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Simulation of fully nonstationary spatially variable ground motions on a canyon site

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ABSTRACT

A new method of deriving evolutionary power spectral density (EPSD) function on surface of a canyon site with multiple soil layers was proposed. After the power spectral density on the base rock was determined, the auto/cross power spectral density function on site surface can be obtained by using the frequency response function (FRF), and a series of ground motions can then be generated. However, the spectral nonstationarity was neglected because the parameters in the FRF varied only with frequency. In the present paper, the time-varying frequency and damping ratio in FRF for each soil layer were incorporated for the derivation of the EPSDs on the surface. The influence of local site conditions on the coherency loss was considered. Spatially variable ground motions (SVGMs) possessing full nonstationarity were then simulated. A set of verifications was conducted, and the results showed that the proposed method is reliable.

1. Introduction

A number of studies demonstrated that the effect of spatial variation of ground motions on the seismic response of extended structures is not negligible [1–5], and this effect can be attributed to wave passage effect, local site effect, and incoherence effect. Several methods that consider these effects for SVGM generation were proposed. Shinozuka and Deodatis [6] proposed the spectral representation method (SRM) which is widely used and is the basis of subsequent studies. Hao et al. [7] proposed a methodology for generating time series that are compatible with the correlation properties in SMART-1 data. Gao and Wu [8] developed a method to improve the calculation efficiency and accuracy of SRM. Wu et al. [9] established a method for the simulation of spatially varying non-Gaussian and nonstationary seismic ground motions.

The temporal nonstationarity and spectral nonstationarity of ground motions are important, particularly in nonlinear response analysis [10]. During an earthquake, the resonant frequencies of degrading structures decay with time, which may coincide with the variation of the predominant frequency of a ground motion in time. Thus, full nonstationarity must be incorporated into synthesized ground motions. Priestley [11] proposed the concept of the evolutionary power spectrum and a method for generating fully nonstationary ground motions. Li et al. [12] found that the time-varying frequency content in a seismic input can have considerable effects on the stochastic properties of a system response. However, directly establishing an EPSD matrix is difficult to achieve in an unconditional simulation of ground motions for a canyon site. Moreover, phase difference-based methods that are applicable to simulation on a canyon site remain lacking owing to the obstacles in the determination of parameters, that is, the mean value and variance of phase difference that correspond to a canyon site.

Synthesizing SVGMs for a canyon site is a special case because of different local site conditions. Der Kiureghian [13] investigated the influence of local site conditions at different stations on coherency function and found that the contribution of site-response to the coherency function is a complex function of unit modulus. Bi and Hao [14] studied the influence of layered irregular sites on coherency functions of spatial ground motions on the ground surface. They found that coherency function is directly related to the spectral ratio of two local sites. Then, Bi and Hao [15] developed a model of simulating SVGMs for a canyon site by using FRF derived from 1D wave propagation theory and considering the effect of local site conditions on seismic waves. Wu et al. [16] developed methods of simulating SVGMs in canyons in which the topographic amplification effect was accounted by considering a 2D wave propagation theory. However, the spectral nonstationarity of generated ground motions is not accounted for in the above methods.

For conditional or unconditional simulation on a flat or uniform site, establishing an EPSD matrix is relatively convenient. However, in a canyon or nonuniform site, it is not. This is because that the influence of

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local site conditions on the coherency loss function cannot be ignored and there is still no suitable coherency model describing the coherency of ground motions on a canyon site surface. In this paper, we propose a new method for deriving EPSD function for unconditional simulation of SVGMs on a canyon site. An example of application has been used to validate the proposed method. The proposed method can be used to simulate fully nonstationary SVGMs that can be applied to the dynamic analysis of long-span structures on canyon or nonuniform sites in engineering practice.

2. Proposed method

In the present study, the FRF proposed by Der Kiureghian [13] was used for the description of the m-th soil layer, and this FRF can be expressed as

$$H_m(\omega) = \frac{\omega_m^2 + 2i\zeta_m\omega_m\omega}{\omega_m^2 - \omega^2 + 2i\zeta_m\omega_m\omega}, \tag{1}$$

where ω_m, ζ_m are frequency and damping ratio, respectively, idealizing the soil layer as a single-degree-of-freedom oscillator; $i = \sqrt{-1}$. According to [17], to obtain the FRF changing with time and frequency, the parameters in this model are assumed to be time-varying with a decay factor as follow:

$$\omega_m = \omega_0 - 7t/T_0, \tag{2}$$

$$\zeta_m = \zeta_0 - 0.2t/T_0, \tag{3}$$

where ω_0, ζ_0 are the initial values of frequency and damping ratio, respectively, and T_0 is the duration of ground motion. According to the local site conditions, ω_0 was determined by an empirical equation as follows:

$$\omega_0 = 2\pi\frac{V}{4H}, \tag{4}$$

where V is wave velocity, and H is the thickness of soil layer. Meanwhile, ζ_0 can be set to 0.6, 0.4, and 0.2, which correspond to firm soil, medium soil, and soft soil [13]. Note that the decay factor of ζ_m for soft soil is set to 0.1 to prevent an FRF value of zero. The time- and frequency-varying FRF can be expressed as

$$H_m(\omega, t) = \frac{\omega_m^2(t) + 2i\zeta_m(t)\omega_m(t)\omega}{\omega_m^2(t) - \omega^2 + 2i\zeta_m(t)\omega_m(t)\omega}. \tag{5}$$

