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Concept of hydraulic porosity and experimental investigation in nonlinear flow analysis through Rubble-mound breakwaters

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SUMMARY

This paper aims to cast light on findings of experimental results and theoretical findings that evaluate hydraulic coefficients for non-linear flow through coarse aggregates. Experimental pilot made use of a physical model consisting of a flume of 13 m in length, being controlled by an electro-mechanical device to create different types of flow regimes. In this regard, two different relatively uniform aggregates ranging in size from 2 to 19 mm at first and 2 to 25 mm at second materials have been selected. The physical characteristics such as size distribution, porosity and fluid viscosity have been measured for each material. To create a set of the reliable hydraulic gradient vs. bulk velocity data, tests have been conducted on the materials. A non-linear mathematical model based on the extended Forchheimer's equation (EFE) has been employed in developing necessary equations needed for the assessments. Findings indicate: in determination of flow velocity within the pores of the media, the porosity term exponent may depend upon the nature of the flow regime. In addition, the proposed general equation for non-Darcy unsteady flow through coarse porous media seems to be a more reliable tool for modeling purposes and engineering applications.

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1. Introduction

Turbulent flow through coarse materials has been an interesting subject in several fields of studies related to environmental, water resources and mechanical engineering. It is generally accepted that theoretical basis of turbulent flow within porous media differs from the laminar flow through it that may be described by the Darcy's equation which is unable to explain flow at high Reynolds number. Non-Linear flow takes place at relatively high seepage velocity through coarse porous media such as Rubble-mound breakwaters, rock-fill, gravel aquifers, valley fill and waste dump. Flow modeling is often required in many disciplines, including groundwater, geotechnical, chemical, and environmental engineering. Several experimental data have been confirmed Forchheimer's equation (Venkataraman and Rao, 1998; Bordier and Zimmer, 2000; Higashino and Stefan, 2011; Samani et al., 2003; Lyn, 2004).

Rubble-mound breakwaters are frequently constructed of a core of quarry run materials; whose geotechnical parameters do affect the structure's armors stability. Therefore, the added mass of the core materials due to oscillatory unsteady loadings by pore fluids should be investigated and the hydraulic porosity determined experimentally. This is mainly because the flow field caused by wave motion is oscillating and, consequently, the flow resistance of porous media is in an unsteady oscillating regime.

As the cores of Rubble-mounds are made of randomly placed granular material characterized by media coefficients (i.e., d_m = average particle diameter, C_c, C_u = are curvature and uniform coefficients), their resistances to flow are dependent on certain random parameters such as porosity, and particle's geometry/orientation, the effects of which cannot be measured correctly even in a laboratory environment. Therefore, assessment of wave–structure interaction in designing these types of breakwaters imposes difficulties. The simplest way to overcome such difficulties is to construct models consisting of capillaries. These models had been used by many researchers in order to correlate the hydraulic conductivity with either an average pore size or with the pore size distribution (Chapuis and Aubertin, 2003; Cheng et al., 2008; Ishaku et al., 2011; Mccorquodale et al., 1978; Morin, 2006; Yamada et al., 2005).

This study represented an attempt to develop theoretical expressions for the hydraulic porosity of the breakwater structure, as influenced by the Reynolds-dependent boundary layer growth on the pores. These expressions used linear wave theory and boundary layer theory to estimate the effective decrease in pore diameter due to growth of the displacement boundary layer thickness in the pore. In this paper, based on the capillary concept and

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in an attempt to cast light upon hydraulic behavior of Rubble-mound breakwaters, an analytical study was conducted using non-Darcy flow equations to model flow of water through core materials.

2. Theoretical background

Based on Ahmed and Sunada approach (1969) used a steady non-Darcy flow equation describing resistance of coarse porous media to non-linear regimes may be expressed as

$$\frac{d\varphi}{dx} = \left(\frac{\mu}{\rho g k} + \frac{1}{g\sqrt{ck}}|V|\right)V \tag{1}$$

where φ and x denote the pore pressure and a characteristic length of the direction of flow respectively, μ, ρ, g, k, V, and c represent dynamic viscosity (pa s), density of fluid (kg m^{-3}), gravitational acceleration (ms^{-2}); intrinsic permeability (ms^{-1}), bulk velocity (ms^{-1}) and a constant, respectively. Several experimental data has been confirmed this equation (Venkataraman and Rao, 1998; Bordier and Zimmer, 2000).

By a commonly used Kozeny–Carman's relationship between hydraulic conductivity and effective porosity (n_e) and integrating a Reynolds type equation over a representative control volume, Hannoura et al. (Mccorquodale et al., 1978) developed a generalized unsteady flow equation for Rubble-mounds that may be rewritten as

$$\frac{1}{n}\left\{\frac{V}{ng}\frac{\partial V}{\partial x} + \left(1 + C_m\frac{1-n}{n}\right)\frac{1}{ng}\frac{\partial V}{\partial t}\right\} = -\frac{d\varphi}{dx} - (a + b|V|)V \tag{2}$$

where C_m, t, and n are the inertial coefficient is associated with added mass, time (s), and porosity (–); and a, and b are the Forchheimer's coefficients defined as

$$a = \frac{c_1\upsilon}{gR_{he}n_e^2} \tag{3}$$

$$b = \frac{c_2}{gR_{he}n_e^2}\left[N_1 + N_2\left(\frac{f_\varepsilon}{f_0}\right)\right]S^p n_e^q \tag{4}$$

where υ, S, R_{he}, f_ε and f_0 are kinematic viscosity, grain shape factor, hydraulic radius representing the characteristic length of the medium, friction factor for smooth surface and rough surface, respectively; and c_1, c_2, N_1, N_2, p, and q are empirical constants.

