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Numerical modelling of liquefaction in loose sand deposits subjected to ocean waves

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ABSTRACT

The failure of marine structures is often attributed to liquefaction in loose sand deposits that are subjected to ocean waves. In this study, a two-dimensional integrated numerical model is developed to characterize the liquefaction behaviours of loosely deposited seabed foundations under various types of ocean waves. In the present model, Reynolds-Averaged Navier–Stokes (RANS) equations are used to simulate the surface wave motion, and Biot's consolidation equations are used to link the solid-pore fluid interactions in a porous medium. A poro-elasto-plastic solution is used to reproduce foundation behaviour under cyclic shearing. Unlike previous investigations, both oscillatory and residual soil responses were considered; they are coupled in an instantaneous approach. Verification of the model results to the previous centrifugal wave tests is carried out, obtaining fairly good agreement. Numerical examples show that foundation behaviour under various types of wave loading, particularly standing waves or a solitary wave, embodies a completely two-dimensional process in terms of residual pore pressure development. The parametric studies demonstrate that liquefaction caused by the build-up of pore pressures is more likely to occur in loosely deposited sand foundations with poor drainage and under large waves.

1. Introduction

Marine installations, such as breakwaters, pipelines, and offshore wind turbines have been widely constructed in coastal regions as a result of ever-increasing ocean engineering activities in the past few decades. One of the main concerns involved in the design of these structures is the instability of seabed foundations subjected to ocean waves. As typical marine sediments, loose sandy soils are widely distributed in the oceanic environment. In the practice of ocean engineering, it is sometimes unavoidable to select loose sand deposits as seabed foundations, i.e., submarine pipelines or cables embedded in loosely packed backfills. Understanding the mechanical behaviours of loose sand deposits to ocean waves could be beneficial for coastal engineers when evaluating the stability of marine structures throughout their design life.

Normally, the loose sandy soil has a low relative density of D_r, and S and P wave speeds, but a low standard penetration test (SPT) value. Under cyclic wave loading, soil particles in the loose sand deposits tend to rearrange their relative positions and become compacted in a manner, associated with the drainage of pore water. In this process, pore water pressure is likely to build up because of the effect of volumetric strain change on pores' storage capacity. Pore pressure can accumulate to a large value when the drainage condition is impeded, causing the soil to become unstable or even liquefied. The intensive use of both wave flume tests and geotechnical centrifugal tests has identified the occurrence of liquefaction in loose sand deposits [1–4]. It has been recognized that the wave-induced cyclic stress ratio is the key parameter affecting the generation of residual pore pressure and the number of loading cycles required to cause liquefaction. The liquefaction resistance of a sandy seabed to cyclic loadings is found to be significantly affected by the soil state (i.e., void ratio, and effective confining pressure), grain characteristics (i.e., grain-size distribution and grain shape) and loading conditions (e.g., loading intensity, duration, frequency and even irregularity). In recent publications, it has been further

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proven to be affected by the shear stress conditions in the initial consolidation state [5,6].

Accompanied by the experimental efforts, numerous theoretical frameworks – primarily involving analytical approximations and numerical modelling – have been developed to investigate the liquefaction susceptibility of loose sand deposits to ocean waves [3,7–11]. For example, Sekiguchi et al. [12] derived an analytical solution for residual pore pressure development using Laplace's transformation. The closed-form solution is capable of taking the cumulative contraction of soils under cyclic loading into account. However, in their analysis, the seabed thickness was much less than the assumed wavelength, which may be questionable. Sassa et al. [11] proposed a 1-D finite difference model to study the post-liquefaction process of loose seabed soils under progressive waves. In [11], the liquefied soil was treated as a heavy fluid based on potential flow theory and differentiated from the sub-liquefied soil using a moving boundary condition. Liu et al. [13] further extended Sassa et al.'s [11] model by considering the viscous effect of liquefied layer and investigate the wave-induced residual liquefaction in the sandy seabed of finite thickness. Their numerical results indicate the need to consider the viscous effect in the post-liquefaction analysis. This framework has been further applied to a random wave case [14].

The aforementioned investigations are limited to 1-D models, neglecting the horizontal effective stress and pore pressure gradient along the wave propagation direction. In the practice of engineering, it is important to know the potential for liquefaction around the structure foundation or pipelines. Because of the presence of marine structures, the water wave field in the vicinity of structures will be modified, subsequently affecting wave-induced shear deformation in the soil profile. Additionally, for the case involving structures interacting with the water waves and seabed foundations, significant lateral forces and overturning momentum will be exerted on the structure, resulting in the foundation soil experiencing cyclic stresses in both the horizontal and vertical directions. With a one-dimensional numerical framework, it is impossible to capture the interactions between a wave, a structure (embedded or sitting on the seabed), and its deposited sandy foundation appropriately.

