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Stochastic analysis of ground response using non-recursive algorithm

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ABSTRACT

During an earthquake, the amplitudes of seismic wave may amplify significantly as it propagates through the soil layers near the ground surface. Analysis of site amplification potential is strongly influenced by the uncertainty associated to the definition of soil thickness and its properties. In this paper, the non-recursive algorithm is used in linear and nonlinear Hybrid Frequency Time Domain (HFTD) approaches for stochastic analysis of site amplification. The non-recursive algorithm causes time reduction of analysis that is the essential base of stochastic analysis. The selected soil stochastic parameters are shear wave velocity, density, damping and thickness. The results of sensitivity analysis also show that the damping ratio is the most effective parameter in PGA at ground surface. The stochastic peak ground acceleration, response spectrum and amplification factor at the ground surface are determined by the two approaches for four sites with different average shear wave velocities. Comparison of the results shows that the nonlinear HFTD approach predicts closer response to real recorded data with respect to linear HFTD.

1. Introduction

Seismic amplification of ground motion at the surface is strongly influenced by the geotechnical characteristics of the soil that affect wave propagation, particularly stiffness and damping. Site response has been studied in large number of earthquakes since 1960 [1].

Generally, methods of predicting the ground seismic response could be divided into three categories of experimental, numerical and empirical methods. Among the experimental methods, Standard Spectral Ratio (SSR) [2] and microtremor measurements [3] could be mentioned. Empirical methods make use of equations such as attenuation relationships [4]. Numerical methods allow one, two and three dimensional analyses. In numerical methods, the differences between characteristics of bedrock excitation and soil deposit movement during an earthquake are analyzed [5]. These methods are mainly categorized into linear and nonlinear methods [6].

The linear approach is the simplest method to evaluate ground response. It is based on the principle of superposition. In this approach nonlinear behavior of soil is approximated by an iterative procedure with equivalent linear soil properties [7–9]. In the nonlinear approach the nonlinearity behavior of the particular soil can be modeled. Nonlinear analysis is usually performed by using a discrete model such as finite element and lumped mass models [6,10,11]. These methods usually provide accurate results but are time-consuming because of their step by step integration procedure in time domain [12].

Available methods of the seismic ground response analysis can also be categorized in terms of their calculation domain. In this respect, these methods are categorized into Time Domain (TD) [13,14], linear [8,9,15] and nonlinear Hybrid Frequency Time Domain (HFTD) [12,16–18] methods. The HFTD method rationally combines the frequency domain and time domain to achieve an optimum solution procedure.

At most sites, the soil profile and the parameters that control the soil dynamic response are not known with certainty and a single analysis does not allow uncertainty assessment of the geotechnical parameters. A stochastic site response analysis allows evaluating the sensitivity of the surface ground motion to the uncertainty associated to geotechnical parameters.

There are many reliability approaches that have been developed to analyze the seismic ground response. These approaches can be grouped into five categories: Monte Carlo simulation (MCs), methods based on finite elements, Random Vibration Theory (RVT), approximate methods and geostatistical approach.

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1.1. Monte Carlo simulation

This simulation uses randomly generated points to cover the range of the values that enter into a calculation [19]. As many as 100,000–1,000,000 generation points may be required to adequately represent a deterministic solution. Some recent research works are described below.

Rota et al. [20] proposed a fully probabilistic procedure for estimating site amplification of ground motion and applied it to a case study at the site of Ancona, in central Italy. The research allows taking into account the uncertainty in dynamic soil properties and in the definition of the soil model. Tarque et al. [21] used MCs to analyze one-dimensional (1D) ground response at the site of San Felice Church (Poggio Picenze) in Italy. They studied the soil profile below the site based on the field geological observations and drilling and geophysical tests retrieved from previous investigation campaigns. The results in terms of accelerograms and acceleration response spectrum indicated a clear amplification of the input motion at the basement of the site due to the lithostratigraphic characteristics of the soil deposits.

