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Numerical model on the flow dynamics around the sediment-water interface in the tidal coastal area

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ABSTRACT

Investigating flow dynamics around the sediment-water interface is one of difficult issues in marine environment. It has important significance to study the physical, chemical and biological activities between the overlying water and sedimentary layer with tidal forcing. In this study, we established a numerical model to investigate the flow dynamics around the sediment-water interface in the tidal coastal area. The model reflected the hydrodynamics of periodic reciprocating unsteady flow in the overlying water layer and the fully coupled simulation of flow movement between the overlying water layer and sedimentary layer. A sedimentary layer, an overlying water layer, and an air layer were all treated as the fluid zone. The unsteady Reynolds-averaged Navier-Stokes equations, and the Reynolds stress model with porosity, were solved by the finite volume method. Moreover, the drag source term in the momentum equation was modified as the Darcy-Forchheimer extended form. The model showed a strong performance in simulating the hydrodynamics of coupled flow around the sediment-water interface with tidal forcing in a coastal area. With considering the sedimentary layer, the benthic boundary layer velocity distributions were more accurate than those obtained by a wall function model. Around the sediment-water interface, there was inertial loss in the flow. Furthermore, velocity increased with increasing porosity, and velocity gradient became larger. Compared with models with Darcy's Law, the numerical model in this study had better performance in the turbulent characteristics of sediment-water interface layer. The model can lead to better understanding of the exchange mechanisms of oxygen, nitrogen and nutrient between overlying water and sediment.

1. Introduction

In coastal areas, tidal effect is significant and the vertical structure of flow changes frequently. The pressure gradient changes significantly between the sedimentary layer (SL) and overlying water layer (OWL), so that flow exchange processes change with flow hydrodynamic conditions. Generally, convection and diffusion are the main dynamic mechanisms of exchange between the SL and OWL. However, their precise role is not well understood. Therefore, investigation of flow above and below a sediment-water interface (SWI) with tidal forcing is significant in the study of marine biology and chemical processes.

Sediment porosity and flow hydrodynamic characteristics of the sediment-water interface layer (SWIL) are important factors controlling exchange process between the SL and OWL. The schematic diagram of SWIL mentioned above presents in Fig. 1. It contains the benthic boundary layer (BBL, including the logarithm law layer and viscous sublayer), SWI, and surficial sedimentary layer (SSL, which is defined as the area of 0.5 m depth below the SWI). When porosity is high, the flow in the SL is weaker than that in the OWL, owing to the decreased flow section. Moreover, it limits the scale of intense flow movement (Boudreau and Guinasso, 1982). The SWIL is an important boundary that connects the SL and OWL, and its flow hydrodynamic characteristics affect convection and diffusion (Archer et al., 1989; Gundersen and Jørgensen, 1990; Svensson and Rahm, 1991; Zhu et al., 2013). At present, in-situ observations (Cook et al., 2007; Ali and Lemckert, 2009; Zhang et al., 2013), flume experiments (Carling et al., 2006; Volkenborn et al., 2010; Blois et al., 2014) and numerical simulations are the major means that are used to study the SWIL.

Numerical simulation is one of the most important methods for investigating the SWIL, with two main approaches used. In the first,

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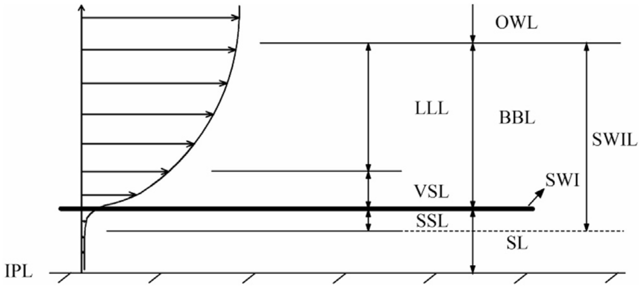

Fig. 1. Schematic diagram of sediment-water interface layer (SWIL). Where IPL is impermeable layer, LLL is logarithm law layer, VSL is viscous sublayer, SSL is surficial sedimentary layer, OWL is overlying water layer, BBL is benthic boundary layer, SL is sedimentary layer, and SWI is sediment-water interface.

the influence of the SL is neglected. Empirical approaches have been applied to study flow movement in the BBL (Richards, 1982; Svensson and Rahm, 1988). However, owing to the periodic change of flow movement in the tidal environment, deviation occurs in BBL structure and dynamics, and its hydrodynamics do not conform to the law of wall completely, as proposed by Lorke et al. (2003). The second approach incorporates the influence of the SL. A semi-coupled model is used to simulate flow movement in the SWIL, while neglecting the water moving from the SL to OWL (Webster et al., 1996; Cardenas and Wilson, 2007; Janssen et al., 2012; Trauth et al., 2013). Flow in the OWL and SL is simulated separately. The seabed pressure distribution obtained from the OWL simulation is used as the upper boundary of the SL. In the SL, velocity is calculated using the general equation of Darcy's Law. The general formulation of Darcy's Law is applied to simulate laminar flow for low Reynolds numbers. However, flow in the surface of the SL is impacted by the overlying water, with extra dissipation caused by inertia and turbulent effects, as proposed by Mohamad et al. (2015). Hence, in coastal areas, with complicated flow movement, the general form of Darcy's Law is unable to represent the hydrodynamics of the SWIL. Therefore, an empirical nonlinear modified form of Darcy's Law is used, with the addition of a quadratic velocity term, as originally put forward by Forchheimer (Irmay, 1958). The effectiveness of the Darcy-Forchheimer Law has been validated experimentally by Fand et al. (1987). Further studies, added the Darcy-Forchheimer modified form in the momentum equation for describing porous medium drag in the SL, and it has been used to simulate flow in the SWIL under steady flow (De Lemos and Silva, 2006; Graminho and De Lemos, 2009).