Then the evolutionary auto/cross power spectral density function (PSDF) on the surface of a canyon site can be expressed as

$$S_{jj}(\omega, t) = [a(t)]^2 \prod_{m=1}^{N_j} |H_m(i\omega, t)|^2 S_g(\omega) \quad j = 1, 2, \ldots n, \tag{6}$$

$$S_{jk}(i\omega, t) = [a(t)]^2 \prod_{m}^{N_j} H_m(i\omega, t) \prod_{l=1}^{N_k} H_l^*(i\omega, t) S_g(\omega)\gamma_{j'k'}(d_{j'k'}, i\omega) \quad j, k = 1, 2, \ldots n, \tag{7}$$

where N_j, N_k are the numbers of soil layers beneath simulation point j and k, respectively, $a(t)$ is a modulating function in time, superscript '*' denotes complex conjugate, $S_g(\omega)$ is the PSDF of the ground motion on the base rock, and $\gamma_{j'k'}(d_{j'k'}, i\omega)$ is the coherency loss function of spatial ground motions on the base rock which is related to the separation distance $d_{j'k'}$ and frequency ω.

After the cross-spectral density matrix of ground motions $\mathbf{S}(\omega, t)$ was determined, 1D-nV nonstationary stochastic process $f_j(t)$, $j = 1, 2, \ldots n$ can be simulated by using Deodatis's method [18]:

To proceed with the simulation of ground motions, $\mathbf{S}(\omega, t)$ must be decomposed at every time instant into the following product:

$$\mathbf{S}(\omega, t) = \mathbf{U}(\omega, t)\mathbf{U}^{T*}(\omega, t), \tag{8}$$

where superscript T denotes the transpose of a matrix. Herein, this decomposition was conducted with the root decomposition proposed by Wu and Gao [9], and $\mathbf{U}(\omega, t)$ was expressed as

$$\mathbf{U}(\omega, t) = \begin{bmatrix} U_{11}(\omega, t) & U_{12}(\omega, t) & \cdots & U_{1n}(\omega, t) \\ U_{21}(\omega, t) & U_{22}(\omega, t) & \cdots & U_{2n}(\omega, t) \\ \vdots & \vdots & \ddots & \vdots \\ U_{n1}(\omega, t) & U_{n2}(\omega, t) & \cdots & U_{nn}(\omega, t) \end{bmatrix}, \tag{9}$$

where the diagonal elements are real and nonnegative functions of ω, and the off-diagonal elements are generally the complex functions of ω. Meanwhile, $U_{jx}(\omega, t)$ can be rewritten in the following form:

$$U_{jx}(\omega, t) = |U_{jx}(\omega, t)|e^{i\theta_{jx}(\omega,t)}, j, x = 1, 2, \ldots n, \tag{10}$$

where

$$\theta_{jx}(\omega, t) = \tan^{-1}\left(\frac{\mathrm{Im}[U_{jx}(\omega, t)]}{\mathrm{Re}[U_{jx}(\omega, t)]}\right). \tag{11}$$

After the decomposition of $\mathbf{S}(\omega, t)$, the nonstationary stochastic vector process can be simulated by the following formula:

$$f_j(t) = 2\sum_{x=1}^{n}\sum_{y=1}^{N} |U_{jx}(\omega_y, t)|\sqrt{\Delta\omega}\cos\left[\omega_y t - \theta_{jx}(\omega_y, t) + \Phi_{xy}\right] \quad j = 1, 2, \ldots n, \tag{12}$$

where

$$\omega_y = y\Delta\omega \quad y = 1, 2, \ldots N, \tag{13}$$

$$\Delta\omega = \frac{\omega_u}{N}, \tag{14}$$

where $\Delta\omega$ denotes the bandwidth, N is the number of frequency interval, ω_u represents an upper cut-off frequency beyond which the elements of the cross-spectral density matrix may be assumed to be zero for any time instant, and Φ_{xy} is a random phase angle uniformly distributed in $[0, 2\pi]$.

3. Numerical examples and verification

A canyon site with multiple soil layers shown in Fig. 1 was selected as an example. In this figure, G is the shear modulus, ρ is the density, and ζ is the damping ratio of soil. Ground motions at three different locations on the site surface indicated in the figure will be simulated. Site 1 corresponded to "medium" site, site 2 to "firm" site, and site 3 to "soft" site. Note that the generated ground motions are SH waves in plane. In other words, only the horizontal ground motion component in the direction transversal to the canyon was considered and generated to illustrate the practicability of the proposed method. The waves in other directions can be simulated by using the same method once the power spectral densities of the incident waves in these directions on the base rock are known.

The filtered Tajimi-Kanai model is used to describe the PSDF on the base rock:

$$S_g(\omega) = \frac{\omega^4}{(\omega_f^2 - \omega^2)^2 + (2\omega_f\omega\zeta_f)^2} \times \frac{\omega_g^4 + 4\zeta_g^2\omega_g^2\omega^2}{(\omega_g^2 - \omega^2)^2 + 4\zeta_g^2\omega_g^2\omega^2} S_0, \tag{15}$$

where ω_g and ζ_g are the central frequency and damping ratio of the Tajimi-Kanai PSDF, respectively, ω_f and ζ_f are the central frequency and damping ratio of the high pass filter, respectively, and S_0 is the scaling factor. According to [15], $\omega_g = 10\pi\,\mathrm{rad}/s$, $\zeta_g = 0.6$, $\omega_f = 0.5\pi$, $\zeta_f = 0.6$, and $S_0 = 0.0034m^2/s^3$. These parameters correspond to a ground motion time history with duration of 20 s and peak ground acceleration (PGA) of 0.2 g.

The Sobczyk model [19] was selected to describe the coherency loss between the ground motions at points j' and k' as follows:

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