In this paper, we will introduce a simple but workable integrated numerical model with the capability of reproducing the liquefaction characteristics of loose sand deposits in two dimensions, using the theory of poro-elasto-plasticity, based on the existing 1-D framework [3,12]. This model is first validated through comparison with centrifugal wave tests available in the literature to ensure its accuracy and effectiveness. After validation, it will be further applied to investigate the effects of key characteristics, including the nonlinearity and irregularity of cyclic loading conditions, the non-homogeneity of soil properties, the plasticity of soil behaviour, etc., on the interactions between progressive waves and loosely deposited sand foundations, through detailed parametric studies. Along with the progressive waves, the foundations' behaviour under both standing waves and a solitary wave are presented and discussed at the end of the study.

2. Theoretical models

2.1. Wave model

In this study, RANS (Reynolds-Averaged Navier–Stokes) equations are used for governing the flow motion over a rigid seafloor. The mass and momentum conservation equations for a RANS solver can be expressed as follows:

$$\frac{\partial \langle u_{fi} \rangle}{\partial x_i} = 0, \tag{1}$$

$$\begin{aligned} \frac{\partial \rho_f \langle u_{fi} \rangle}{\partial t} + \frac{\partial \rho_f \langle u_{fi} \rangle \langle u_{fj} \rangle}{\partial x_j} &= -\frac{\partial \langle p \rangle^f}{\partial x_i} + \rho_f g_i \\ &+ \frac{\partial}{\partial x_j}\left[\mu_f \left(\frac{\partial \langle u_{fi} \rangle}{\partial x_{fj}} + \frac{\partial \langle u_{fj} \rangle}{\partial x_{fi}}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho_f \langle u'_{fi} u'_{fj} \rangle\right), \end{aligned} \tag{2}$$

where u_{fi} is the flow velocity, x_i is a Cartesian coordinate, t is the time, ρ_f is the density of the fluid, p is the pressure, g_i is the acceleration caused by gravity, μ_f is the dynamic viscosity, and the relationship between the Reynolds stress term $-\rho_f \langle u'_{fi} u'_{fj} \rangle$ and the rates of strain of the flow field can be specified by the sophisticated $k - \epsilon$ turbulence model [15] as:

$$-\rho_f \langle u'_{fi} u'_{fj} \rangle = \mu_t \left[\frac{\partial \langle u_{fi} \rangle}{\partial x_j} + \frac{\partial \langle u_{fj} \rangle}{\partial x_i}\right] - \frac{2}{3}\rho_f \delta_{ij} k \tag{3}$$

where μ_t is the turbulent viscosity, which is considered a function of the turbulence kinetic energy (k) and turbulence dissipation rate (ϵ); and δ_{ij} is the Kronecker delta. Based on Eq. (3), Eq. (2) can be rewritten as follows:

$$\begin{aligned} \frac{\partial \rho_f \langle u_{fi} \rangle}{\partial t} + \frac{\partial \rho_f \langle u_{fi} \rangle \langle u_{fj} \rangle}{\partial x_j} &= -\frac{\partial}{\partial x_i}\left[\langle p \rangle + \frac{2}{3}\rho_f k\right] \\ &+ \frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial \langle u_{fi} \rangle}{\partial x_j} + \frac{\partial \langle u_{fj} \rangle}{\partial x_i}\right)\right] + \rho_f g_i \end{aligned} \tag{4}$$

in which $\mu_{eff} = \mu + \mu_t$ is the total effective viscosity. The symbol $\langle\rangle$ stands for Darcy's volume averaging operator, which can be defined as follows:

$$\langle a \rangle = \frac{1}{\forall} \int_{\forall_f} a d\forall \tag{5}$$

in which $\forall$ is the total averaging volume, and $\forall_f$ is the portion of $\forall$ that is occupied by the fluid. The relationship between the Darcy's volume averaging operator and intrinsic volume averaging is $\langle a \rangle = n\langle a \rangle^f$.

To generate the incident waves considered in this study, the internal wave maker method developed by Lin and Liu [16] is used; in that method, a mass source function ($S(x_i, t)$) is added in the continuity equation (Eq. (1)) in the source region, i.e. $\partial\langle u_i \rangle/\partial x_i = S(x_i, t)$. The value of $S(x_i, t)$ depends on both wave characteristics, and wave types. For a fifth-order Stokes wave, for example, the mass source function $S(x_i, t)$ can be expressed as follows:

$$S(x_i, t) = \sum_{i=1}^{5} \frac{2C}{A} a_i \cos i\left(\frac{\pi}{2} - \omega t - \delta_p\right) \quad in \quad \Omega \tag{6}$$

in which C is the wave phase velocity; ω is the wave frequency; δ_p is the phase shift constant; a_i is the wave amplitude associated with the ith wave mode [17], which is a function of wave parameters including wave height (H), water depth (d) and wave period (T); Ω is the source region; and A is the area of source region. For a solitary wave, the corresponding source function is

$$S(x_i, t) = \frac{CH}{A}\mathrm{sech}^2\left[\sqrt{\frac{3H}{4d^3}}\left(4d/\sqrt{H/d} - Ct\right)\right] \tag{7}$$

In this study, the area (denoted by A) of the source region in which the source term wave-maker is acting, is predefined and remains constant during the simulation, as shown in Fig. 1. As recommended by [16], the source region has a height of 10% of the water depth (0.65–0.75d) and a width of 5% of the wavelength. More details can be found in [16].