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A semi-analytical solution for random wave-induced soil response and seabed liquefaction in marine sediments

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Abstract

In this study, unlike most previous investigations for wave-induced soil response, a simple semi-analytical model for the random wave-induced soil response is established for an unsaturated seabed of finite thickness. Two different wave spectra, the B-M and JONSWAP spectra, are considered in the new model. The influence of random wave loading on the soil response is investigated by comparing with the corresponding representative regular wave results through a parametric study, which includes the effect of the degree of saturation, soil permeability, wave height, wave period and seabed thickness. The maximum liquefaction depth under the random waves is also examined. The difference on the soil response under the two random wave types, B-M and JONSWAP frequency spectra, is also discussed in the present work.

Keywords: Soil response; Seabed liquefaction; Pore pressure; Random waves

1. Introduction

When water waves propagate over a porous seabed, the dynamic pressure on the sea floor fluctuates with the passing waves. Such fluctuations further induce variations of the pore pressure and effective stress within the seabed, and cause the deformation or even failure of the seabed skeleton. Numerous coastal structures and offshore installations, such as pipelines, breakwaters and marine platforms, have been damaged by the wave-induced seabed instability such as liquefaction (Sumer and Fredsøe, 2002). Furthermore, the wave-induced pore pressure within marine sediments is a key factor to estimate the seepage exchange between the seawater body and bottom sediments, which is important for studying the water pollution in coastal areas.

In the last few decades, numerous studies have been carried out to investigate the wave-induced pore pressure and effective stresses within marine sediments using physical or mathematical approaches. As for experimental studies, wave-induced pore pressure measurements inside the sand bed were conducted in the wave tank experiments using various methods, i.e., pressure trappings in Sleath (1970) or pore-water pressure transducers in Yamamoto et al. (1978) and Tsui and Helfrich (1983).

Accompanying with the experimental efforts, numerous theoretical investigations, including analytical and numerical approaches, were carried out to examine the soil response based on different assumptions of the relative rigidity of pore fluid and soil skeleton, such as soil thickness (infinite or finite depth), soil permeability (hydraulically isotropic or anisotropic) and pore fluid compressibility related to the degree of saturation. Among these, Yamamoto et al. (1978) and Okusa (1985) developed the analytical solutions for soil response in case of infinite soil depth; Mei and Foda (1981) and Jeng (1997) proposed the analytical solutions with a finite depth. Incidentally; Thomas (1989, 1995) developed a 1-D finite element model to investigate the soil response inside the seabed. However, all aforementioned works are based on the regular wave theory as the first approximation, even though the random waves always occur in the realistic ocean environments.

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To date, only a few studies have been carried out to consider the variations on the soil responses inside the marine sediments under random wave loadings. Sumer et al. (1999) performed experimental tests to investigate the effect of irregular wave on soil response, and they found the process of build-up of pore pressure in irregular waves occurs in much the same way as in the case of the regular wave. Later, Wang et al. (2005) developed a finite element model to numerically examine the effects of random waves on the wave-induced pore pressure and effective stress based on the dynamic model of Zienkiewicz and Chang (1980). Recently, Liu and Jeng (2006) set up an analytical solution for the random wave-induced soil response within an infinite soil thickness. Difference on the soil response between regular and random wave loadings, together with the effects of several soil characteristics, was investigated. However, as mentioned in Jeng (1997), using the solutions of infinite soil thickness will lead to errors in pore pressure and other response variables.

In this paper, based on the framework proposed by Jeng (1997), we will establish a semi-analytical solution for the random wave-induced soil response within a finite seabed thickness. Two typical frequency spectra, B-M spectrum and JONSWAP spectrum, will be utilized to generate the random waves. The objective of this study is to investigate the random wave-induced soil response in the marine sediments with a finite soil thickness. A set of numerical calculations for pore pressure, effective normal stresses and shear stress will be carried out and compared with the representative regular wave results to demonstrate the effect of wave randomness. Influence of various soil and wave parameters as well as the effect of porous seabed thickness on the random wave-induced soil response will also be considered in this study. Finally, random wave-induced maximum liquefaction depth will be investigated and compared with the corresponding regular wave results.