By employing pipe analogy to estimate a, and b one may reach to a parametric equation that describes hydraulic resistance of a uniform non-stationary flow (Niven, 2002) as

$$\frac{\partial\varphi}{\partial x} = \alpha_0\frac{(1-n)^2\upsilon S_0^2}{gn^3}V + \beta_0\frac{(1-n)S_0}{8gn^3}V|V| \tag{5}$$

where α_0, β_0, and S_0 are non-dimensional coefficients, and the specific surface. This equation is called Ergun's equation with $\alpha_0 = 4.167\,(-)$ and $\beta_0 = 2.333\,(-)$ and $S_0 = \frac{6}{d_p}\,(m^{-1})$ (Ergun, 1952).

In oscillatory flow through porous media, the additional resistance resulted from convective acceleration has to be considered by a quadratic resistance term whose coefficient c may be determined in accordance with:

(a) Inertial force owing to accelerating flow.
(b) Virtual mass due to the accelerated fluid passing stationary grains.

It should be noted that, if pore shape factor (C_0) and tortuosity (T) are to be used in calculating these coefficients one obtain $\alpha_0 = C_0T^2$ that is identical with C_{ck} in the Kozeny–Carman equation. Furthermore, by means of pipe analogy, it may be shown that $\beta_0 = 8fT^3$, where f is the friction factor .The latter causes the fluid to behave as a denser material having a greater mass than physically exists (Hannoura and McCorquodale, 1978). Therefore, for unsteady flow, Eq. (5) may be rewritten as

$$\frac{\partial\varphi}{\partial x} = \frac{C_0T^2}{g}\frac{(1-n)^2}{n^3}\upsilon S_0^2 V + \frac{fT^3}{8g}\frac{(1-n)}{n^3}S_0V|V| + \frac{1+\frac{C_m(1-n)}{n}}{gn}\frac{dV}{dt} \tag{6}$$

where $\frac{dV}{dt}$ denotes convective acceleration(Burcharth and Andersen, 1995; Hosseini and Joy, 2007). For the sake of simplicity, the specific surface in Eq. (6) may be replaced with representative grains' diameter (d) so may be written as

$$\frac{\partial\varphi}{\partial x} = \frac{36C_0T^2\upsilon}{gd^2}\frac{(1-n)^2}{n^3}V + \frac{6fT^3}{8gd}\frac{(1-n)}{n^3}V|V| + \frac{1+\frac{C_m(1-n)}{n}}{gn}\frac{dV}{dt} \tag{7}$$

Hannoura and McCorquodale (1978) employed a concise version of Eq. (7) to analyze their experimental results. The core of Rubble-mound breakwaters is commonly constructed with rather finer materials than those investigated by these researchers. Therefore, the added mass coefficient may be safely neglected in Eq. (7).

3. Effects of boundary-layer growth on the hydraulic porosity

We have employed Eq. (7) as a basis for examining compatibility of some reported values for a, and b. Accordingly, such experimental data published by previous investigators (Hannoura and McCorquodale, 1978; Burcharth and Andersen, 1995; Fourar et al., 2004; Hall, 1991; Hall et al., 1994; Shokri, 2004; Reddy and Rao, 2006; Shokri et al., 2013) have been used to plot Fig. 1. The scatter in a plot indicates that Eq. (7) provides a more reliable estimate of b coefficient than for a given set of data. This may be contributed to the fundamental role of porosity in calculating these coefficients and; therefore, it seems reasonable to focus upon accuracy in reported porosity values. A modeling of the flow assuming that soil pores are a set of capillary tubes leads to the Forchheimer's relationship. In a microscopic scale, variation of the boundary-layer thickness (δ) within the pores of media may be considered as a cause of inconsistencies. Boundary layer is known to be that layer of fluid in the immediate vicinity of a bounding surface in which rapid changes occur in the flow velocity (Qian et al., 2011). Theoretically, a displacement thickness (δ^*) may be defined to represent the distance by which a boundary should be moved towards a reference plane in an ideal fluid stream of velocity V_m to give the same discharge as occurs between the surface and the reference plane in a real fluid having a similar velocity. The two definitions are demonstrated in Fig. 2.

Accordingly, the displacement thickness, δ^*, may be calculated as

$$\begin{aligned}
&q = \int_0^\delta V dy = \int_{\delta^*}^\delta V_m dy \Rightarrow \int_0^\delta V dy = \int_0^\delta V_m dy - V_m \\
&\delta^*\delta^* = \int_0^\delta \left(1 - \frac{V}{V_m}\right)dy \\
&0 \leqslant y \leqslant \delta
\end{aligned} \tag{8}$$

By assuming a velocity profile similar to equation ($V = \alpha y^3 + \beta y + c$), subjected to the initial and boundary conditions.

$$V(y=0) = 0; V(y=\delta) = V_0; \left.\frac{\partial V}{\partial y}\right|_{y=\delta} = 0 \tag{9}$$

One may estimate the velocity profile as

$$V = \frac{3V_0}{2\delta}y - \frac{V_0}{2\delta^3}y^3 \tag{10}$$

On the other hand, boundary-layer thickness may be estimated by

$$\left(\frac{dV}{dy} = \frac{3}{2}\frac{V_0}{\delta} - \frac{3}{2}\frac{V_0}{\delta^3}y^2\right) \times \frac{\delta^3}{\left(\frac{dV}{dy}\right)} \to \delta^3 - \frac{3}{2}\frac{V_0}{\left(\frac{dV}{dy}\right)}(\delta^2 - y^2) = 0 \tag{11}$$

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