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A characteristic friction diagram for the numerical quantification of the hydraulic performance of different breakwater types

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ABSTRACT

This paper presents a robust method to calculate numerically the hydraulic performance of different breakwater types. For this purpose, a characteristic friction diagram was obtained to evaluate the wave transformation inside the porous medium. The friction diagram is based on a linear coefficient that does not vary within the porous medium volume and it is stationary in the wave cycle. It was calibrated by minimizing the error in the hydraulic performance (reflection and transmission coefficients and wave phase) between experimental measurements and numerical calculations (IH-2VOF numerical model). Tests were done with irregular waves, normal wave incidence and non-overtoppable conditions. Results show that the friction coefficient depends on the breakwater type and geometry, mainly on the relative diameter of the granular material, *Dk*, where *D* is the diameter and *k* is the wave number. It is expected that this method reduces costs and saves time in the breakwater predesign stage. The present study is innovative compared to other existing works because it addresses two relevant issues for breakwater design: (1) it not only provides the optimal values of the moduli of the reflection and transmission coefficients and wave energy dissipation rate, but also the phase values, given that the phase of the reflection coefficient is a key factor in defining the wave regime in front of, inside, and leeward to the breakwater; (2) it uses only one friction coefficient to calculate friction forces with a minimum error.

1. Introduction

A breakwater is a maritime structure built to protect a harbor, sheltered area, or shoreline from the full impact of waves. Breakwaters differ in the way that they deal with impinging waves. The selection of breakwater type and the dimensioning of its sections and elements depend on the project requirements, site characteristics and wave climate. Accordingly, such choices should be made after analyzing alternatives in order to select the one that best guarantees the operationality and safety of the breakwater at the lowest cost.

The performance and efficiency of each alternative can be evaluated calculating the wave energy balance by means of the modulus and phase of the wave reflection coefficient, the wave transmission coefficient, and the rate of energy dissipation derived from the interaction between the waves and the breakwater.

Vílchez et al. (2016) experimentally obtained the hydraulic performance of different breakwater types using a large number of laboratory tests. The hydraulic performance is evaluated by means of the wave reflection coefficient (modulus and phase), wave transmission coefficient and wave energy dissipation rate. The rate of wave energy dissipation is calculated applying the energy conservation. These parameters were determined experimentally by virtue of a series of non-dimensional parameters (parameter list) representing the breakwater geometry, characteristics of the granular material and incident wave conditions. A sigmoid equation (Eq. (1)) to describe the variation of these coefficients was proposed.

$$Y_i = (Y_{i1} - Y_{i0})\left[1 + \left(\frac{A_{eq}/L^2}{a_{X,i}}\right)^{\gamma_i}\right]^{-1} + Y_{i0} \qquad \begin{matrix} A_{eq}/L^2 > 0 \\ Y_{i0} < Y_i < Y_{i1} \textit{ for } i = K_R \textit{ and } K_T \\ Y_{i1} < Y_i < Y_{i0} \textit{ for } i = \phi_R \end{matrix} \tag{1}$$

where i is an index denoting the wave reflection (modulus and phase) and transmission coefficients. The sigmoid function depends on four parameters: γ_i, a blending coefficient; $a_{X,i}$, a parameter of the process; and Y_{i1} y Y_{i0}, two asymptotic values corresponding, respectively, to small and large values of the independent variable, $X = A_{eq}/L^2$ (see Fig. 1). A_{eq}/L^2 is the 2D scattering parameter, where A_{eq} represents the area of the porous material beneath the reference sea level, and L is the wavelength. Fig. 1 shows an example of these curves for the wave reflection coefficient (modulus, K_R, and the non-dimensional phase, x_0/L), the wave transmission coefficient (K_T), and the wave energy dissipation rate (D^*) for a high mound breakwater typology (HMB). $x_0/L = \phi/4\pi$ is the non-dimensional distance between the toe of the breakwater

