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Momentary liquefaction of porous seabed under vertical seismic action

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ABSTRACT

The evaluation of potential liquefaction is an important part in the design of marine structures and offshore installations. However, the liquefaction phenomenon of porous seabed under the action of strong earthquake is traditionally been ignored. This paper aims to explore the momentary liquefaction mechanism of porous seabed through the newly analytical solutions of seabed response induced by vertical seismic excitation. Based on the boundary conditions at the surface and bottom of the seabed, the induced displacements and pore pressure in the sediment are rigorously derived as a function of seawater depth, seabed parameters and seismic characteristics of bedrock. A criterion of earthquake liquefaction in the seabed is developed, employing the concept of induced excess pore pressure. The representative cohesionless marine soils with different properties are selected in the parametric analysis. The results show that the liquefaction of seabed could be influenced by seawater parameters, seabed parameters and earthquake ground motion parameters. The significant finding is that current understanding that the vertical motion effect on soil liquefaction is negligible may not always hold true.

1. Introduction

Liquefaction is a process that material transforms from initially solid state into liquid state. Theoretical analysis of this phenomenon has for decades been a great challenge in geomechanics, earthquake engineering as well as marine engineering [1–3]. In the marine environment, liquefaction also plays an important role around and beneath offshore structures, as it often occurs in saturated or nearly saturated granular materials, like noncohesive seabed soils. The liquefaction of seabed may lead to destructive consequences, such as floating up of pipelines in the seabed, tilting of caissons and deformation of undersea tunnel. Hence the evaluation for liquefaction behavior of seabed is of practical significance in the design and construction of marine structures and offshore installations.

Massive liquefaction of the seabed happens as a result of pore pressure change and the corresponding degradation of the soil's macroscopic properties. Generally, the pressure change of the water trapped in soil skeleton pore comes from external excitation such as ocean-waves and earthquake. The issue of ocean-waves induced seabed response and instability has attracted great attention from geotechnical and coastal engineers since 1970s [4–7]. The water waves propagating on the ocean could create significant dynamic wave pressure on the seabed surface and cyclic pore pressure in marine sediments [8]. Owning to the phase lags and damping of the dynamic wave pressure, the excess pore pressure is produced from the difference between the wave pressure on the seabed surface and pore pressure in the sediment. When the value of the excess pore pressure directly exceeds a certain mean level, the vertical effective stress vanishes and the momentary liquefaction may happen in the seabed [9]. Other mechanism is wave-induced residual liquefaction, which is due to the build-up of excess pore pressure caused by the volumetric compaction under cyclic wave loading [10].

On the other hand, apart from the ocean-waves, catastrophic damage to offshore structures has also been recorded in the past earthquakes [11,12]. However, the analytical and numerical investigations on seismic dynamics of porous seabed are still limited to date [13–16]. The behaviors of the loads from ocean-waves and earthquake are both periodic but have notably different characteristics (see Table 1). In general, seismic waves propagate in the form of shear and compressional waves, which depends on the vibrating

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Table 1
Comparison between wave-induced and vertical-earthquake induced liquefaction in seabed.

	Ocean-waves	Earthquake
Loading type	Oscillating pressure	Stochastic acceleration
Loading position	Seabed surface	Lower bedrock surface
Drainage condition	Partially drained	Approximately undrained
Duration	Few hours or longer	Few minutes or shorter
Location of liquefaction	Near seabed surface	Near seabed surface
Liquefaction type	Cumulative or instantaneous	Mostly instantaneous

direction of the substrate bedrock. The behavior of external cyclic shearing of saturated soil have been confirmed experimentally by dozens of independent laboratories [17–19]. Most of these tests have simulated the liquefaction triggered by shear waves, revealing that the build-up of excess pore pressure in the response could reduce the effective stresses and subsequently the shearing resistance of the soil skeleton. This mechanism results from the 'residual' nature of the excess pore pressure, which accumulates gradually after a certain number of wave cycles. This phenomenon is similar to the residual liquefaction induced by ocean waves, caused by the build-up of the excess pore pressure [10].

The other potential liquefaction induced by compressional waves, however, was rarely regarded in geotechnical earthquake engineering, especially through theoretical analysis. As discussed by Yang [20], the understanding that the effect of vertical motion on liquefaction is negligible may not always hold true and the effect is dependent on the saturation condition. The purpose of this study is to explore the momentary liquefaction mechanism in the marine porous sediment which is subjected to vertical seismic action. A new analytical solution for the induced displacements and pore pressure in the seabed are mathematically obtained based on the poro-elastic theory. The effects of several pertinent parameters on the earthquake-induced distribution of liquefied area are then discussed in detail.