2. Random wave generation

In this study, we consider a series of random waves propagating over a porous seafloor with a finite thickness above a rigid impermeable bottom, as shown in Fig. 1. In realistic environments, random waves instead of regular linear wave loadings always occur. Such random waves characterizing with irregular water surface elevation introduce the relevant change on the wave dynamic pressure acting at the seabed, which further induce the variation of pore water pressure and effective stresses inside the marine sediments.

Herein, we consider the flow is two-dimensional and presuming the random waves with still water level (SWL) located at $z = d$ are traveling along the positive x-direction, and assume the vertical z-axis is upward from the surface of the seabed (water–soil interface, $z = 0$) as illustrated in Fig. 1. A porous seabed with finite soil thickness h is located between the seabed surface and a rigid impermeable bottom.

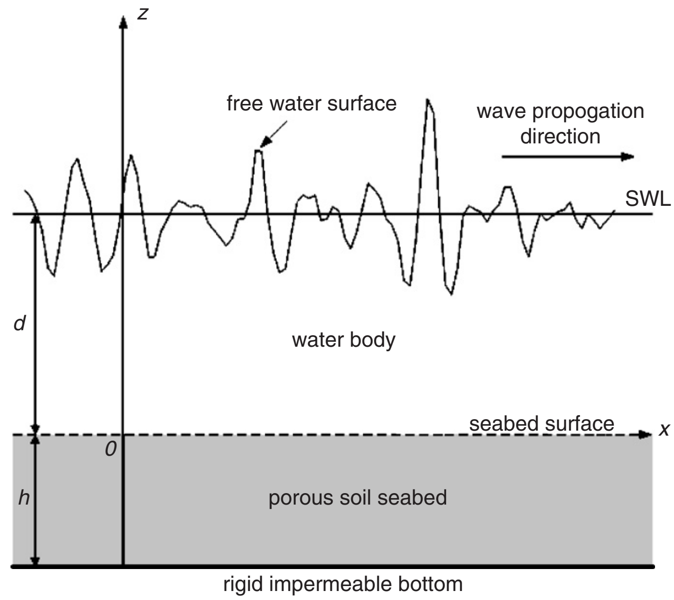

Fig. 1. Definition sketch of random wave propagating over a porous seabed.

The profile of random sea waves can be regarded as a stationarity stochastic process, which follows the Gaussian (normal) distribution. Such process satisfies the property of ergodicity. When we consider the profile of random sea waves, following the mathematical representations of Longuet-Higgins (1957), the wave profile or the water surface elevation $\eta(x,t)$ can be represented by

$$\eta(x,t) = \sum_{i=1}^{\infty} a_i \cos(k_i x - 2\pi \tilde{f}_i t + \varepsilon_i) \approx \sum_{i=1}^{M} a_i \cos(k_i x - 2\pi \tilde{f}_i t + \varepsilon_i), \quad (1)$$

with M being a sufficiently large number. In (1), a_i denotes the amplitude of the component wave in the ith frequency, $\tilde{f}_i$ is the ith representative frequency, which is evenly distributed in the range of (f_{i-1}, f_i), and εi is a random initial phase angle and equally distributed in the range of $(0, 2\pi)$. In this equation, wave number of the ith component (k_i) can be determined from the dispersion relationship after knowing the corresponding representative frequency $\tilde{f}_i$ and water depth d

$$(2\pi \tilde{f}_i)^2 = gk_i \tanh k_i d. \quad (2)$$

The component wave amplitude a_i is determined from a given function of the frequency spectrum $S(f)$ by

$$a_i = \sqrt{2S(\hat{f}_i)\Delta f_i}, \quad \hat{f}_i = (f_i + f_{i-1})/2, \quad \Delta f_i = f_i - f_{i-1}. \quad (3)$$

In this study, two commonly used frequency spectra, B-M spectrum and JONSWAP spectrum, are adopted for further discussions. Here, we summarized these