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Numerical investigation of dynamic soil response around a submerged rubble mound breakwater

H.Y. Zhao [a,b], Z.D. Liang [b], D.-S. Jeng [a,b], J.F. Zhu [c], Z. Guo [d], W.Y. Chen [e,*]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China
[b] School of Engineering & Built Environment, Griffith University Gold Coast Campus, Queensland 4222, Australia
[c] Faculty of Architectural Civil Engineering and Environment, Ningbo University, Ningbo 315211, China
[d] College of Civil Engineering and Architecture, Zhejiang University, Zhejiang 310058, China
[e] Institute of Geotechnical Engineering, Nanjing Technical University, Nanjing 210009, China

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ABSTRACT

A better understanding of physical process of the fluid-seabed-structure interaction (FSSI) is beneficial for engineers involved in the design of marine infrastructures. Most previous studies for the problem of FSSI have considered wave-only conditions, despite the co-existence of wave and current in the real ocean environment. Unlike the previous studies, currents are included in the present study for the numerical modelling of FSSI, using an integrated FVM-FEM scheme, in which the VARANS equation is used to simulate fluid field, while Biot's poro-elastic model is used for porous flow in a seabed. Numerical examples show the important influences of currents on the local hydrodynamic process and the resulting dynamics of seabed foundation around a submerged rubble mound breakwater. The structure is relatively stable in the presence of counter-current waves, whereas the co-current waves would significantly compromise the instability of structure due to potential of shear failure and liquefaction in its sandy seabed foundation.

1. Introduction

Protection of coastal zone has become a priority for coastal communities in the last few decades. Submerged breakwaters, which are advantageous in terms of environmental considerations, have been commonly constructed in the offshore regions to enhance the utility of coastlines. One of the main concerns involved in the design of submerged breakwaters is the dynamic response of its underlying soil layers due to ocean wave loading. This is particularly important for the evaluation of the stability of a marine infrastructure during the entire design life (Oumeraci, 1994; Jeng, 2013; Sumer, 2014).

A large number of studies for the dynamic soil response around marine structures have been conducted for years, mainly involving analytical approximations (Hsu and Jeng, 1994; Jeng, 1996; Jeng and Ou, 2010), numerical modeling (Jeng, 2003; Ulker et al., 2010), or laboratory experiments (Sumer et al., 2008; Kirca et al., 2013). Among these, an analytical approximation is an efficient tool in the early stage due to its simplicity and low computational cost. It also rises the difficulty in handling the complex boundary value problems. As such, the configuration of structure considered in the analytical approximations is normally oversimplified and far from the realistic situations. Compared to the analytical solutions, numerical modeling is more flexible in terms of geometrical complexities. Jeng (2003) developed a generalized FEM model by introducing the complex into Biot's equations and applying the Galerkin method, in which all wave-induced soil response parameters were to fluctuate periodically in the time domain. This model was reported to have been used in two applications: wave-seabed-pipeline interactions (Jeng et al., 2001b) and wave-seabed-caisson interactions (Jeng et al., 2001a). Ulker et al. (2010) developed a FEM model to study the elastic seabed underneath a caisson breakwater for three different Biot's formulations: the quasi-static, partially dynamic and fully dynamic. They concluded that for the frequency range of loading of the seabed underneath a breakwater induced by the structural rocking motions, the fully dynamic formulation should be considered.

In the aforementioned investigations, analytical solutions are used as pressure boundary conditions, whereas potential flow theory is incapable of capturing the local hydrodynamic processes involved in the fluid-structure interactions in many aspects, i.e. contraction of flow, vortex shedding, turbulence generation and wave breaking. In fact, computational fluid dynamics (CFD) models for fluid-structure interactions is a

* Corresponding author.
E-mail address: cwy@njtech.edu.cn (W.Y. Chen).

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relatively mature research project that has been intensively developed before (Lin and Liu, 1998; Lara et al., 2006), in which structures were considered to be fixed, or flexible with porous media being considered as non-deformable body that has added resistance to fluid flow. In these investigations, the use of Navier-Stokes equation with an Eulerian framework has proven to be useful in reproducing local hydrodynamic processes and is highly accurate. From this point of view, recent models have been developed as an integrated system, in which the CFD models and geotechnical models are semi-coupled through pressure continuity at common boundaries or other ways. The use of advanced computational fluid dynamics in these multi-physics models enhances the understanding of FSSI in many cases, i.e., breaking wave impacts on caisson and subsequently on the foundation (Ye et al., 2014; Elsafti and Oumeraci, 2017), porosity of structure on wave field and subsequently dynamics of their seabed foundation (Hur et al., 2010; Zhang et al., 2011).

Most previous investigations for the wave-seabed interactions around marine structures have considered wave-only conditions. However, in the realistic oceanic environments, the propagation of ocean waves is usually accompanied with currents. The presence of currents may be further complicate the wave transformations around the structure, and the subsequent dynamics of underlying soil layers that are intensively related to the stability of structure. To better understand the physical process involved in the wave (current)-seabed-structure interactions, an integrated FVM-FEM model is developed in this study by semi coupling the VARANS equation and Biot's poro-elastic solution through pressure continuity at the fluid-porous material interfaces. The proposed model will be validated by comparing with the previous experimental data first. Both the hydrodynamic and geotechnical process associated with the fluid-soil-submerged breakwater interactions will be examined. Finally, the influence of the key parameters on the seabed instability around a structure will be quantified through parametric studies.