2. Governing equations and general solutions

2.1. Governing equations for the seabed

In this study, the marine sediment is considered as a mixture consisting of solid skeletal frame, liquid phase, and gas phase. Some basic assumptions are introduced to derive the analytical solutions for the phenomenon described, such as:

- the partially saturated sediment is homogeneous and hydraulically isotropic material;
- the seabed is elastic, porous, horizontal and of finite thickness;
- both the soil skeleton and the pore fluids are compressible;
- the soil skeleton generally obeys Hooke's law, implying linear, reversible and non-retarded mechanical properties;
- the flow in the porous seabed is governed by Darcy's law.

The governing equations for the dynamic response of porous seabed is developed in this section, following the formulation in Zienkiewicz et al. [21] and Ulker and Rahman [22]. The equilibrium equation for the overall porous medium can be written as

$$\sigma_{ij,j} + \rho g_i - \rho \ddot{u}_i - \rho_f \ddot{\bar{w}}_i = 0 \tag{1}$$

where σ_{ij} is total stress, g_i is the gravitational acceleration, ρ denotes the total density of porous medium,$\rho = (1-n)\rho_s + n\rho_f$, ρ_s ρ_f is the fluid density, u_i represents the displacement of soil skeleton,$\bar{w}$is the average pore fluid displacement relative to solid frame and is defined as

$$\bar{w} = n\left(w_f - u\right) \tag{2}$$

where w_f is the total displacement of the pore fluid.

The equilibrium of fluid can be written as

$$-p_{,j} + \rho_f g_i - \rho_f \ddot{u}_i - \frac{\rho_f}{n}\ddot{\bar{w}}_i - \frac{\rho_f g_i}{k_f}\dot{\bar{w}}_i = 0 \tag{3}$$

where p is the pore fluid pressure, k_f is the hydraulically isotropic permeability of porous seabed.

The mass conservation equation can be expressed as

$$\dot{u}_{i,i} + \dot{\bar{w}}_{i,i} = -n\beta\dot{p} \tag{4}$$

where β is the compressibility of pore fluid defined as [23,24]

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

where K_w is the true bulk modulus of water, S_r is the saturation degree, p_{w0} is the absolute water pressure, i.e., $p_{wo} = \rho_f g d$, d is the water depth.

The constitutive relationship between effective stress σ'_{ij} and pore fluid pressure p can be represented by [21,22]

$$\sigma_{ij} = \sigma'_{ij} - \delta_{ij}p \tag{6}$$

where δ_{ij} is Kronecker delta; Note that total stress σ_{ij} and effective stress σ'_{ij} are considered to be positive; p is pore pressure and tension is taken a s positive in this equation.

The strain ε_{ij} is defined as:

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right) \tag{7}$$

where $u_{i,j}$ and $u_{j,i}$ denote the derivatives of the solid displacement with respect to spatial coordinates.

The constitutive relations of the skeleton can be defined incrementally in terms of effective stress changes as

$$\Delta\sigma'_{ij} = D_{ijkl}\Delta\varepsilon_{kl} \tag{8}$$

where D_{ijkl} is the tangent coefficient matrix and $\Delta\varepsilon_{kl}$ is the strain change from initial state. In plane strain, the effective stress change can be rewritten as

$$\Delta\sigma'_{ij} = \lambda\Delta\varepsilon_{kk}\delta_{ij} + 2\mu\Delta\varepsilon_{ij} \tag{9}$$

where λ and μ are Lame's parameters, $\Delta\varepsilon_{kk}$ is volumetric strain change. μ is also called shear modulus and $\lambda = 2\mu\nu/(1-2\nu)$ with the Poisson's ratio ν.

Herein, a porous sediment layer lying on the bedrock is considered, as depicted in Fig. 1. The depth of upper seawater is d and the thickness of poroelastic seabed is L. The z-direction is measured as positive upwards from the bedrock surface, while x-direction is parallel to the horizontal seabed surface. The steady-state displacement of seismic excitation is specified vertically on the impermeable bedrock surface. Accordingly, the variables $\tilde{u}$ and $\tilde{w}$ are adopted to represent the earthquake-induced soil skeleton displacement and average fluid relative displacement in z-direction, respectively. In this linear elastic system, the Eqs. (1)–(3) in absence of body force can reduce to:

$$\left(\lambda+2\mu+\frac{1}{n\beta}\right)\frac{\partial^2\tilde{u}}{\partial z^2} + \frac{1}{n\beta}\frac{\partial^2\tilde{w}}{\partial z^2} - \rho\frac{\partial^2\tilde{u}}{\partial t^2} - \rho_f\frac{\partial^2\tilde{w}}{\partial t^2} = 0 \tag{10}$$

$$\frac{1}{n\beta}\left(\frac{\partial^2\tilde{u}}{\partial z^2} + \frac{\partial^2\tilde{w}}{\partial z^2}\right) - \frac{\rho_f g}{k_f}\frac{\partial\tilde{w}}{\partial t} - \rho_f\frac{\partial^2\tilde{u}}{\partial t^2} - \frac{\rho_f}{n}\frac{\partial^2\tilde{w}}{\partial t^2} = 0 \tag{11}$$