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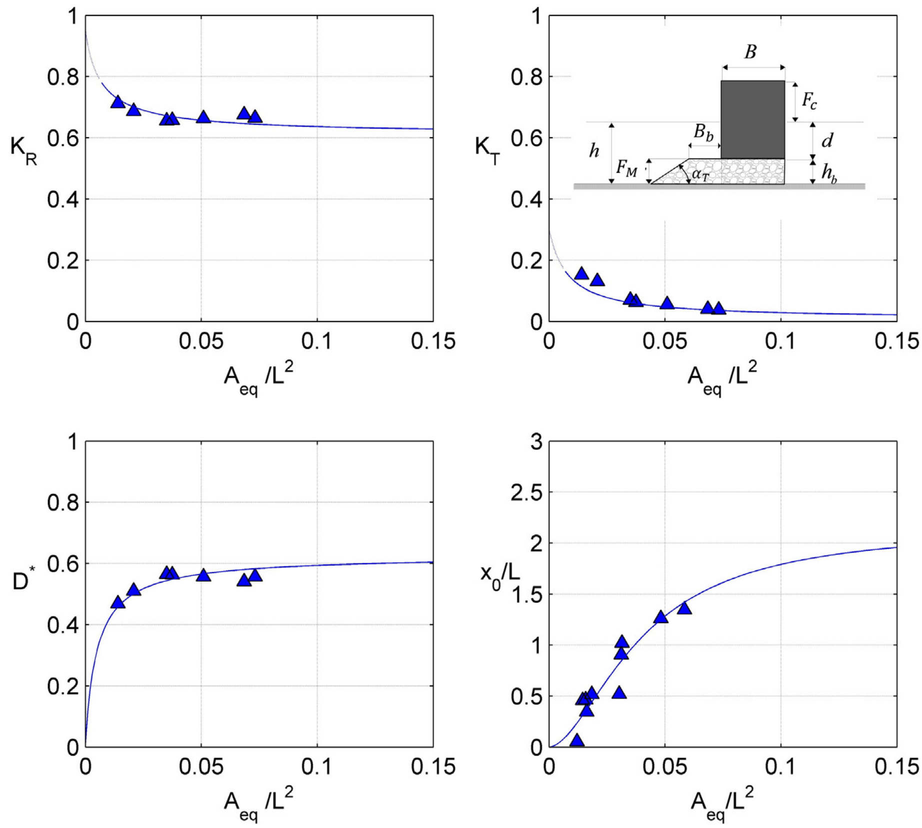

Fig. 1. Design curve of K_R, K_T, D^*, and x_0/L for a high mound breakwater (Vílchez et al., 2016). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

and a reflection point, which produces the same characteristics as the reflected wave train. The blue triangles represent the experimental data (Vílchez et al., 2016).

Usually, data to analyze the hydraulic performance are obtained by experimental methods. However, numerical models are being increasingly used in last years to solve this type of problems. Since most breakwaters are either partially or totally composed of granular material, the quality of the numerical results depends on correctly defining the wave transformation inside the porous medium.

The representation of the flow resistance forces inside the porous medium is generally based on the extended Darcy–Forchheimer equation

$$F_{NL} = a\,u\,n + b\,u|u|\,n^2 + c_A \frac{d(u\,n)}{dt} \tag{2}$$

where u is the seepage velocity through the voids, which is related to the discharge velocity by means of the expression $u_d = u \cdot n$ (where n is the porosity); and a, b, and c_A are local coefficients. This expression includes a linear term, which represents a Darcy's type of flow for a laminar flow behavior, a non-linear term, which considers the turbulent flow characteristics, and an inertial term that accounts for the added mass effect due to transient effects (Polubarinova-Kochina, 1962). The added mass defines the extra momentum needed to accelerate the same volume of water in a porous medium (Van Gent, 1995). Since the inertial term represents the effect of the porous medium on the acceleration of the fluid, it is usually combined with the acceleration term in the Navier–Stokes equations as it can be seen later in Section 2. Accordingly, the flow resistance forces equation can be written as follows:

$$F_{NL} = a\,u\,n + b\,u|u|n^2. \tag{3}$$

Several approaches to determine the Darcy–Forchheimer coefficients can be found in literature. Ward (1964) established coefficients in term of porosity, turbulent friction, and the intrinsic permeability. However, the preferred formula for a uniform porous medium is based on porosity and fluid viscosity (Hannoura and Barends, 1981; Smith, 1990). Following Ergun (1952) and Engelund (1953), Burcharth and Andersen (1995) analyzed these coefficients and established their relationship with the flow conditions for different hydraulic regimes. They proposed analytical expressions to calculate a and b:

$$a = \alpha \frac{\nu(1-n)^2}{n^3 D^2} \tag{4}$$

$$b = \beta \frac{1-n}{n^3 D} \tag{5}$$

where α and β are two empirical parameters and ν is the kinematic viscosity. Van Gent (1995) developed a model based on the Navier–Stokes equations, which expressed the coefficients as a function of porosity, diameter, and the Keulegan–Carpenter number. Most of numerical models based on the Volume-Averaged/Reynolds Averaged Navier–Stokes equations (VARANS) include the Darcy–Forchheimer equation to evaluate the flow in the porous medium. In this context, it is necessary to calibrate the coefficient values based on laboratory data (see Liu et al. (1999), Hsu et al. (2002), Losada et al. (2008); del Jesus et al. (2012); Lara et al. (2012); Jensen et al. (2014) and Higuera et al. (2013) for a full review of the derivation procedure). Similar procedures can be found in Metallinos and Memos (2015) and Zhang and Li (2014) but using a numerical model based on Boussinesq equations.

Despite the previously mentioned research, the problem of the flow in a porous medium has not been definitively solved. Forchheimer coefficients have to be chosen depending on breakwater typology, material characteristics and flow conditions. However, different authors have proposed different coefficients for the same wave and breakwater