2. Numerical model

2.1. Geotechnical model

In general, geomaterials selected as foundations for coastal and offshore structures are inherently heterogeneous; which basically consisting of a solid phase (with soil skeleton) and a fluid phase (with water and air). Herein, a 2-D geotechnical model is developed, in which the"$u-p$" approximation (Zienkiewicz et al., 1980) (also known as partially dynamic equation (Ulker et al., 2009)) is employed. The governing equations for a porous flow can be expressed as the follows:

$$\frac{\partial \sigma'_x}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} = -\frac{\partial p_s}{\partial x} + \rho \frac{\partial^2 u}{\partial t^2} \tag{1}$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \sigma'_z}{\partial z} + \rho g = -\frac{\partial p_s}{\partial z} + \rho \frac{\partial w^2}{\partial t^2} \tag{2}$$

$$k_s \nabla^2 p_s - \gamma_w n_s \beta_s \frac{\partial p_s}{\partial t} + k_s \rho_f \frac{\partial^2 \varepsilon_s}{\partial t^2} = \gamma_w \frac{\partial \varepsilon_s}{\partial t}, \tag{3}$$

where p_s is the pore water pressure; u_s and w_s represent the horizontal and vertical components of soil displacements; σ'_x and σ'_z are the horizontal and vertical components of effective normal stresses, respectively; τ_{xz} is the shear stress; n_s is the porosity of soil; γ_w is the unit weight of pore water; $\rho = n_s\rho_f + (1-n_s)\rho_s$ is the average density of porous medium; k_s is the Darcy's permeability coefficient, which should be the same in all directions for isotropic porous seabed considered in this study. In (1), volumetric strain (ε_s) and compressibility of pore fluid (β_s) and are defined as

$$\varepsilon_s = \frac{\partial u_s}{\partial x} + \frac{\partial w_s}{\partial z}, \ \beta_s = \frac{1}{K_f} + \frac{1-S_r}{p_{w0}}, \tag{4}$$

in which p_{w0} is the absolute static pressure and K_f is the bulk modulus of the pore water, which is taken as $1.95 \times 10^9\ \mathrm{N/m^2}$ for pore-water,

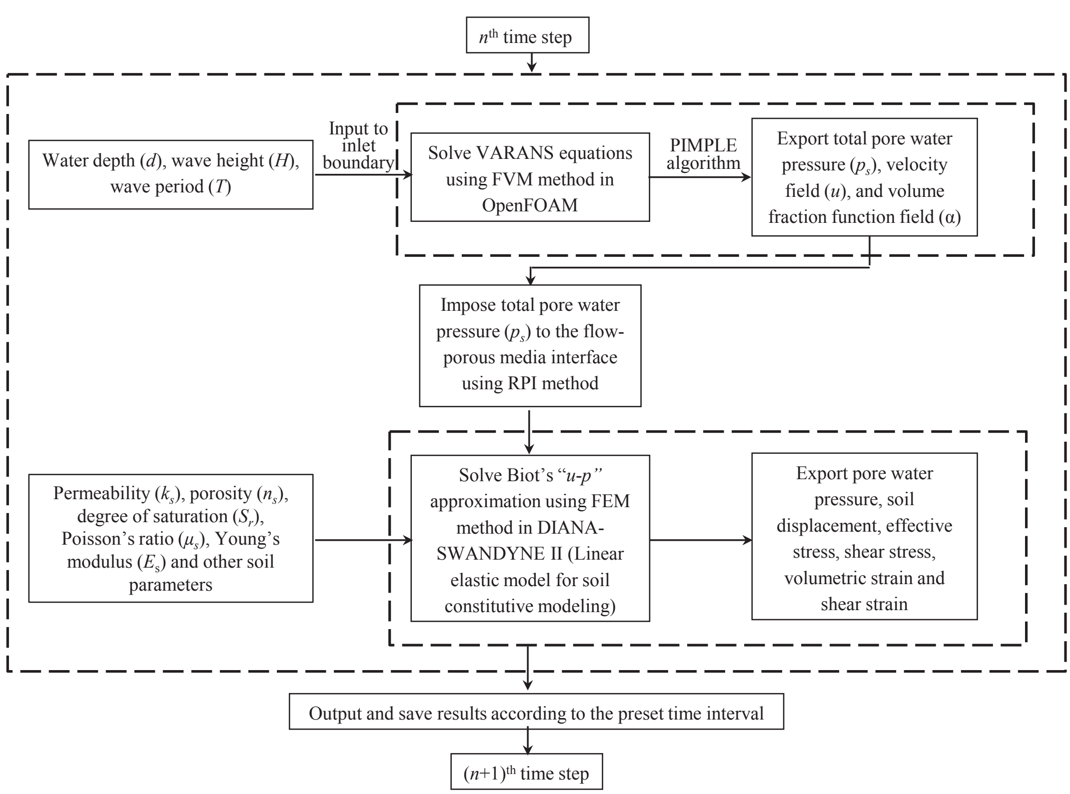

Fig. 1. Coupling process employed in the FVM-FEM model.