Soil Dynamics and Earthquake Engineering 99 (2017) 56–67

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Wavelet-based simulation of scenario-specific nonstationary accelerograms and their GMPE compatibility

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ARTICLE INFO

Keywords:
Wavelet coefficients
Energy arrival
Amplitude modulation
Scenario-specific
GMPE-compatible

ABSTRACT

In seismic hazard analysis ground motion prediction equation (GMPE) plays a pivotal role because it provides the statistical distribution of hazard parameter for a chosen seismic scenario. However, GMPEs in general do not provide nonlinear response statistics, and the latter should be ideally obtained by time-history analyses of a scenario-specific suite of motions. In the present study a new wavelet-based method is proposed to simulate scenario-specific ensemble of accelerograms with realistic variability of time-frequency characteristics. Firstly, a methodology is proposed to stochastically characterize the nonstationarity of a recording process from the energy arrival curve of the wavelet coefficients of the recorded ground motion. Then a new empirical scaling model is developed to estimate the instantaneous energy arrival, with model uncertainty. Further, a reconstruction method is formulated to simulate the scenario-specific ensemble of accelerograms from the estimated scenario-specific energy arrival curves. It is found that the simulated ensemble exhibits realistic variation of time-frequency characteristics and hence, it naturally becomes comparable with GMPEs (in terms of median estimates for response spectrum and strong motion duration) developed using the same database. Finally, an algorithm is proposed to tune the estimated energy arrival such that the ensemble of simulated motions can be made compatible with the target GMPEs, both in terms of median estimates and standard deviations. It is found that the GMPE-compatible ensemble, obtained for 5% damping PSV spectra, shows good agreement with respect to PSV scaling models developed for a wide range of damping ratio.

1. Introduction

The seismic hazard at a site for a given seismic scenario can be conveniently characterized by site-specific ground motion prediction equation (GMPE). The GMPEs generally predict spectral quantities, e.g., spectral acceleration (SA), pseudo spectral velocity (PSV) [1–3], or sometimes provide other intensity measures like strong motion duration (SMD) [4]. For earthquake resistant design, often detailed nonlinear time-history analysis is required to be carried out to check structural adequacy [5,6]. When the adequacy is intended to be checked with a level of confidence a statistical estimate is necessary for the nonlinear response. Hence, a suite or ensemble of ground motions with realistic variation of time-frequency characteristics are necessary to accomplish that task. Since hazard is characterized by GMPE it is imperative that such an ensemble emulates the same statistics for the response quantity as envisaged by the GMPE (i.e. it is GMPE compatible).

Physics based models for earthquake ground motion simulation are available [7–10], however, these methods of simulation require thorough knowledge of the seismic parameters, which may be not available in many regions [11]. On the other hand, stochastic simulation methods [12–17] have evolved in order to address the time and frequency nonstationarity of a recording process and to generate several samples of the process without knowing several seismological parameters. Yamamoto and Baker [18] have recently proposed a stochastic simulation method to generate ensemble of ground motions for a specific scenario that is also comparable with a GMPE developed using the same database. However, their methodology does not guarantee that the underlying earthquake recording process is Gaussian, which is widely accepted [13,14,19–24], and the method provides little room for modification of the formulation so that the simulated motions become compatible to any target GMPE.

It is most critical to properly maintain the realistic nature of the time and frequency nonstationarities (i.e. the time-frequency characteristics) of a simulated motion because the nonlinear response is quite sensitive to them. Because of that it has become increasingly popular to get design (or response) spectrum compatible accelerograms that preserve the time-frequency characteristics of an as recorded seed

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http://dx.doi.org/10.1016/j.soildyn.2017.05.007
Received 5 February 2016; Received in revised form 15 February 2017; Accepted 5 May 2017
0267-7261/

motion [25–30]. Usually, these methods are used when all motions are intended to exhibit a specified nonstationarity, often described by the recorded motions, and thus, are not suitable when a realistic variability of nonstationarities is sought after within a scenario specific ensemble. Priestley process based simulation techniques are efficient for characterizing the time-frequency properties of a recording process, which can preserve the nonstationarity of the recorded motion by a frequency dependent deterministic slow varying envelope function [12–14]. Also Priestley process based simulation can ensure that the samples obey nonstationary Gaussian process assumption. Such a simulation technique will be very useful for scenario specific ensemble if the slow varying envelopes can be conveniently estimated for a given scenario along with their variability. It is therefore important that the envelopes should be extracted from a physically meaningful quantity that can be estimated confidently from known seismological parameters. It is further expected that by suitable modification of the frequency dependent envelopes GMPE compatible ensembles can be simulated. However, scenario specific ensemble simulation based on Priestley process assumption is not available in the literature.

In the present study the main objective is to propose a versatile method to simulate scenario specific ensemble of ground motions with realistic variability of time-frequency characteristics that is also flexible to be tuned such that the simulated motions become any target GMPE compatible. The objective is achieved by three new propositions, viz., (1) proposing a Priestley process based simulation of ground motion samples from the instantaneous energy arrivals of wavelet coefficients of a recorded motion, (2) proposing an empirical scaling model to predict the instantaneous energy arrivals along with their variability for a given seismic scenario, and (3) proposing an effective method to tune the instantaneous energy arrivals such that the scenario specific simulated ensemble is compatible to any target GMPE.

