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An approach for predicting multi-support seismic underground motions in layered saturated soil under surface water

Guohuan Liu[a,b], Haitao Yu[c,*], Yaqiang Liu[b], Jijian Lian[a]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin, China
[b] School of Civil Engineering, Tianjin University, Tianjin, China
[c] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China

A R T I C L E I N F O

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A B S T R A C T

Simulation of multi-support (i.e. spatially variable) seismic underground motions in sea areas plays a significant role in the seismic analysis of cross-sea structures such as cross-sea bridges or subsea tunnels. However, existing approaches for predicting multi-support seismic motions mainly focus on the dry site soils without overlying surface water. This paper proposes an approach for predicting multi-support seismic underground motions in layered saturated half space under surface water, subjected to oblique incident *P* waves. The transfer function in saturated soil under surface water, as the theoretical basis of the subsequent numerical simulation, is first derived based on wave propagation theory and the calculated reflection coefficients of *P* wave–induced *P1*, *P2*, *SV* waves in saturated soils. The derived transfer function is further employed to deduce and obtain the underground (sub-seabed) power spectral density function and response spectrum function. The two obtained functions, combined with the additional cross-coherence function, are subsequently employed to construct the cross power spectral density matrix and thus to simulate multi-support seismic underground motions. The solutions are validated against the target power spectral density, target response spectrum and target cross-coherence functions. A parametric analysis is presented where the effects of the soil thickness, the incident angle and the overlying water depth are investigated. Results show that the soil thickness, incident angle and overlying water depth have significant influences on the amplitude of transfer functions, which further affect the ratios between seismic ground and underground motions.

1. Introduction

Various components including wave scattering, wave passage, and site simplification effects cause the ground motion to vary spatially [1,10,12,21,39,9]. It has been observed that the spatial variation of seismic motions has significant influence on the dynamic response of engineering structures, especially for those structures such as long-span bridges, transmission tower-lines systems, tunnels and dams [2,41–44]. Therefore, the reasonable simulations and predictions of multi-support seismic motions are necessary for a reliable structural response analysis [21,23,3,33,46].

Generally, it is necessary for simulating the multi-support seismic motions to construct the cross power spectral density matrix, which need the target PSD (power spectral density) function, target response spectrum and coherence function [20,22,24,27,31,35]. Based on this research framework, a number of methods have been developed, proposed and employed. In particular, Deodatis [15] presented a method to simulate spatial ground motions with different power spectral densities at different locations and investigated the influence of the spatial variation of ground motions on the seismic response of large embankment dams. This method was then extended to generate spatially varying seismic ground motion time histories by Deodatis et al. [16]. Considering the influence of layered irregular sites and random soil properties on coherence functions, [4,5] presented an approximate method to simulate the spatially varying ground motions on the surface of non-uniform sites. Their method was then paid close attention and was extensively developed by many researchers [26,28,45]. Furthermore, the impact of the spatially varying seismic motions on the seismic response of different types of structures, such as transmission tower-lines, large dams and large-span bridges, were also investigated by [1,37,14,30,48,19,34].

Current researches on the multi-support seismic motions mainly focus on the seismic response in the dry soil sites without overlying surface water [49,50]. However, for those long-span cross-sea

* Corresponding author.
E-mail address: yuhaitao@tongji.edu.cn (H. Yu).

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structures, such as cross-sea bridges and subsea tunnels, the site soils (or sub-seabed) are saturated and overlain by the surface water. Thus, the theoretical models or functions that are applicable to simulate seismic motions in dry soil are not appropriate. Therefore, it is very necessary to investigate the specific theoretical functions that are applicable to predict multi-support seismic motions in saturated soils with overlying surface water. Based on the Biot theory [6–8], researchers extensively investigated the wave propagation in the saturated soils and further emphases were given to the investigation on the complex reflection and refraction in saturated solid and at medium-fluid interface. Such representative works include [18,17,32,11,47,40], etc. In addition, [38] particularly investigated the effects of random variations of soil properties on site amplification of seismic waves considering soil saturation, considered as a development of the study on seismic motions in saturated soils, despite not considering the overlying surface water. Recently, Liu and Liang investigate the approach for simulating the multi-support earthquake underground motions, but the research is only limited to the dry soil without considering the overlying surface water.

