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Comparison of alternative stochastic ground motion models for seismic risk characterization

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ABSTRACT

Stochastic ground motion models facilitate a versatile description of earthquake acceleration time-histories by modulating a stochastic sequence (for example, white noise sequence) through functions that address spectral and temporal properties of the excitation. This is established by relating the parameters of these functions to earthquake and site characteristics though appropriate predictive relationships. For evaluating the effect of these relationships and of the white noise itself on the resultant seismic risk the authors recently presented a sensitivity analysis framework for an efficient identification of the importance of the different risk-factors, interpreted here to correspond to the various uncertain model-characteristics. This paper extends this work to comparison between two alternative ground motion models, one 'source-based' and one 'record-based', in terms of both linear and nonlinear structural behavior. The comparison is primarily based on the way their model characteristics impact seismic risk and is facilitated through the aforementioned sensitivity analysis. Different performance quantifications are considered for describing seismic risk, including both peak response quantities as well as cumulative structural-damage indicators. To establish a direct comparison between the different ground motion models considered, the framework is also extended to identification of the importance of resultant quantities describing the seismic hazard (such as peak ground acceleration or maximum incremental velocity), beyond the primary risk factors related to each model. The discussions reveal the importance of the parameters for each model but also provide insight on the differences between these two models in the way they ultimately characterize seismic hazard.

1. Introduction

One of the most important aspects of probabilistic seismic risk assessment is the characterization of the earthquake hazard through appropriate models that adequately address its variability for different seismicity levels, while providing a description appropriate for the specific application of interest. For applications involving dynamic analysis this description corresponds to the entire ground motion acceleration time-history, $\ddot{a}(t)$. The growing interest in the last decade in performance-based earthquake engineering (PBEE) [1–3] and in simulation-based risk mitigation approaches [4–8] has increased the relevance of this need. PBEE addresses the entire spectrum of structural response, ranging from linear to nonlinear to structural collapse, requiring a realistic characterization of earthquake acceleration time-histories. In parallel, simulation-based approaches provide a versatile framework for risk mitigation, established through augmentation of proper excitation, structural, and performance evaluation models and through appropriate quantification of the uncertainties related to these models [8]. Within this approach, a description of earthquake hazard in the form of acceleration time-histories is needed for a realistic, comprehensive characterization of seismic risk.

Though numerous methodologies exist for establishing such a description for ground motion time-histories for structural design applications, for example spectra and spectrum compatible approaches [9–12] or the scaling/selection of ground motions for different hazard levels characterized through some chosen intensity measures [13–15], the focus of this study is on the use of stochastic ground motion models [16–19]. These models are based on modulation of a stochastic sequence, $\mathbf{Z}$, through functions that address spectral and temporal characteristics of the excitation. Their parameters can be related to earthquake (type of fault, moment magnitude and rupture distance) and site characteristics (shear wave velocity, local site conditions) by appropriate predictive relationships [20,21]. Description of the uncertainty for the earthquake characteristics and the predictive relationships leads then to a probabilistic description of potential future ground motion time-histories and of seismic risk. In this setting, the uncertain model characteristics (including the sequence $\mathbf{Z}$) can be considered as the

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risk factors, ultimately generating the seismic risk. Though concerns do exist for use of stochastic ground motion models – like they exist for all other methodologies for describing ground motion time-histories [22] – this modeling approach has gained increasing support within the structural engineering community [4,7,21] since (i) it provides a complete probabilistic characterization for seismic risk addressing all potential sources of uncertainty [15] within a modeling foundation which is consistent with system-engineering (modeling of the earthquake process itself based on parameters directly related to the primary characteristics of the excitation event), and (ii) it fits well with a simulation-based framework for risk assessment/mitigation [4,23]. In general, two types of stochastic ground motion models can be distinguished, 'source-based' (or 'physics-based') models [17,20,24] that describe the fault rupture at the source and propagation of seismic waves through the ground medium, and 'site-based' (or 'record-based') models that are developed by fitting a preselected mathematical model to a suite of recorded ground motions [16,18,19,25,26].

Most of the studies related to stochastic ground motion models have, though, focused on development of such models or on their implementation for describing seismic hazard. Recently the authors proposed an efficient framework [27], based on stochastic sampling concepts, for a global sensitivity analysis, aiming at identifying the importance of the various risk factors (or of groups of them) towards the total seismic risk, thus providing a deeper understanding of the seismic hazard characterization when stochastic ground motion models are utilized. That study, though, focused on a single family of ground motion models (the point-source models [17] with the Atkinson and Silva [20] selection for source spectrum), and on linear structural response for quantifying structural behavior (and ultimately risk). This paper offers an extension with respect to both aspects. It utilizes the proposed global sensitivity analysis to draw comparisons between different stochastic ground motion models related to their influence on the seismic hazard. One source-based and one record-based model are selected for this purpose, the first one corresponding to the point-source model considered in [27] and the second to the model recently developed by Rezaeian and Der Kiureghian [16,21]. For a more consistent comparison between the two models, the concept of sensitivity analysis is extended in this work to address resultant response quantities related to the primary risk factors. These quantities are chosen common for the two models (facilitating the consistent comparison) and correspond to important characteristics of the ground motion such as the peak ground acceleration or maximum incremental velocity. The sensitivity analysis for them is efficiently established using the same sampling-based computational framework as for the primary risk factors. Additionally, the comparisons in this study extend to both linear and nonlinear response, the latter described through a peak-oriented hysteretic model.

