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Cyclic characterization of wave-induced oscillatory and residual response of liquefiable seabed

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ABSTRACT

The paper presents a robust modeling method for a fully coupled effective stress analysis of the wave-induced liquefaction scenarios, based on the Biot consolidation theory. In this context, emphasis is placed on the implementation of a well-calibrated cyclic soil model and an empirical shear-volume coupling equation, which links the increment of volumetric strain per cycle of wave with the shear strain occurring during that particular cycle. Unlike most of the previous investigations using the amplitude of shear stress over the wave period (or the phase-resolved oscillatory shear stresses) as the source term for calculating the residual pore pressure, in this study, the source term is related to the rate of plastic volumetric deformation and implemented into the Biot consolidation equation to consider both generation and partial dissipation of excess pore pressure during wave propagation. Then, the proposed modeling method is incorporated into a dynamic finite difference analysis procedure. Model calibrations are carried out in terms of individual soil element behavior and seabed response under progressive waves, respectively. Overall good agreement demonstrates the reliability of the modeling method for the prediction of wave-induced seabed response. Finally, the paper highlights the potentials of proposed modeling framework to simulate the basic features of wave-induced seabed response (i.e., the coupling of progressive buildup of pore pressure and cyclic softening of soil skeleton), by means of numerical examples. The obtained results show that the cyclic behavior of liquefiable seabed under wave actions can be well captured by the proposed model.

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1. Introduction

Wave-induced liquefaction has long been recognized as the main cause of seabed instability likely to occur in saturated (or nearly saturated) marine sediments of the noncohesive soils, and in some cases, the mixture such as silty sand or clayey sand (hereafter described as “sand” for simplicity) (de Groot et al., 2006; Kirca et al., 2014), which may have catastrophic consequences for marine structures, such as large horizontal displacements of immersed tunnels (Kasper et al., 2008), floating up of pipelines (Teh et al., 2006; Sumer et al., 2006b), tilting of caissons (Puzrin et al., 2010), and shear failure of breakwater slopes (del Campo and Negro, 2011). Therefore, it is vital to evaluate wave-induced seabed response including the excess pore pressure and resulting liquefaction phenomenon for marine engineers involved in the design of marine structures with or on saturated sands. The phenomena and problems associated with liquefaction can be put in

perspective by considering two different mechanisms encountered in the marine environment, i.e., momentary liquefaction and residual liquefaction (Zen and Yamazaki, 1990; Jeng, 2013). The present paper concerns the residual liquefaction of sandy seabed under progressive wave actions, which experiences cyclic softening due to progressive buildup of excessive pore pressure under the wave-induced cyclic shear strains in the soil.

A large number of computational models have been, and continue to be developed for the simulation of wave-induced seabed response. Extended review can be found in the state-of-the-art papers by Ishihara (1993), Jeng (2001), Sawicki and Mierczynski (2006), de Groot et al. (2006), Sumer (2014) and Brennan et al. (2015). Among the notable recent advances is the successful implementation of effective stress analysis method using the Biot consolidation theory of coupled flow and deformation, in which triggering of liquefaction, post-liquefaction stability and resulting displacements can be considered in a single time domain analysis (Madsen, 1978; Yamamoto et al., 1978; Zienkiewicz et al., 1980; Zienkiewicz and Shiomi, 1984; Elgamal et al., 2003; Byrne et al., 2004; Zhuang et al., 2015). The residual liquefaction is a result of accumulation of pore pressure under the volumetric compaction of soil by

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cyclic wave actions. Nevertheless, the major challenge still remains for reliable computational modeling of the wave-induced pore-pressure buildup. The process of pore-pressure buildup and resulting liquefaction is followed by partial dissipation of the accumulated pore pressure caused by volumetric compaction of soil (Kirca et al., 2013). Seed and Rahman (1978) recognized the significance of pore-pressure dissipation and incorporated this effect into a simple one-dimensional (1D) finite-element model for earthquake-induced liquefaction to describe the buildup of pore pressure under progressive waves. Sumer and Fredsøe (2002) and Jeng et al. (2007) introduced into the Biot equation an additional source term to evaluate both generation and dissipation of excess pore pressure, which was an empirical relation from Seed and Rahman (1978). Later, Jeng and Zhao (2015) re-derived the previously mentioned 1D model to create a 2D model, in which the source term was redefined as a time-dependent function using the phase-resolved oscillatory shear stresses (rather than the amplitude of shear stress over the wave period). The 2D model thereby considered shear-induced pore pressures at each time step rather than at each cycle or half cycle. More recently, Zhao et al. (2016) and Liao et al. (2015) considered with 2D elasto-plastic solution, using the source term function proposed by Jeng and Zhao (2015).

