Coastal Engineering 88 (2014) 88–100

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Numerical simulation of wave interaction with porous structures using an improved smoothed particle hydrodynamic method

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ARTICLE INFO

Article history:
Received 1 December 2013
Received in revised form 13 February 2014
Accepted 19 February 2014
Available online 18 March 2014

Keywords:
SPH
Porous structure
Breaking waves
Large eddy simulation

ABSTRACT

A smoothed particle hydrodynamic (SPH) model is developed to simulate wave interaction with porous structures. The mean flow outside the porous structures is obtained by solving Reynolds Averaged Navier–Stokes (RANS) equations and the turbulence field is calculated by a large eddy simulation (LES) model. The porous flow is described by the spatially averaged Navier–Stokes type equations with the resistance effect of the porous media being represented by an empirical frictional source term. The interface boundaries between the porous flow and the outside flow are modeled by means of specifying a transition zone along the interface. The model is validated against other available numerical results and experimental data for wave damping over porous seabed with different levels of permeability. The validated model is then employed to investigate wave breaking over a submerged porous breakwater and good agreements between the SPH model results and the experimental data are obtained in terms of free surface displacement. In addition the predicted velocity, vorticity and pressure fields near the porous breakwater and in the breaking wave zone are also analyzed.

1. Introduction

Artificial porous structures such as rubble-mound breakwaters, submerged structures, and armor layers are widely constructed for the purpose of protecting harbors and beaches from wave attack. Therefore, the knowledge of the flow motions in and around the porous structures and the corresponding pressure variations are crucial to understand the mechanism of wave energy transmission, dissipation and reflection due to the presence of porous structures.

The model proposed by Sollitt and Cross (1972) was widely used as a basis for solving Non-Darcy seepage flows through porous structures. In their momentum equations, the resistance forces exerted by the solid skeleton on the pore flow include an additional inertial term and a linear or nonlinear frictional term. The convective term was ignored on the assumption that finite amplitude waves are quickly dissipated within the coarse granular media. As a further generalization of the approach of Sollitt and Cross (1972), the studies based on linear potential theory are carried out to investigate wave transmission, reflection and dissipation from composite breakwaters (Sulisz, 1985; Yu and Chwang, 1994).

Since 1990s Navier–Stokes type models have been used to describe the unsteady flows in porous structures (Huang et al., 2003; Liu et al., 1999; Van Gent, 1995). Liu et al. (1999) derived the spatially averaged governing equations of the flow in the porous media from the N–S equations. To close the equations, the widely used empirical formula by Van Gent (1995) was adopted as the resistance force terms. While keeping the inertial and nonlinear porous resistance coefficients as suggested by Van Gent (1995), the linear porous coefficient was modified. The flow outside the porous media was solved using the RANS equations along with an improved k–ε turbulence model. The turbulence boundary layer adjacent to the porous wall boundary was modified by including the effects of percolation velocity along the boundary. According to Liu et al. (1999) the turbulence inside the porous media is usually very weak and negligible, as long as the permeability of the porous medium is very small. But when the pore size is relatively large, the turbulence effect could become significant. Hsu et al. (2002) introduced the small-scale turbulence effects as part of the porous flow by solving the RANS along with the k–ε turbulence closure model to describe the flows both in and outside the porous medium.

Recently, particle-based SPH method was applied to fluid wave mechanics (Dalrymple and Knio, 2001; Dalrymple and Rogers, 2006; Gao et al., 2012). Being Lagrangian in nature the SPH model does not require the explicit surface capturing scheme in treating strong nonlinear flows with large free surface deformation and enables the easy modeling of coastal structures with complex geometrical boundaries (Liu and Liu, 2010). Another obvious advantage of using the SPH techniques to simulate the porous flow is that the discrete solid skeleton could be fully discretizing using the SPH particles at adequate resolution without introducing further simplifying assumptions as shown by Zhu et al. (1999). However, modeling the porous medium at the pore scale is

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http://dx.doi.org/10.1016/j.coastaleng.2014.02.006
0378-3839/

extremely computationally expensive. Based on solving the pressure Poisson equation (PPE) and a two-step semi-implicit solution process (Shao and Lo, 2003), Shao (2010) developed the Incompressible SPH (ISPH) and modeled wave interaction with porous structures by solving the NS type equations similar to that of Liu et al. (1999).

The accuracy of the numerical approach for simulating the wave-porous structure interaction depends largely on the treatment of the interface between the outside flow and the porous flow. There are two kinds of matching conditions at the interface used in the Eulerian grid-based approaches. One is the continuity of the mass flux and the dynamic pressure across the interface of porous media and outside flow developed by Yu and Chwang (1994). The other is the continuity of the velocity and stress in both normal and tangential directions proposed by Deresiewicz and Skalak (1963). By means of placing an imaginary grid line at the interface together with a coupling procedure Shao (2010) implemented the velocity and stress continuity condition in his ISPH model. By defining different porosity values in the total computational domain using the SPH integration technique, Akbari and Namin (2013) introduced a boundary treatment in the ISPH model to solve simultaneously the porous flow and outside flow using one equation. In this way the continuity of the velocities and the pressures at the interface are fulfilled without the need for any matching conditions because the particles are moving continuously in or out of the porous boundary. However, this treatment resulted in a large boundary thickness of nearly 4 times of smoothing length and a varying smoothing length is necessary to ensure the simulating accuracy because the particle apparent density may change gradually in the boundary zone.

