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Wave induced instantaneously-liquefied soil depth in a non-cohesive seabed

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ABSTRACT

Instantaneous liquefaction can be induced by the upward seepage force generated in a sandy seabed under wave troughs. The wave-induced pore-pressure distribution in the non-cohesive seabed with an instantaneously-liquefied layer is investigated analytically. Based on the analytical solution to Biot's consolidation equations for the response of a poro-elastic bed to water waves, the expressions of liquefied soil depth are derived with modifying the criterion for instantaneous liquefaction, which is verified with existing offshore field observations and multi-scale numerical simulations. Analytical investigation indicates that, in the instantaneously-liquefied soil layer, the buoyant weight of soil is essentially balanced by upward seepage force into a quasi-static state. Underneath the fully liquefied layer, the effective stress can be remarkably reduced. An excess pore-pressure ratio is then proposed to quantitatively evaluate the instantaneous liquefaction degree and its corresponding influential depth. Parametric studies indicate that, for a certain excess pore-pressure ratio, the influential depth decreases with increasing saturation degree, permeability of soil or water depth, but increases with increasing wave height. The influential depth of a non-cohesive seabed under waves increases significantly with reducing the threshold value of excess pore-pressure ratio, which may have much influence on the stability design for submarine structures.

1. Introduction

In the wave-dominated coastal locations or the surf zones, seabed liquefaction can take place during severe storms. Wave-induced excess pore-pressure and the resulting loss of soil strength could produce catastrophic consequences to marine structures, e.g., the sinking or floatation of pipelines (Sumer et al., 1999; Qi et al., 2017), the instability of breakwaters (Groot et al., 2006), and the local scour around pile foundations (Qi and Gao, 2014). Liquefied soil depth should be well evaluated in the foundation design for marine structures.

As for the pore-pressure responses to waves, two primary mechanisms, including oscillatory and residual pore-pressure, have been observed in flume experiments and offshore in-situ measurements (see Zen and Yamazaki, 1990a). The residual pore-pressure, i.e. the buildup of excess pore-pressure, is mainly induced by the compression tendency of soil skeleton while the cyclic wave loading is being exerted. It has been well recognized that residual liquefaction may be initiated once the effective stress of soil is reduced to zero while the residual pore-pressure is being increased, which corresponds to a complete loss of shear strength (see Sumer, 2014).

In contrast to the residual liquefaction, the instantaneous liquefaction (also termed as “momentary liquefaction”) is induced essentially by the upward seepage force in the upper layer of the seabed under wave troughs. Similar to the quicksand phenomenon, the instantaneous liquefaction is particularly prone to occur in a sandy or non-plastic silty seabed. In the state of instantaneous liquefaction, the buoyant weight of soil is totally balanced by the seepage force and the confining stress would vanish consequently.

In the past a few decades, several analytical solutions have been obtained for wave-induced oscillatory pore-pressure responses. Under the assumption of a permeable rigid seabed with incompressible pore-water, Putnam (1949) presented an analytical solution for wave-induced oscillatory pore-pressure in an isotropic seabed with finite thickness, which was described by Laplace's equation as a potential flow. Diffusion equation was later employed for describing compressible pore-water in a hydraulically isotropic rigid seabed (Moshagen and Torum, 1975). On the basis of Biot's theory framework for porous elastic media, a few porous models for wave-seabed interactions have been established under various assumptions (see Sumer, 2014). Among them, the analytical solution by Yamamoto et al. (1978) took into account of compressible pore-water in a compressible isotropic porous seabed with infinite thickness. Madsen (1978) presented general analytical methods for pore

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pressures and effective stresses in a homogeneous porous seabed of arbitrary thickness as well as in a horizontally layered seabed. Hsu and Jeng (1994) later derived the analytical solution to Biot's equations for the case of finite soil thickness, which can converge to the above solution by Yamamoto et al. (1978) while the soil thickness gets large enough. Besides analytical analyses, numerical modeling was also employed to investigate wave-induced oscillatory pore-pressure under complex boundary and wave conditions, e.g. Mase et al. (1994), Cheng et al. (2001), Higuera et al. (2014), Sui et al. (2016, 2017) and Zhang et al. (2016). It was indicated that the numerical results (e.g. Cheng et al., 2001) by solving Biot's equations are in good agreement with the above analytical solutions (see Sumer, 2014).

Accurate evaluation of instantaneously-liquefied soil depth is crucial for the design of submarine foundations. Sakai et al. (1992) analytically investigated (revised later by Law (1993)) the liquefied soil depth of a sandy seabed under waves, adopting the boundary-layer approximation by Mei and Foda (1981). The liquefied soil depth was evaluated with "iteration calculation method": if the vertical effective stress at a certain tentative depth becomes negative, the tentative depth is further increased and the calculation is repeated until the vertical effective stress approaches zero to finally determine the liquefaction depth (see Sakai et al., 1992). In such an iteration calculation, the force balance at the soil element-scale could not be strictly satisfied, which will be detailed in Section 2.

