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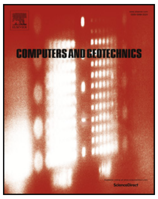

Research Paper

Effect of vertical seismic motion on the dynamic response and instantaneous liquefaction in a two-layer porous seabed

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ABSTRACT

The evaluation of seismic-induced responses in a porous seabed is a fundamental problem in geotechnical and coastal engineering. Although ground motions generally include both horizontal and vertical components, a majority of previous theoretical investigations assumed vertically propagating shear waves in a horizontally layered soil–rock system and simply ignored the effect of site response to vertical earthquake motion. In this paper, the dynamic response and instantaneous liquefaction of a porous seabed that is induced by vertical earthquake loading is studied using an analytical method. The seabed is treated as a two-layer poroelastic medium and characterized by the dynamic formulation of Biot theory. The analytical solutions for the response variables, such as induced displacement, pore pressure and vertical effective stress, are derived individually, and the mechanism of instantaneous liquefaction in liquefiable sediment is investigated based on the excess pore pressure criterion. A set of parametric analysis is performed to discuss the effects of seawater, the seabed and earthquake parameters on the seismic response and maximum liquefaction depth. It is worth noting that the properties of the surface seabed layer have a significant influence on the seismic response and, consequently, the potential stability of the seabed, which is important in the analysis of offshore structure foundations.

1. Introduction

In recent decades, an increasing number of offshore structures, such as submarine tunnels, cross-sea bridges and oil platforms, have been constructed in the continental margins of the global oceans. In the design of coastal structures, the foundation instability under environmental loading has been an important issue for a long time. Generally, particular concerns are often addressed for two types of conventional loading in offshore areas: ocean waves and earthquakes. The effect of ocean-wave loading on the seabed and marine structures has been extensively studied. However, attention has rarely been given to the dynamic behavior of the seabed under seismic activities in existing the literature, which is surprising regarding the failures of seabed and marine structures as a result of many earthquakes [1–4]. Such accidents and their destructive consequences show that it is essential to consider seismic-induced responses in the seabed when designing the foundations of marine structures in active seismic regions.

In the marine environment, liquefaction plays an important role around or beneath offshore structures, as it often occurs in saturated or nearly saturated granular materials, such as cohesionless seabed soils. Ocean-waves induced response and seabed instability have already attracted great attention in geotechnical engineering and coastal engineering during the last few decades [5–8]. It is generally accepted that the liquefaction of the seabed is closely associated with pore pressure changes and the resultant degradation of the soil's macroscopic properties. Two mechanisms for wave-induced liquefaction have been reported in previous laboratory and theoretical studies depending on how the excess pore pressure was generated [9,10]. One mechanism is wave-induced (residual) liquefaction, which results from the pore pressure accumulation due to the volumetric compaction under cyclic wave loading [11]. Another alleged transient liquefaction occurs when the instantaneous value of the (oscillatory) pore pressure directly exceeds a certain mean level, and the vertical effective stress vanishes.

In addition to ocean-waves, seismic loading is another external factor leading to liquefaction in the seabed. The full elastic seismic wavefield that propagates through an isotropic earth consists of shear and compressional waves depending on the vibrating direction of the substrate bedrock. In addition, the dynamic response of marine waters under the incidence of seismic events is significant [12] and could also be viewed as another important underlying cause of liquefaction in the

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seabed. Thus far, considerable interest has been paid to study the liquefaction triggered by horizontal motion associated with the propagation of shear waves [13,14]. These studies concluded that liquefaction was associated with substantial soil non-linearity and the build-up of pore pressure. On the other hand, the analysis of vertical motion directly related with compressional waves was quite limited, especially for the seabed. Based on the in-situ field measurements and analytical solutions for various responses, Yang [15] revealed that the effect of vertical motion on liquefaction was not negligible, and the effect was dependent on saturation conditions. A decrease in the nonlinearity of the soil was found to affect the vertical motion by mainly involving the propagation of the compressional wave [16]. Based on dynamic Biot equations for the porous seabed, Ye [17] and Ye and Wang [18] adopted the FEM numerical model to investigate both the vertical and horizontal seismic responses of composite breakwater and its seabed under the Pacific coast during Tohoku earthquake.

In addition, a majority of previous investigations modeled the seabed as a uniform, single layer of either finite or infinite thickness [10,19]. In the real ocean environment, the seabed may consist of two or more layers with different soils, and only a few dynamic studies attempted to treat the porous seabed as non-homogenous layered medium [20–22]. As summarized above, although the dynamic response of the porous seabed has received extensive concern, to our knowledge, the corresponding literature for the seismic response of a layered seabed has not been published to date.

Aimed at this goal, an analytical study is conducted to determine the response of the layered seabed induced by vertical seismic loading and understand how it differs from that of the conventional single-layer approach. The analytical solutions for the response variables, such as induced displacement, pore pressure and vertical effective stress, are derived based on fully dynamic formulations of the governing equations. Then, the mechanism of the potentially instantaneous liquefaction in liquefiable sediment is investigated. A set of parametric analyses is performed to discuss the effect of the related parameters on the maximum liquefaction depth.

