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Numerical study of wave-induced soil response in a sloping seabed in the vicinity of a breakwater

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ABSTRACT

In this study, a mathematical integrated model is developed to investigate the wave-induced sloping seabed response in the vicinity of breakwater. In the present model, the wave model is based on the Volume-Averaged/Reynolds Averaged Navier–Stokes (VARANS) equations, while Biot's consolidation equation is used to govern the soil model. The influence of turbulence fluctuations on the mean flow with respect to the complicated interaction between wave, sloping seabed and breakwater are obtained by solving the Volume-Averaged $k-\epsilon$ model. Unlike previous investigations, the phase-resolved absolute shear stress is used as the source of accumulation of residual pore pressure, which can link the oscillatory and residual mechanisms simultaneously. Based on the proposed model, parametric studies regarding the effects of wave and soil characteristics as well as bed slopes on the wave-induced soil response in the vicinity of breakwater are investigated. Numerical results indicate that wave-induced seabed instability is more likely to occur in a steep slope in the case of soil with low relative density and low permeability under large wave loadings. It is also found that, the permeability of breakwater significantly affect the potential for liquefaction, especially in the region below the breakwater.

1. Introduction

The phenomenon of seabed stability around marine infrastructures such as pipelines, breakwaters, seawalls and offshore wind turbine foundations has attracted great attentions among coastal geotechnical engineers, due to growing activities in marine environments. In natural ocean environments, the pore pressures within the seabed may become excessive when it cannot dissipate as fast as the water waves propagation over a porous seabed. With the excess pore pressure and accompanying decreases in effective stress, part of seabed may become unstable or even liquefied. The wave-induced liquefaction has been identified as one of main processes in the analysis of seabed instability around marine installations [1]. Thus, the evaluation of wave-induced pore pressures and effective stresses are important for coastal engineers involved in the design of foundation for breakwaters.

Based on the observations in laboratory experiments and field measurements, two mechanisms for the wave-induced liquefaction in sandy bed have been identified: transient or momentary liquefaction and residual liquefaction [2,3]. The transient liquefaction most generally occurs within unsaturated marine soils under wave troughs when there is an upward seepage force due to the dissipation of pore pressure induced by the encapsulated air [4–6]. On the other hand, the residual liquefaction is normally seen in fully saturated seabed due to the build-up of excess pore pressure caused by the volumetric contraction under the action of cyclic loading [7–9].

Adopting the poro-elastic theory [10], there have been various analytical investigations of the problem for wave–seabed interaction, including [4,5,11], in which an elastic soil skeleton and a Darcy's flow with compressible pore water are coupled together. In these investigations, there was no any marine structure on seabed, and the linear and nonlinear Stokes waves were used to apply dynamic force on seabed surface. Later, this framework has been further applied in the analysis of the wave induced seabed response in the vicinity of a vertical seawall [6,12–15], in which the boundary conditions are simple with simplified configuration of breakwaters.

Besides the development of analytical solutions, numerical methods have been widely applied in the analysis of seabed response with a structure. Among these Mase et al. [16] developed a two-dimensional finite element model to investigate the wave-induced pore pressures and effective stresses in a sandy seabed as well as those in a rubble mound foundation of a composite caisson-type breakwater subject to linear standing wave. In their analysis, the lateral boundary conditions are provided by the analytical solution proposed by Yamamoto et al. [5]. Jeng et al. [17] further investigated the effect of wave and soil characteristics on the wave-induced soil response near the composite breakwater located at a finite, isotropic and homogeneous seabed. Mizutani

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and Mostafa [18] and Mostafa et al. [19] developed a BEM–FEM combination numerical model to investigate the interaction of wave–seabed–breakwater. In their models, the Laplace equation for fluid domain and the modified Navier–Stokes equation for the porous flow in seabed and rubble mound are solved using BEM while the determination of stress status in seabed foundation are obtained by solving the Biots consolidation using FEM. Ulker et al. [20] may be the first to consider the effect of pre-consolidation due to the self-weight of a composite breakwater in the assessment of the momentary liquefaction subject to standing wave loading. Their research concluded that there was always a liquefaction zone at the toe of the rubble-mound foundation, which would directly result in the instability of the breakwater. However, the wave models in all aforementioned numerical models are based on the potential flow theory, which is incapable of capturing complicated wave motion (i.e., wave breaking, turbulence fluctuations).

Recently, some numerical models were further developed to overcome the disadvantage mentioned above by combing the Reynolds-Averaged Navier–Stokes equations (RANS) for wave field and the Volume-Averaged Reynolds-Averaged Navier–Stokes (VARANS) equations for the porous flow in a porous medium in which the flow field in the whole computational domain, and the flux at the interface between the porous seabed/marine structures and the seawater, are all continuous [21–26]. However, the wave-induced pore pressure and effective stress changes within the seabed have not been concerned in these models. Later, Jeng et al. [27] developed an integrated model (PORO-WSSI 2D) for the problem of wave–seabed-structure interaction, in which the Volume-Averaged Reynolds Averaged Navier–Stokes (VARANS) equations are used to govern the wave motion and porous flow in seabed/breakwater, the dynamic Biots equations are used to govern the behaviors of porous seabed and marine structures. Due to the fact that the VARANS equations are adopted in PORO-WSSI II, the complicated wave motion can be simulated [28].