The analytical results by Sakai et al. (1992) indicated that it would be difficult to reproduce instantaneous liquefaction in a small-size wave flume using a normal sand bed (e.g. silica sand). As such, offshore in-situ tests play a vital role for understanding the phenomenon of instantaneous liquefaction. The wave-induced instantaneous liquefaction was observed in the offshore field by Mory et al. (2007). In their field observations, the pore-pressure responses at different depths of the sandy seabed were continuously measured. High pore-pressure gradients were generated in the seabed, resulting in a number of instantaneous liquefaction events. The instantaneous liquefaction was found to be quite sensitive to the presence of gas content in the sands, which enhances the compressibility of the porous seabed (Gratiot and Mory, 2000). Following the field observations by Mory et al. (2007), Michallet et al. (2009) further analyzed the same field data to examine the effects of saturation degree (approximately ranging from 0.950 to 0.995) on the pore-pressure responses under waves. For such high saturation degree, it would be reasonable to consider the entrapped gas content as the constituent part of the pore-water (Groot et al., 2006), and thereby to assume the sandy seabed as a two-phase media with variable pore-water compressibility to reflect the effect of saturation degree. In addition, the cylindrical-shaped apparatuses were ever employed (Zen and Yamazaki, 1990b; Chowdhury et al., 2006; Liu et al., 2015) for one-dimensional simulations of the wave-seabed interaction to understand the upward seepage induced liquefaction as a kind of quicksand.

There exist two typical criteria to evaluate the critical state for wave-induced instantaneous liquefaction:

(1) The criterion (denoted as "criterion-I") firstly proposed by Bear (1972) was from the perspective of soil-element scale. The vertical gradient of excess pore-pressure j_z $(= dp/dz)$, inducing the upward seepage force in the instantaneously-liquefied soil layer under wave troughs, must locally overcome the buoyant unit weight of soil (γ'), i.e.

$$j_z - \gamma' \geq 0 \tag{1}$$

where $\gamma' = (G_s - 1)(1 - n)\gamma_w$ (in kN/m^3), which can be obtained according to the phase relationships between soil particles and pore water (see Craig (2004)), G_s is the specific gravity of sand particles, n is the porosity of the sand ($n = e/(1 + e)$, in which e is the void ratio of the sand, i.e. the ratio of the volume of voids to the volume of solid particles), γ_w is the unit weight of water (in kN/m^3). Note that the positive value of "j_z" indicates that the seepage force is upward (z-axis is downward).

(2) The other criterion for instantaneous liquefaction (denoted as "criterion-II") was later deduced by Zen and Yamazaki (1990a) from the force analysis on the vertical soil-column rather than the above analysis on soil-element in the criterion-I. The criterion-II can be expressed with the following inequality:

$$p(z) - P_b \geq \sigma'_{z0} \tag{2}$$

where $p(z)$ is the wave-induced transient pore-pressure at the depth (z) in the seabed; P_b is the wave-induced pressure (negative under wave troughs) at the seabed surface ($z = 0$); $\sigma'_{z0}(= \gamma' z)$ is the initial vertical effective stress for a homogenous sandy seabed. The criterion-II implies that instantaneous liquefaction may occur when the excess pore-pressure difference between a certain depth and the soil surface becomes greater than the overburden soil pressure.

Note that, if adopting the existing criteria for instantaneous liquefaction, an upward resultant force would be induced unreasonably in a sandy (non-cohesive) seabed, which will be detailed in Section 2.

In this study, the vertical distribution of wave-induced pore-pressure in a non-cohesive seabed with instantaneously-liquefied layer will be investigated analytically. Based on the classical solution to Biot's consolidation equations for porous media, the expressions for liquefied soil depth are derived with modifying the liquefaction criterion. Parametric study is further made to investigate the influential factors for liquefied soil depth.

2. Wave-induced excess pore-pressure and instantaneous liquefaction: analytical investigation

2.1. Re-examination of excess pore-pressure distribution by using existing liquefaction criteria: A case study

To examine the excess pore-pressure distribution in an instantaneously-liquefied sandy seabed, a case study is made for the given values of wave parameters and soil properties as follows: The water depth $h = 10.0$ m, the wave height $H = 3.0$ m, the wave period $T = 8.0$ s and the wave length $L \approx 70.9$ m; the coefficient of permeability of the sand $k_s = 1.0 \times 10^{-4}$ m/s, the soil elasticity modulus $E = 30.0$ MPa, $\gamma' = 8.82$ kN/m^3, the saturation degree $S_r = 0.98$, $n = 0.45$, and the Poisson ratio of the sand $\nu = 0.3$.

As mentioned in Section 1, the liquefied soil depth used to be evaluated with the "iteration calculation method", once the distribution of excess pore-pressure under wave troughs are obtained, and at the same time the liquefaction criterion is chosen as the criterion-I (Eq. (1)) or the criterion-II (Eq. (2)). The analytical solution by Yamamoto et al. (1978) (referred as "Yamamoto solution" later, see Appendix A) is employed for calculating the wave-induced excess pore-pressure in a poro-elastic seabed.

Fig. 1 gives the vertical distribution of the excess pore-pressure difference (p-P_b) under wave troughs calculated with the solution by Yamamoto et al. (1978). The vertical distribution of the initial vertical effective stress $\sigma'_{z0}(= \gamma' z)$ in the homogeneous sandy seabed is also provided in this figure. When adopting the different criterion for instantaneous liquefaction (criterion-I or criterion-II), the calculated values of liquefaction depth are different, denoted as "z_s" for the criterion-I, and "z_p" for the criterion-II, respectively (see Fig. 1). As indicated in the expressions for the existing liquefaction criteria (Eqs. (1) and (2)), the liquefaction depth z_s (=0.45 m; under the given wave and soil conditions in this case study) is obtained according to the effective stress analysis on soil-element, i.e. Eq. (1) for the criterion-I; whereas z_p (=0.93 m) was derived from the force balance of the "soil-column AB" see Fig. 1, i.e. Eq. (2) for the criterion-II.

As shown in Fig. 1, for the selected three typical elements (i.e. the element-1, -2 and -3) at various depths, only the elememt-2 (where