In Section 2, the sensitivity analysis framework is presented; then (Section 3) the two ground motion models are reviewed, with enough details to facilitate a complete understanding of the comparisons discussed in the case studies. In Section 4, the characteristics of the considered SDOF models and of the risk quantification measures are presented. Results of the study are then discussed in Section 5 in terms of both the calculated risk as well as of the influence of the different risk factors (including the white noise stochastic sequence) towards this risk. Extensive comparisons between the different ground motion models and risk quantifications (linear and nonlinear structural response) are presented. For describing seismic risk, both peak response quantities as well as cumulative structural-damage indicators (hysteretic energy dissipated) are considered. The discussions reveal what is the importance of the model parameters for each model but also provide insight on the differences between these models in the way they characterize seismic hazard.

2. Seismic risk quantification and global sensitivity analysis

2.1. Risk quantification

For quantifying seismic risk, the augmented modeling approach depicted in Fig. 1 is adopted, facilitating a description of seismic risk through dynamic, time-history analysis. Input to the model is the stochastic sequence $\mathbf{Z} \in Z$, with dimension n_z, and the uncertain model parameter vector $\boldsymbol{\theta} = [\boldsymbol{\theta}_e \ \boldsymbol{\theta}_g \ \boldsymbol{\theta}_s \ \boldsymbol{\theta}_p] \in \Theta$, with dimension n_θ. $Z \subset \mathfrak{R}^{n_z}$ and $\Theta \subset \mathfrak{R}^{n_\theta}$ denote the space of possible values for $\mathbf{Z}$ and $\boldsymbol{\theta}$, respectively. Here the focus in on the excitation model, as such vector $\boldsymbol{\theta}$ corresponds only to the excitation model parameters, which may include (i) the earthquake characteristics (moment magnitude and rupture distance) and local site conditions $\boldsymbol{\theta}_e$ as well as (ii) the parameters for the ground motion model (frequency content, duration and so forth) $\boldsymbol{\theta}_g$ related through predictive relationships to these characteristics/conditions. Note, though, that the approach can be extended to a model parameter vector that includes the characteristics of the structural and performance evaluation models (these will be considered as deterministic quantities for this study). The uncertainty in the model parameters is addressed by assigning appropriate probability distributions to them: $p(\boldsymbol{\theta})$ for vector $\boldsymbol{\theta}$, and $p(\mathbf{Z})$ for the stochastic sequence. For the earthquake characteristics, these distributions are based on the regional seismicity [21], whereas for the stochastic ground motion model they depend on the type of the model. For record-based models, they directly stem from the regression analysis when fitting the parameters of the model to selected ground motions [21], whereas for source-based models they are chosen based on the assumed epistemic uncertainty related to the predictive relationships they involve [27].

If, now, the overall performance of the augmented model, for specific $\boldsymbol{\theta}$ and $\mathbf{Z}$, is given by the risk consequence measure $h(\boldsymbol{\theta}, \mathbf{Z}) : \mathfrak{R}^{n_\theta n_z} \to \mathfrak{R}^+$, then risk is ultimately expressed by the *probabilistic integral*

$$H = \int_{\Theta} \int_{Z} h(\boldsymbol{\theta}, \mathbf{Z}) p(\boldsymbol{\theta}) p(\mathbf{Z}) d\boldsymbol{\theta} d\mathbf{Z} \tag{1}$$

that corresponds to its expected value over the established probability models. Different selections for $h(\boldsymbol{\theta},\mathbf{Z})$ facilitate different quantification of the seismic risk, H [27], which may be then easily calculated using stochastic (Monte Carlo) simulation techniques [28]. Based on this definition for risk, the group of uncertain model

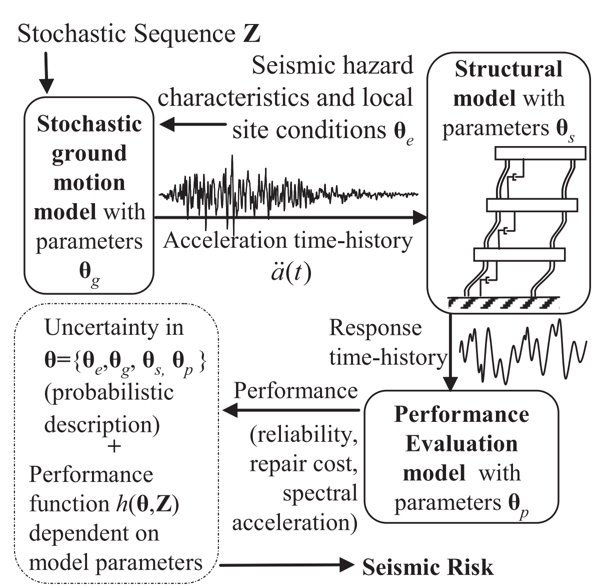

Fig. 1. Augmented model description for seismic risk characterization.