This paper focuses on a feasible approach for predicting multi-support seismic motions in the layered saturated soil under surface water, which can be used for the seismic analysis of large-span cross-sea structures. Firstly, the potential functions of saturated elastic-solid media overlying with ideal fluid are deduced and the corresponding transfer functions, the theoretical basis of the subsequent numerical simulation, are derived in this paper. Subsequently, the underground power spectral density (PSD) function and response spectrum function for generating the multi-support seismic underground motions are obtained with the derived transfer functions. Furthermore, the two key functions combined with the additional cross-coherence function are subsequently employed to construct the cross power spectral density matrix and thus to simulate multi-support seismic underground motions. Finally, the multi-support seismic underground motions are simulated and validated against the target functions. In addition, a parametric analysis on the effects of the soil thickness, incident angle and overlying water depth are investigated.

2. Wave equations and transfer function in saturated soil under surface water

First, the theoretical formula of seismic waves in saturated soil with overlying water are deduced. Fig. 1 schematically shows the considered multi-layer saturated soil with overlying surface water. In the figure, H and h_j represent the depth of the overlying water and the thickness of the (j)th layer respectively; ρ_w and K are the density and bulk modulus of the overlying water respectively; ρ_s, ρ_f, μ and ϕ respectively represent the soil density, fluid density, shear modulus, porosity; K_s, K_f, K_b and K_0 denote bulk modulus of the solid, bulk modulus of the fluid, bulk

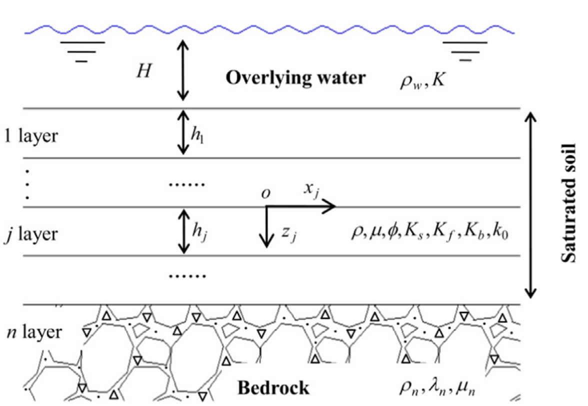

Fig. 1. Schematic diagram of a layered half-space saturated soil with an overlying water layer.

modulus of the solid skeleton and permeability coefficient, respectively; ρ_n is the density of the bedrock and λ_n, μ_n represent Lame constants respectively.

2.1. Basic theory: potential functions in different media

The governing equations for the displacement of the solid medium and liquid portion of porous skeleton are obtained by taking the effect of dissipation due to flow of the viscous liquid relative to the solid.

According to the Biot porous media theory [6–8], the potential functions of saturated soil can be expressed as

$$\phi_k = E_{Pk} e^{i[\omega t-\delta_k(xw_{k1}-zw_{k3})]} + F_{Pk} e^{i[\omega t-\delta_3(xw_{31}+zw_{33})]}, \quad (k=1,2) \tag{1}$$

$$\psi_1 = E_S e^{i[\omega t-\delta_3(xw_{31}-zw_{33})]} + F_S e^{i[\omega t-\delta_3(xw_{31}+zw_{33})]} \tag{2}$$

where φ_1, φ_2 and ψ_1 are the potential functions of the $P1$, $P2$ and SV waves respectively; E_{P1}, E_{P2} and E_S are the potential amplitudes of the corresponding upward-travelling waves; F_{P1}, F_{P2} and F_S are the potential amplitudes of the corresponding downward-travelling waves; w_{kx} and w_{kz} denote the components of the unit vector in the x-direction and z-direction.