2. Priestley process based characterization of ground motion

Wavelet analysis is very useful for characterization of fully nonstationary ground acceleration process because wavelet coefficients capture adequate information about both time and frequency description of a motion. In the present study, the modified Littlewood-Paley (L-P) wavelet basis as proposed by Basu and Gupta [31] has been used because these level-wise wavelet basis functions are strictly narrowband-limited in frequency domain – a property that is essential for Priestley process based simulation. A brief review of the wavelet transform with essential details is provided next for the sake of completeness.

2.1. Review of wavelet transform

Any finite energy signal, $f(t)$, can be transformed into wavelet domain and reconstructed back from there by using the wavelet transformation and the inverse wavelet transformation, respectively. The continuous wavelet transformation of $f(t)$ is defined with respect to a real wavelet basis, $\psi_{a,b}(t)$, as

$$W_\psi f(a, b) = \langle f, \psi_{a,b} \rangle = \int_{-\infty}^{\infty} f(t)\psi_{a,b}(t)\mathrm{d}t \tag{1}$$

where

$$\psi_{a,b}(t) = \frac{1}{a^{1/2}}\psi\left(\frac{t-b}{a}\right) \tag{2}$$

and $\psi(t)$ is called the mother wavelet. Here, $a > 0$, the scale parameter, controls the frequency content of the dilated wavelet basis, and $b \in \Re$, the shift parameter, localizes the basis at $t=b$. The function $f(t)$ can be reconstructed back from the wavelet coefficients, $W_\psi f(a, b)$, as

$$f(t) = \frac{1}{2\pi C_\psi}\int_{-\infty}^{\infty}\int_0^{\infty}\frac{1}{a^2}W_\psi f(a, b)\psi_{a,b}(t)\mathrm{d}a\,\mathrm{d}b \tag{3}$$

with

$$C_\psi = \int_0^{\infty}\frac{|\hat{\psi}(\omega)|^2}{\omega}\mathrm{d}\omega < \infty \tag{4}$$

In Eq. (4), $\hat{\psi}(\omega)$ is the Fourier transform of the basis function, $\psi(t)$, defined as

$$\hat{\psi}(\omega) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\psi(t)e^{-i\omega t}\mathrm{d}t \tag{5}$$

In the present study, the modified L-P wavelet basis is used, for which the mother wavelet is defined as

$$\psi(t) = \frac{1}{\pi\sqrt{\sigma - 1}}\frac{\sin(\sigma\pi t) - \sin(\pi t)}{t} \tag{6}$$

with σ taken as $2^{1/4}$ [31]. On discretizing and taking $a_j = \sigma^j$, where j is the index of (dilation) level, the wavelet coefficient corresponding to jth level is expressed by

$$W_\psi f(a_j, b) = \langle f, \psi_{a_j,b} \rangle = \int_{-\infty}^{\infty} f(t)\psi_{a_j,b}(t)\mathrm{d}t \tag{7}$$

Further, $W_\psi f(a_j, b)$ has energy in the period band $(2a_j/\sigma, 2a_j)$ s and it can be considered as a narrowband signal in b. Typically $W_\psi f(a_j, b)$ looks like an amplitude modulated signal of pseudo period T_j $(=0.5(2a_j/\sigma + 2a_j))$. A total number of 32 levels are considered with $j = -21$ to 10, so that $W_\psi f(a, b)$ $(= \sum_{j=-21}^{10} W_\psi f(a_j, b))$ spans over the period band (0.044–11.32)s which is deemed sufficient for any earthquake signal. Further, for practical purpose of reconstruction it is sufficient to consider a range for b which will start 12 s before the beginning of a signal and end 12 s beyond the endpoint of the signal. It may be noted that, any level-specific reconstructed motion, $f_j(t)$ (obtained by inverse transform of $W_\psi f(a_j, b)$ only without summation over j), from any Gaussian white-noise signal becomes a band-limited Gaussian white-noise within the narrow period range $(2a_j/\sigma, 2a_j)$ s.

A fully nonstationary process is usually characterized by the evolutionary power spectral density function (EPSDF). The EPSDF, $\Phi_F(t, \omega)$, for a recorded ground motion process, $F(t)$, can be conveniently modelled using the wavelet functional as [32].

$$\Phi_F(t, \omega) = \sum_j \frac{K}{2\pi a_j}\mathrm{E}[W_\psi^2 f(a_j, b = t)]\,|\hat{\Psi}_{a_j,b=t}(\omega)|^2 \tag{8}$$

where,

$$K = \frac{1}{2C_\psi}\left(\sigma - \frac{1}{\sigma}\right) \tag{9}$$

and

$$\hat{\Psi}_{a_j,b}(\omega) = \begin{cases}\sqrt{a_j/(\sigma-1)}\;e^{-b\omega} & \forall\;\pi/a_j < |\omega| < \sigma\pi/a_j\\ 0 & \text{Otherwise}\end{cases} \tag{10}$$

and $\mathrm{E}[\cdot]$ indicates the statistical expectation.

2.2. Modelling of time-frequency characteristics

A random nonstationary process, $F(t)$, like earthquake ground motion process can be modelled as Pristley process [12]:

$$F(t) = \int_{-\infty}^{\infty} A(t, \omega)e^{i\omega t}\,\overline{\mathrm{d}Z}(\omega) \tag{11}$$

where, $A(t, \omega)$ is a frequency dependent deterministic slow varying amplitude modulation or envelope and $\overline{\mathrm{d}Z}(\omega)$ is a stationary orthogonal incremental process. Hence, it can be inferred that a nonstationary signal, $f(t)$, for the $F(t)$ process can be simulated by several narrowband-limited white-noise signals and different deterministic slow varying amplitude modulations, specific for the corresponding frequency bands as [13,14].