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Three-dimensional interaction of waves and porous coastal structures Part I: Numerical model formulation

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ABSTRACT

This paper and its companion paper (Lara et al. (2012)) describe the capability of a new model, called IH-3VOF, to simulate wave–structure interaction problems using a three-dimensional approach, when porous structures are present. The lack of a universal approach for the formulation of porous media flow equations has motivated a new derivation in the present work. Applications dealing with heterogeneous media, where porosity varies along the porous body, such as the study of multilayered rubble-mound breakwaters, are the final objective of the study. In this first paper, a new derivation of the equations, eliminating the limitations imposed by previous approaches is presented. The model integrates a new set of equations which covers physical processes associated with flow interaction with porous structures. The model considers the multiphase VARANS equations, a volume-averaged version of the traditional RANS (Reynolds-Averaged Navier–Stokes) equations. Turbulence is modeled using a k–ε approach, not only at the clear fluid region but also inside the porous media. A VOF technique is used to track the free surface. In this first paper, the model has been validated using laboratory data of a two-dimensional flow. In the companion paper the model is further validated with new experimental data sets, considering porous and solid structures as well as the presence of air. The model predictions present an excellent agreement with the laboratory measurements.

1. Introduction

Wave interaction with coastal structures is, in essence, mainly a three-dimensional problem. The most relevant hydraulic processes to be considered in wave–structure interaction encompass wave reflection, wave dissipation, wave transmission resulting from wave overtopping and wave penetration through porous structures, wave diffraction, run-up, and wave breaking. Although some of these processes have been studied using a two-dimensional approach, a correct assessment of flow characteristics and the consequent functional response of the structure needs to be performed considering three-dimensionality.

Three-dimensional wave–structure interaction has been traditionally studied by means of physical model tests. Wave diffraction patterns, reflection–transmission mechanisms and also wave overtopping under oblique wave incidence have been studied among others. Only a few empirical formulations have been derived from these studies to be specifically applied to three-dimensional scenarios, these studies being focused on tailored experiments for specific problems.

In recent years, a great effort has been made in improving numerical models to study wave–structure interaction problems. Among existing approaches, two-dimensional Reynolds-Averaged Navier–Stokes (RANS) models (Guanche et al., 2009; Lara et al., 2008; Losada et al., 2008) have revealed that structural functionality and stability can be studied with a high degree of accuracy, even in the presence of granular material layers. Volume-Averaged Reynolds-Averaged Navier–Stokes equations (VARANS), first presented by Hsu et al. (2002), have been solved to characterize wave-induced flows within porous structures. VARANS models in a two-dimensional form have shown that they can overcome the inherent limitations presented in Nonlinear Shallow Water (NSW) and Boussinesq equations models related mainly to wave dispersion and breaking, vertical flow characterization, non-hydrostatic pressure field and flow inside porous coastal structures.

However, three-dimensional wave-induced processes such as wave radiation and diffraction around breakwater trunks and heads, or oblique wave incidence, can only be studied based on a three-dimensional approach. SPH (Smoothed Particle Hydrodynamics, see Dalrymple and Rogers (2005) for a general introduction) is an important tool for the study of three-dimensional flows, that has been recently applied to coastal engineering. This approach solves the flow in a Lagrangian framework, solving the kinematics of each particle and its interaction with neighboring particles. The Lagrangian nature of SPH makes it well suited to simulate free surface flows with rapid changes of the flow field. Recently, Shao (2010) has presented a two-dimensional model which takes into account wave interaction with a porous flow structure.

On the other hand, several approaches based on the use of Eulerian three-dimensional Navier–Stokes (NS from now on) sets of equations can be found in the literature, for example Li et al. (2004); Liu and Lin (2009); Losada et al. (2005); Lubin et al. (2003); Wang et al. (2009)),

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among others. However, none of them solved porous media flow, and coastal structures are considered as impermeable. Hur (2003), and more recently Hur et al., (2008) presented wave interaction with permeable structures using a three-dimensional approach. Porous media flow equations used in the simulations follow a different approach to the one presented by Hsu et al. (2002). Although resistance forces due to the presence of flow across porous materials are represented in the same form, by drag and inertia terms, the NS equations are not volume averaged. Aerial and volume porosities are defined and applied to the different terms of the NS equations, as aperture coefficients.

This last statement reveals that there is not a unique method to model porous media flow. Differences are found not only in the closure model but also in the different terms considered in the NS equations. There are mainly two approaches: based on volume averaging the RANS equations (i.e.: VARANS, Hsu et al., 2002; Slattery, 1999) or based on time averaging volume-averaged equations (de Lemos, 2006). Even within the former, different sets of equations appear because of additional assumptions carried out by the authors during the equations transformation. As will be shown, none of the previously presented equations are comprehensive enough to cover the necessary applications in coastal engineering. In this regard, it would be necessary to determine the correct assumptions to derive the most general set of equations to model porous media flow.

The aim of this paper is to review porous flow equations and to derive a complete set of equations to be used to study three-dimensional flow problems. It will be shown that this new set of equations includes porous media flow in the NS equations on general domains, where heterogeneous porous media can be found. Equations are solved by a new three-dimensional NS model, called IH-3VOF.