The turbulence modeling is another challenging issue for the porous flow simulation. Despite that the turbulence effect is significant under breaking and overtopping waves, in order to simplify the matching conditions with the porous flow region, neither Shao (2010) nor Akbari and Namin (2013) included the turbulence effects in their model, assuming that the effect of the turbulence on the macroscopic behavior of external flows is not significant and flow velocity inside the porous media is turbulent free. However, as they both have mentioned, the turbulence may not be neglected in some real cases such as wave breaking.

In this study, a practical SPH model that includes the Corrective Smoothed Particle Method (CSPM) and enhanced dynamic boundary conditions is developed to investigate wave interaction with porous structures. In order to consider the influence of turbulence, for the wave field outside of the porous structure the mean flow is obtained by solving the RANS equations and the corresponding turbulence field is modeled by a LES model. For the flow inside the porous structure, the effects of small-scale turbulence are neglected and the NS equations derived by Liu et al. (1999) are used, except the resistance forces which are of the form as proposed by Sollitt and Cross (1972). The interface boundary between the porous flow and the outside flow is modeled by specifying a transition zone of appropriate width along the interface and calculating the velocity of each fluid particle within the transition zone as the average of the velocities of neighboring particles using a cubic-spline smoothing kernel. The model is validated by comparing the results of the present model on wave damping over a porous seabed with that of other models. The validated model is then used to simulate wave breaking over a submerged porous breakwater. Time series of the wave surface at different locations are compared with the available experimental data. The flow fields and pressure distribution near and within the porous breakwater as well as the effects of porosity are discussed. In addition the vorticity field near the porous structure and in the breaking wave zone is analyzed.

2. Governing equations

In this model, the fluid outside of the porous media is assumed to be weakly compressible and the governing equations included the LES model as proposed by Dalrymple and Rogers (2006) can be written as

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\mathbf{u} \tag{1}$$

$$\frac{d\mathbf{u}}{dt} = -\frac{1}{\rho}\nabla P + \mathbf{g} + \upsilon\nabla^2\mathbf{u} + \frac{1}{\rho}\nabla\cdot\vec{\tau} \tag{2}$$

where $\mathbf{u}$ is the velocity vector; $\mathbf{g}$ is the gravitational acceleration; υ is the kinematic coefficient of viscosity; and τ is the sub-particle-scale (SPS) turbulence stress, which is the equivalent of the sub-grid scale (SGS) in an Eulerian grid method.

Following Monaghan (1994), the relationship between pressure and density can be written as the following expression

$$P = B\left[\left(\frac{\rho}{\rho_0}\right)^\gamma - 1\right] \tag{3}$$

where γ is a constant, and for water $\gamma = 7$ is suggested; ρ_0 is the reference density, $\rho_0 = 1000\ \text{kg/m}^3$. The parameter B can be taken as $B = c_0^2\rho_0/\gamma$; c_0 is the speed of sound at the reference density, the value of which must be at least ten times faster than the maximum fluid velocity to keep density variations within less than 1%.

In order to close the governing equations, the eddy viscosity assumption is used to model the SPS turbulence stress as

$$\frac{\tau_{ij}}{\rho} = 2\nu_t S_{ij} - \frac{2}{3}k\delta_{ij} \tag{4}$$

where ν_t is the turbulence eddy viscosity; S_{ij} is an element of the SPS strain tensor, $S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$; k is the SPS turbulence kinetic energy; and δ_{ij} is the Kronecker sign function.

In this paper, a modified Smagorinsky model formulated by Bradbrook et al. (2000) is used to calculate the turbulence eddy viscosity and it is written as follows

$$\nu_t = [\min(C_s\Delta l, \kappa l_v)]^2|S| \tag{5}$$

where C_s is the Smagorinsky constant and is equal to 0.1; κ is the von Karman constant ($\kappa = 0.4$); l_v is the distance from the particle to the closest boundary; Δl is the particle–particle spacing; and $|S| = (2S_{ij}S_{ij})^{1/2}$. As shown in Eq. (5), the first term on the right-hand side dominates for flows far away from the solid boundary, and the second term dominates for flows in the vicinity of the boundary. The second term is used to overcome the drawback of the standard Smagorinsky model which can sometimes be over-dissipative near the boundary (Gotoh et al., 2004).

If we further neglect the turbulence effect following Liu et al. (1999) and Karunarathna and Lin (2006), the flow inside the porous media then can be described by the spatially averaged NS-type equations as in Liu et al. (1999) except that the resistance forces are of the form proposed by Sollitt and Cross (1972).

$$\frac{d\rho}{dt} = -\frac{\rho}{n_w}\nabla\cdot\mathbf{u} \tag{6}$$

$$\frac{1}{n_w}\frac{d\mathbf{u}}{dt} = -\frac{1}{\rho}\nabla P + \mathbf{g} + \frac{\upsilon}{n_w}\nabla^2\mathbf{u} - \frac{\upsilon}{K_p}\mathbf{u} - \frac{C_f}{\sqrt{K_p}}\mathbf{u}|\mathbf{u}| \tag{7}$$

where $\mathbf{u}$ is Darcy velocity and physically understood as a spatially averaged quantity, and n_w is the porosity of the porous media.