There are some laboratory experiments for the wave-induced pore pressure build-up mechanism in the literature [29,30]. Based on laboratory tests [30], it has been recognized that the pore pressure accumulation is mainly related to the cyclic shear stress ratio, the period of cyclic loading and the cyclic loading number required to reach the residual liquefaction value. Seed and Rahman [7] may be the first to investigate a simple 1-D finite element model to describe the build-up of pore pressure under progressive wave. This model has been further extended or modified to examine the wave-induced residual response analytically and numerically [8,31–33]. Sassa and Sekiguchi [34] developed a 2-D elasto-plastic constitutive model where the principal stress axes rotation in the sand is incorporated and compared the numerical solutions with their experimental measurements conducted in a centrifuge wave tank [35]. Regarding the build-up mechanism for the wave–seabed-structure interactions, Li and Jeng [36] proposed a 3D analytical solution to investigate wave-induced soil response around breakwater heads, including both oscillatory and residual mechanisms. Later, a more sophisticated constitutive elasto-plastic model for determining the dynamic response and residual liquefaction potential around breakwater head was investigated by Jeng and Ou [37]. In both of their analysis, the breakwaters are simplified as a line without width and weight. And the effects of configuration of structure on the wave field and the structure weight on the stress field on the seabed foundation are totally neglected.

All aforementioned studies have only concerned a breakwater built on a flat seabed foundation. A few research has been done for the interaction between wave, sloping seabed and breakwater, but limited to the oscillatory mechanism in seabed foundation or rubble mound breakwaters [38,39]. Among these, Ye et al. [38] considered the case with tsunami loading, while Ye et al. [39] considered the case with breaking waves. However, all these investigations were limited to oscillatory mechanisms, rather than residual mechanisms. In reality, the wave-induced pore pressure accumulation accompany with the residual liquefaction in seabed is much easier to occur than the oscillatory pore pressure and momentary liquefaction in engineering practice.

In this study, the wave model is based on the VARANS equation, in which the turbulence fluctuations due to the interaction between wave, slope seabed and breakwater are obtained by solving the volume-averaged $k-\epsilon$ model. In addition to the wave model, another new feature of this paper is the new definition of residual mechanism of porous seabed model, in which the source term is determined by the phase-resolved shear stress rather than the shear stress amplitude over wave period used in previous studies [8,32,36]. As the phase-resolved shear stress is related to the oscillatory mechanism of soil response, both the wave-induced oscillatory mechanisms and residual mechanisms around a breakwater will be discussed. Regarding the liquefaction, we will focus on the wave-induced residual liquefaction.

2. Theoretical formulations

The computational domain and dimension sizes are shown in Fig. 2. An impermeable rubble mound breakwater is constructed on a sloped seabed (gradient angle 1:50). The internal wave maker is placed over flat part of seabed foundation. In this study, the fifth-order stokes wave theory was used to generated the incident waves. The oscillatory and residual mechanisms of seabed response are modelled by a poro-elastic model. Both wave and seabed models are integrated into a single model.

2.1. Seabed model

In general, two mechanisms for the wave-induced soil response have been observed in field measurements and laboratory experiments [2], as shown in Fig. 1, which can be expressed as

$$b = \tilde{b} + \bar{b}, \quad \text{where} \quad \bar{b} = \frac{1}{T}\int b\,dt \tag{1}$$

where T is the wave period, b denotes the wave-induced soil response variables (including soil displacements, stresses and pore pressures), $\tilde{b}$ represents the oscillatory component, $\bar{b}$ represents the residual component. In the following sections, both components will be considered.

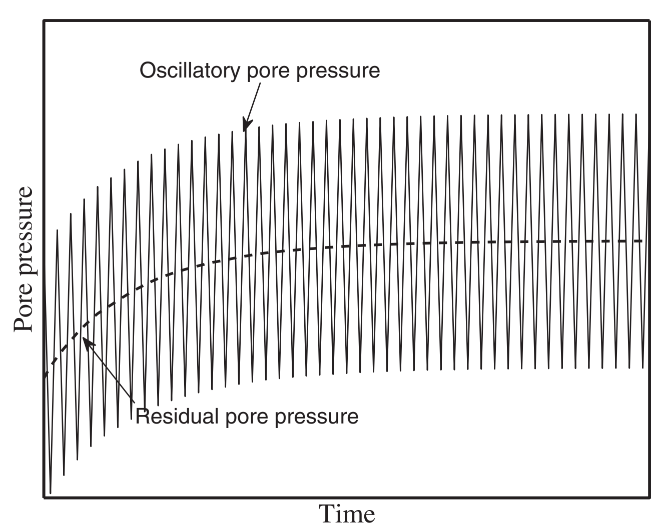

Fig. 1. Mechanisms of wave-induced pore pressures.