Previous studies have widely investigated the hydrodynamics of unidirectional flow in the SWIL. Considering flow transfer in the SL, both steady flow (Cook et al., 2007; Chen et al., 2015) and unsteady flow (Boano et al., 2007; Lee et al., 2012) have been simulated. However, flow movement in coastal areas is periodic reciprocating and unsteady, and the water level and velocity of tidal current periodically vary. Previous studies have not been able to fully reflect tidal current activity in the SWIL.

The aims of this study were to reflect the hydrodynamics of periodic reciprocating unsteady flow in the OWL and implement a fully coupled simulation of flow movement above and below the SWI. In this study, a SL, an OWL, and an air layer were all treated as the fluid zone in the calculations. The unsteady Reynolds-averaged Navier-Stokes equations and Reynolds stress model with porosity were solved by the finite volume method. Additionally, the volume of fluid method was used to track the free surface. The drag source term in the momentum equation was modified as the Darcy-Forchheimer extended form, and porosity was added in the unsteady terms. Finally, flow movement above and below the sediment-water interface was simulated with tidal forcing in a coastal area. The simulated results were compared with measured data and previous studies to assess the reasonableness of the numerical model used in this study. Furthermore, the influence of SL on simulations was analyzed.

2. Numerical model

2.1. Governing equations

In this study, a SL, an OWL, and an air layer were all treated as fluid zone in the calculations. The SL was regarded as a rigid porous medium without considering sediment formation mechanisms. Meanwhile, the OWL was considered to meet the conditions of $\varphi = 1$ and $S_i = 0$, where φ is porosity and S_i is the drag source term. Velocity, pressure, turbulent kinetic energy and turbulent dissipation rate, and their fluxes across the SWI, were considered to be continuous (Graminho and De Lemos, 2009). In order to reflect the characteristics of porous medium, the unsteady Reynolds-averaged Navier-Stokes equations with porosity (Pope, 2000) were written as follows:

$$\frac{\partial(\varphi\rho)}{\partial t} + \frac{\partial}{\partial x_i}(\varphi\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\varphi\rho u_i) + \frac{\partial}{\partial x_j}(\varphi\rho u_i u_j) = -\frac{\partial(\varphi p)}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\varphi\mu\frac{\partial u_i}{\partial x_j} - \varphi\rho\overline{u'_i u'_j}\right) + S_i \tag{2}$$

where u_i is the velocity component; x_i is coordinates/position; $-\rho\overline{u'_i u'_j}$ is the Reynolds stress; t is time; ρ is density; and μ is the dynamic viscosity coefficient.

The SL was treated as a fluid zone. When flow moves in the SL, there is a loss in momentum, so a drag source term was added in the momentum equation. The drag source term represents the pressure gradient in a porous medium, which is proportional to velocity (or velocity squared). The drag source term contains a viscous loss term and an inertial loss term. In the momentum equation, the source term (De Lemos and Silva, 2006) is described as follow:

$$S_i = -\left(\sum_{j=1}^{3}\varphi^2 D_{ij}\mu u_j + \sum_{j=1}^{3}\varphi^3 C_{ij}\frac{1}{2}\rho|u_j|u_j\right) \tag{3}$$

where D_{ij} is the viscous loss coefficient matrix, and C_{ij} is the inertial loss coefficient matrix. They are described as follows:

$$D_{ij} = \begin{pmatrix} D_1 & 0 & 0 \\ 0 & D_2 & 0 \\ 0 & 0 & D_3 \end{pmatrix},\ C_{ij} = \begin{pmatrix} C_1 & 0 & 0 \\ 0 & C_2 & 0 \\ 0 & 0 & C_3 \end{pmatrix} \tag{4}$$

The viscous loss coefficient and the inertial loss coefficient are estimated by empirical formulas proposed by Irmay (1958) and Ergun (1952), respectively, which are shown as follows:

$$D_i = \frac{1}{\alpha_i},\ C_i = \frac{3.5}{D_p}\frac{1-\varphi}{\varphi^3} \tag{5}$$

where α_i is permeability; D_p is the mean particle diameter. The SL is assumed to be composed of silty clay, with porosity, horizontal permeability, and vertical permeability of 0.5, 1.4×10^{-16} m^2 and 1.1×10^{-16} m^2, respectively (Hu and Luo, 2013). In order to investigate the effect of porosity on the simulations, porosity conditions of $\varphi = 0.2$, $\varphi = 0.5$, and $\varphi = 0.8$ were used in this study. Values of the viscous loss coefficient and inertial loss coefficient for each