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Effects of cross-correlated multiple spatially random soil properties on wave-induced oscillatory seabed response

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ABSTRACT

The evaluation of seabed response under wave loading is important for prediction of stability of foundations of offshore structures. In this study, a stochastic finite element model which integrates the Karhunen-Loève expansion random field simulation and finite element modeling of wave-induced seabed response is established. The wave-induced oscillatory response in a spatially random heterogeneous porous seabed considering cross-correlated multiple soil properties is investigated. The effects of multiple spatial random soil properties, correlation length and the trend function (the relation of the mean value versus depth) on oscillatory pore water pressure and momentary liquefaction are discussed. The stochastic analyses show that the uncertainty bounds of oscillatory pore water pressure are wider for the case with multiple spatially random soil properties compared with those with the single random soil property. The mean pore water pressure of the stochastic analysis is greater than the one obtained by the deterministic analysis. Therefore, the average momentary liquefaction zone in the stochastic analysis is shallower than the deterministic one. The median of momentary liquefaction depth generally decreases with the increase of vertical correlation length. When the slope of the trend function increases, the uncertainty of pore water pressure is greatly reduced at deeper depth of the seabed. Without considering the trend of soil properties, the wave-induced momentary liquefaction potential may be underestimated.

1. Introduction

When ocean waves propagate over the ocean, dynamic pressure fluctuations on the sea floor will further cause variations in pore water pressure and effective stresses within the seabed [1]. Due to this wave-induced soil response, instability of the seabed in the vicinity of marine structures and liquefaction of marine sediments may happen [2–4]. In general, the wave-induced liquefaction in marine deposits is generated by two different mechanisms [5,6]. One is the progressive buildup of pore pressure (the residual liquefaction) caused by contraction of the soil under the action of cyclic loading. The other is the upward-directed vertical gradient of oscillating pore pressure during the passage of a wave trough (momentary liquefaction), which is accompanied by attenuation of the amplitude and phase lag in the pore pressure changes. The present study only deals with the momentary liquefaction.

Several key seabed soil properties that influence the wave-induced response have been identified as soil permeability, shear modulus, and degree of saturation [7–13]. The soil permeability is a measure of how rapidly fluid is transmitted through the voids between grains. As soil permeability increases, the oscillatory pore pressure is greater near the seabed surface and attenuates more gently so that the maximum liquefaction depth decreases [6]. The pore pressure attenuates faster with the increase of shear modulus [13]. The possibility of the momentary liquefaction of the seabed and the depth of liquefaction increase as soil shear modulus increases [14].

Substantial research studies have been conducted to investigate the effects of heterogeneous soil characteristics [15,16], anisotropic soil behavior [17–19] and multi-layered seabed [20–23] on the wave-induced porous seabed response. In these studies, the soil properties are deterministic variables and usually considered as a specific function (e.g., linear or exponential) of depth. Hence, only a limited number of scenarios can be explored.

In reality, the marine deposits in a seabed are subject to natural spatial variability [24–28]. The response of a natural seabed is

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much more complicated with the natural variability of seabed soil properties. The deterministic methods may lead to significant risk in evaluating seabed responses and the stochastic analysis methods are more rational approaches [29–32].

Some researchers considered the effects of random waves on seabed by stochastic analyses [33–38]. For example, Liu and Jeng [39] 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. Sumer et al. [40] presented an experimental study where the sinking and floatation of pipelines and marine structures under both regular and irregular progressive waves. Xu and Dong [41] conducted a numerical study to investigate the effect of random waves on excess pore pressure build-up and liquefaction processes. Some researchers considered the spatial variability of soil properties for geotechnical engineering problems, such as settlement and consolidation [42–45], water flow [46,47], slope stability [48–52], foundations [53–55]. However, the stochastic analysis of wave-induced seabed responses considering the spatial variability of a seabed is limited. Recently, Zhang et al. [32] conducted a stochastic analysis for wave-induced seabed response using the covariance matrix decomposition random field simulation method. The effects of spatial varied soil shear modulus, soil permeability, and degree of saturation, are investigated. However, different soil properties are assumed to be spatial random individually in Zhang et al. [32]. The correlations among these random soil properties are not considered.