The paper is organized as follows. In the next section, the derivation of the equation is presented and discussed. Next, the numerical model is developed, including the mathematical description and the numerical implementation. A preliminary porous flow calibration-validation is presented next for a classic dam-break problem, both in two-dimensional and three-dimensional geometries. Finally, the conclusions of this work are listed. The complete validation of the model for its application to wave-structure interaction is presented in part II of this study, Lara et al. (2012).

2. Model equations

A set of volume-averaged equations is derived in this section. The direct resolution of the flow field inside the voids of porous media is impractical, because of the complex structure of porous materials and the stochastic nature of their geometry. Rubble-mound coastal structures are made of individual rocks or armor units with a random structure. Moreover, solving the flow characteristics inside the gaps implies a very fine grid, increasing the computational cost. In order to solve the flow equation within porous structures some assumptions should be made in advance.

It is assumed that porous media properties are independent of time, i.e. the solid matrix deformation under the effect of the external dynamics is such that it does not affect overall magnitudes such as porosity distribution. Moreover, it is also considered that the flow inside and outside the porous medium can be modeled with the same set of equations, implicitly coupling the flow outside the porous (clear fluid region) and the flow within the porous media. This approach avoids the need to specify matching conditions in the clear fluid porous medium interface, as followed by de Lemos and Pedras (2001), in which interface and jump conditions were defined for velocity and shear stresses. Matching conditions introduce uncertainty in the solutions because the matching conditions are not perfectly known, and also because the position of the interface is defined somewhat arbitrarily. In the following procedure, fluid is assumed to be incompressible.

2.1. Volume-averaged model equations

The volume-averaged Reynolds-averaged Navier–Stokes (VARANS) equations are obtained by volume averaging the Reynolds-averaged Navier–Stokes (RANS) equations. Flow within the porous media is volume-averaged in a control volume larger than the porous structure but smaller than the characteristic length scale of the flow. The following spatial average operator is introduced and applied to the RANS equations:

$$\langle a\rangle^f = \frac{1}{V_f}\int_{V_f} a dV \tag{1}$$

where the superscript f means intrinsic magnitude and V_f refers to the fluid volume contained in the averaging volume. Intrinsic magnitudes refer to the portion of fluid existing within the gaps of the solid skeleton. They can be related to averaged magnitudes (also called Darcy's magnitudes) with: $\langle a\rangle = \phi\langle a\rangle^f$, where ϕ is the porosity, and is defined as: $\phi = V_f/V$, where V is the averaging volume. The application of this operator implies that the Reynolds-averaged magnitudes ($\bar{a}$) are split into a spatially averaged quantity ($\langle\bar{a}\rangle$) and a spatial fluctuation ($\bar{a}''$) part as follows:

$$\bar{a} = \langle\bar{a}\rangle^f + a'' \tag{2}$$

It is important to note that this operation transforms a porous media made of a solid skeleton and gaps into a continuous and homogeneous medium, characterized by material properties such as porosity and nominal diameter. This approach is very similar to the one presented by (Sollitt and Cross, 1976). When the operator is applied, small scale spatial fluctuations disappear from the solution, and then the small details of the porous channel geometry are no longer needed in order to obtain solutions. Mean spatial averaged quantities ($\langle\bar{a}\rangle$) are assumed to be constant in the whole averaging volume. Moreover, at the clear fluid region, porosity becomes unity and the spatial fluctuation (a'') vanishes, recovering the original situation where no averaging is needed. This fact makes it possible to couple clear fluid and porous fluid regions with the same set of equations.

Introducing the aforementioned decomposition and applying the volume-averaging operator, the volume-averaged Reynolds-averaged Navier–Stokes equations become as follows:

$$\frac{\partial}{\partial x_i}\langle\bar{u}_i\rangle^f = 0 \tag{3}$$

$$\begin{aligned}\frac{\partial}{\partial t}\langle\bar{u}_i\rangle^f + \langle\bar{u}_j\rangle^f\frac{\partial}{\partial x_j}\langle\bar{u}_i\rangle^f = &\\ -\frac{1}{\rho}\frac{\partial}{\partial x_i}\langle\bar{p}\rangle^f - \frac{1}{V_f}\int_{\partial V_s}\frac{1}{\rho}(\bar{p}+p'')\mathbf{n}dA&\\ -\frac{\partial}{\partial x_j}\langle u''_i u''_j\rangle^f + g_i + \frac{\partial}{\partial x_j}\left(\nu\frac{\partial}{\partial x_j}\langle\bar{u}_i\rangle^f\right)&\\ +\frac{1}{V_f}\int_{\partial V_s}\nu\left(\frac{\partial}{\partial x_j}\bar{u}_i^f + \frac{\partial}{\partial x_j}u''_i\right)\mathbf{n}dA&\\ -\frac{\partial}{\partial x_j}\left\langle\overline{u'_i u'_j}\right\rangle^f&\end{aligned} \tag{4}$$

where $\langle\rangle^f$ indicates the intrinsic average value of the variable in the fluid domain, $\bar{u}_i$ being the ensemble-averaged velocity, $\bar{p}$ the ensemble-averaged pressure, primed variables are turbulent fluctuations and double-primed variables are spatial fluctuations. The last two terms,