It is to note that the seabed response under wave loading (in terms of pore-pressure buildup and resulting liquefaction) is cyclic in nature. Indeed, the essence of this problem is the formulation of cyclic stress-strain relations and the contractive effects (shear-volume coupling) of soil skeleton. However, in all the aforementioned studies, with the exception of Sassa and Sekiguchi (2001), no model is yet available incorporating the cyclic stress-strain behavior (i.e., nonlinear and hysteretic), especially the coupling effect of progressive buildup of pore pressure and cyclic softening of soil skeleton. In this respect, Sassa and Sekiguchi (2001) developed a cyclic-plastic constitutive model including the shear-volume coupling effects for repeated load cycles, in which the source term was related to the rate of plastic volumetric deformation. However, such a stress-strain law is very complex and will require many parameters to adequately model the observed laboratory and field behavior under cyclic loading conditions.

The present investigation aims to develop a simple but workable modeling method for a fully coupled effective stress analysis of the wave-induced liquefaction scenarios, based on the Biot consolidation theory (Biot, 1941). In this regard, emphasis is placed on the implementation of a well-calibrated cyclic soil model and an empirical shear-volume coupling equation (linking the increment of volumetric strain per cycle of wave with the shear strain occurring during that particular cycle). In particular, the predicted rate of plastic volumetric strain is taken as the source term of pore-pressure buildup (Dobry et al., 1982) and implemented into the Biot consolidation equation to consider the partial pore-pressure dissipation effect during wave propagation.

Then, the model is incorporated into a dynamic finite difference analysis procedure. Model calibrations are carried out against a series of cyclic laboratory tests for the individual soil element behavior, and against the previous analytical solutions and the experimental data for the seabed response under progressive waves, respectively. In the following, the formulation of this modeling framework and the calibration process are presented and discussed.

2. Governing equations and constitutive model

2.1. Problem layout

In this study, we consider ocean wave trains over a porous seabed, as depicted in Fig. 1. Herein, the linear wave theory is applied to obtain the dynamic pressure exerted by water waves at the seabed surface for simplicity and without loss of generality, as a typical storm can be generally regarded as superposition of a number of different waves having characteristics in accordance with linear wave theory (Seed and Rahman, 1978).

The wave-induced liquefaction is the result of a complex interaction between waves and seabed. The corresponding response of the seabed consists of two aspects: i) excess pore pressure response, and ii) cyclic softening of soil skeleton. In the following sections, the coupling effects of these two aspects will be integrated in the proposed modeling method.

2.2. Governing equations

The propagation of ocean waves exerts significant dynamic loading on the seabed surface. The porous seabed consequently responds to the wave loading and undergoes partial pore-pressure dissipation. The coupling response of soil skeleton and pore water in resisting the waves requires the solution of coupled pore fluid flow and deformation equations proposed by Biot (1941) under prescribed boundary conditions (Zienkiewicz et al., 1980; Ulker and Rahman, 2009).

Based on the Biot's consolidation equation, the governing equations for the force equilibrium in (nearly) saturated soil can be written as follows:

$$G\nabla^2 u_i + \left(\frac{G}{1-2\nu}\right)\varepsilon_{jj,j} = p_{,i} + \rho\ddot{u}_i \quad (1)$$

where u = soil displacement vector; ε = soil strain tensor; ρ = total density; p = excess pore pressure; ν = Poisson's ratio; and G = shear modulus of soil.

A saturated porous seabed is assumed to be hydraulically isotropic (i.e., the same permeability, k , in all directions) and obey Darcy's law.

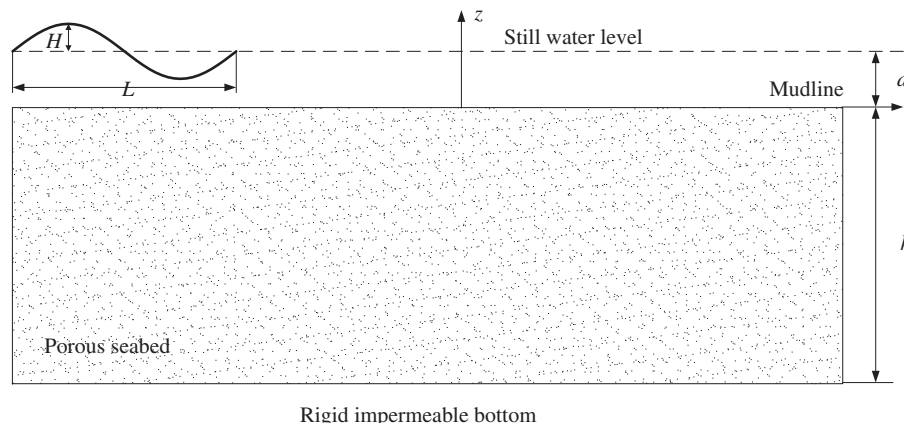


Fig. 1. Sketch of wave-seabed interaction.

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