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Seismic dynamics of offshore breakwater on liquefiable seabed foundation

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ABSTRACT

Offshore structures, such as composite breakwaters, are generally vulnerable to strong seismic wave propagating through loose or medium-dense seabed foundation. However, the seismically induced failure process of offshore structures is not well understood. In this study, seismic dynamics of a composite breakwater on liquefiable seabed foundation is investigated using a fully coupled numerical model FSSI-CAS 2D. The computation results show that the numerical model is capable of capturing a variety of nonlinear interaction phenomena between the composite breakwater and its seabed foundation. The numerical investigation demonstrates a three-stage failure process of the breakwater under seismic loading. In this process, the far-field seabed can become fully liquefied first, inducing excessive settlement of the structure, followed by significant lateral movement and tilting of the structure when the near-field soil progressively liquefies. The study demonstrates great promise of using advanced numerical analysis in geotechnical earthquake design of offshore structures.

1. Introduction

Composite breakwaters have been widely constructed as a kind of coastal defense structure to protect ports and harbors. Engineers mainly concern about the stability of these offshore structures under environmental loading, such as ocean waves and earthquakes. A detailed review on the dynamic response of breakwaters under wave loading can be found in [1]. On the other hand, devastating damage to offshore structures has been recorded in the past earthquakes, including failure of offshore structures in Los Angeles (USA) in 1994, Kobe (Japan) in 1995, Kocaeli (Turkey) in 1999, Athens (Greece) in 1999 and Sumatra (Indonesia) in 2003 for examples [2–7]. Therefore, seismic analysis should be well considered for important offshore structures built in active seismic regions.

To date, experimental and numerical investigations on seismic dynamics of offshore structures are still limited. Among limited literature, Yuksel et al. [6] analyzed the earthquake-induced deformation of a breakwater at the Eregli Fishery port during the 1999 Koceali Turkey earthquake. Kiara et al. [8] and Memos et al. [9] conducted a series of experimental tests to investigate the seismic response and stability of a rubble-mound breakwater on a shaking table. In their experiment, they found the response acceleration is negatively correlated to the buried depth in sandy bed, and the sandy bed deformation played a dominant role in breakwater failure. Numerical analysis was also performed in their study, where the dynamic water pressure acting on outer surface of the rubble-mound breakwater was considered using Westerggard formulation. Similar shaking table tests were also conducted by Ozaki and Nagao [10]. Mohajeri et al. Earthquake-induced sliding displacement of a caisson wall was also studied in a shaking table test [11].

Based on the work of [8,9], numerical analysis of seismic response of a rubble-mound breakwater was performed using a coupled numerical model [12]. However, the input excitation is only a harmonic motion, not a real seismic wave. The finite difference program FLAC^{2D} was also adopted to estimate the permanent displacement of a rubble-mound breakwater on a sandy bed under seismic wave loading [13]. In their study, the Mohr–Coulomb constitutive model and the pore pressure built-up model proposed in [14] were used. Obviously, soils and pore water are not coupled in their analysis. Recently, deformation of a rubble-mound breakwater under horizontal harmonic motion was also experimentally and numerically investigated [15]. However, the seabed foundation is not considered as a part of the analysis.

In engineering practice, newly deposited Quaternary sediments are often encountered in offshore areas, and a great number of offshore structures have been constructed on these materials. Under seismic loading, the seabed foundation may liquefy due to progressive build up of residual pore pressure. As a result, the overlying offshore structures could translate, tilt, or even collapse.

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Therefore, studying the liquefaction behaviors of the seabed foundation is important in the seismic design of offshore structures. In the past 30 years, significant progress has been made to advance the state-of-the-art modeling of liquefiable soils [17–23]. However, these advanced models have not yet been used to study the nonlinear interaction mechanism of offshore structures with seabed foundation. Most of the previous investigations on seismic dynamics of offshore structures used simple constitutive models such as elastic [24,25] or Mohr–Coulomb model to model the seabed soil. These simple models are not capable of simulating the complicated nonlinear cyclic behaviors of soils and failure process of offshore structures. Intensive nonlinear interaction between seabed foundation and the structure can not be effectively captured. Iai et al. [16] conducted effective stress analyses of port structures in Kobe port during the Hyogoken–Nambu earthquake in 1995. The numerical analyses calculated that the composite breakwater constructed on loose seabed soil settled about 2 m during the event, which is consistent with the field observation. The work highlighted the importance of using effective stress analyses with well-calibrated cyclic soil model to realistically capture the nonlinear structure–seabed interaction.

In this study, the seismic dynamics of a composite breakwater on liquefiable seabed foundation is investigated using a fully coupled numerical model FSSI-CAS 2D. An advanced soil constitutive model – Pastor-Zienkiewics Mark III (PZIII) [17] is used to describe the complicated nonlinear dynamic behavior of the seabed soil. The variation of void ratio and corresponding change in the permeability of the soil are considered in the simulation. Additionally, the hydrostatic pressure acting on outer surface of the composite breakwater and its seabed foundation is updated in real time in accordance to the movement of the composite breakwater and the deformation of seabed foundation. A real recorded seismic wave off Pacific coast in the event of March 11, 2011 Tohoku-Oki earthquake in Japan is adopted as the input motion. The computational results show that the coupled numerical model FSSI-CAS 2D is capable of capturing the progressive liquefaction of the far-field and near-field seabed soil, as well as subsidence, translation and tilting of the composite breakwater in the failure process.

