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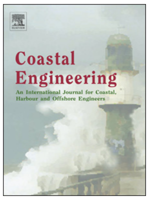

Modified moving particle method for modeling wave interaction with multi layered porous structures

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A B S T R A C T

Modified Moving Particle method in Porous media (MMPP) is introduced in this study for simulating a flow interaction with porous structures. By making use of the sub-particle scale (SPS) turbulence model, a unified set of equations are introduced for the entire computational domain and a proper boundary treatment is suggested at the interfaces between fluid and the porous media. Similar to the Incompressible Smoothed Particle Hydrodynamic (ISPH) method, a robust two-step semi-implicit scheme is utilized to satisfy the incompressibility criterion. By means of the introduced model, different flow regimes through multi-layered porous structures with arbitrary shapes can be simulated and there is no need to implement calibration factors.

The developed MMPP model is then validated via simulating the experiments of Liu et al. (1999) i.e. linear and turbulent flows through porous dams and the experiments of Sakakiyama and Liu (2001) i.e. wave overtopping on a caisson breakwater protected by multi layered porous materials. Good agreements between numerical and laboratory data present the ability of the introduced model in simulating various flow regimes through multi-layered porous structures. It is concluded that the turbulent flow is an important issue particularly at the interface between the free fluid and porous media and consequently, the accuracy of the previous Lagrangian models that were based on neglecting the turbulence effect can be improved significantly by means of the present model. In addition, to satisfy the continuity criteria in the SPH models, it is necessary to modify density of particles in accordance with their porosity.

1. Introduction

Coastal structures particularly breakwaters in different types such as submerged, berm or conventional breakwaters are usually constructed with different layers of porous materials. In order to design and check the stability of these structures against coastal waves, it is necessary to have a proper knowledge about wave interaction with multilayered porous media. On the other hand, different hydraulic processes such as wave reflection, dissipation, breaking, run-up, overtopping and wave penetration to porous structures can be studied by means of numerical models. Several attempts have been made in recent years to improve numerical models involved in simulating wave interaction with porous structures. After Brinkman (1947) added a viscous term to the Darcy equation as the earliest equation governing a flow through porous media, many efforts have been made to introduce a unified equation for this purpose. Akbari and Namin (2013) reported a good historical background of these efforts. Sakakiyama and Kajima (1992) extended Navier–Stokes (NS) equations by implementing inertial and convective coefficients and used linear and nonlinear terms to present the porous resistance forces. Liu et al. (1999) studied flow (both linear and turbulent) through porous dams by solving spatially averaged NS equations and Reynolds averaged NS (RANS) equations inside and outside the porous medium, respectively. They introduced a new linear porous coefficient by comparing their numerical results with their experimental data. Hsu et al. (2002) presented Volume Averaged RANS equations (VARANS) to characterize flow in porous medium and Huang et al. (2003) simulate wave interaction with submerged breakwaters via utilizing modified NS equations in porous media. Later, Huang et al. (2008) studied solitary wave propagation over porous bed and verified his model through empirical and experimental data. After discussing about different introduced equations, del Jesus et al. (2012) proposed a new unified equation for simulating flow interaction with porous media by means of VARANS equations. They validated their three dimensional model by utilizing Lara et al.'s (2012) experiments. All of the above-mentioned studies were based on the Eulerian framework until Shao (2010) proposed utilizing the Smoothed Particle Hydrodynamics (SPH) method in simulating flow interaction with porous media. As reported by del Jesus et al. (2012), the Lagrangian

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nature of the SPH model makes it well suited to simulate free surface flows with rapid changes of flow field. In addition, no numerical diffusion occurs in the SPH method because of a direct calculation of advection term. Although the SPH model was originally developed for the astrophysics (Monaghan, 1992), it has been applied extensively to fluid dynamics and a lot of researchers have tried to remove its difficulties by introducing some modifications such as developing the Incompressible SPH (ISPH) method by Shao and Lo (2003). Later, by implementing the SPS turbulence model, Shao (2006) studied wave overtopping over an impermeable slope by means of the ISPH method. However, since moving particle methods have been recently applied to study flow interaction with porous media, more researches are required to introduce an accurate model based on these strong methods. By utilizing the ISPH method, Shao (2010) was the first researcher who studied wave interaction with porous medium by solving two independent sets of NS equations inside and outside the porous medium. However, he neglected the inertia coefficient and effect of the turbulent flow. In addition, to satisfy boundary conditions, Shao (2010) used grid lines at the interface between porous and free fluid media and integrated flow parameters over these grids during each time-step. Since the ISPH method is a Lagrangian particle-based method and particles move continuously in computational domain, definition of such a grid line is not an optimized and proper method. This difficulty can be even more significant in simulating flow through several porous layers. Pu and Shao (2012) solved this problem by making use of a unified equation inside and outside the porous medium and studied wave overtopping over porous breakwater, yet similar to Shao (2010), they forgot about utilizing correct occupied volume by particles. Later, Akbari and Namin (2013) modified moving particle methods in porous media by applying the apparent density instead of the fluid density in their introduced ISPHP model. They solved a unified NS equation inside and outside the porous medium and improved the accuracy of the former models particularly at interface boundary locations. Akbari and Namin (2013) concluded that the physical characteristics of porous material is not sufficient to calculate porous resistance forces because the linear and nonlinear porous coefficients relate to the flow conditions too. Although they validated their model by simulating several experiments such as wave propagation over porous seabed, flow through porous dam and wave interaction with a caisson breakwater protected by porous materials, turbulent flow was neglected in their model similar to the former mentioned studies. Some researchers claimed that the turbulence is not a significant item in simulating macroscopic behavior of hydrodynamic flows (Gotoh et al., 2005; Khayyer et al., 2008) and flow in porous medium is usually turbulent free because of the low velocity field (Akbari and Namin, 2013). Even if we suppose that the effect of the turbulent flow is negligible inside and outside the porous medium, yet more studies are required to investigate its effect at interface boundaries between porous medium and free fluid where significant flow gradients may occur.

