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Wave-induced oscillatory response in a randomly heterogeneous porous seabed

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ABSTRACT

The seabed response under wave loading is important for the stability of foundations of offshore structures. Unlike previous studies, the wave-induced seabed response in a spatially random porous seabed is investigated in this study. A stochastic finite element model which integrates random field simulation of spatially varied soil properties and finite element modeling of wave-induced seabed response is established. Spatial variability of soil shear modulus, soil permeability, and degree of saturation, are simulated using the covariance matrix decomposition method. The results indicate that the pore water pressure and stress distribution in the seabed are significantly affected by the spatial variability of the shear modulus. The mean of maximum oscillating pore pressure in a randomly heterogeneous seabed is greater than that in a homogenous seabed. The uncertainty of the maximum oscillating pore pressure first increases and then reduces with the correlation length. The effects of spatial variability of permeability and degree of saturation are less significant than that of shear modulus. The spatial variability of soil permeability increases the uncertainty of oscillating pore pressure in the seabed at shallow depths. The spatial variability of shear modulus and degree of saturation affects the uncertainty of oscillating pore pressure of the whole seabed.

1. Introduction

Evaluation of the wave-induced soil response is vital for the design of foundations around marine structures. When a wave propagates over the ocean, it generates dynamic fluctuations of excess pore water pressure and effective stress in the seabed. This wave-induced soil response may become significant enough to cause instability of the seabed in front of marine structures and may induce liquefaction. Three types of theories have been used to analyze the wave-induced seabed response with different assumptions about the compressibility of the pore fluid and the soil skeleton (Jeng, 2013): (i) Laplace's equation (Sleath, 1970); (ii) Terzaghi's theory of consolidation (Moshagen and Torum, 1975) and (iii) Biot's consolidation theory for poroelastic media (Madsen, 1978; Yamamoto et al., 1978; Mei and Foda, 1981; Okusa, 1985; Gatmiri, 1990; Thomas, 1989, 1995; Hsu et al., 1993; Jeng and Hsu, 1996; among others). The important seabed soil properties that influence the wave-induced response have been identified as soil permeability, shear modulus, and degree of saturation (Jeng, 2013).

Generally, the physical properties of soils vary in marine sediments due to complicated natural geological processes. Researchers have attempted to consider heterogeneous soil characteristics (Jeng and Seymour, 1997; Jeng and Lin, 1996), anisotropic soil behavior (Hsu and Jeng, 1994; Jeng, 1997; Kitano and Mase, 1999), and multi-layered seabed (Hsu et al., 1995; Gao et al., 2003; Zhou et al., 2011). In their studies, soil properties of a seabed are usually considered as a specific form (e.g., linear or exponential) of function of depth because marine sediments may undergo consolidation due to both the overburden soil pressure and the water pressure, which may result in a general decrease in soil permeability and an increase of soil rigidity with depth.

Inherent spatial variability exists in a supposedly homogeneous soil layer due to small-scale variations in mineral composition, environmental conditions during deposition, past stress history, variations in moisture content, and so on (Ang and Tang, 2007; Dasaka and Zhang, 2012; Lloret-Cabot et al., 2014). The inherent spatial variability cannot feasibly be characterized by deterministic approaches. Some researchers considered the spatial variability of soil properties using probabilistic approaches for various

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geotechnical engineering problems, such as consolidation and settlement (Fenton and Griffiths, 2002; Badaoui et al., 2007; Huang et al., 2010; Le et al., 2013; Manjari et al., 2014), water flow and contaminant transport (Tartakovsky et al., 2003; Li et al. 2009, 2012; Mousavi Nezhad et al., 2013; Kanning and Calle, 2013), slope stability (Cho, 2007; Srivastava et al., 2009; Santoso et al., 2011; Zhu et al., 2013; Li et al. 2014, 2015a; Jiang et al. 2014a,b; Zhang et al., 2008; Zhu et al., 2015; Jamshidi Chenari and Alaie, 2015), foundations (Fan et al. 2014; Fan and Liang 2015; Li et al., 2015b; Zhang and Chen, 2012; Zhang et al., 2014; Bari and Shahin, 2015), and so on. However, most of the previous studies of seabed or marine soils focused generally on the characterization of field spatial variability of marine deposits (Keaveny et al., 1990; Valdez-Llamas et al., 2003; Goff et al., 2008; Cheon, 2011; Gilbert et al., 2014). The effects of random waves on seabed have been considered by many researchers (Suh et al. 1997; Liu and Jeng, 2007; Myrhaug et al. 1998 among others). Suh et al. (1997) used the Green's second identity and Lagrangian formula to develop two ultimately equivalent hyperbolic equations for random waves. Liu and Jeng (2007) developed a semi-analytical solution for the random wave induced soil response. The influence of random wave loading on the soil response was investigated by comparing with the two different wave spectra. Myrhaug et al. (1998) investigated the seabed shear stresses under random waves and compared the model predictions with field measurements. The sediment transport and scour of seabed by random waves were investigated assuming the random waves to be a stationary Gaussian narrow-band random process (Myrhaug and Ong 2010; Myrhaug et al. 2014). Xu and Dong (2011) conducted a numerical study to investigate the effect of random waves on excess pore pressure build-up and liquefaction processes. However, the effects of randomly heterogeneous soil properties on wave-induced seabed response have not been investigated.

