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Stochastic modeling and simulation of ground motions using complex discrete wavelet transform and Gaussian mixture model

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ABSTRACT

The aim of this research is to develop a stochastic model for generating synthetic ground motions in accordance with a recorded ground motion. In this model, Complex discrete wavelet transform is used to extract wavelet coefficients of a ground motion, and the Gaussian mixture distribution to capture the statistical behavior and simulate these coefficients. Synthetic ground motion is generated by applying inverse wavelet transform to synthetic wavelet coefficients that are extracted based on the fitted Gaussian mixture models and a random sign generator. This model is able to generate an ensemble of synthetic ground motions with temporal and spectral nonstationary characteristics similar to those of the recorded ground motion. In contrast to the previous models, the Gaussian mixture model is able to simulate several dominant frequency peaks at each time, multiple peaks in the temporal amplitude of ground motions, and near-fault ground motions containing several pulses. Also, the Gaussian mixture model provides good estimates of the energy distribution and the inelastic response spectrum of recorded ground motions. Besides these capabilities, the proposed model demands much less computational effort than the previous models.

1. Introduction

Recorded ground motions (RGMs) are the most important tool for dynamic analysis of structures. These ground motions should be proportional to conditions of the site of interest and seismotectonic surrounding it. In addition, recorded ground motions that are suitable for various sites and sources, are few, and for some conditions, are not available. Therefore, it is essential to use synthetic ground motions (SGMs) for seismic assessment of structures. Various models are developed to generate SGMs for different source and site conditions. These models are classified into two categories [1] :1) the models that simulate the fault rupture mechanism, the seismic wave propagation, and site conditions 2) the models developed only based on recorded ground motions. The former models are named source-based models and the latter models as site-based models. To use source-based models for generating SGMs, sufficient information about the earthquake source characteristics, the effects of wave propagation path, and site conditions should be available. For example, Boore [2] has proposed a stochastic source-based model based on the parametric modeling of the Fourier amplitude spectrum as a function of source, path and site conditions. In Boor's model [2], the causative fault is modeled as a point-source that is appropriate for simulation of far-field ground motions. Recently, the point-source stochastic models are modified to consider a double-corner-frequency source model, finite-fault effects, and a new model for duration of ground motions, and to simulate SGMs for near-fault sites [3,4]. The source-based models are useful for simulating the high frequency components of ground motions. To simulate both the low and high frequency components of ground motion, these models should be combined with site-based models known as hybrid models [5–7].

In site-based models, ground motions recorded during past earthquakes are used to generate SGMs for a site. For this purpose, a parametric model should be first developed for generating an ensemble of SGMs proportional to a recorded ground motion. Then its parameters should be estimated as a function of seismological parameters by using a database of RGMs. The previous site-based models are often nonparametric, so it is impossible to generate SGMs for a site. They can only generate SGMs with the statistical characteristics proportional to a recorded ground motion (i.e., Wang et al. [8]). Also in some researches, a method for matching the response spectrum of a recorded ground motion to a target response spectrum is proposed (i.e., Zhang et al. [9], and Zhang and Zhao [10]). These models and other nonparametric methods are often used to evaluate the structural response variability in a specified seismic hazard level.

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In few studies, it is possible to generate SGMs for a site, because of developing a parametric model and estimating its parameters as a function of seismological parameters. For example, Sabetta and Pugliese [11] have proposed a stochastic model based on the summation of the Fourier series with random phases and time-dependent coefficients, where the model parameters are related to seismological parameters by using a database of RGMs. In this model, the natural variability of RGMs is underestimated, because the only source of uncertainty considered is the random phase angle. The model proposed by Stafford et al. [12] takes into account only the temporal nonstationarity of RGMs. Therefore, the SGMs generated by this model are not suitable for nonlinear structural analysis. A stochastic model based on the modulated filtered white-noise process is proposed by Rezaeian and Der Kiureghian [1], where both the spectral and temporal nonstationary characteristics of RGMs are taken into account. In this model, a random white noise is passed through a filter with time-varying parameters. Then the filter output is normalized to its standard deviation to have unit variance. Finally, by imposing time-modulating function on the scaled filtered white-noise, desired SGM would be extracted. In this model, by normalizing the filter output, the spectral and temporal nonstationarity are separated. Also, the above model is employed for simulation of two orthogonal horizontal ground motions for a far-field site [13]. The Rezaeian's model [1] can only simulate a single dominant frequency of the ground motion at each time, because of using a single-degree-of-freedom linear filter. Also, it cannot simulate pulse-like near-fault ground motions. This model was used later by Medel-Vera and Ji [14] to simulate synthetic ground motions for special seismic scenarios in the Northwest (NW) European areas. They used a set of 220 ground motions recorded in the NW European areas to extract appropriate ground motion prediction equations (GMPEs) for the model parameters. Also, some modifications to the Rezaeian's model [1] were recently made to match it to both elastic and inelastic GMPEs [15] and to target intensity measures for a specific site and structure of interest [16].