1.2. Methods based on finite element

These methods are divided into two general categories namely Stochastic Finite Element Method (SFEM) and Random Finite Element Method (RFEM). They are an extension of the classical deterministic finite element approach to the stochastic framework [10,22]. Some new researches by these methods are described below.

Schevenels et al. [23] used SFEM, applied to a hybrid thin layer, to study the influence of (small scale) variations of the dynamic shear modulus on Green's functions of a soil excited at the surface. Their method is based on the analytical solution of the wave equation for a homogeneous layer and a homogeneous half-space. Lopez-Caballero and Modaressi-Farahmand-Razavi [24] studied the effect of the randomness of both soil parameters and input motion on the seismic response of a sandy soil profile through MCs. In their research, special attention was given to estimate the relative contribution of model input parameters on the probability of liquefaction apparition and the surface seismic response. Sanchez Lizarraga and Lai used RFEM for a two-dimensional seismic analysis of an embankment dam taking into account the spatial variability of soil properties [25].

1.3. Random vibration theory

This theory based site response is an extension of stochastic ground motion simulation procedures developed by seismologists to predict peak ground motion parameters as a function of earthquake magnitude and site-to-source distance (e.g. [26,27]).

Rathje and Ozbey [28] employed site response analyses with time history input motions, which are commonly used in geotechnical engineering practice, to validate the RVT-based site response approach, which is rarely used in geotechnical engineering practice. The results indicated that RVT site response analysis can provide a response spectrum that is similar to the median response spectrum from analyses performed using a suite of input rock motions. Rathje et al. [29] used this method to study the influence of input motion and site property variabilities on seismic site response analysis. Kottke and Rathje [30] developed the Strata [31] software to perform one-dimensional linear-elastic and equivalent-linear site response analyses using time series or random vibration theory ground motions.

1.4. Approximate methods

These methods use a series of point estimates of the response function at selected values of the input random variables to compute the moments of the response variable. Most of the approximate methods are modified version of two methods namely: First Order Second Moment (FOSM) method [32] and Point Estimate Method [33].

Wang and Hao [34] used PEM to evaluate the effects of random variations of soil properties and ground water level on site amplification of seismic waves. Liang and Hao [35] performed a statistical study of the effects of random fluctuations of the seismic source parameters on simulated strong ground motions and used PEM to estimate the mean and standard deviation of peak ground acceleration, peak ground velocity and response spectrum. Zhang et al. [36] used PEM to obtain the mean and standard deviation of site transfer function for proposing synthesizing spatially varying ground motion.

1.5. Geostatistical approach

The essence of the geostatistical approach is to recognize the inherent variability of natural spatial phenomena and the fragmentary character of data and incorporate these notions in a model of a stochastic nature. It identifies the structural relationships in the data and uses them to solve specific problems. [37].

Thompson et al. [38] developed and validated a method to estimate site response with greater spatial resolution and accuracy for regions where additional effort is warranted. The method consists of three components: region-specific data collection, a spatial model for interpolating seismic properties, and a theoretical method for computing spectral amplifications from the interpolated seismic properties. Rota [39] proposed a methodological approach for the evaluation of uncertainty in 3D models, with the aim of investigating how uncertainty in the model propagates to the results.

In this study, a probabilistic procedure is proposed for estimating the site response to surface ground motion in soil deposits with uncertain properties. The method is applied to four real sites in south of Iran. For the stochastic analysis in this method, the non-recursive dynamic stiffness matrix is implemented in linear HFTD and nonlinear HFTD instead of recursive algorithm. The influence of soil characterization uncertainty is assessed through MCs, where the variations in the shear-wave velocity, density, thickness of profile and nonlinear soil properties are considered. Stochastic analysis of site response based on iterative methods such as MCs for determining accurate results needs a lot of generations and time. The non-recursive algorithm used in this research reduced the time of generation to about one-fourth and as result more generations and greater accuracy in probability density function can be achieved. In particular, their effects on peak ground acceleration, response spectra and amplification function at the ground surface are evaluated for the sites. The