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Modelling wave-induced 3D non-homogeneous seabed response

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ABSTRACT

Marine seabed is often composed of non-homogeneous soil in various directions, where its response to dynamic wave loading shows much difference from the case of homogeneous soil. Most existing numerical models for wave-induced non-homogeneous seabed response have been limited to vertically layered seabed. In this study, a new model is developed to simulate wave-induced seabed response considering non-homogeneous soil properties in three dimensions. The present model (1) directly solves the original fully dynamic governing equations for the overall equilibrium of soil, the equilibrium of pore fluid flow and the mass balance of porous seabed, (2) allows non-uniform distribution of eight soil parameters in the three-dimensional space, and (3) retains all the spatial derivative terms of soil parameters to fully represent the three-dimensional non-homogeneous seabed behavior. The model well reproduces the existing experimental data, numerical solution and field observation. Two preliminary model tests are performed to investigate the effects of horizontally non-homogeneous soil property on the local seabed response, and the three-dimensional non-homogeneous seabed response around a mono-pile. It is found that the presence of coarser soil will reduce the liquefaction depth of the adjacent finer soil. This impact is more pronounced for larger wave period, wave height, soil permeability, saturation degree, and smaller water depth. The seabed response around a mono-pile can be considerably modified if the soil sorting due to long-time lateral rocking of mono-pile is taken into account, which decreases the liquefaction depth in the vicinity of the mono-pile.

1. Introduction

Wave-induced seabed instability is an important factor in the design of foundations for marine structures, such as breakwaters, pipelines, and piles [1]. Seabed liquefaction and scour induced by coastal dynamics greatly threaten the foundations of marine structures, attracting constant attention from engineers and researchers [2–5]. Soil liquefaction could occur if excess pore pressure exceeds the overburden pressure at a certain location inside the seabed, and this phenomenon more likely occurs for a seabed with poor drainage. The liquefied soil loses its bearing capacity, leading to the structure's destruction [6]. Therefore, it is important to develop a robust numerical model to evaluate wave-induced seabed response and liquefaction potential around marine structures for practical use.

It was found in previous studies that the non-homogeneity of seabed significantly affected pore pressure distribution and soil stresses [7–14]. In reality, the seabed would be non-homogeneous in three-dimensions (3D) [15,16], i.e., soil properties are non-uniform in both horizontal and vertical directions. For example, soil properties are non-uniform over the depth of the seabed because of the long-term consolidation process, for which the seabed can be seen as a vertically layered medium. On the other hand, a horizontally non-homogeneous seabed exists when a coarse material to protect the structure foundation artificially replaces the local seabed. In this case, an obvious interface appears between the coarser soil close to the structure and the finer soil away from the structure. Moreover, soil densification and grain migration have been reported to occur near a laterally loaded pile or wall [17]. Based on experimentation, Cuéllar et al. [16] found that long-term mono-pile rocking resulted in sand grain redistribution around the piles, and the surrounding seabed exhibited an obvious non-homogeneous 3D pattern. These studies indicated that the non-homogeneous 3D soil distribution could play an important role in wave-induced seabed response.

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Many numerical models have been developed to deal with wave-induced non-homogeneous seabed response. Yamamoto [7] proposed a semi-analytical model assuming that the seabed had multiple layers in the vertical direction, i.e., the vertically layered (non-homogeneous) seabed. It was found that the depth of seabed up to 0.25 times the wavelength might be the most unstable area. Rahman et al. [8] presented a semi-analytical solution for the response of a vertically layered seabed around a vertical structure under short-crest wave loading. Jeng and Lin [9] developed a finite element model for wave-induced dynamic response of a vertically non-homogeneous seabed. In their model, the soil permeability and shear modulus was assumed to vary continuously over the seabed depth. They suggested that the non-homogeneous soil properties should not be neglected, especially in an unsaturated seabed. Hua and Yu [10] used a finite element model to investigate the dynamic response of an anisotropic and vertically layered seabed under wave action. Their study indicated that the vertically non-uniform elastic modulus significantly decreases the shear failure depth, which is beneficial to seabed protection in practical use. Based on the transmission and reflection matrices (TRM) method, Zhou et al. [11] presented an analytical solution for the response of vertically layered seabed. They also proposed replacing the surface layer with coarse soil to suppress seabed liquefaction. Zhou et al. [12] further investigated the response of vertically layered seabed around a buried pipeline under the combined wave-current loading, and highlighted the significance of the anisotropic and non-homogeneous soil properties. Recently, the analytical studies of Ulker [13,14] demonstrated the importance of inertial terms of pore water and soil skeleton for a vertically layered seabed. However, these numerical or analytical studies only considered the vertical derivative terms of non-uniform soil parameters, neglecting the horizontal derivative terms. Therefore, their applicability was limited to one-dimensional vertically (1DV) non-homogeneous seabed.