The wave-induced seabed response is actually affected by different soil properties simultaneously. The effects of the natural spatial variability of multiple soil properties are much more complicated due to the cross-correlations among soil properties [56,57]. In this study, a stochastic finite element model which integrates simulation of multiple cross-correlated spatial random soil properties and finite element modeling of wave-induced seabed response is established. The Karhunen-Loève (K-L) expansion method is adopted to generate random realizations of spatially heterogeneous seabed. Each realization is a random sample of the field with spatially varied soil property and can be considered as one possible scenario of the real seabed. An illustrative example is used to investigate the wave-induced seabed response with multiple spatially random soil properties. The effects of multiple spatial variables, correlation lengths and the trend functions on oscillatory pore-water pressure profiles and the potential liquefaction zone are investigated.

2. Stochastic finite-element model of a random heterogeneous seabed

2.1. Oscillatory response of porous seabed under wave loading

2.1.1. Governing equations

Consider a two-dimensional problem with a porous seabed of the finite thickness h (Fig. 1). The x-axis is on the seabed surface and the z-axis is vertically downward from the seabed surface. The waves travel from left to right along the positive direction of the x-axis.

The governing equations of porous seabed based on the force equilibrium of the soil skeleton and the effective stress concept can be written as [58]

$$\begin{cases} \dfrac{\partial \sigma'_x}{\partial x} + \dfrac{\partial \tau_{zx}}{\partial z} = \dfrac{\partial p}{\partial x} \\[2ex] \dfrac{\partial \tau_{xz}}{\partial x} + \dfrac{\partial \sigma'_z}{\partial z} = \dfrac{\partial p}{\partial z} \end{cases} \tag{1}$$

where σ_x' and σ_z' are the effective normal stresses in the x- and z- direction, respectively; 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, p is the wave-induced oscillating pore pressure.

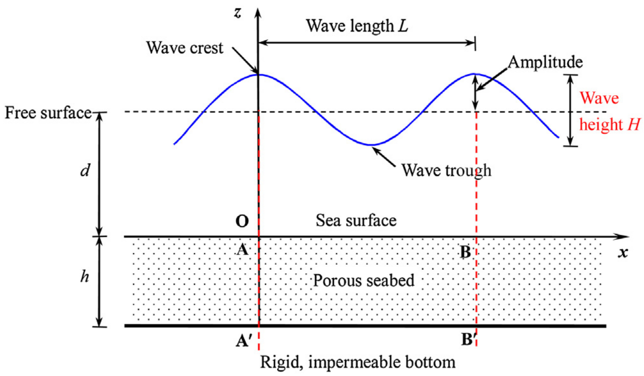

Fig. 1. Schematic plot of wave propagation above a porous seabed.

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

$$\begin{cases} G\nabla^2 u + \dfrac{G}{(1-2\mu)}\dfrac{\partial \varepsilon}{\partial x} = \dfrac{\partial p}{\partial x} \\[2ex] G\nabla^2 w + \dfrac{G}{(1-2\mu)}\dfrac{\partial \varepsilon}{\partial z} = \dfrac{\partial p}{\partial z} \end{cases} \tag{2}$$

where G is the shear modulus with $G = E/2(1+\mu)$ where E is the Young's modulus and μ is the Poisson's ratio.

Based on the Biot's consolidation theory [58] and the storage equation of a compressible porous media [59], the governing equation for the wave–soil interaction within a compressible pore fluid in a compressible porous seabed is given as

$$\frac{\partial}{\partial x}\left(-K_x\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial z}\left(-K_z\frac{\partial p}{\partial z}\right) + \gamma_w n\beta\frac{\partial p}{\partial t} + \gamma_w\frac{\partial \varepsilon}{\partial t} = 0 \tag{3}$$

where K_x and K_z are the permeability of soil in the x and z directions, respectively; 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; and ε is the volume strain of the compressible seabed, which is defined by

$$\varepsilon = \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} \tag{4}$$

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 [60],

$$\beta = \frac{1}{K_w} + \frac{1-S_r}{P_{w0}} \tag{5}$$

where K_w is the true bulk modulus of water (1.95×10^9 N/m^2); and P_{w0} is the absolute pore-water pressure.

2.1.2. Boundary conditions

The governing equations, Eqs. (2) and (3), describing the water–soil interaction problem, can be solved by incorporating the boundary conditions specified at the seabed surface and the impermeable bottom, respectively. Here, the wave is assumed to be a progressive wave. It is commonly accepted that the vertical effective normal stresses and shear stresses vanish at the seabed surface, and the wave-induced oscillating pore pressure is equal to the wave pressure at the seabed surface [13],

$$\sigma'_z = \tau_{xz} = 0 \, at \, z = 0 \tag{6}$$