Soil Dynamics and Earthquake Engineering 111 (2018) 119–130

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Improved hilbert spectral representation method and its application to seismic analysis of shield tunnel subjected to spatially correlated ground motions

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ARTICLE INFO

Keywords:
Shield tunnel
Intersegment opening width
Multiple support excitation
Identical support excitation
Spatially correlated ground motions

ABSTRACT

A novel and efficient method for simulation of spatially correlated earthquake ground motions (SCEGMs), named as improved Hilbert spectral representation method, was presented. By using Hilbert–Huang transform (HHT), the known record can be decomposed into a series of intrinsic mode functions (IMFs) and a residual function. Targeting on each IMF, simulated IMFs for every field point were derived through a spatial correlation model. The frequency dependence of the spatial correlation structure was simplified such that only the correlation at the predominant frequency of each target IMF was considered. SCEGMs can then be obtained by superposition of simulated IMFs and the original residual function. Taking the Suai shield tunnel project in China as reference, the intersegment opening width response of shield tunnel under multiple support excitation (MSE) and identical support excitation (ISE) were investigated and compared. First, numerous accelerograms, including horizontal and vertical components, were generated based on selected real records and artificial acceleration time histories on bedrock to realize MSE. The generalized response displacement method (GRDM) in combination with a large-scale FEM model was then utilized to proceed with the study. Results showed that the MSE can lead to a higher opening width of tunnel in general. The distribution of longitudinal opening width under MSE is also different from that under ISE. The sharp variation of soil layer stiffness along the longitudinal direction of tunnel may lead to extremely large intersegment opening width or severe damage.

1. Introduction

Spatially variable earthquake ground motions (SVEGMs) have remarkable influence on the response of large-scale structures [1–5]. Many unconditional simulation methods of SVEGMs [6–15] have been developed and employed to facilitate the seismic response analyses of extended structures. However, natural characteristics of earthquake ground motions are not considered in this type of method. Thus, information on the spatial variation of natural ground motions is required. Such information may be obtained from data recorded at dense instrument arrays but is limited [16] or may be unsuitable for the concerned site. Therefore, the conditional simulation of spatially correlated earthquake ground motions (SCEGMs) based on known records is necessary in this case. Conditional simulation used to be implemented by using the Kriging method [17] or the conditional probability density function (CPDF) method [18–20]. In recent years, numerous other methods were proposed to conduct the conditional simulation of SCEGMs. Jankowski and Wilde [21] developed a CPDF-based iteration procedure for simulation of SCEGMs, where only the predominant frequency of the target record was considered to simplify the spatial correlation relationship. Wen and Gu [22] established the Hilbert spectral representation model, where the Hilbert–Huang transform (HHT) [23] and a set of functionally related random phase shifts were adopted to simulate SCEGMs. Based on an evolutionary power spectral density matrix, Hu et al. [24] presented a Kriging-based method to simulate non-stationary SCEGMs conditioned by known records. Huang and Wang [25] established a spatial cross-correlation model of wavelet packet parameters based on regionalized ground motion data and then adopted the cokriging technique to synthesize regionalized ground motions. However, owing to a few limitations (e.g., complicated derivation and/or excessive calculations), these methods may be inconvenient for application to practical engineering.

In addition, many studies have investigated the effect of SVEGMs on the seismic behaviors of long tunnels. Park et al. [26] developed a longitude displacement profile-based method for tunnel response simulation under SVEGM and performed a series of pseudo-static three-

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https://doi.org/10.1016/j.soildyn.2018.04.050
Received 2 February 2018; Received in revised form 26 April 2018; Accepted 26 April 2018
0267-7261/

dimensional (3D) finite element analyses. By using time–history analysis method, Chen et al. [27] studied the influence of SVEGM on seismic responses of the long-immersed tunnel. Results demonstrated that the wave passage and incoherence effects involved in SVEGM can remarkably increase seismic responses of the immersed tunnel. Yan et al. [28], Yuan et al. [29], and Yu et al. [30,31] carried out a series of shaking table tests on the long-immersed tunnels subjected to non-uniform seismic loadings. Their results indicated that tunnel responses under multiple support excitation (MSE) are higher than those under identical support excitation (ISE), and the spatial variation of ground motion should be considered in the design of immersed tunnels. Zhang et al. [32] derived the analytical solutions to internal forces of tunnel lining induced by incident Rayleigh wave, simultaneously considering the soil–structure interactions and temporal and spatial seismic response variations. Although many contributions have been devoted to the study of non-uniform earthquake load effect on the seismic response of tunnel, studies on the intersegment opening width response of shield tunnel under MSE of earthquake are still currently lacking. The intersegment opening width of shield tunnel is an important criterion for the safety evaluation of shield tunnels because excessive intersegment opening width may lead to seepage and thus affect the safety of subway operation. Therefore, special attention is provided to the intersegment opening width response under SCEGMs in this study.

