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Three-dimensional interaction of waves and porous coastal structures using OpenFOAM®. Part I: Formulation and validation

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ABSTRACT

In this paper and its companion (Higuera et al., 2014–this issue), the latest advancements regarding Volume-averaged Reynolds-averaged Navier–Stokes (VARANS) are developed in OpenFOAM® and applied. A new solver, called IHFOAM, is programmed to overcome the limitations and errors in the original OpenFOAM® code, having a rigorous implementation of the equations. Turbulence modelling is also addressed for k-ϵ and k-ω SST models within the porous media. The numerical model is validated for a wide range of cases including a dam break and wave interaction with porous structures both in two and three dimensions. In the second part of this paper the model is applied to simulate wave interaction with a real structure, using an innovative hybrid (2D–3D) methodology.

1. Introduction

One of the determining factors to generalize the use of numerical models for coastal engineering is that the most advanced ones can handle flow through porous media, thus being able to simulate any structural typology. Should the models lack porous media flow, they would only be suitable to calculating impervious coastal structures.

Following this reasoning, the importance of porous media flow is clear, as the vast majority of coastal structures have a porous portion. Rubble mound breakwaters have armour layers that are built of concrete pieces or crushed rocks. Even vertical breakwaters, which may be seen as an impervious structure, have a porous foundation which affects the stability of the caisson due to the uplift pressure. We will comment on the different approaches to simulate porous media in the following paragraphs.

The first approach worth mentioning is the Smoothed Particle Hydrodynamics (SPH) method. Works by Dalrymple and Rogers (2006) and Shao (2006) can be remarked as the first real applications of SPH to coastal engineering.

SPH methods are in an early stage of development. Recently (Shao, 2010) presented a precursory application of wave interaction with porous media. The main drawback is that it can only be applied in 2D, which restricts the range of applicability, as we will comment on the second part (Higuera et al., 2014–this issue). More recent works present significant advancements, as Akbari and Namin (2013). However still no one has published a 3D porous model for SPH.

The other relevant approach is Reynolds-Averaged Navier–Stokes (RANS) equations. Unlike the previous method, RANS is an Eulerian approach, as these equations represent the continuum properties rather than the behaviour of individual particles. RANS equations have been extensively used for coastal engineering applications. The first remarkable application was presented almost 20 years ago by van Gent et al. (1994), and it should be noted that it already included flow through porous media.

The period of time in which RANS has been applied to coastal engineering is very long compared to SPH. Therefore, RANS codes have already been able to deal with a great number of applications. A brief list of such cases includes all kinds of wave generation and absorption (Higuera et al., 2013a; Jacobsen et al., 2012; Lara et al., 2011; Lin and Liu, 1999; Troch and De Rouck, 1999) and wave interaction with coastal structures (del Jesus et al., 2012; Guanche et al., 2009; Higuera et al., 2013b; Lara et al., 2006; Lara et al., 2008; Lara et al., 2012; Losada et al., 2008; Luppes et al., 2010).

One of the strong points of RANS is that they are accessible to the whole community through commercial codes, but also free and open source models are available. Some examples of CFD codes applied to coastal engineering include IH-2VOF Lara et al. (2006), IH-3VOF Lara et al. (2012), COMFLOW Luppes et al. (2010), VOFbreak Troch and De Rouck (1999) or OpenFOAM® Higuera et al. (2013b). However, to the authors' knowledge and until this work, there is no three-dimensional open source model available in which porous media flow is treated for two-phase flows.

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This paper is structured as follows. After this introduction, the different ways of implementing porous media flow in RANS models are discussed. Then, further development of existing derivations leads to an implementation procedure in OpenFOAM®. Next, the model IHFOAM is validated using a wide range of cases, including a dam break and oscillatory flow experiments both in two- and three-dimensions. Finally, the conclusions of this work are highlighted.

2. Porous media equation discussion

The main methods to treat porous media flow in numerical models are described in the first part of this section. Then, the VARANS equations, as developed in del Jesus et al. (2012), are introduced. Finally, OpenFOAM® is described and the implementation of VARANS in OpenFOAM® is detailed.

2.1. Porous media flow for Navier–Stokes equations

There is not a universal or unique way to simulate flow through porous media, therefore, in this section we will introduce the two main methods to treat porous media flow in NS numerical models, the microscopic and macroscopic approaches.

The most intuitive way to simulate the flow through a porous material is the microscopic approach. In it each of the elements of which the material is formed (e.g. each of the concrete blocks of a breakwater, each of the stones…) is represented in the mesh. It is impossible to apply such procedures in our field for several reasons: there is no way to have the complete and exact description of the geometry, and it is not possible to mesh with such a great variation of scales (from blocks to sand grains). Furthermore, it is of greater interest to understand the global effects of porous media in the flow than obtaining an accurate solution of the flow within.

