Soil Dynamics and Earthquake Engineering 111 (2018) 77–86

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

A Site-specific ground-motion simulation model: Application for Vrancea earthquakes

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ARTICLE INFO

Keywords:
Synthetic earthquakes
Site-specific
Non-stationary
Non-Gaussian
Ground-motion simulation
Earthquake engineering
Vrancea earthquakes
Limited data
Bayesian statistics

ABSTRACT

A large number of ground-motion time histories is required for a reliable probabilistic seismic-hazard analysis. However, insufficient ground-motion records has been a major issue in earthquake engineering even in high-seismicity areas. Stochastic and seismological ground-motion models are used to simulate time histories in order to overcome this issue. Many times these models require a large number of records for calibration, are available only for regions with a wealth of data, or fail to characterize well specific sites.

The current paper introduces a novel stochastic ground-motion model that allows simulation of realistic non-stationary, non-Gaussian time histories that are statistically consistent with data even at sites with very low numbers of records. This goal is achieved by combining the prior knowledge from a seismological model, calibrated to global data, with the site-specific data within a Bayesian framework. The proposed model uses the specific barrier model as the seismological model and numerical results consistent with records from a nuclear powerplant site in Romania are presented.

1. Introduction

Detailed seismic-risk assessment is a requirement for various applications, from the design of high-value structures to the development of risk-management solutions and risk-transfer solutions for the (re) insurance market. An accurate evaluation of the seismic risk of structures at specified sites requires the dynamic analyses of those buildings subjected to site-specific records. This is usually constrained by the limited number of recorded ground motions available at individual sites. The methods proposed to overcome this issue can be split in two classes: methods that select ground-motion records from large datasets, and scale them to desired intensity measures; and methods that simulate artificial ground-motion records.

A review of ground-motion selection is provided in [1]. A popular procedure is to select ground-motion records to match a response target-acceleration spectrum [2–4]. Computational methods for selecting ground motions and selection algorithms were developed in [5,6]. The selected records are then used for probabilistic seismic-hazard analyses by scaling them to obtain ground motions of various intensities. This procedure has limitations since it only changes the amplitude of the motion, but not its frequency content [7]. The alternative to scaling selected ground motions is the simulation of ground motions by using either stochastic models or seismological models. For the purpose of this discussion, we define seismological models as the models whose calibration involves event characteristics of a physical nature, such as stress drop, rupture model, etc., while stochastic models are mathematical models calibrated just to recorded time histories and their description in terms of magnitude, epicentral distance, soil type, etc.

Seismological models, such as the point-source model SMSIM [8] or the finite-fault model EXSIM [9], used for ground-motion simulation show that important work has been developed in this area. Note that these two models are defined as stochastic in the seismological community [12]. Detailed comparisons between the two models have been presented in [10,11]. Usually seismological and physics-based models are very complex and target specific events, such as a hypothetical 7.8-magnitude event on the San Andreas fault in California [13]; the 1915 Marsica earthquake in Italy [14]; the 1999 7.1-magnitude earthquake in Turkey [15]; or the 2011 9.1-magnitude event in Japan [16,17]. A model in [18] is called "semi-stochastic", since it combines a physics-based model for the low-frequency and a stochastic model for the high-frequency contributions.

The stochastic models for ground-motion simulations represent more of an engineering approach which relies on the idea of earthquakes as filtered Gaussian noise with finite duration [19,20]. Stochastic models are usually defined as parametric models which can be

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https://doi.org/10.1016/j.soildyn.2018.04.025
Received 21 February 2018; Received in revised form 13 April 2018; Accepted 20 April 2018
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fit to specified regions, such as north-western Europe in [22], or calibrated to generate ground motions compatible with design response spectra [21,23] or given ground-motion prediction equations [24]. However, models with a large number of parameters, such as [25–27], may be difficult to calibrate reliably in regions with poor ground-motion records. Others [28] postulate mathematical models, in this case the Karhunen-Loève expansion, to produce artificial records, by estimating the distributions and the second-order moment properties from recorded ground motions. Special attention has been given to the representation of the non-stationary character of the ground motions [29] in stochastic models. Many formulations of the evolutionary power-spectral density for ground-motion simulations [30–32] use the model introduced by Priestley [33]. Other models [25,34] use a frequency filter to achieve this goal, while in a newer approach [26,27] a multimodal Kanai-Tajimi spectrum is used to describe the time dependency of the frequency content. In Ref. [35,36] a spectral density estimated by wavelets is used to describe the evolution in time of the spectral values of simulated ground motions. In a more comprehensive context of utilizing wavelets, a recent paper [37] proposes the construction of a power-spectral density function for non-stationary processes based on a compressive-sensing approach, for the purpose of reconstructing stochastic processes with scarce or incomplete data. In a different approach [38], empirical ground-motion prediction models are used to produce realistic Fourier spectra for the ground-acceleration processes, whose non-stationary character is modelled by log-normal distributions of the P- and S- pulse arrivals.

