). The determination of hydrodynamic characteristics of breakwater using eigenfunction expansion method utilizes the values of friction coefficient and added mass coefficient. In the case of permeable structures, the effect of added mass is usually small in most practical conditions (Mei et al., 1974; Urashima et al., 1986). So that, the added mass coefficient can be considered as zero (Isaacson et al., 1998, 1999; Koraim, 2011; Koraim et al., 2011; Koraim and Rageh, 2013; Losada et al., 1993).

The friction coefficient is an empirical coefficient that accounts for the viscous effects related to the flow through a porous material and arises from a linearization of the velocity squared term associated with the head loss (Isaacson et al., 2000). Usually the values of friction coefficient are determined by means of a best fit between the predicted values and experimental results of various hydrodynamic coefficients with a fixed added mass coefficient (Ji and Suh, 2010; Koraim, 2011; Koraim and Rageh, 2013; Rageh and Koraim, 2010; Suh et al., 2010; Suh and Kim, 2008). An experimental study of these type of breakwaters is time-consuming and laborious; moreover, it requires an excellent laboratory facility. An empirical formula for determining the friction coefficient enables direct estimation of hydrodynamic characteristics of vertical permeable breakwaters with reasonable accuracy.

Suh et al. (2011) proposed an empirical formula to calculate the friction coefficient of a perforated wall in terms of porosity and thickness of the perforated wall and the water depth. They carried out experiments and used the results of other researchers to obtain the empirical formula. The proposed formula was employed to predict the reflection and transmission coefficients of different types of structures including a perforated wall. Li et al. (2006) proposed an empirical equation for estimating the friction coefficient f in terms of b/h, where b is the thickness of the perforated wall and h is the water depth. This equation was obtained by using the least square technique and it compared well with the suggestions of several previous authors (Kondo, 1979; Tanimoto and Yoshimoto, 1982; Twu and Lin, 1991; Zhu and Chwang, 2001). Koley and Sahoo (2017) developed a coupled eigenfunction expansion-boundary element method to analyze the interaction of surface gravity waves with a submerged semicircular porous breakwater placed on a porous seabed in water of finite depth. The friction coefficient defined in Sollitt and Cross model is computed by approximating the spatial dependency of the seepage velocity with the average velocity within the porous media. An algorithm for determining the friction coefficient is provided.

The wave absorbing ability of double walled breakwater is higher than that of a single walled structure (Fugazza and Natale, 1992; Huang, 2007; Williams et al., 2000). However, to the best of the authors' knowledge, direct estimation of the friction coefficient for double walled permeable vertical breakwaters has not been reported in the published literature so far. An empirical formula would be very beneficial for engineers to compute the friction coefficient of a double walled permeable vertical breakwater.

In this work, an empirical formula is proposed to determine the friction coefficient of a double walled permeable vertical breakwater. The methodology involves experimental and theoretical investigation of the hydrodynamic characteristics viz. transmission, reflection and energy dissipation coefficients of a structure consists of two vertical porous walls separated by some space. In order to evaluate the variation in friction coefficient in terms of porosity (ε), the gap between the vertical walls (B) and water depth (h), three pairs of vertical walls are fabricated with porosities, $\varepsilon = 0.1$, 0.3 and 0.5. A theoretical model based on the eigenfunction expansion method is used to predict the hydrodynamic characteristics of the structure. The values of friction coefficient in the permeability parameter of the structure are estimated by means of best fit between the predicted and experimental values of hydrodynamic coefficients. To evaluate the validity of the proposed empirical formula, physical model studies are carried out with a prefabricated porous double walled breakwater supported by piles. For further validation, the theoretical results of this study are compared with the results of a double walled breakwater presented by Koraim et al. (2011).

2. Formulation of theoretical model

The structure considered in this study consists of two vertical permeable walls, separated by some space, $B=2a$. A schematic diagram of the structure considered is shown in Fig. 1. The structure is assumed to be interacting with a monochromatic linear wave of height H_i and angular