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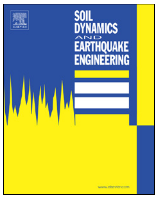

Simulation of spatially varying seafloor ground motions with random seawater layer and complex terrain

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ABSTRACT

The seismic response of ocean structures would be overestimated if the ground motions recorded at land stations are used without corrections. Considering the effect of soft soil layer and soil saturation with site transfer function, a new method was presented for studied the effect of seawater layer on vertical in-plane motions base on a simple model of Crouse and Quilter. The simulate theory of spatially varying ground motions was proposed to consider the influence of seawater layer and soil saturation of seafloor soil layer. Compared with different site conditions, four unique locate sites with the same spatial distance were chose, and two cases of with seawater and without seawater were studied. The comparison results show that the seafloor vertical in-plane motions are noticeable attenuation under seawater layer. The saturation soft soil layer has more influence on seafloor vertical in-plane motions than seawater. Due to considering the complex submarine topography, the synthesized seafloor ground motions can be applied on numerical simulation in most seafloor seismic hazard analyses.

1. Introduction

The study of seafloor ground motions has played an important role in the design of seismic resistant seafloor structures. For offshore structures with long-span dimensions, such as sea-crossing bridges, subsea tunnels and submarine pipelines, their foundations were usually built on uneven seafloor terrain with randomly varying soil properties and a new methodology is required to predict seafloor seismic motions [1–4]. Since the recordings of seafloor ground motions were rare, some methods were presented to simulate the spatially varying seafloor ground motions [5–7]. Hao [8] developed a numerical method to assess the effect of earthquake time histories on the ground motion by assuming that the seismic waves consist of SH, and combined P and SV waves. Bi and Hao [9] investigated the influence of irregular topography and random soil properties on the coherency loss under spatial seismic ground motions. Results showed that the more randomly varying are the soil properties, the larger is the influence of local site effect on the spatial surface ground motion. Konakli and Kiureghian [10] proposed several methods to simulate the spatially varying ground motions by considering the effects of incoherence, wave-passage and differential site-response. During the simulation, the theory of vertical wave propagation was employed in a single soil layer that laid over the bedrock. Bi and Hao [11] simulated the spatially varying earthquake ground motions at sites with varying conditions. Nakamura [12] novelly researched the anomalously large seismic amplifications in the seafloor area using strong-motion data recorded on the ground surface of the Kii peninsula and on the seafloor near the Nankai trough. The authors pointed out that the magnitude of earthquakes would be overestimated if the earthquake motions observed at land are used to ocean-specific structures without corrections. Zhang et al. [13] also simulated the spatially correlated, site-reflected, and non-stationary ground motions by employing phase difference spectrum.

The studies mentioned above concentrated on the simulation of onshore ground motions, in which the water layer and soil saturation effects were neglected. Recent studies have shown that pore-water saturation of soil layer under water may strongly affect the amplitudes of vertical in-plane motions. Yang [14] studied the effects of soil saturation on the horizontal and vertical motions of a layered soil-bedrock system. Wang and Hao [15] investigated the effects of random variation of soil properties and soil saturation level on the site amplifications of ground motions. Yang and Sato [16] studied the influence of water saturation on the horizontal and vertical motions of a porous soil layer. Zhang and Xie [17] synthesized spatially correlated ground motions at varying sites based on vector-valued seismic hazard disaggregation. Yang [18] examined the saturation effects of soils on ground motion at free surface. However, none of these studies examined the effect of

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seawater layer on the seismic ground motions in offshore environments.

The seawater layer could strongly affect the propagation of P wave on the seafloor. Boore and Smith [19] analyzed the earthquake recordings obtained from the seafloor earthquake measurement system that deployed off the coast. Theoretical calculations found that the seawater layer had negligible effect on the horizontal components of the ground motion. However, a strong spectral null was observed on the vertical component of P wave at the resonant frequency for the seawater layer. Ken Hatayama [20] evaluated the effects of seawater on the seismic ground motion. Iida and Hatayama [21] analyzed the effect of seawater on short-period strong ground motion in Tokyo bay. Petukhin et al. [22] simulated on the effect of the oceanic water layer on strong ground motion. Diao et al. [23] evaluated the effect of seawater on the incident planes of P and SV waves at ocean bottom and studied the engineering characteristics of offshore ground motion records off the coast in southern California, USA. Moreover, the simple model of vertical incident P wave at ocean bottom was used based on the conclusion made by Tsai, Crouse and Quilter. Li et al. [24] presented the theory of modeling and numerical simulation of seismic motions at seafloor.

In this study, the site transfer function was adopted in order to account for the effects of seawater layer and water saturation of subsea soil layers on the ground motions. Based on the conclusion made by Tsai, Crouse and Quilter developed a simple model by assuming that the vertical component of ground motion was composed entirely of vertically propagating P waves. A new method of modeling water transfer function was proposed in this paper, where the water layer was modeled as an elastic half-space for vertically incident P wave. The seafloor site transfer function was theoretically derived by utilizing fundamental hydrodynamics equations and one-dimensional wave propagation theory. By considering the effects of seawater layer and soil saturation of seafloor soil layer on the site amplification of ground motions, a synthetic method of simulating seafloor ground motions was proposed in the paper.