The current study proposes a new stochastic model that can simulate site-specific ground motions statistically consistent with site data. The model proposed combines site records with a seismological model within a Bayesian framework in order to describe the frequency content of the motions, and assumes a non-Gaussian distribution for the motion in order to incorporate the contribution of site records to other statistical moments, besides the mean and variance. The importance of hazard-consistent ground motions has been addressed before in [39], and a recent study [40] shows the significant effects of soil amplifications on ground motions. The seismological model adopted as part of our development is the specific barrier model (SBM) [41], calibrated to regional data in [42]. An augmented version of the model with additional source characteristics is presented in [43,44]. The SBM describes the frequency content of ground motions as a function of magnitude, epicentral distance, seismological regime and soil type. Our paper is structured in three main parts: model description, model calibration, and model evaluation. In summary, our model is a zero-mean, non-Gaussian stochastic process with second-order moment properties defined by a parametric seismological-based, one-sided, power-spectral density. The non-stationary character of the motion is achieved using both amplitude- and frequency-modulation parametric functions. In the model-calibration part, the probability distributions of the frequency-related parameters are updated to the site records. In the final part, the model is evaluated by comparison with an independent regional ground-motion prediction model in terms of intensity distributions. Calibration and numerical examples shown in the paper are for the Cernavodă site of a nuclear power plant in Romania, which lacks a large number of records, but which would require an accurate seismic-hazard analysis in case of a disaster-risk-reduction study.

2. Ground-motion model

The analysis of real ground-motion records shows that they are samples $x(t)$, $0 \le t \le t_f$ with time length t_f of complex stochastic processes $X(t; \Theta, \Psi)$, which can be simplified in three natural distinct time-sections [45]: (1) a built-up part, in which amplitudes $\max_{0\le t\le t_f}\{x(t)\}$ increase with time until they reach their highest-intensity range, (2) a stationary part, in which amplitudes preserve their highest-intensity characteristics, and (3) a decaying part, in which amplitudes decay exponentially over time. Fig. 1 (a) shows this split for a ground-motion record. A further analysis in the frequency domain of these three parts of the record shows that the frequency content of the three parts is significantly different, as seen in Fig. 1 (b). Thus, not only the ground-motion amplitudes are non-stationary but also their frequency content.

More techniques used to perform time-frequency analyses of non-stationary signals are shown in [46], or more recently in [47] by using a Hilber spectrum. Following the observations above, the ground-motion model proposed for the simulation of site-specific ground motions is a non-stationary stochastic process

$$X(t; \Theta, \Psi) = c(t)Y(h(t; \Psi); \Theta),\ 0 \le t \le t_f, \tag{1}$$

where t_f is the duration of the motion, and Θ and Ψ are stochastic parameters calibrated to site records. Functions $c(t)$ and $h(t; \Psi)$ are the amplitude- and frequency-modulation functions. The process $Y(t; \Theta)$ is a zero-mean, stationary process with second-order moment properties governed by the parametric one-sided power-spectral density function $g_Y(\nu; \Theta)$, with the random parameter Θ. Function $g_Y(\nu; \Theta)$ is an updated version of the one-sided power-spectral density function $g_{SBM}(\nu)$ provided by the specific-barrier model (SBM) [41,42]. The SBM is a seismological model calibrated to global data, and provides as an output the function $g_{SBM}(\nu)$, as a function of the moment magnitude m, epicentral distance r, type of soil and seismic regime. Note that for simplification purposes, the notation regarding these parameters is not used in the remainder of the paper. The random vector Θ in $g_Y(\nu; \Theta)$ is used to update $g_{SBM}(\nu)$ to site records, as shown previously in [48], a methodology which is described in the next section.

A gamma model [31] is used for the amplitude-modulation function:

$$c(t) = \alpha t^{\beta} \exp\{-\gamma t\},\ \ 0 \le t \le t_f, \tag{2}$$

where t_f, α, β and γ are also outputs of the SBM, and are deterministic functions of (m, r), soil class, and seismic regime. Note that these parameters could be randomized, too, but our model calculates site-specific probability distributions only for the parameters affecting the frequency content of the motions for two reasons: (1) the response of structures is highly sensitive to the frequency content of the input, and (2) a large number of random parameters would limit the usefulness of the model in regions with little data.

A power-spectral density model which uses a positive, real-valued, increasing frequency-modulation function $h(t; \Psi)$, with zero slope at $t = 0$, to describe the time evolution of the frequency content is adopted [30]. A log-normal parametric model is considered for $h(t; \Psi)$:

$$h(t; \Psi) = \frac{1}{\Psi_2\sqrt{2\pi}}\int_0^t u^{-1}\exp\left(\frac{-(\ln(u) - \Psi_1)^2}{2\Psi_2^2}\right)du, \tag{3}$$

where Ψ is a random vector with coordinates $[\Psi_1, \Psi_2]$. The log-normal cumulative function was chosen because besides the fact that it fulfils all the requirements for $h(t; \Psi)$, it also covers a large range of possibilities with just two parameters, which control both the position of the function on the t axis as well as the function's shape. Finally, we can conclude that the process $X(t; \Theta, \Psi)$ is obtained from the stationary process $Y(t; \Theta)$ by (1) scaling its amplitudes to $c(t)$, and (2) associating its scaled amplitudes to time-dependent frequencies.

A Gaussian distribution for the ground-motion process $X(t; \Theta, \Psi)$ is the common assumption in previous studies [21,31,34]. However, the analysis of the ground-motion records in the PEER NGA-West dataset suggests that a normal distribution may not be appropriate. Fig. 2 shows the kurtosis κ calculated for all records in the dataset in comparison with the value $\kappa = 3$, characteristic for Gaussian processes. The kurtosis in the data is most of the time well above 3 which suggests a limited usefulness of the Gaussian assumption. High kurtosis indicates heavy tails of the ground-motion distributions, and therefore higher peaks [49,50]. Hence, a non-Gaussian process with marginal distribution $F_Y(y) = \mathbb{P}(Y(t; \Theta) \le y),\ \forall\ 0 \le t \le t_f$ must be chosen for process

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