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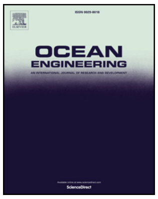

Stability analysis of a composite breakwater at Yantai port, China: An application of FSSI-CAS-2D

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ABSTRACT

In offshore areas, quaternary loose seabed soils widely distribute around the world, and a great number of offshore structures actually have been constructed on quaternary seabed floors. In practical engineering, it is highly necessary to evaluate the stability of offshore structures built on quaternary seabed floors under the impact of extreme ocean waves. Based on the VARANS equation and the dynamic Biot's equation, an integrated numerical model FSSI-CAS 2D has been developed by Ye et al. (2013b) to investigate the interaction between ocean waves, marine structures and their seabed foundations. In this study, taking the composite breakwater project in the west harbour zone of Yantai port in China as an engineering case, the integrated numerical model FSSI-CAS-2D is used to evaluate the stability of the composite breakwater under the impact of fortified ocean waves with a 50 years recurrence period. Computational results indicate that the composite breakwater at west harbour zone of Yantai port would be generally stable during its service life. This application demonstrates that the integrated model FSSI-CAS-2D is applicable, and suitable for practical engineering. The case study illustrated in this study can provide ocean engineers with an excellent case demonstration of engineering application, to evaluate the stability of offshore structures under the impact of extreme ocean waves.

1. Introduction

In last 20 years, a great number of marine structures, such as breakwaters, have been constructed in offshore areas. The stability of offshore marine structures under ocean wave loading is the main concern of ocean engineers involved in design. In offshore environment, newly deposited Quaternary seabed soil is widely distributed, for example, the loose silty soil in the zone of the estuary of Yellow River in China. Actually, a great number of offshore structures have been built on Quaternary sediments. The particle arrangement of Quaternary seabed soil generally is relatively loose, far from being very dense. Under cyclic ocean wave loading, seabed soil particles re-arrange their relative positions to a more dense status, accompanied by a pore water drainage process. In this process, the pore water pressure builds up, making soil liquefy, or soften. As a result, the overlaying marine structures would lose their stability. Therefore, it is of great importance to quantitatively evaluate the stability of offshore marine structures constructed on quaternary loose seabed floors.

The preconditions for evaluating the stability of offshore marine structures include two aspects: (1) understanding the mechanism of wave-structure-seabed interaction, (2) development of numerical models for stability evaluation. In early stage, analytical solutions were widely proposed to study the mechanism of wave-seabed interaction, in which marine structures could not be considered. Due to the limitation of analytical methods, seabed soil must be very dense in which elastic deformation is dominant under wave loading. In analytical solutions, the dense seabed could be infinite (Yamamoto et al., 1978; Madsen, 1978) or finite (Hsu and Jeng, 1994; Jeng and Hsu, 1996) in depth; it also could be isotropic or anisotropic. The waves adopted in these analytical solutions were all based on Stokes wave theory, involving progressive wave, standing wave or short-crested wave (Hsu and Jeng, 1994). The governing equation for seabed soil could be the consolidation equation, the ‘u-p’ approximation, and the ‘u-w’ equation (Liao et al., 2015). Actually, the uncoupled method was adopted in these analytical solutions. There was no feedback from seabed soil to ocean wave when seabed responding to ocean wave. Besides, numerical methods are also powerful tool to investigate the wave-seabed interaction. However, most previous numerical investigations were also limited to very dense elastic seabed soil, such as those in Ye and Jeng (2012), Gatmiri (1990), Jeng and Lin (1996), Zhou et al. (2005) and

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Luan and Wang (2001). For the interaction between ocean waves and loose seabed floors, few investigations were undertaken. Until recently, Yang and Ye (2017) and Yang and Ye (2018) systematically study the dynamics characteristics of loose seabed floor under the impact of standing wave, and wave-current.

For the scientific problem of wave-structure-seabed interaction, it seems that numerical methods are the only feasible ways, due to the complexity of the interaction between ocean wave, marine structures and their seabed foundations. Mase et al. (1994) developed a FEM numerical model to investigate the wave-induced pore water pressures and effective stresses in a sandy seabed foundation beneath a composite caisson-type breakwater based on Biot's consolidation equation. After that, Mizutani et al. (1998) and Mizutani et al. (1999) developed a BEM-FEM combination numerical model to study the wave-seabed-structure interaction by adopting a prototype model. Their work greatly promoted the progress on wave-structure-seabed interaction. However, the numerical models proposed by Mase et al. (1994) and Mizutani et al. (1998) could not yet be applied in practice engineering due to the following two reasons. First, the potential flow theory involving Laplace's equation used in Mizutani et al. (1998) could not simulate the complicated motion of seawater in extreme ocean waves, such as breaking and turbulence, in real-life large scale cases. Second, only a poro-elastic soil model could be used in their numerical models. As presented above, a great number of offshore structures have been built on Quaternary loose seabed floor. The wave-induced behaviour of loose seabed foundation must be characterized using poro-elasto-plastic soil models.