2. Theoretical background

2.1. Model of vertical incident P wave at seafloor

A simple model was developed by Crouse and Quilter based on the assumption that the vertical component of ground motion is only composed of vertically propagating P waves [23]. For the seafloor site, the P wave will be transmitted through the seawater, and reflected back towards the seafloor, and then a phase change will result in the reduction in the amplitude of vertical ground motion at the natural frequency of seawater layer [25,26]. The model that describes the response of seafloor site with water layer is given as follows:

$$F(f,\alpha_1) = \frac{\cos(2\pi f\frac{H_1}{c_1})e^{i(-\Phi)}}{\sqrt{\cos^2(2\pi f\frac{H_1}{c_1}) + \alpha_1^2\sin^2(2\pi f\frac{H_1}{c_1})}} \tag{1}$$

where, f is the frequency, H_1 is the height of seawater layer, c_1 is the P wave velocity in seawater and$??_1 = (??_1??_1)/(??_2??_2)$ is the impedance ratio between seawater layer and seafloor soil, in which, c_2 is the P wave velocity in seafloor site, ρ is density, and the subscript 1 is seawater layer, 2 means seafloor site. And the modulus of $F(f,\alpha_1\quad)$ is as follows,

$$|F(f,\alpha_1)| = \frac{\left|\cos(2\pi f\frac{H_1}{c_1})\right|}{\sqrt{\cos^2(2\pi f\frac{H_1}{c_1}) + \alpha_1^2\sin^2(2\pi f\frac{H_1}{c_1})}} = \frac{1}{\sqrt{1 + \alpha_1^2\tan^2(2\pi f\frac{H_1}{c_1})}} \tag{2}$$

It is evident that$??\ (??,??_1) \le 1.??_1 = ????_1$, K is the bulk modulus of seawater;$??_2 = (?? + 2??)??_2$, in which, λ is Lame constant, G is the shear modulus of seafloor site. The graph of the transfer function was shown in Fig. 1.

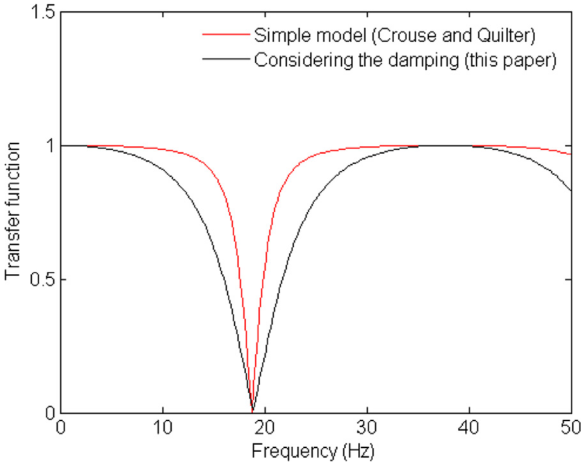

Fig. 1. The transfer function of seawater.

Considering the damping of the seafloor site and the fluid, the complex values of bulk modulus of seawater and shear modulus of seafloor site are expressed as,

$$K^* = K(1 + 2i\xi_1),\ \ G^* = G(1 + 2i\xi_2) \tag{3}$$

where ξ is the damping coefficient, i is imaginary part. The comparison of transfer functions was plotted in Fig. 1. The plot indicates that the magnitudes computed by Crouse and Quilter model are larger than those estimated from the proposed model. This positive difference qualitatively corresponds to the effect to damping of the seafloor site and the seawater. Seawater transfer function should be considered.

2.2. Wave propagation theory and site amplification effect

The ground motions of base rock are assumed to consisting of out-of-plane SH wave and in-plane combined P-SV waves that propagating into soil layer with a defined incident angle [27,28]. In theory, compressional (P) waves can propagate through seawater layer, while shear (SV) waves cannot. Since P and SV waves can generate refracted P waves transmitting into seawater layer at the elastic half-space, the vertical in-plane motions contain P and SV waves [9].

Based on the theory of one-dimensional wave propagation, the dynamic equilibrium equations can be written as

$$\nabla^2 e = -\frac{\omega^2}{c_p^2}e,\ \ \nabla^2\{\Omega\} = -\frac{\omega^2}{c_s^2}\{\Omega\} \tag{4}$$

where c_p and c_s are the wave velocities of P wave and S wave, respectively; $\nabla^2 e$ and $\nabla^2\Omega$ are Laplace operators acting on volumetric strain e and rotational strain vector Ω, respectively.

In the frequency domain, the dynamic equations Eq. (4) for SH wave and P-SV wave can be expressed as

$$[K_{SH}]\{u_{SH}\} = \{P_{SH}\},\ \ [K_{P-SV}]\{u_{P-SV}\} = \{P_{P-SV}\} \tag{5}$$

where $\{u_{SH}\}$ and$??_{????}$ are the out-of-plane displacements and the load vectors of SH wave, respectively; $\{u_{P-SV}\}$ and$??_{??-????}$ are the in-plane displacements and the load vectors of combined P-SV waves, respectively; $[K_{SH}]$ and$??_{??-????}$ are the stiffness matrices.

The relationship between the amplitude of base rock and those of each soil layer can be formed by site transfer function $H(\omega)$, and the transfer function can be calculated by solving Eq. (5).

For example, by defining a site consisting of a single homogeneous layer on a half-space, the stiffness matrices, displacements and load vectors of SH wave can be expressed as