First, a novel and efficient method is developed for simulation of SCEGMs and described in detail in Section 2, where the relevant verification and error assessment of the proposed method were also presented. The engineering background of the reference shield tunnel project is then briefly introduced. Based on the concept of generalized response displacement method (GRDM), the setup of numerical models, including free site and soil–tunnel interaction system, are presented in Section 3 in detail. Subsequently, the intersegment opening width response of tunnel subjected to ISE and MSE of earthquakes are investigated, and the results are shown in Section 4. Finally, concluding remarks are provided in Section 5.

2. Simulation of spatially correlated ground motions

2.1. Review of the Hilbert spectral representation model

Through HHT, a time series can be decomposed into several IMFs. The extraction of IMFs from a time series entails a repeated “sifting” procedure called empirical mode decomposition (EMD). After EMD, the original time series $X(t)$ can be expressed in terms of IMFs as follows:

$$X(t) = \sum_{j=1}^{N} I_j(t) + r(t), \tag{1}$$

where N is the number of IMFs;$I_j(t)$ denotes the jth IMF, and $r(t)$ indicates the residual function. Generally, this function is too small to be of any consequence or becomes a monotonic function from which IMF can no longer be extracted. The use of the Hilbert transform of $I_j(t)$ yields

$$Q_j(t) = H[I_j(t)] = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{I_j(\tau)}{t-\tau} d\tau, \tag{2}$$

where P denotes the Cauchy principal value. An analytical function can be formulated as follows:

$$Z_j(t) = I_j(t) + iQ_j(t) = a_j(t)e^{i\theta_j(t)}, \tag{3}$$

where time functions $a_j(t)$ and $\theta_j(t)$ are instantaneous amplitude and instantaneous phase functions, respectively, and $i^2 = -1$. The instantaneous frequency of an IMF is given by

$$\omega_j(t) = \frac{d\theta_j(t)}{dt}. \tag{4}$$

$a_j(t)$ and $\omega_j(t)$ define the Hilbert amplitude spectrum or simply Hilbert spectrum [23]. The original time series can then be represented as follows:

$$X(t) = \mathrm{Re}\left\{\sum_{j=1}^{N} a_j(t)e^{i\theta_j(t)}\right\} + r(t). \tag{5}$$

Using the HHT, Wen and Gu [22] constructed the underlying random process model based on the observational data by introducing a random element as follows:

$$X(t) = \mathrm{Re}\left\{\sum_{j=1}^{N} a_j(t)e^{i[\theta_j(t)+\varphi_j]}\right\} + r(t), \tag{6}$$

where φ_j's are independent random phase angles that are uniformly distributed between 0 and 2π. The mean and variance of the process are as follows:

$$\mu_x(t) = \mathrm{Re}\left\{\sum_{j=1}^{N} a_j(t)e^{i\theta_j(t)}E[e^{i\varphi_j}]\right\} + r(t) = r(t), \tag{7}$$

$$\sigma_x^2(t) = E\{[X(t) - \mu_x(t)]^2\} = \frac{1}{2}\sum_{j=1}^{N} a_j^2(t). \tag{8}$$

Then, the mean and variance of each component IMF of $X(t)$ can be expressed as

$$\mu_{x,j}(t) = \mathrm{Re}\{a_j(t)e^{i\theta_j(t)}E[e^{i\varphi_j}]\} = 0 \quad j = 1, 2, \ldots N \quad , \tag{9}$$

$$\sigma_{x,j}^2(t) = E\{[X_j(t) - \mu_{x,j}(t)]^2\} = \frac{1}{2}a_j^2(t). \tag{10}$$

The Hilbert spectrum of each simulated sample is the same as that of the record when the model is used as previously described; thus, the ensemble average is also identical with the target.

2.2. Proposed method

Taking the IMFs of the underlying random process derived from the record as target, a new procedure for simulating SCEGMs is proposed and presented in this section.

Among the simulated and target IMFs of the same order, the standard variance σ and instantaneous frequency are assumed to be the same, which is a reasonable trade off when the focus of an earthquake is far from the site as compared to the site dimension [6]. It is assumed that the predictable wave propagation effect has been removed temporally and that the spatial correlation structures are known a priori. The covariance matrix **COV** can be expressed in terms of variance σ^2, and spatial correlation coefficient matrix **C** as

$$COV = \sigma^2 C = \sigma^2 \begin{bmatrix} 1 & C_{12} & \cdots & C_{1L} \\ C_{21} & 1 & \cdots & C_{2L} \\ \vdots & \vdots & \ddots & \vdots \\ C_{L1} & C_{L2} & \cdots & 1 \end{bmatrix}_{(L\times L)} , \tag{11}$$

in which C_{mn} (m,n = 1,2,…L) is typically a real function of frequency and separation distance, and L is the number of simulation stations.

To realize the compatibility of the generated ground motions with the individual function in **COV**, the ground motion at the mth station is assumed to be

$$\begin{aligned} x_m(t) = \textstyle\sum_{k=1}^{m}\sum_{j=1}^{N} F_{km,j}(t)\{A_{kj}\cos[\theta_j(t)] \quad m = 1, 2, \ldots L \\ + B_{kj}\sin[\theta_j(t)]\} + r(t) \end{aligned} , \tag{12}$$

where A_{kj} and denotes independent and normally distributed zero mean numbers with unit variance, obeying the following orthogonal relationships [33]: