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Numerical simulation of the wave-induced dynamic response of poro-elastoplastic seabed foundations and a composite breakwater

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ABSTRACT

In this study, an integrated numerical model FSSI-CAS 2D (previously known as POROWSSI 2D) is developed for the problem of wave-elasto-plastic seabed-structure interactions, where the Volume Average Reynolds Average Navier–Stokes (VARANS) equation is taken as the governing equation for wave motion and porous flow in porous medium; the dynamic Biot's equation known as "$u-p$" is taken as the governing equation for the dynamics of porous seabed soil under wave loading. The Pastor–Zienkiewicz Mark III proposed by Pastor et al. (1990) [45] is used to describe the dynamic behaviour of poro-elasto-plastic seabed under wave loading. This developed integrated numerical model is validated by a centrifuge test conducted by Sassa and Sekiguchi (1999) [30]. The developed integrated numerical model is applied to investigate the wave-induced dynamic response of a composite breakwater and its elasto-plastic seabed foundation. The numerical results indicate that the pore pressure in an elasto-plastic seabed builds up under wave loading, leading to the reduction of the contact effective stresses between soil particles. The residual liquefaction occurs when the effective stresses decrease to a value approaching zero. The wave-induced residual liquefaction in seabed is progressive downward. A parameter considering the cohesion and friction angle of soil is defined to evaluate the residual liquefaction potential. Analysis results illustrate that the friction angle of soil has significant effect on the soil liquefaction; and Nevada dense sand becomes liquefied if the defined parameter exceeded 0.86. Parametric study shows that wave characteristics and soil properties have significant effects on the wave-induced progressive residual liquefaction in loose elasto-plastic seabed foundation.

1. Introduction

In the last 20 years, numerous marine structures such as breakwaters, pipelines, turbines, and oil platforms have been widely constructed in offshore area to protect the coastline or port from erosion and damage, for fluid transport (petroleum, natural gas, or freshwater), to generate green energy, and for extracting crude oil from the seabed, respectively. However,

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these marine structures are vulnerable to wave-induced liquefaction in their seabed foundations because of excessive pore pressure. Some examples of breakwater failures have been reported in previous studies [1–9]. The main reason for the failure of breakwaters built on porous seabed in offshore areas is the lack of a good understanding of the wave–seabed structure interactions by the coastal engineers involved in the design and maintenance of marine structures.

According to Oumeraci [6], wave–structure interactions were always the key point addressed by engineers during the design of marine structures before the 1990s. Thus, the effect of the porous seabed on the stability of marine structures was not considered. Subsequently, the importance of the seabed foundations for a structure's stability was recognized gradually, where wave-induced liquefaction of the seabed foundations was frequently found to play a key role in the collapse of marine structures.

Since the 1990s, numerous studies have investigated wave–seabed structure interactions. The methods employed include analytical solutions, decoupled numerical models, and integrated numerical models. However, the analytical solutions can only deal with simple boundary conditions [10–13], e.g., the breakwater is normally simplified as a line without width and weight. In decoupled numerical models, the linear or nonlinear Stokes wave has generally been used to apply the wave-induced dynamic force that acts on the seabed and structures. Thus, the effects of the outer shapes of structures and the porosity of the seabed foundations on the wave field could not be considered using these approaches [14–16]. The integrated numerical model [17,18] can overcome the shortcomings of the decoupled models, where the Navier–Stokes equation governs the wave motion and the porous flow in the seabed, and Biot's equation governs the dynamics of the seabed soil. Thus, the effects of the outer shapes of marine structures and the porosity of the seabed foundations can be considered using these approaches. However, the complex wave motion in front of marine structures, such as breaking waves, cannot be modeled and the seabed foundations have been limited to poro-elasticity in previous investigations.

The soil types of the marine deposits found in offshore environment are generally sands, silts, and clays etc. Based on the deformation characteristics under external loading, the seabed soil can generally be classified into two types: elastic seabed and elastoplastic seabed. For elastic seabed soil, there is no unrecoverable deformation under external loading. Very dense marine deposited sand can be treated as an elastic seabed soil. The Quaternary newly deposited loose sand soil in offshore area is a typical elastoplastic soil. Normally, it has a low relative density D_r, S, and P wave speed, but a low standard penetration test (SPT) value. Its bearing capacity is generally weak and it readily liquefies under cyclic loading. Therefore, the elastoplastic seabed is generally not suitable for use as the foundations of marine structures. Under dynamic loading, such as seismic or wave loading, the soil particles of elastoplastic soils rearrange to reach their optimal potential arrangement (more dense), thereby leading to the compaction of the soil and pore pressure buildup. After long-term dynamic loading, the soil particles in elastoplastic seabed soil tend to make contact with each other in a dense manner, thereby reaching an optimum state. The relative density D_r, S, and P wave speed increase, whereas SPT value increases. Finally, under dynamic loading, the soil compaction due to plastic volumetric deformation is unlikely to occur again. In this situation, the seabed soil becomes an elastic porous medium. It should be mentioned that elastic and elastoplastic seabed soils are relative concepts because even the same seabed soils may be elastic or elastoplastic under different external loadings. The deformation characteristics of seabed soils depend on the soil properties, such as the particle size and relative density, as well as the characteristics of the external loading, such as its magnitude and application rate.

Corresponding to elastic and elasto-plastic seabed, there are two liquefaction mechanism: transient liquefaction and residual liquefaction, respectively. Transient liquefaction can only occur in an elastic seabed due to the phase lag of the wave-induced pore pressure in the elastic seabed. Normally, this appears periodically under a wave trough and it depends mainly on the permeability and saturation of the seabed soil. Residual liquefaction can only occur in an elastoplastic seabed due to the pore pressure buildup caused by the compaction of soil under cyclic wave loading. Residual liquefaction is the main risk for the stability of marine structures built on elastoplastic seabed foundations. Both types of liquefaction have been observed in laboratory tests and field trials [19–30].

Wave-induced transient liquefaction in an elastic seabed has been investigated widely in previous studies [31–35]. However, few investigations have addressed wave-induced residual liquefaction in an elastoplastic seabed. In addition, analytical approximation [36–38] and decoupled numerical models [39–44] were applied in previous studies. There is no an integrated numerical models have been developed for the interactions between waves, marine structures, and elastoplastic seabed foundations. As mentioned above, the elastoplastic seabed is not suitable for use as the foundations of marine structures due to its weak bearing capacity and residual liquefaction. However, coastal engineers have to cope with this situation if no other choice is available in specific working sites. Therefore, it would be useful to develop an integrated numerical model to evaluate the stability of marine structures built on elastoplastic seabed foundations under wave loading, which may help engineers to understand the mechanism of wave-elastoplastic seabed structure interaction.

In this study, an integrated numerical model is developed where the Volume Average Reynolds Average Navier–Stokes (VARANS) equation is used as the governing equation for wave motion and porous flow in a porous medium. In addition, the dynamic Biot's equation known as "$u - p$" is used as the governing equation for the dynamics of a porous seabed soil under wave loading. In this developed integrated model, the complex wave motion is modeled, which can consider the effects of the complex outer shapes of marine structures and the porous flow in an elastoplastic seabed on the wave field in front of marine structures. The acceleration of pore water and soil particles are both considered in the dynamic Biot's equation. This is essential for modeling the porous flow in a seabed with high porosity and permeability, such as a coarse sand bed. The Pastor–Zienkiewicz Mark-III (PZIII) constitutive model proposed by Pastor et al. [45] is used to describe the dynamic behavior of poro-elastoplastic seabed under wave loading. The integrated numerical model was validated using