In this study, a Modified Moving Particle method in Porous media (MMPP) is proposed for simulating the wave interaction with porous structures. Unified set of NS equations in the Lagrangian framework is introduced and turbulent flow inside and outside the porous medium as well as the proper interface boundary between porous and free fluid media is modeled. To get rid of calibrating the porous coefficients, proper formulation is used and validity of the earlier consumptions about utilizing unmodified density is studied by solving a simple test case by both modified and unmodified methods. Then, the modified model is verified by simulating experiments of Liu et al. (1999) i.e. linear and turbulent flows through porous dams and experiments of Sakakiyama and Liu (2001) i.e. wave overtopping on a caisson breakwater protected by multi layered porous materials. These experiments are selected to study the effect of turbulence flow and show the model ability in simulating flow through different porous layers.

2. Governing equations

By following Shao (2010) and implementing the turbulence viscosity, the continuity and momentum equations for the outside flow field are:

$$\nabla \cdot \overrightarrow{U}_f^w = 0, \tag{1}$$

$$\frac{D\overrightarrow{U}_f^w}{Dt} = \frac{-1}{\rho_w}\overrightarrow{\nabla}P + (\upsilon_w + \upsilon_T)\nabla^2\overrightarrow{U}_f^w + \overrightarrow{g}, \tag{2}$$

where ρ_w and $\overrightarrow{U}_f^w$ are the fluid density and fluid velocity outside the porous medium, respectively. p is the total pressure and $\overrightarrow{g}$ is the gravitational acceleration vector and υ_w and υ_T are the kinematic viscosity of the fluid (1.0 E−6 for water) and turbulent viscosity, respectively. Inside the porous medium with the porosity of n_w, the Lagrangian form of governing equations are:

$$\nabla \cdot \overrightarrow{U}_f^p = 0 \tag{3}$$

$$C_r \cdot \frac{D\overrightarrow{U}_f^p}{Dt} = \frac{-1}{\rho_w}\overrightarrow{\nabla}P + (\upsilon_w + \upsilon_T)\nabla^2\overrightarrow{U}_f^p - an_w\overrightarrow{U}_f^p - bn_w^2\overrightarrow{U}_f^p\left|\overrightarrow{U}_f^p\right| + \overrightarrow{g}, \tag{4}$$

where $\overrightarrow{U}_f^p$ is the fluid velocity inside the porous medium. a, b are the linear and nonlinear coefficients, respectively, for adjusting the resistance forces in porous medium. C_r is the inertia coefficient suggested by Van Gent (1995b) via the experimental studies of one dimensional flow through different porous materials:

$$C_r = 1 + \frac{1-n_w}{n_w}\gamma; \quad \gamma = 0.34\,. \tag{5}$$

As reported by Akbari and Namin (2013), the effect of the inertia coefficient on the flow pattern is very little particularly in comparison with the effect of the linear and nonlinear porous coefficients and therefore, some researchers such as Shao (2010) neglected inertia coefficient in their study.

If two different sets of equations are used inside and outside the porous medium, proper interface boundary condition shall be utilized to fulfill the continuity between these two media. Following Huang et al. (2003) and in order to satisfy the velocity limitations at the interface boundary, Shao (2010) used the following criterion:

$$\overrightarrow{U}_f^w = n_w\overrightarrow{U}_f^p. \tag{6}$$

Instead of solving two different equations separately and combining them through an interface treatments, a set of unified governing equations for the entire domain is used in this study as the unified continuity and momentum equations:

$$\overrightarrow{\nabla} \cdot \overrightarrow{U}_D = 0 \tag{7}$$

$$\frac{C_r}{n_w} \cdot \frac{D\vec{u}_D}{Dt} = \frac{-1}{\rho_w}\overrightarrow{\nabla}P + \upsilon_E\nabla^2\vec{u}_D - a\vec{u}_D - b\vec{u}_D|\vec{u}_D| + \overrightarrow{g}. \tag{8}$$

U_D is the Darcian or averaged velocity which is equal to the intrinsic fluid velocity ($\vec{u}_f$) multiplied by the porosity (n_w) of the domain i.e.

$$\vec{u}_D = n_w \cdot \vec{u}_f. \tag{9}$$

Akbari and Namin (2013) used similar equations for modeling the wave interaction with porous media by means of a moving particle