2. Coupled numerical model: FSSI-CAS 2D

2.1. Governing equations

The dynamic Biot's equation, known as "$u-p$" approximation proposed in [26], is used to describe the dynamic response of the porous medium under earthquake loading. In this formulation, the relative displacements of pore fluid to soil particles are ignored, but the acceleration of the pore water and soil particles are included:

$$\frac{\partial \sigma'_x}{\partial x}+\frac{\partial \tau_{xz}}{\partial z}=-\frac{\partial p_s}{\partial x}+\rho\frac{\partial^2 u_s}{\partial t^2}, \tag{1}$$

$$\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \sigma'_z}{\partial z}+\rho g=-\frac{\partial p_s}{\partial z}+\rho\frac{\partial^2 w_s}{\partial t^2}, \tag{2}$$

$$k\nabla^2 p_s-\gamma_w n\beta\frac{\partial p_s}{\partial t}+k\rho_f\frac{\partial^2 \epsilon_v}{\partial t^2}=\gamma_w\frac{\partial \epsilon_v}{\partial t}, \tag{3}$$

where (u_s, w_s) are displacements of the soil in horizontal and vertical directions, respectively; n is soil porosity; σ'_x and σ'_z are effective normal stresses in the horizontal and vertical directions, respectively; τ_{xz} is shear stress; p_s is the pore water pressure; $\rho=\rho_f n+\rho_s(1-n)$ is the average density of porous seabed; ρ_f is the fluid density; ρ_s is solid density; k is the Darcy's permeability; g is the gravitational acceleration; γ_ω is unit weight of the water and ϵ_v is the volumetric strain. In Eq. (3), the compressibility of pore fluid β and the volume strain ϵ_v are defined as

$$\beta=\left(\frac{1}{K_f}+\frac{1-S_r}{p_{w0}}\right) \quad \text{and} \quad \epsilon_v=\frac{\partial u_s}{\partial x}+\frac{\partial w_s}{\partial z}, \tag{4}$$

where S_r is the degree of saturation of seabed, p_{w0} is the absolute static pressure and K_f is the bulk modulus of pore water. In general, $K_f=2.24\times 10^6$ kPa.

The finite element method is used to solve the above governing equations (1)–(3). The discretized governing equations are

$$\mathrm{M}\ddot{\mathbf{u}}+\mathrm{K}\mathbf{u}-\mathrm{Q}\mathbf{p}=f^{(1)} \tag{5}$$

$$\mathrm{G}\ddot{\mathbf{u}}+\mathrm{Q}^{\mathrm{T}}\dot{\mathbf{u}}+\mathrm{S}\dot{\mathbf{p}}+\mathrm{H}\mathbf{p}=f^{(2)} \tag{6}$$

The Generalized Newmark pth order scheme for jth order equation is adopted as the numerical integrator when solving the above discretized equations. The definition of coefficient matrices M, K, Q, G, S, H, $f^{(1)}$, $f^{(2)}$, and the detailed information for the numerical method to solve the Biot's equation can be found in [1,27–29]. In this seismic dynamics simulation, the stiffness-proportional Rayleigh damping model is applied for the purpose of stabilizing the numerical results. In computation, $\alpha=0$, and $\beta=0.0003$ is chosen as used in [30]. In this study, large deformation occurs in loose liquefiable seabed under the earthquake shaking. The updated Lagrangian method is adopted to handle the large deformation problem. The coordinates of nodes, variables dependent on the effective stress history, such as void ratio e and permeability k, are updated in each time step based on deformation. Correspondingly, the coefficient matrices M, K, Q, G, S, H, $f^{(1)}$, $f^{(2)}$, as well as prescribed boundary values are also updated.

From the physics point of view, the void ratio e and related Darcy's permeability k vary according to the deformation of granular materials. In most previous studies, this variation process is not considered based on the assumption of small deformation. In this study, large deformation occurs in the seabed foundation under seismic loading. Therefore, variation of void ratio e and permeability k cannot be ignored in the near-field region, i.e., the seabed foundation close to the offshore breakwater. The practice of numerical implementation in this study indicated that the void ratio and permeability should be updated in each time step following the deformation of the soil. Otherwise, non-convergence may be encountered in the numerical analysis. Using large deformation assumption, the void ratio e is updated in each time step according to the following expression:

$$e_{n+1}=(1+e_n)\exp\left(\frac{\Delta p}{Q}+\Delta\epsilon_v\right)-1 \tag{7}$$

where Q is the compressibility of pore water, Δp is the pore pressure increment and $\Delta\epsilon_v$ is the volumetric strain increment of the soil in this time increment. Accordingly, Darcy's permeability k can be updated [31]:

$$k_{n+1}=C_f\frac{e^3_{n+1}}{1+e_{n+1}} \tag{8}$$

in which C_f is an empirical coefficient, depending on the dynamic viscosity, size and arrangement of soil particles. Recently, [32] also proposed a similar equation to relate e and k based on the fractal characteristics of pore space geometry. If the initial void ratio e_0 and permeability k_0 are known, the empirical coefficient C_f can be back-calculated as [33]

$$C_f=k_0\frac{1+e_0}{e_0^3} \tag{9}$$

2.2. Constitutive model: Pastor–Zienkiewics–Mark III

Based on classical plasticity theory [34], the constitutive relationship for the effective stress and strain of the soil can be