In the work of Dabaghi and Der Kiureghian [17], the far-field ground motion model of Rezaeian and Der Kiureghian [1] is combined with the velocity-pulse model of Mavroeidis and Papageorgiou [18] for simulation of pulse-like near-fault ground motions. In order to detect the pulse-like motions from recorded near-fault ground motions and extract their velocity-pulses, they have used the method proposed by Baker [19] that is based on the coefficients of the continuous wavelet transform. One of the other site-based models, where parametric uncertainty is considered, is the model proposed by Yamamoto and Baker [20]. This model is implemented into the time-frequency domain, and its parameters are estimated as a function of seismological parameters. In this model, by applying the wavelet packet transform to an RGM, its wavelet coefficients (WCs) are extracted and separated into two categories: 1- Major coefficients with 70% of total energy and 2- Minor coefficients with 30% of total energy. For each category, the amplitudes of wavelet coefficients are modeled by exponential distribution, and their time and frequency locations are simulated by bivariate lognormal distribution. Because of using mono-component statistical distributions, this model can only simulate a peak value of WCs. The study conducted by Huang and Wang [21] has attempted to stochastically develop correlation models for 13 wavelet packet parameters used in the model of Yamamoto and Baker [20]. For this purpose, they have characterized spatial correlations and spatial cross-correlations of important stochastic measures of ground motions, based on well-populated regionalized ground-motion data recorded from the 1994 Northridge earthquake in California and the 1999 Chi-Chi earthquake in Taiwan. The spatial correlation model that they have developed for the wavelet parameters extends the Yamamoto's model [20] to regional-scale applications, by simulating spatially correlated ground motions at multiple locations for a given seismic scenario.

In studies conducted by Hazirbaba and Tezcan [22] and Tezcan et al. [23], the time-frequency distribution of ground motion is extracted using the continuous wavelet transform and then, it is simulated using image processing methods. Also, in order to relate their model parameters to seismological parameters, they have used nonparametric methods, such as machine learning algorithm. Besides being time consuming, physical interpretation of the relation of model parameters with the seismological parameters could not be extracted from these models. A stochastic-parametric model that is based on the simulation of evolutionary power spectral density (EPSD) of ground motions is proposed by Wang et al. [24]. In this model, generalized harmonic wavelets are used to estimate the EPSD of real ground motions. Then, the estimated EPSD is modeled by a frequency-domain energy distribution function and a series of normalized time-dependent envelop functions for different frequencies. Although in their model, the temporal variation of the energy of each frequency component is simulated by different model parameters, but the spectral nonstationarity of seismic ground motions is not modeled, accurately. Also, their model has a large number of parameters, so nonparametric methods should be used for extracting the GMPEs. Vlachos et al. [25] have proposed a multi-modal, parametric, nonstationary spectral version of the Kanai-Tajimi model to simulate the time-varying spectral energy distribution of recorded ground motions. Also, the NGA-West2 database was used to relate their model parameters to the seismological parameters [26]. This model cannot simulate well the time-frequency distribution of wide-band ground motions or the ground motions that have multiple peaks in their temporal amplitude. According to the results of Vlachos et al. [25], there is significant differences between the temporal and spectral nonstationary characteristics of synthetic and real ground motions.

Although previous site-based models (such as the model of Rezaeian and Der Kiureghian [1] and the model of Yamamoto and Baker [20]) are simple and have few parameters, but they cannot simulate multiple peaks in the temporal amplitude of ground motion, several dominant frequency peaks at each time, and the near-field pulse-like ground motions containing several pulses. Also, at short periods, they cannot predict peak values of the target response spectrum. These shortcomings will cause the previous models to provide a poor estimate of the time-frequency energy distribution of recorded ground motions. The simulation results of the model proposed by Vlachos et al. [25] also showed this low accuracy. To solve these shortcomings and to estimate well the energy distribution of RGMs, a stochastic model is developed using complex discrete wavelet transform and Gaussian mixture distribution in this paper. This model is named as the Gaussian mixture (GM) model. The results of the GM model are compared with the results of mono-component statistical models. One of them appropriate for modeling the temporal nonstationarity of RGMs is the Gamma distribution that was first used by Saragoni and Hart [27] and then by Rezaeian and Der Kiureghian [1]. For this reason, the SGMs generated by the GM model would be compared with those generated by Gamma model. The Gamma model is the same with the GM model, except that in the former, WCs are modeled by the Gamma distribution function, where in the latter, they are modeled by the GM function. The results of the Gamma model are close to the results of the Yamamoto's model [20], because in both models, mono-component statistical distributions are used to simulate WCs. Therefore, an indirect comparison of the results of the GM model with those of the Yamamoto's model [20] would be provided in this paper. Also, the results of the proposed model are compared with the results of a recently proposed model by Vlachos et al. [25]. This model predicts the time-varying power spectral density of RGMs.

In the proposed model, an RGM is first decomposed into several frequency components by using the complex discrete wavelet transform (CDWT), and the wavelet coefficients of each sub-band are extracted. Then, the GM distribution is used to simulate WCs. After that, for each sub-band, the synthetic wavelet coefficients are extracted using the fitted GM distribution. Finally, by applying the inverse wavelet transform to the synthetic wavelet coefficients, appropriate SGM would be generated. Because of using the CDWT and the GM distribution in the