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A 3-D semi-coupled numerical model for fluid–structures–seabed-interaction (FSSI-CAS 3D): Model and verification

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ABSTRACT

In this study, a semi-coupled 3-D numerical model for fluid–structures–seabed-interaction is developed. The dynamic Biot's equation known as "*u*–*p*" approximation, and modified Navier–Stokes equation in which the linear drag force between the flowing pore water and the solid matrix of porous medium is included, is respectively adopted as the governing equation in the soil sub-model and the wave sub-model. A coupling algorithm is developed to integrate the two sub-models together, in which non-match mesh and non-match time scheme are used based on the shepherd interpolation method. The data exchange is implemented at the interface between fluid domain and seabed/marine structures domain adopting the coupling algorithm. Finally, the developed 3-D numerical model is validated by an analytical solution and a laboratory wave flume test.

1. Introduction

In recent two decades, more and more marine structures, such as breakwater, oil platform and turbine, have been constructed in offshore areas. The response of seabed foundation, and the stability of marine structures built on seabed foundation under ocean wave loading becomes the main issue most concerned by coastal engineers involved in design of marine structures. In coastal zones, the breakwaters are widely used to protect the coastline from damage and erosion, and also could protect the people living in the zones near the coastline from death and properties loss induced by the probable tsunami attack. However, the breakwaters built on porous seabed are vulnerable to the liquefaction and the shear failure of seabed foundation (Chung et al., 2006; Franco, 1994; Lundgren et al., 1989). In the practice of engineering, an inappropriate design and maintenance of a breakwater would result in the collapse of breakwater after construction, and further bring great economic loss. Therefore, it is meaningful to develop an effective analysis tool for coastal engineers to predict and evaluate the stability (liquefaction and shear failure) of seabed foundation beneath the marine structures under wave loading.

Some investigations have been conducted on the problem of fluid–breakwater–seabed interaction (FSSI) in the last 20 years. These investigations included analytical solutions (Hsu et al., 1993; Tsai, 1995; Tsai et al., 2000), decoupled numerical model (Mase et al., 1994; Ulker et al., 2010, 2012) and coupled numerical model (Cheng et al., 2007; Hur and

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Mizutani, 2003; Hur et al., 2008, 2010; Mizutani and Mostafa, 1998; Mizutani et al., 1998, 1999; Mostafa et al., 1999). Among these proposed analytical solutions for the FSSI problem, only the cases in which simple boundary conditions were involved could be dealt with; for example, the Stokes waves were used to apply the wave-induced pressure on seabed; and the breakwater was simplified as a line without width and weight; the wave-induced pressure on breakwater could not be taken into consideration. The application of decoupled numerical models to the FSSI problem also deserved some inevitable constraints. The linear or nonlinear Stokes waves were adopted to apply the wave-induced pressure acting seabed and breakwater in numerical computation. Hence, the effect of the outer shape of breakwater and the porosity of seabed and rubble mound on the wave characteristics near the breakwater was ignored. For example, the linear standing wave was used to apply the loading on seabed and breakwater in Mase et al. (1994) and Ulker et al. (2010, 2012). Actually, the wave field in front of the breakwater was not a standing wave due to the fact that the front lateral side of breakwater was not a vertical wall.

The coupled numerical model is an ideal method for the FSSI problem. At present, there are two types of coupled numerical models available for the FSSI problem in literatures. The first type coupled model emphasizes its attention on the interaction between the seawater and the pore water in seabed and porous marine structures, such as rubble mound breakwater (Hur and Mizutani, 2003; Hur et al., 2008, 2010). The effect of the outer shape of breakwater and the porosity of seabed and rubble mound on the wave characteristics near the breakwater could be sufficiently considered. However, the wave induced effective stress status in seabed and breakwater could not be determined. The second type coupled model further integrates the governing equation of fluid into Biot's equation to study the FSSI problem. The wave induced effective stress status in seabed and breakwater can be determined (Cheng et al., 2007; Mizutani and Mostafa, 1998; Mizutani et al., 1998, 1999; Mostafa et al., 1999,). Due to the fact that the Navier–Stokes equation, and k–ε turbulence model are used for the wave motion in seawater, the interaction between a complex wave (such as breaking wave), seabed and breakwater is possible to be simulated. For example, most recently, adopting the 2-D coupled model developed by Ye (2012) and Ye et al. (submitted for publication) investigates the interaction between a breaking wave, porous coastal slopes and a composite breakwater, and studies the wave-induced momentary liquefaction in the seabed foundation in front of the composite breakwater. Detailed review for the wave–seabed–breakwater interaction can be found in Ye (2012).

To the author's knowledge, all previous coupled numerical models are limited to two dimensional cases. There is no 3-D coupled numerical model to investigate the FSSI problem. In this study, a 3-D coupled numerical model is developed for the 3-D FSSI problem, in which two sub-models are included: soil model and wave model. Biot's dynamic equation is used as the governing equation in the soil model; the modified Navier–Stokes equation, in which the linear drag force between the flowing pore water and the solid matrix of porous medium is included, is used to govern the wave motion in the wave model. A coupling algorithm is developed to integrate the two sub-models together. Finally, the developed model is validated by an analytical solution and a laboratory wave flume test. Actually, this 3-D numerical model is a continuation of the previous 2-D numerical model for FSSI problem developed by Ye et al. (submitted for publication, in press).

2. Semi-coupled 3-D numerical model

2.1. Soil model

It is well known that the seabed is a porous medium consisting of the soil particles, pore water and trapped air. Biot's theory is widely adopted to describe the mechanical behaviors of porous medium. In this numerical model, the dynamic Biot's equation known as "u–p" approximation proposed by Zienkiewicz et al. (1980) is used as the governing equation for 3-D porous seabed. The relative displacements of pore water to the soil particles are ignored; however, the acceleration of the pore water and soil particles are considered in the governing equation.

The equilibrium equations are

$$\frac{\partial \sigma_x'}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}=-\frac{\partial p_s}{\partial x}+\rho\frac{\partial^2 u_s}{\partial t^2}, \tag{1}$$

$$\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \sigma_y'}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}=-\frac{\partial p_s}{\partial y}+\rho\frac{\partial^2 v_s}{\partial t^2}, \tag{2}$$

$$\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \sigma_z'}{\partial z}+\rho g=-\frac{\partial p_s}{\partial z}+\rho\frac{\partial^2 w_s}{\partial t^2}. \tag{3}$$

The mass continuity of pore water is

$$k\nabla^2 p-\gamma_w n\beta\frac{\partial p_s}{\partial t}+k\rho_f\frac{\partial^2 \varepsilon_v}{\partial t^2}=\gamma_w\frac{\partial \varepsilon_v}{\partial t}, \tag{4}$$

where u_s, v_s, and w_s are the soil displacements in the x, y, and z directions, respectively; n is the porosity of soil; σ'_x, σ'_y and σ'_z are the effective normal stresses in the horizontal and vertical directions; τ_{xy}, τ_{yz} and τ_{xz} are the shear stresses; p_s is the pore pressure in porous medium; $\rho=n\rho_f+(1-n)\rho_s$ is the average density of porous medium; ρ_f is the fluid density; ρ_s is the solid density; k is Darcy's permeability; g is the gravitational acceleration and γ_w is the unit water weight. ε_v is the