2. Dynamic response of the seabed: governing equations

In this paper, marine sediment is considered to be a mixture consisting of three phases: a solid phase that forms a skeletal framework, a liquid phase that occupies a major portion of the pore space, and a gas phase that occupies a small portion of the pore space. The air phase is assumed to be fully dissolved in the fluid phase, which results in a single compressible fluid. To develop the governing equations for the dynamic response of the porous seabed, three relationships should be included: the stress-strain relation, momentum balance equations and the mass balance equation. In a majority of previous studies [10,17,18], the so-called "*u-p*" approximate formulation, which ignores the displacement of pore fluids relative to soil particles, was used in dynamic analyses. For seismic issues in a relatively high frequency range, however, all the inertial terms should be considered to obtain more accurate solutions. This formulation is called fully dynamic formulation [19]. The dynamic Biot's equations [23], developed by Zienkiewicz et al. [24], are briefly summarized to describe the dynamic response of the porous seabed.

The effective stress controlling the deformation of the porous medium is written as

$$\sigma_{ij} = \sigma'_{ij} + \delta_{ij} p \quad (i,j = x,z) \tag{1}$$

where σ_{ij} is total stress; σ'_{ij} is effective stress; δ_{ij} is Kronecker delta; p is pore pressure. Compression is taken as positive for the pore pressure.The strain ε_{ij} is defined as:

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{2}$$

where $u_{i,j}$ and $u_{j,i}$ are the derivatives of the soil skeleton displacement with respect to the spatial coordinates.Using Lame's parameters λ and μ, the effective stress is written as

$$\sigma'_{ij} = \lambda\varepsilon_{kk}\delta_{ij} + 2\mu\varepsilon_{ij} \tag{3}$$

where μ is also known as the shear modulus of soil, and $\lambda = 2\mu\nu/(1-2\nu)$ based on Poisson's ratio, ν.The overall equilibrium of the system and the equilibrium of the pore fluid are respectively written as

$$\sigma_{ij,j} + \rho g_i - \rho\ddot{u}_i - \rho_f\ddot{\bar{w}}_i = 0 \tag{4}$$

$$-p_{,j} + \rho_f g_i - \rho_f\ddot{u}_i - \frac{\rho_f}{n}\ddot{\bar{w}}_i - \frac{\rho_f g_i}{k_f}\dot{\bar{w}}_i = 0 \tag{5}$$

where g_i the body force acceleration, ρ is total density of the porous medium, $\rho = (1-n)\rho_s + n\rho_f$, ρ_s is the density of the solid skeleton, n is the soil porosity; ρ_f is density of the liquid, and k_f denotes the coefficient of hydraulic conductivity. $\ddot{u}_i$ denotes the acceleration of the solid skeleton, and $\ddot{\bar{w}}_i$ is the average pore fluid acceleration relative to the solid frame. Noting that the relative displacement of the average pore fluid is denoted as [25]

$$w_i = n(W_i - u_i) \tag{6}$$

where u_i is the displacement of the solid skeleton, W_i is the total fluid displacement.The law of conservation of mass yields

$$\dot{\varepsilon}_{kk} + \dot{\bar{w}}_{i,i} - n\beta\dot{p} = 0 \tag{7}$$

where β is the compressibility of the pore fluid accounting for slight unsaturation based on the degree of saturation, S_r, as follows [26]

$$\beta = \frac{1}{K_w} + \frac{1-S_r}{p_{w0}} \tag{8}$$

where K_w is the true bulk modulus of water and p_{w0} is the pore water pressure, (i.e., $p_{wo} = \rho_f gd$), and d represents the depth of seawater.

3. Analytical solutions for the seismic response variables

In this study, we consider a two-layer porous seafloor with a finite thickness, L, above a half-space (i.e., bedrock), as shown in Fig. 1. The flexibility of an underlying half-space could be influential for earthquake behaviors in the porous seabed [27,28]. For the seismic issue under consideration, the underlying half-space is assumed to be an impermeable and rigid bedrock, where the ground motion is considered to be a seismic input [29]. This assumption is widely accepted in seismic analyses of geotechnical earthquake engineering. The relative ratio of decreased layer thickness, m, is adopted to define various layer

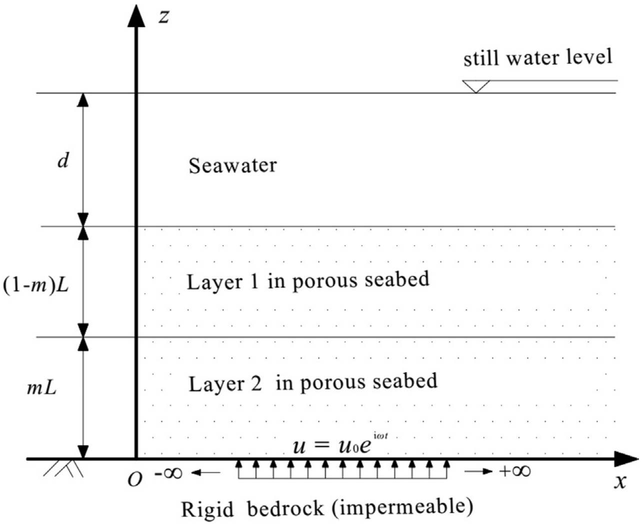

Fig. 1. Two-layer porous seabed under vertical seismic action.