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Consolidation of unsaturated seabed around an inserted pile foundation and its effects on the wave-induced momentary liquefaction

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A R T I C L E I N F O

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A B S T R A C T

Seabed consolidation state is one of important factors for evaluating the foundation stability of the marine structures. Most previous studies focused on the seabed consolidation around breakwaters standing on the seabed surface. In this study, a numerical model, based on Biot's poro-elasticity theory, is developed to investigate the unsaturated seabed consolidation around a nearshore pile foundation, in which the pile inserted depth leads to a different stress distribution. Seabed instabilities of shear failure by the pile self-weight and the potential liquefaction under the dynamic wave loading are also examined. Results indicate that (1) the presence of the inserted pile foundation increases the effective stresses below the foundation, while increases and decreases the effective stresses around the pile foundation for small ($de/R <=3.3$) and large ($de/R > 3.3$) *inserted depths, respectively, after seabed consolidation, (2) the aforementioned effects are relatively more significant for small inserted depth, large external loading, and small Young's modulus, (3) the shear failure mainly occurs around the inserted pile foundation, rather than below the foundation as previously found for the located marine structures, and (4) wave-induced momentary liquefaction near the inserted pile foundation significantly increases with the increase of inserted depth, due to the change of seabed consolidation state.*

1. Introduction

Seabed stability around marine structures is one of the main factors that must be considered in the foundation design. It has been well known that the seabed would suffer long-time consolidation under the gravity loading of the marine structures (Krost et al., 2011). This long-time consolidation may cause the complex stress distribution, the excess pore pressure dissipation and the seabed continuous subsidence (Ye, 2012b). Inappropriate design of the foundation may result in the shear failure of the surrounding soil and the structure collapse (Chung et al., 2006). Most of previous studies focused on the seabed liquefaction and scour under the dynamic wave and current loadings (Ye and Jeng, 2012; Sui et al., 2016; Sumer, 2014; Zhang et al., 2015; Zhou et al., 2015), but less attention was paid to the shear failure within the seabed during the consolidation process. Due to its practical importance for engineering construction, reliable and appropriate assessment of the seabed consolidation state is therefore required.

The classic Biot's poro-elasticity theory (Biot, 1956) has been commonly used to describe the relationship between the pore water flow and the deformation of soil skeleton, as well as to study the consolidation problems (Ferronato et al., 2010). Using a finite element model, Krost et al. (2011) simulated the seabed consolidation beneath the partially embedded pipeline. Ulker et al. (2010) considered the pre-consolidation of the unsaturated seabed in the investigation of the standing-wave induced seabed response. Ye (2012b) investigated the long-time seabed consolidation under the permeable composite breakwater, in which the effect of buoyancy force was considered. Jeng and Ye (2012) developed a 3D consolidation model, and discussed the distributions of seabed stresses and displacements under the rubble mound breakwater. Ye et al. (2012) further extended this model to deal with the seabed consolidation around an impervious rigid caisson breakwater, and used the consolidation state as the initial condition for simulating dynamic seabed response under 3D wave loading. Though these studies have demonstrated some features of the consolidation, they mainly focus on the seabed consolidation around the breakwaters which stand on the seabed.

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The behavior of seabed consolidation around an inserted pile foundation is considerably different from that below a breakwater, since a part of the pile foundation is inserted into the seabed and this would cause a more complex seabed-structure interaction with a three-dimensional (3D) interface. The seabed stresses and displacements will be affected by the inserted depth of the pile. Some previous studies in this field focused on the pile behavior affected by the consolidated soil, which neglected the excess pore pressure dissipation, effective stresses and seabed subsidence during the consolidation process (Abdrabbo and Ali, 2015; Lee and Ng, 2004). There are a few analytical solutions for the seabed consolidation at the sides of the pile (Castro and Sagaseta, 2009; Lu et al., 2011; Randolph and Wroth, 1979). However, in these studies, the effects of the pile on its surrounding soil were simplified as the external loading or initial deformation at the soil-pile interface, which did not consider the gravity of the pile and could not fully represent the 3D soil-pile interactions. In addition, the aforementioned studies have not investigated the effects of saturation degree on the pore pressure dissipation during the seabed consolidation process around a pile foundation.

Since the effective stresses are strengthened around the structures because of the seabed consolidation, this will affect the soil liquefaction under the dynamic wave loading. Jeng et al. (2013) and Ye et al. (2014) considered effects of the seabed consolidation in simulating wave-induced seabed liquefaction around the composite breakwater. Zhao et al. (2014) studied the effects of initial seabed effective stresses on the liquefaction depth around a buried pipeline. It is found that the increased gravity of the pipeline would suppress the liquefaction in its vicinity. However, these studies focused on the marine structures that are located on the seabed and were limited to two-dimensional (2D) cases. When a pile is inserted into seabed, the effective stresses of its surrounding seabed would be significantly changed and exhibit a different distribution pattern compared to a located structure. The change of the overburden pressure would result in a different liquefaction zone under dynamic wave loading. Li et al. (2011) and Zhang et al. (2015) used 3D models to examine the wave-induced liquefaction zone around a pile foundation. However, effects of the seabed consolidation state around an inserted pile on wave-induced liquefaction have not been considered in previous studies.

In this study, a 3D numerical model is developed to systematically investigate the unsaturated seabed consolidation around an inserted pile foundation. The gravity of the pile is considered. The behavior of the seabed consolidation for various inserted depths of pile foundation, external loadings, soil permeability, saturation degree and Young's modulus is studied. The shear failure zone around the pile foundation is discussed. Finally, an analysis on the seabed liquefaction under a progressive wave is presented, in which effects of the seabed consolidation around an inserted pile are highlighted.

2. Numerical model

2.1. Governing equations

In general, the grains or particles constituting the soil are more or less bound together by certain molecular forces and constitute a porous material with elastic properties, and the voids are filled with pore water. These concepts were first applied by Terzaghi (1925) in the analysis of the settlement of a soil column under a constant load. Based on this assumption, the elastic model for soil response under the dynamic wave loading was proposed by Biot (1956). Based on Biot's poro-elasticity theory, the governing equations which considers the acceleration of fluid and soil skeleton (FD model) could be expressed as (Zienkiewicz et al., 1980):

$$\sigma_{ij,j} + \rho g_i = \rho \ddot{u}_i + \rho_f \ddot{w}_i \tag{1}$$

$$-p_{,i} + \rho_f g_i = \rho_f \ddot{u}_i + \frac{\rho_f \ddot{w}_i}{n} + \frac{\rho_f g_i}{k_i}\dot{w}_i \tag{2}$$

$$\dot{u}_{i,i} + \dot{w}_{i,i} = -n\beta\dot{p} \tag{3}$$

where σ_{ij} is the total stress, ρ *is the average density of the porous medium,* p is the pore pressure, ρ_f is the density of water, g_i is the gravitational acceleration in the i-*direction,* u_i *is the displacement of the soil matrix in the i*-direction, w_i is the average relative displacement of the fluid to the solid skeleton in the i-*direction,* k_i *is the permeability of the porous medium in the i*-direction, n *is the porosity of the solid phase. It should be noted that, ignoring the acceleration due to pore fluid or/and soil motion reduces these general formulations to the conventional "Partial-dynamic (PD)" or the "Quasi-dynamic (QS)" model. For seabed consolidation under the static gravity force of the pile, "QS" or "PD" model is sufficient for this process simulation. However, for wave-induced seabed dynamic response around the marine structure which allows slight displacements, the "FD" model is highly recommended to be used for obtaining a reliable numerical accuracy (Ulker et al., 2010). In this study, besides seabed consolidation process, the seabed liquefaction potential under dynamic wave loading around a pile is also discussed. Therefore, the fully-dynamic (FD) model is used here for the consistency of the governing equations in the present study.*

The equivalent compressibility of pore water and entrapped air β is defined as (Yamamoto et al., 1978):

$$\beta = \frac{1}{k_w} + \frac{1 - S_r}{\rho_f g d} \tag{4}$$

where d *is the water depth,* S_r *is the saturation degree,* k_w *is the bulk modulus of the pure water which is taken as* 1.95×10^9 N/m^2*. This expression takes the saturation degree into account in the deformation of the porous medium. It is noted that this definition is only valid for a high saturation degree (e.g.* $S_r > 0.95$*) (Pietruszczak and Pande, 1996).*

The total stresses can be expressed in terms of the effective stresses (σ_{ij}) *and pore pressure* (p):

$$\sigma_{ij} = \sigma'_{ij} - \delta_{ij} p \tag{5}$$

The effective stress-strain relation can be written as:

$$\sigma'_{i,j} = \lambda \varepsilon_{kk}\delta_{ij} + 2G\varepsilon_{ij} \tag{6}$$

$$\varepsilon_{ij} = \frac{u_{i,j} + u_{j,i}}{2} \tag{7}$$

where δ_{ij} is the Kronecker delta denotation, σ'_{ij} is the effective stress, ε_{ij} is the soil strain, $\lambda=2G\mu(1-2\mu)$, G is the shear modulus, μ *is Poisson's radio. Note that the above definition implies a positive tensional stress.*

2.2. Boundary conditions

Fig. 1 shows the (a) 3D Sketch and (b) appropriate boundary conditions of the present model. Three elements of water, seabed and pile are considered in the current model. The inserted pile is presented at the center of the computational domain. The lateral and bottom boundaries of the seabed are considered as impermeable and rigid, where the displacements of the seabed and the normal gradient of pore pressure are zero ($u_{soil}=0$, $\partial p/\partial n=0$ (n *is the unit normal on the boundaries)). Pore pressure at the seabed surface is equal to the water pressure* ($p_b=\rho_f g d$). The normal stress and shear stress vanish at the seabed surface. At the top of the pile foundation, an external loading P_v in the vertical direction is applied, which represents the weight of the upper structures (e.g., sea-crossing bridge, oil platform and wind turbines).