In this study, a new model is developed by retaining all spatial derivative terms of eight soil parameters in three dimensions, based on the poro-elastic fully dynamic governing equations. This enables the model to fully represent three-dimensional (3D) non-homogeneous seabed behavior. This model has been validated by experimental, numerical, and field data. Two preliminary model tests are performed to investigate the effects of 3D soil non-homogeneity on seabed response.

2. Numerical model

2.1. Governing equations

The present seabed model is an extended version of the model presented in Sui et al. [18] and Zhang et al. [19], considering 3D non-homogeneous soil properties in addition to properties considered in previous models. The model solves poro-elastic fully dynamic (FD) equations [20]; including the inertial terms of both pore-water, and soil skeleton. They are expressed as

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

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

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

where σ_{ij} is the total stress, ρ is the average density of the porous medium, p is the pore water pressure, ρ_f is the density of water, g_i is the gravitational acceleration in the i-direction, u_i is the displacement of soil matrix in the i-direction, w_i is the average displacement of the fluid relative to the soil skeleton in the i-direction, k_i is the permeability of the porous medium in the i-direction, and n is the porosity.

The equivalent compressibility of pore water and entrapped air (β) can be expressed as,

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

where S_r is the saturation degree, d is the water depth, and k_f is the bulk modulus of pure water.

The total stress can be written as,

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

where δ_{ij} is the Kronecker delta denotation which equals 0 for $i=j$ or 1 for i or j, respectively. σ'_{ij} denotes the normal effective stresses and shear stresses, that is, $\sigma'_{ij}=\sigma'_{xx}$ or σ'_{yy} or σ'_{zz} for $i=j$, and $\sigma'_{ij}=\tau_{xz}$ or τ_{yz} or τ_{xy} for $i \neq j$.

The model considers the cross-anisotropic seabed behavior:

$$\frac{\mu_{vh}}{\mu_{hv}} = \frac{E_h}{E_v} = \Omega \tag{6}$$

$$G_h = \frac{E_h}{2(1+\mu_{hh})} = \frac{\Omega E_v}{2(1+\mu_{hh})} = G E_v \tag{7}$$

$$G_v = \Lambda E_v \tag{8}$$

where μ_{vh}, μ_{hv}, and μ_{hh} are the Poisson ratios in different directions, E_h and E_v are Young's modulus in the horizontal and vertical directions, respectively, G_h and G_v are shear modulus in the horizontal and vertical directions, respectively, Ω is a non-dimensional parameter, and Λ is the anisotropic constant. Note that for an isotropic seabed, $\mu_{hh}=\mu_{vh}$, $\Omega=1$, and $\Lambda=1/2(1+\mu_{hh})$.

The soil skeleton generally obeys Hooke's law, which has linear, reversible, and non-retarded mechanical properties. The relationships between soil stresses and soil displacements are expressed as:

$$\sigma'_{xx} = E_v\left[C_{11}\frac{\partial u_x}{\partial x} + C_{12}\frac{\partial u_y}{\partial y} + C_{13}\frac{\partial u_z}{\partial z}\right] \tag{9}$$

$$\sigma'_{yy} = E_v\left[C_{12}\frac{\partial u_x}{\partial x} + C_{11}\frac{\partial u_y}{\partial y} + C_{13}\frac{\partial u_z}{\partial z}\right] \tag{10}$$

$$\sigma'_{zz} = E_v\left[C_{13}\frac{\partial u_x}{\partial x} + C_{13}\frac{\partial u_y}{\partial y} + C_{33}\frac{\partial u_z}{\partial z}\right] \tag{11}$$

$$\tau_{xy} = G E_v\left[\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right] = \tau_{yx} \tag{12}$$

$$\tau_{xz} = \Lambda E_v\left[\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right] = \tau_{zx} \tag{13}$$

$$\tau_{yz} = \Lambda E_v\left[\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y}\right] = \tau_{zy} \tag{14}$$

where,

$$C_{11} = \Omega\left[1-\mu_{hv}\mu_{vh}\right]/\Delta \tag{15}$$

$$C_{12} = \Omega\left[\mu_{hv}\mu_{vh}+\mu_{hh}\right]/\Delta \tag{16}$$

$$C_{13} = \Omega\mu_{vh}\left[1+\mu_{hh}\right]/\Delta \tag{17}$$

$$C_{33} = (1-\mu_{hh}^2)/\Delta \tag{18}$$

$$\Delta = (1+\mu_{hh})(1-\mu_{hh}-2\mu_{hv}\mu_{vh}) \tag{19}$$

In the present model, behaviour of a 3D non-homogeneous seabed is described by allowing eight seabed parameters, which are functions of the 3D spatial locations (x, y, z). They are the porous media density $\rho(x, y, z)$, water density $\rho_f(x, y, z)$, permeability $k(x, y, z)$, the porosity of the solid phase $n(x, y, z)$, the bulk modulus of pore water $k_f(x, y, z)$, vertical Young's modulus $E_v(x, y, z)$, vertical Poisson's ratios $u_{vh}(x, y, z)$, and horizontal Poisson's ratios $u_{hh}(x, y,$