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Ground seismic response analysis based on the probability density evolution method

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ABSTRACT

Based on an overview of pertinent literature, the work presented in this paper focuses on the simulation of non-stationary ground motion processes and the stochastic seismic response analysis of site-specific soils. Using the random process orthogonal expansion method and the concept of random functions, initial earthquake ground motion is expressed as a random process based on only one random variable. Then, by discretizing the random acceleration process, we obtained 628 non-stationary earthquake acceleration time history samples with assigned probabilities. By comparing second-order statistical quantities of the random acceleration process between the sampled ensembles and an initial random targeting process, we demonstrate the advantages and effectiveness of this hybrid approach. The first part of this process also laid a foundation for subsequent stochastic seismic response analysis. Then, during the next part of the procedure, the calculation accuracy of the probability density evolution method (PDEM) was verified for a single-degree-of-freedom system with random excitation. The site-specific stochastic seismic response of the ground was then analyzed using the PDEM with the previously mentioned 628 acceleration time history samples. Abundant information was obtained on the probability of the ground seismic response, and the amplification effect on the target soil was verified from a random viewpoint. According to the performance-based method and PDEM, the reliability of the Shanghai soft engineering site was determined to be 0.7959. Furthermore, this new research introduces the use of PDEM techniques for modern geotechnical engineering problems.

1. Introduction

In recent years, seismic damage investigations, strong motion observations and other records have indicated that the damage inflicted by earthquakes on particular engineering structures is not uniform under the same ground motion for the same earthquake. The field conditions encountered within an earthquake zone, in particular the amplification of peak ground acceleration and the spectrum of response characteristics of ground motion; strongly affect the amount and degree of seismic damage to a particular structure. The site-specific soil amplification of earthquake ground motion is the peak ground acceleration magnified on the surface, relative to the bedrock peak ground acceleration, that occurs when earthquake waves propagate through the overlying soil. During many earthquakes, site-specific surface peak ground accelerations have been 4 to 5 times the bedrock peak ground accelerations (Tezcan and Ipek, 1973; Whitman et al., 1974; Cassaro and Romeo, 1987; Wang et al., 2003). In the 1999 M_w7.4 İzmit earthquake, the maximum surface ground acceleration recorded was 0.25 g, while the bedrock peak ground acceleration was only 0.04 g at the Ambarli Thermal Power Plant near Avcilar, about 120 miles from the epicenter. The amplification factor was as high as 6.25 (Tezcan et al., 2002). As early as the 1906 San Francisco and 1923 Kanto earthquakes, examinations of the site-specific effect of soil on the frequency characteristics of earthquakes showed that building damage varied widely from location to location with serious damage appearing in buildings with natural vibration periods close to the soil eigenperiod. Therefore, fundamental research on the seismic response characteristics of site-specific soils is critical. Such seismic analyses generally include frequency-domain equivalent linear analysis and time domain non-linear analysis (e.g., Hashash et al., 2010; Wang et al., 2005; Chen et al., 2012, 2014) that are most often based on a deterministic method. However, earthquake ground motion is well known to have remarkable randomness. Therefore, it is necessary to study site-specific seismic responses using stochastic methods.

Housner (1947) was first to describe earthquake ground motion as a stochastic process. Since then, extensive earthquake engineering research on stochastic earthquake ground motion has been undertaken (Douglas and Aochi, 2008). More recently, many researchers have

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used stochastic process theory to investigate ground movement and the seismic response of structures. Typically, stochastic ground response analysis is conducted in the time domain for horizontally layered soil deposits exposed to random excitations. Statistical responses based on the mean maximum surface acceleration plus or minus one standard deviation have been obtained (Pires, 1996). Additionally, the variability of seismic responses has been studied employing a Monte Carlo simulation approach based on the stochastic finite element method; in this case, second-order moment process responses were obtained (Rahman and Yeh, 1999). The surface response spectrum was predicted employing random vibration theory (Rathje and Ozbey, 2006). Another study focused on the stochastic characteristics of seismic excitations for a non-uniform site (Zerva and Stephenson, 2011).

All the above-mentioned stochastic research on site-specific seismic responses focused on the ensemble numerical characteristics of the seismic response. In such studies, it is difficult to determine a probability density function (PDF) for the seismic response of the soil under stochastic excitation. Additionally, because of the coupling effect between the randomness of earthquake excitation and the dynamic nonlinearity of soils, the analysis of the nonlinear stochastic seismic response of soil layers is an extremely complex problem. This complexity is manifested in two ways. On the one hand, a large number of ground motion samples must be generated by stochastic simulation. The number of ground motion samples could be in the tens if not hundreds of thousands, which greatly increases the difficulty of determining the seismic response of soil layers. On the other hand, to meticulously evaluate the seismic reliability of deep soft layers, we need to obtain high-order statistics or PDFs for the seismic response of soil layers. However, it is an enormous challenge to obtain a PDF other than a Gaussian distribution for classical random vibration theory, which is based on second-order statistics. Because of these conditions, we can only choose ground motion excitations for the deterministic nonlinear seismic analysis of soil layers at present. However, employing deterministic seismic analysis only, the randomness of an earthquake and the abundant probability information concerning the seismic response of site-specific soil layers cannot be fully examined. It is thus necessary to investigate the stochastic seismic response of the soil deposits from a random point of view, and the stochastic method based on modern probability theory should be adopted in the seismic response analysis. Certainly, scholars have discussed the limits of the probabilistic seismic hazard analysis approach, such as the theoretical limits and limits related to earthquake probability (Kossobokov and Nekrasova, 2012). However, we have to acknowledge the strong randomness of earthquakes and the highly variant characteristics of rock and soil properties, as well as the fact that there is insufficient information available for a detailed mechanics-based analysis of the seismogenic mechanism. It is difficult to predict earthquakes precisely and analyze the seismic hazard employing traditional deterministic methods for the above reasons. It is thus inevitable to resort to probabilistic seismic hazard analysis to find field seismic parameters. This approach has been the most effective in recent years. Meanwhile, probabilistic seismic hazard analysis methods, especially the probability density evolution method (PDEM) used in this paper, are based on objective physical laws. The PDEM is based on a series of deterministic analyses. Therefore, any innovative deterministic approach for seismic hazard assessment, such as the new-generation analytic neo-deterministic seismic hazard approach (NDSHA) (Parvez et al., 2011; Panza et al., 2012, 2013), can also be used in the PDEM. The development of the deterministic method is also a powerful development in probabilistic analysis, and therefore, probabilistic seismic hazard analysis methods are being developed with the development of deterministic seismic hazard methods.