The second procedure is the macroscopic approach, which relies in obtaining a mean behaviour of the flow within the porous media by averaging its properties along control volumes. Volume averaging NS equations allows considering the porous zone as a continuous medium, characterized by its macroscopic properties only, thus eliminating the need of a detailed description of its complex geometry. This simplification, however, introduces new terms in the equations that need to be modelled.

Averaging the NS equations can be done in several ways. This paper is focused in Volume-averaged Reynolds-averaged Navier–Stokes (VARANS) equations Hsu and Liu (2002), but time-averaged volume-averaged methods also exist, as presented in de Lemos (2006).

The VARANS equations can have different terms, depending on the assumptions applied by the author. For example, the work presented in Hsu and Liu (2002) has been a reference for almost 10 years. It is based on the previous work by Liu et al. (1999), and extends it to include a k-ϵ turbulence model closure within the porous media, as presented by Nakayama and Kuwahara (1999), which made it the most suitable formulation for coastal engineering at the time. However, porosity is taken out of the differential operators, which is not applicable if spatial gradients of porosity exist.

The most recent advance is the VARANS formulation presented in del Jesus et al. (2012). This work includes a discussion about the different equations found in literature, commenting on the underlying assumptions and ranges of application. A new model called IH-3VOF is developed to simulate two-phase flows within porous media, solving a new set of VARANS equations and the volume of fluid (VOF) technique.

del Jesus et al. (2012) extend the range of applicability of VARANS to the most general scenario, in which spatial variation of porosity is also taken into account. The equations are developed keeping the porosity inside the differential operators. This approach is very important for coastal engineering, as the structures can present several layers of different porous materials. Otherwise, the flux across the interfaces of such porous media would not be accurately solved.

The advantages of VARANS equations are numerous. The solving process yields very detailed solutions, both in time and space. Pressure and velocity fields are obtained cell-wise, even inside the porous zones, so the whole three-dimensional flow structure is solved. Furthermore, non-linearity is inherent to the equations, and therefore all the complex interactions among the different processes are also taken into consideration. Finally, the effects of turbulence within the porous zones can also be easily incorporated with closure models.

There is also another approach to consider porous media flow, presented in Hur et al. (2008). Although the NS equations are not volume-averaged, the resistance due to the porous material is represented in a similar fashion using drag forces. The momentum equation is also modified to include area and volume fractions to represent the porosity.

2.2. VARANS equations in IH-3VOF

The VARANS equations proposed by del Jesus et al. (2012) and implemented in IH-3VOF are presented next. They include conservation of mass (Eq. (1)), conservation of momentum (Eq. (2)) and the VOF function advection equation (Eq. (3)).

$$\frac{\partial}{\partial x_i}\frac{u_i}{n} = 0 \tag{1}$$

$$\begin{aligned}\frac{\partial}{\partial t}u_i + u_j\frac{\partial}{\partial x_j}\frac{u_i}{n} \\ = -\frac{n}{\rho}\frac{\partial}{\partial x_i}p + ng_i + n\frac{\partial}{\partial x_j}\left(\nu\frac{\partial}{\partial x_i}\frac{u_i}{n}\right) - a\, u_i - b\, u_i|u_i| - c\frac{\partial}{\partial t}u_i\end{aligned} \tag{2}$$

$$\frac{\partial \alpha_1}{\partial t} + \frac{\partial}{\partial x_i}\frac{u_i}{n}\,\alpha_1 = 0. \tag{3}$$

in which u is the so-called extended averaged or Darcy velocity; n is the porosity, defined as the volume of voids over the total volume; ρ is the density; p is the pressure; g is the acceleration of gravity; ν is the kinematic viscosity; and α_1 is the VOF indicator function, and is defined as the quantity of water per unit of volume at each cell.

The three last elements in Eq. (2) appear as closure terms to account for physics that cannot be solved when volume-averaging (i.e. frictional forces, pressure forces and added mass due to the individual elements of the porous media).

Since Darcy (1856) introduced a study of water flowing through sand, the study of flow through porous media has been characterized by drag forces. This first approach included only one linear term (first term in Eq. (4)), which was appropriate to model laminar flows. It was not until Forcheimer (1901), with the addition of a quadratic term (second term in Eq. (4)), that the more energetic flows (in terms of larger Reynolds numbers) could be modelled. Polubarinova-Kochina (1962) extended the model proposed by Forcheimer (1901) to account for unsteady flows, adding a third term (third term in Eq. (4)), which is transient and represents an inertial acceleration. The final expression of the drag forces, as applied in Eq. (2), is presented next:

$$I = a\, u + b\, u\, |u| + c\frac{\partial u}{\partial t} \tag{4}$$

where I is the hydraulic gradient (proportional to the drop in pressure), and u is the Darcy velocity. Three coefficients (a, b and c), which depend on the physical properties of the material, control the balance between each of the friction terms.

In this work Engelund (1953) formulas, as applied in Burcharth and Andersen (1995), have been used for the friction coefficients. Nevertheless, and as it is explained later, these parameters need calibration from physical tests to obtain results close to reality.