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Numerical calculation of hydrodynamic characteristics of tidal currents for submarine excavation engineering in coastal area

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Abstract

In coastal areas with complicated flow movement, deposition and scour readily occur in submarine excavation projects. In this study, a small-scale model, with a high resolution in the vertical direction, was used to simulate the tidal current around a submarine excavation project. The finite volume method was used to solve Navier-Stokes equations and the Reynolds stress transport equation, and the entire process of the tidal current was simulated with unstructured meshes, generated in the irregular shape area, and structured meshes, generated in other water areas. The meshes near the bottom and free surface were densified with a minimum layer thickness of 0.05 m. The volume of fluid method was used to track the free surface, the volume fraction of cells on the upstream boundary was obtained from the volume fraction of adjacent cells, and that on the downstream boundary was determined by the water level process. The numerical results agree with the observed data, and some conclusions can be drawn: after the foundation trench excavation, the flow velocity decreases quite a bit through the foundation trench, with reverse flow occurring on the lee slope in the foundation trench; the swirling flow impedes inflow, leading to the occurrence of dammed water above the foundation trench; the turbulent motion is stronger during ebbing than in other tidal stages, the range with the maximum value of turbulent viscosity, occurring on the south side of the foundation trench at maximum ebbing, is greater than those in other tidal stages in a tidal cycle, and the maximum value of Reynolds shear stress occurs on the south side of the foundation trench at maximum ebbing in a tidal cycle. The numerical calculation method shows a strong performance in simulation of the hydrodynamic characteristics of tidal currents in the foundation trench, providing a basis for submarine engineering construction in coastal areas.

Keywords: Small-scale model; Tidal current; Hydrodynamic characteristic; Coastal area; Submarine excavation engineering; Reynolds stress model

1. Introduction

Submarine excavation projects should be constructed precisely when they involve complicated construction conditions, such as channel excavation engineering, submarine pipeline engineering, and submarine immersed tube tunnel engineering. Back silting and slope damage usually occur in excavation projects, owing to deposition and scour. This problem has crucial implications for engineering construction. For example, the 15th immersed tube of the Hong Kong-Zhuhai-Macau Bridge could not be placed in the foundation trench due to serious sedimentation (Li, 2015). When immersed tubes were sunk and installed, the lateral force, drifting force, and mooring force acting on the tubes changed significantly because of the hydrodynamic change (Lu et al., 2014). Therefore, investigation of the hydrodynamic characteristics for submarine excavation projects in coastal areas is highly significant.

Tidal action is one of the most important impact factors in a coastal area. The horizontal scale of a tidal current is much greater than its vertical scale. Based on the static pressure hypothesis, three-dimensional shallow water equations have

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been derived using the water level variable instead of the pressure variable (Liu and He, 2000). According to previous studies, three-dimensional large-scale hydrodynamic models, such as the Princeton ocean model (POM) (Ohashi and Sheng, 2013; Gao et al., 2013), the environmental fluid dynamics code model (EFDCM) (Zhou et al., 2014; Ren et al., 2015), the estuarine, coastal, and ocean model (ECOM) (Ningsih and Azhar, 2013), the coupled hydrodynamical ecological model for regional and shelf seas (COHERENS) (Shi et al., 2010; Tuomi et al., 2012), and the finite-volume coastal ocean model (FVCOM) (Chen et al., 2007), have been commonly used to study the spatial and temporal variability of tidal current movement. Their commonly used turbulence sub-models are the Smagorinsky, the Mellor and Yamada, and the k-ε models (Abbott, 1997). The sigma coordinate mode along the vertical direction has also been used to fit both the free surface and bed topography (Berntsen and Furnes, 2005).

The large-scale hydrodynamic models mentioned above have been limited to two-dimensional or weakly three-dimensional flows over a large calculation range, meaning that they are only meshed at a low resolution in the vertical direction, considering the effect of computational efficiency. If the terrain changes drastically, the sigma coordinate mode cannot achieve a high resolution in both shallow and deep waters (Gräwe et al., 2015; Berntsen et al., 2015). It is also difficult to densify the local water area in the vertical direction (Tao and Zhang, 2007). Therefore, a small-scale model should be used to study the tidal current in a study region around submarine excavation projects.

Small-scale models have been used to solve the Navier-Stokes equations and analyze flow structures in complicated calculation domains (Tang et al., 2015). They have the advantages of smaller grids, more layers, and higher resolutions in the vertical direction (Tang et al., 2014). Using the small-scale model in the simulation, the characteristics of unidirectional flow around the submarine structures were focused on, and the currents at the upstream boundary were considered the inflow to the calculation domains (Wu and Wang, 2009; Lubin et al., 2010; Nielsen et al., 2013). However, the results could not reflect the entire process of reciprocating motion due to tidal currents, even though the hydrodynamic characteristics during ebbing and flooding were also studied. Lefebvre et al. (2014) investigated the dynamic behavior of the bedform-influenced flow field and roughness lengths over a large bedform during a tidal cycle by establishment of a small-scale model with more than 50 layers in the vertical direction. However, their study essentially simulated unidirectional flow in ebbing and flooding, respectively, and the hydrodynamic characteristics for transition were not studied.

In this study, we aimed at obtaining the hydrodynamic characteristics of tidal currents for submarine excavation projects. The finite volume method was used to solve the Navier-Stokes equations and the Reynolds stress transport equation. With the foundation trench excavation in the Hong Kong-Zhuhai-Macau Bridge Project in the Pearl River Estuary as an example, the processes of tidal movement after the foundation trench excavation were simulated, and the numerical results were compared with the observed data for the purposes of analyzing the reasonability of the numerical calculation method used in this study.

2. Mathematic model descriptions

2.1. Governing equations

The basic governing equations for mass and momentum conservation (Pope, 2000; Zhao et al., 2013) are as follows:

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

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

where u_i and u_j are the velocity components in the x_i and x_j directions, respectively, and i, j = 1, 2, 3; p is the pressure; $-\rho\overline{u_i'u_j'}$ is the Reynolds stress; t is time; ρ is the density of fluid; μ is the dynamic viscosity coefficient; and S_i is the momentum source term.

Considering anisotropics of turbulent viscosity, the Reynolds stress model (Versteeg and Malalasekera, 2007) was used in this study. The Reynolds stress transport equation and turbulent dissipation rate transport equation (Pope, 2000; Duan et al., 2015) are shown below:

$$\frac{\partial}{\partial t}(\rho\overline{u_i'u_j'})+\frac{\partial}{\partial x_r}(\rho u_r\overline{u_i'u_j'})=D_{\mathrm{T},ij}+D_{\mathrm{L},ij}+P_{ij}+G_{ij}+\phi_{ij}+\varepsilon_{ij}+F_{ij}+S_{\mathrm{RS}} \tag{3}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_\mathrm{t}}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_i}\right]+\frac{1}{2}C_{\varepsilon1}(P_{ii}+C_{\varepsilon3}G_{ii})\frac{\varepsilon}{k}-C_{\varepsilon2}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{4}$$

where the subscript r means the x_r direction; $D_{\mathrm{T},ij}$ is the turbulent diffusion term; $D_{\mathrm{L},ij}$ is the molecular diffusion term; P_{ij} is the stress production term; G_{ij} is the buoyancy production term; ϕ_{ij} is the pressure strain term; ε_{ij} is the dissipation term; F_{ij} is the production term according to the system rotation; k is the turbulent kinetic energy; ε is the turbulent dissipation rate; μ_t is the turbulent viscosity; S_{RS} and S_ε are the source terms; σ_ε is the Prandtl number for ε with a value of 1.3; and $C_{\varepsilon1}$, $C_{\varepsilon2}$, and $C_{\varepsilon3}$ are constants with the values of 1.44, 1.92, and 0, respectively. $D_{\mathrm{L},ij}$, P_{ij}, and F_{ij} only contain two-order correlation terms, and $D_{\mathrm{T},ij}$, G_{ij}, ϕ_{ij}, and ε_{ij} contain uncertain correlation terms, which can be calculated as follows:

$$D_{\mathrm{T},ij}=\frac{\partial}{\partial x_r}\left(\frac{\mu_\mathrm{t}}{\sigma_k}\frac{\partial\overline{u_i'u_j'}}{\partial x_r}\right) \tag{5}$$

$$G_{ij}=0 \tag{6}$$