The present paper estimates the seismic response of deep saturated soil deposits in Shanghai from a random point of view; we mainly focus on the stochastic response of the soil layers and the seismic effect of the site seismic response on engineering under earthquake motions transmitted from the bedrock. For the reasons mentioned above, the ground seismic response was analyzed employing the PDEM in a stochastic approach (Li and Chen, 2009; Chen and Li, 2005). A probability density description is well known to be the most accurate expression of the ensemble average of a stochastic dynamic system. Essentially, the physical relationships reflect the transformation or transmission relationships between basic physical quantities. The essence of the probability density description is thus to establish a probability density evolution relationship between the stochastic source and target physical quantities. Therefore, the starting point and final goal of the PDEM is to obtain a PDF for the stochastic dynamic system. Spanos' (2010) reviews suggest that the PDEM is a refreshing and promising method, and practicing engineers will benefit by applying the new method. Some researchers have considered that the PDEM has revolutionized the status of probabilistic methods in the area of new material research (Ajith and Gopalakrishnan, 2010).

Combined with the recently developed PDEM, a stochastic seismic response analysis can readily be undertaken for typical soil layers in Shanghai. Some general conclusions concerning this analysis are presented at the end of the paper. This paper provides a reference for the meticulous assessment of soft deep soil layers based on the PDEM.

2. PDEM equation and dynamic reliability

2.1. PDEM equation

Considering the effect of the groundwater, without loss of generality, to determine the dynamic response of soil layers as the result of stochastic excitation, the stochastic dynamic equation could be written as.

$$(\mathbf{M}+\Delta\mathbf{M})\ddot{\mathbf{X}}+\mathbf{C}\dot{\mathbf{X}}+\int_V \mathbf{B}^{\mathrm{T}}\sigma \mathrm{d}V=-\mathbf{M}\mathbf{I}\ddot{X}_g(\mathbf{\Theta},t)+\mathbf{T}_F, \quad (1)$$

where $\mathbf{X}$ is the node displacement vector; $\mathbf{M}$ and $\mathbf{C}$ are the mass and damping matrix, respectively; $\ddot{X}_g(\mathbf{\Theta},t)$ is the random earthquake ground motion excitation; $\int_V \mathbf{B}^{\mathrm{T}}\sigma \mathrm{d}V$ is the node force vector of nonlinear material elements; $\mathbf{B}$ is the element strain matrix; σ is the element stress; V is the element volume; $\Delta\mathrm{M}=-\mathbf{S}_F^{\mathrm{T}}\tilde{\mathbf{H}}\mathbf{S}_F$ is the fluid mass matrix; $\tilde{\mathbf{H}}$ is a function matrix that reflects the distribution of fluid pressure; $\mathbf{S}_F$ is the hydrodynamic pressure increment matrix; $\mathbf{T}_F$ is the surface force load vector; $\mathbf{\Theta}$ is a vector that reflects the randomness of the stochastic ground motion excitation, recorded as $\mathbf{\Theta}=(\xi_1(\theta),\xi_2(\theta),\cdots,\xi_r(\theta))$; and the PDF of $\mathbf{\Theta}$ is known as $p_\Theta(\boldsymbol{\theta})$. In this paper, $\ddot{X}_g$ is a stochastic seismic excitation vector that can be expressed as a linear combination of a series of time history function samples, which are generated by the aforementioned orthogonal expansion and employing the concept of a stochastic function.

Obviously, for general well-posed dynamic systems, there is a unique physical solution of Eq. (2) that is continuously dependent on the basic parameter $\mathbf{\Theta}$. The solution of Eq. (1) is conveniently recorded as.

$$\mathbf{X}=\mathbf{H}(\mathbf{\Theta},t), \quad (2)$$

while the velocity process can be expressed as

$$\dot{\mathbf{X}}=\mathbf{h}(\mathbf{\Theta},t), \quad (3)$$

where $\mathbf{H}=(H_1,H_2,\cdots,H_n)^{\mathrm{T}}$ and $\mathbf{h}=(h_1,h_2,\cdots,h_n)^{\mathrm{T}}$.

More generally, we note the physical quantities that interest us as $\mathbf{Z}=(Z_1,Z_2,\cdots,Z_m)^{\mathrm{T}}$ in a coupled system, which requires.

$$\mathbf{Z}=\mathbf{H}_{\mathbf{Z}}(\mathbf{\Theta},t), \quad (4)$$

and

$$\dot{\mathbf{Z}}=\mathbf{h}_{\mathbf{Z}}(\mathbf{\Theta},t). \quad (5)$$