According to Snell's law, the horizontal wave numbers (k_x) of harmonic waves are the same in x-direction

$$k_x = \delta_k w_{kx} = \sin\theta\cdot\omega/c_k, \quad w_{kx} = (\omega/c_k\cdot\sin\theta)/\delta_k, \quad w_{kz} = (1-w_{kx}^2)^{1/2}, \quad (k=1,2,3) \tag{3a}$$

$$c_k = (M/\rho)^{1/2}/\mathrm{Re}(\Omega_k^{1/2}), \quad (k=1,2,3) \tag{3b}$$

where ω is the circular frequency of the incident wave; θ is the incident angle; c_k are the phase velocity and $k = 1, 2, 3$ denoting the $P1$, $P2$, and SV waves respectively; Re denotes the real part of the parameter. For more introduction, the following expressions are given and defined as

$$\rho = \rho_{11} + 2\rho_{12} + \rho_{22} \tag{4a}$$

$$\rho_{11} = (1-\phi)\rho_s + \phi(\alpha-1)\rho_f, \quad \rho_{12} = -\phi(\alpha-1)\rho_f, \quad \rho_{22} = \phi\alpha\rho_f \tag{4b}$$

$$A = (\phi K_b + (1-\phi)K_f(1-\phi-K_b/K_s))/(\phi + K_f/K_s(1-\phi-K_b/K_s)) - 2\mu/3 \tag{4c}$$

$$Q = \phi K_f(1-\phi-K_b/K_s)/(\phi + K_f/K_s(1-\phi-K_b/K_s)) \tag{4d}$$

$$R = \phi^2 K_f/(\phi + K_f/K_s(1-\phi-K_b/K_s)) \tag{4e}$$

$$N = \mu, \quad P = A + 2N, \quad M = P + R + 2Q \tag{4 f}$$

$$\sigma_{11} = P/M, \quad \sigma_{12} = Q/M, \quad \sigma_{22} = R/M, \quad \gamma_{11} = \rho_{11}/\rho, \quad \gamma_{12} = \rho_{12}/\rho, \quad \gamma_{22} = \rho_{22}/\rho \tag{4 g}$$

$$E = \sigma_{11}\sigma_{22} - \sigma_{12}^2, \quad F = \gamma_{11}\sigma_{22} + \gamma_{22}\sigma_{11} - 2\gamma_{12}\sigma_{12}, \quad G = \gamma_{11}\gamma_{22} - \gamma_{12}^2 \tag{4 h}$$

$$b = \sigma_{12} + \sigma_{22}, \quad g = \gamma_{11}\sigma_{22} - \gamma_{12}\sigma_{12}, \quad h = \gamma_{22}\sigma_{12} - \gamma_{12}\sigma_{22}, \quad f = \eta/\rho\omega \tag{4i}$$

$$\delta_0^2 = \rho\omega^2/M, \quad \Delta^2 = F^2 - 4EG - 2if(F-2E) - f^2 \tag{4j}$$

$$\Omega_{1,2} = (F - if \mp \Delta)/2E, \quad \Omega_3 = (M/N)(G - if)/(\gamma_{22} - if) \tag{4k}$$

$$\delta_j^2 = \delta_0^2 \boldsymbol{\Omega}_j \quad (j=1,2,3) \tag{4 l}$$

In Eq. 4b, $\alpha = 1 + \gamma(1+\varphi)/\varphi$ with γ as the coefficient of the induced inertia on the solid phase (due to the oscillation of solid skeleton in fluid).

The displacements of the solid fluid phase can be expressed by the potential functions as

$$u_x = \frac{\partial\varphi_1}{\partial x} + \frac{\partial\varphi_2}{\partial x} + \frac{\partial\psi_1}{\partial z}, \quad u_z = \frac{\partial\varphi_1}{\partial z} + \frac{\partial\varphi_2}{\partial z} - \frac{\partial\psi_1}{\partial x} \tag{5a}$$