To overcome the above two difficulties, Ye et al. (2013b) developed an integrated model FSSI-CAS 2D for the problem of fluid-structures-seabed interaction (FSSI). In the integrated model FSSI-CAS 2D, the Volume Average Renolds Average Navier Stokes (VARANS) equation was adopted to simulate the complicated motion of seawater in ocean waves, as well as porous flow in porous seabeds; the dynamic Biot's equation was adopted to describe the nonlinear behaviour of marine structures and their seabed foundations. A one-way integrating algorithm, based on the radial point interpolation method, was developed to link the two equations by guaranteeing the continuity of pressure and velocity at interfaces between the seawater domain and the seabed foundation, marine structures. The integrated model FSSI-CAS 2D has been widely validated by an analytical solution and a series of wave flume tests (Ye et al., 2013b). Most importantly, several poro-elasto-plastic soil models, such as Mohr-Coulomb, Modified Cambridge Clay, Pastor-Zienkiewics-Mark III etc., are available to describe the behaviour of loose seabed foundation in FSSI-CAS 2D. So far, this integrated numerical model has been successfully applied to investigate the dynamics of composite breakwater and its seabed foundation involving breaking wave (Ye et al., 2014), tsunami wave (Ye et al., 2013a) and loose seabed soil (Ye et al., 2015). It is indicated by these successful cases that the integrated model FSSI-CAS 2D can be applied in practice engineering to evaluate the stability of offshore marine structures.

In this study, taking the composite breakwater project at the west harbour zone of Yantai port in China as the engineering case, the integrated numerical model FSSI-CAS-2D was adopted to evaluate the stability of the composite breakwater under the impact of fortified ocean waves with a 50 years recurrence period. Computational results indicate that the composite breakwater at west harbour zone of Yantai port would be generally stable in its service life. This case application demonstrates that the integrated model FSSI-CAS-2D is applicable in the practical engineering; and this integrated model also can be utilized to optimize the design of offshore structures in the future.

2. Integrated model FSSI-CAS 2D

2.1. Governing equations

The dynamic Biot's equation, known as "$u - p$" approximation proposed in Zienkiewicz et al. (1980), is used to describe the dynamic response of porous medium under earthquake loading. In this formulation, the relative displacements of pore fluid to soil particles are ignored, but the acceleration of the pore water and soil particles are included:

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

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

$$k \nabla^2 p_s - \gamma_w n \beta \frac{\partial p_s}{\partial t} + k \rho_f \frac{\partial^2 \varepsilon_v}{\partial t^2} = \gamma_w \frac{\partial \varepsilon_v}{\partial t}, \tag{3}$$

where (u_s, w_s) are displacements of the soil in horizontal and vertical directions, respectively; n is soil porosity; σ'_x and σ'_z are effective normal stresses in the horizontal and vertical directions, respectively; τ_{xz} is shear stress; p_s is the pore water pressure; $\rho = \rho_f n + \rho_s(1 - n)$ is the average density of porous seabed; ρ_f is the fluid density; ρ_s is solid density; k is the Darcy's permeability; g is the gravitational acceleration; γ_ω is specific weight of water and ε_v is the volumetric strain. In equation (3), the compressibility of pore fluid (β) and the volume strain (ε_v) are defined as

$$\beta = \left(\frac{1}{K_f} + \frac{1 - S_r}{p_{w0}} \right), \quad \text{and} \quad \varepsilon_v = \frac{\partial u_s}{\partial x} + \frac{\partial w_s}{\partial z}, \tag{4}$$

where S_r is the degree of saturation of seabed, p_{w0} is the absolute static pressure and K_f is the bulk modulus of pore water. In general, $K_f = 2.24 \times 10^6$ kPa.

The finite element method is used to solve the above governing equations (1)–(3). The discretized governing equations are

$$\mathrm{M}\ddot{\mathbf{u}} + \mathrm{K}\mathbf{u} - \mathrm{Q}\mathbf{p} = f^{(1)} \tag{5}$$

$$\mathrm{G}\ddot{\mathbf{u}} + \mathrm{Q}^{\mathrm{T}}\dot{\mathbf{u}} + \mathrm{S}\dot{\mathbf{p}} + \mathrm{H}\mathbf{p} = f^{(2)} \tag{6}$$

The Generalized Newmark p^{th} order scheme for j^{th} order equation is adopted as the numerical integration when solving the above discretized equations. The definition of the coefficient matrices M, K, Q, G, S, H, $f^{(1)}$, , and the detailed information for the numerical method to solve the Biot's equation can be found in Ye (2012); Ye et al. (2013b); Zienkiewicz et al. (1999).

For the problem of Fluid-Structure-Seabed Interaction (FSSI), a coupled numerical model FSSI-CAS 2D was developed by Ye (2012). In FSSI-CAS 2D, the Volume Average Reynolds Average Navier Stokes (VARANS) equation (Hsu et al., 2002) governs wave motion and porous flow in porous seabed. The above dynamic Biot's equation governs the dynamic behaviour of offshore structure and its seabed foundation. A coupled algorithm is developed to couple the VARANS equation and Biot's dynamics equation together. More detailed information about the coupled model can be found in Ye et al. (2013b), Ye (2012) and Zienkiewicz et al. (1999).

In this study, large deformation occurs in the seabed foundation near to breakwater built on loose liquefiable seabed under seismic wave shaking. The updated Lagrangian method is adopted to deal with this large deformation problem. In the computation, the coordinates of nodes, status variables of soil, which are dependent on the effective stress history, such as void ratio e and permeability k are updated in each time step based on deformation. Correspondingly, the coefficient matrices M, K, Q, G, S, H, $f^{(1)}$, , as well as boundary values on boundaries are also updated.

2.2. Constitutive model: Pastor-Zienkiewics-Mark III

Based on classical plasticity theory, the constitutive relationship for the effective stress and strain of the soil can be written as:

$$\sigma'_{ij} = \mathrm{D}^{ep}_{ijkl} \varepsilon_{kl} \tag{7}$$