In this paper, a stochastic finite element model which integrates random field modeling of spatially varied soil properties and finite element modeling of wave-induced seabed response is established to investigate the effect of a randomly heterogeneous seabed on wave-induced response. The spatial variability of soil properties, including shear modulus, soil permeability, and degree of saturation, is simulated using the covariance matrix decomposition method based on the random field theory. The simulated spatially random soil properties are imported into an interactive finite element software environment, COMSOL, to solve the governing partial differential equations (PDEs) for wave-induced seabed response. The effects of randomly heterogeneous soil properties on the uncertainties of the oscillating excess pore water pressure and wave-induced incremental change in effective stresses are discussed.

2. Theory of wave-induced seabed response

2.1. Governing equations

The problem considered in this paper is two-dimensional. Assume a porous seabed of finite thickness h (Fig. 1). The x-axis is taken on the seabed surface and the z-axis is taken vertically downward from the seabed surface. The waves travel from left to right along the positive direction of the x-axis. Based on Biot's consolidation theory (Biot, 1941), together with the storage equation (Verruijt, 1969), the governing equation for the wave–soil interaction problem within a compressible pore fluid in a compressible porous seabed is given as:

$$\frac{\partial}{\partial x}\left(-K_x\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(-K_z\frac{\partial p}{\partial z}\right)+\gamma_w n\beta\frac{\partial p}{\partial t}+\gamma_w\frac{\partial \varepsilon}{\partial t}=0 \quad (1)$$

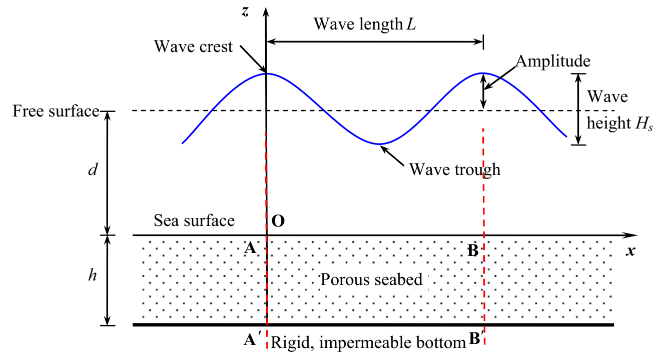

Fig. 1. Sketch of wave propagation above a porous seabed.

where K_x and K_z are the hydraulic permeability of soil in the x and z directions, respectively; p is the wave-induced oscillating pore pressure; γ_w is the unit weight of the pore water; n is the soil porosity; β is the compressibility of the pore-fluid; t is time; ε is the volume strain for the two-dimensional problem, which is defined by

$$\varepsilon=\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z} \quad (2)$$

where u and w are the soil displacements in the x and z directions, respectively. The compressibility of the pore fluid β can be related to the bulk modulus of the pore-water and the degree of saturation S_r (Verruijt, 1969),

$$\beta=\frac{1}{K_w}+\frac{1-S_r}{P_{w0}} \quad (3)$$

where K_w is the true bulk modulus of water (which can be taken as 1.95×10^9 N/m^2, Yamamoto et al., 1978), and P_{w0} is the absolute pore-water pressure.

The governing equations of porous seabed based on the force equilibrium of the soil skeleton and the effective stress concept can be written as (Biot, 1941):

$$\begin{cases}\frac{\partial \sigma'_x}{\partial x}+\frac{\partial \tau_{zx}}{\partial z}=\frac{\partial p}{\partial x}\\ \frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \sigma'_z}{\partial z}=\frac{\partial p}{\partial z}\end{cases} \quad (4)$$

where σ'_x is the effective normal stress in the x direction, σ'_z is the effective normal stress in the z direction, τ_{xz} is the shear stress in the z direction on the plane perpendicular to the x axis, and τ_{zx} is the shear stress in the x direction on the plane perpendicular to the z axis.

Assume the soil skeleton is an elastic material, which follows the generalized Hooke's law; then the equations of force equilibrium within the soil matrix can be rewritten as:

$$\begin{cases}G\nabla^2 u+\frac{G}{(1-2\mu)}\frac{\partial \varepsilon}{\partial x}=\frac{\partial p}{\partial x}\\ G\nabla^2 w+\frac{G}{(1-2\mu)}\frac{\partial \varepsilon}{\partial z}=\frac{\partial p}{\partial z}\end{cases} \quad (5)$$

where G is the shear modulus, and μ is the Poisson's ratio. G is related to Young's modulus E and the Poisson's ratio μ in the form of $E/2(1+\mu)$. In these formulations of the wave–seabed interaction problem, the soil shear modulus G, soil permeability, and degree of saturation are expressed as constant parameters, but they will be simulated as spatially random soil properties by random field simulation in this study.

2.2. Boundary conditions

The governing equations, Eqs. (1) and (5), describing the water–soil interaction problem, can be solved by incorporating the boundary conditions specified at the seabed surface and the impermeable bottom, respectively. It is commonly accepted that