Soil Dynamics and Earthquake Engineering 38 (2012) 128–143

Contents lists available at SciVerse ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Global sensitivity analysis for stochastic ground motion modeling in seismic-risk assessment

Christopher Vetter, Alexandros A. Taflanidis*

University of Notre Dame, Department of Civil Engineering and Geological Sciences, 156 Fitzpatrick Hall, Notre Dame, IN 46556, United States

ARTICLE INFO

Article history:
Received 3 November 2011
Received in revised form
24 December 2011
Accepted 8 January 2012
Available online 17 February 2012

ABSTRACT

Seismic risk assessment requires adoption of appropriate models for the earthquake hazard, the structural system and for its performance, and quantification of the uncertainties involved in these models through appropriate probability distributions. Characterization of the seismic hazard comprises undoubtedly the most critical component of this process, the one associated with the largest amount of uncertainty. For applications involving dynamic analysis this hazard is frequently characterized through stochastic ground motion models. This paper discusses a novel, global sensitivity analysis for the seismic risk with emphasis on such a stochastic ground motion modeling. This analysis aims to identify the overall (i.e. global) importance of each of the uncertain model parameters, or of groups of them, towards the total risk. The methodology is based on definition of an auxiliary density (distribution) function, proportional to the integrand of the integral quantifying seismic risk, and on comparison of this density to the initial probability distribution for the model parameters of interest. Uncertainty in the rest of the model parameters is explicitly addressed through integration of their joint auxiliary distribution to calculate the corresponding marginal distributions. The relative information entropy is used to quantify the difference between the compared density functions and an efficient approach based on stochastic sampling is introduced for estimating this entropy for all quantities of interest. The framework is illustrated in an example that adopts a source-based stochastic ground motion model, and valuable insight is provided for its implementation within structural engineering applications.

1. Introduction

Description of seismic risk in structural engineering requires adoption of appropriate models for structural systems, for their performance quantification, and for the natural hazard itself, and characterization and propagation of the uncertainty (aleatoric or epistemic) related to these models. Undoubtedly the most important component of this process is the description of the earthquake hazard since significant variability is expected in future earthquake excitations. Moreover, for applications involving dynamic analysis, characterization of the entire ground motion history is needed. The growing interest in performance-based earthquake engineering (PBEE) in the last decade [1–3] has intensified this need. PBEE addresses the entire spectrum of structural response, ranging from linear to grossly nonlinear, up to structural collapse, and this approach requires a realistic characterization of the earthquake acceleration time-history.

Though numerous methodologies have been proposed for describing ground motion time histories for structural design applications (for example spectra and spectrum compatible approaches [4–6] including extensions to describe spatial variability [7,8]), two are typically acknowledged [9,10] as the main approaches for accomplishing this task for *probabilistic seismic risk assessment*. The most common one relies on adoption of Intensity Measures (IMs) that represents the dominant features of the seismic excitation, and subsequent scaling/selection of ground motion records to different hazard levels (different IM values) [11,12], as prescribed by a probabilistic seismic hazard analysis. Though popular, this approach suffers, to some extent, from concerns regarding the validity for ground motion scaling [10,13] and from the fact that the inherent variability of the ground motions is somewhat arbitrarily addressed [9] by the exact selection of the ground motions, which does not necessarily correlate well with the true uncertainties for all sites. The alternative approach, which will be the topic of this study, is use of stochastic ground motion models [10,14–16]. These models are based on modulation of a stochastic sequence **Z** through functions that address spectral and temporal characteristics of the excitation. Their parameters can be related to earthquake (type of

---

* Corresponding author. Tel.: +574 631 5696.
E-mail address: a.taflanidis@nd.edu (A.A. Taflanidis).

0267-7261/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.soildyn.2012.01.004

Nomenclature

b_M	seismicity factor for exponential distribution for moment magnitude
$D(.\|.)$	relative entropy
$e(t;M,r)$	temporal envelope function
e_a e_b e_e	auxiliary variables used to quantify uncertainty in f_a f_b e
e_t	auxiliary variables used to quantify uncertainty in T_w
f	frequency
f_a f_b e	lower and upper frequencies and the weighing parameter for source spectrum
f_{max}	high-frequency diminution parameter
H	risk
$h(\boldsymbol{\theta},\mathbf{Z})$	risk consequence measure
$K(t)$	epanechnikov kernel
KDE	kernel density estimation
ko	diminution parameter
M	moment magnitude
$p(.)$	probability distribution function
PGA	average peak ground acceleration
PGV	average peak ground velocity
$q(.)$	proposal density for stochastic simulation
$q_p(.)$	proposal density for stochastic sampling
r	epicentral distance
r_{mead}	median value for epicentral distance
R	probability maximum displacement will exceed threshold β
RA	probability peak ground acceleration will exceed threshold β_a
R_r	radial distance
t	time
T_s	natural period of SDOF oscillator
T_w	strong ground motion duration
w_i	bandwidth for epanechnikov kernel
x_m	maximum absolute displacement
$\mathbf{y}$	subset of vector $\boldsymbol{\theta}$
y_i^k	sample of y_i
$\mathbf{Z}$	white noise sequence
β	threshold used for reliability of maximum displacement
β_a	threshold used for reliability of peak ground acceleration
$\boldsymbol{\theta}$	vector of uncertain model parameters
λ_t η_t	parameters defining temporal envelope
$\pi(.)$	auxiliary probability distribution function

fault, moment magnitude and epicentral distance) and site characteristics (shear wave velocity, local site conditions) by appropriate predictive relationships [17,18]. Description of the uncertainty for the earthquake characteristics and the predictive relationships leads then to a complete probabilistic description of potential future ground-motion time-histories. Though concerns are also expressed for stochastic ground motion models, in particular that they cannot fully address physical characteristics of actual time histories, this modeling approach has gained increasing support within the structural engineering community [18–20] since it provides a complete probabilistic characterization for seismic risk applications [9] within a modeling framework which is consistent with system-engineering (modeling of the earthquake process itself).

Two types of stochastic ground motion models can be distinguished, 'source-based' models [14,17,21] 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 [10,15,16,22,23]. Use of such stochastic ground motion models, accompanied by appropriate structural and performance evaluation models facilitates then the simulation-based, augmented model, illustrated in Fig. 1, for detailed estimation of the seismic response. Addressing the uncertainty in the properties of all components of this model, by appropriate probabilistic descriptions, leads to efficient seismic risk quantification, which can be defined as the expected value of the system performance [19,20,24]. In this setting the uncertain model parameters can be considered as the risk factors, ultimately generating seismic risk.

The focus of the aforementioned studies has been, though, on the development of such stochastic ground motion models or on their implementation for describing seismic risk. Limited attention has been given to understanding the influence of such a seismic hazard characterization in the context of probabilistic seismic risk assessment. This paper directly focuses on this topic; it offers an innovative, global sensitivity analysis for quantifying the importance of the various risk factors or of groups of them towards the total seismic risk. Such an analysis identifies which of the model parameters contributed overall (i.e., globally) more to the estimated risk and can facilitate a better understanding of the correlation between the various risk factors and the risk itself, providing valuable insight for future research developments. A novel framework is discussed for this purpose, based on definition of an auxiliary density function and on comparison of this density to the initial probability distribution for each model parameter. The difference between the distributions is quantified through the relative information entropy and an approach based on stochastic sampling is introduced for efficiently estimating the latter. The framework is illustrated in an example considering the

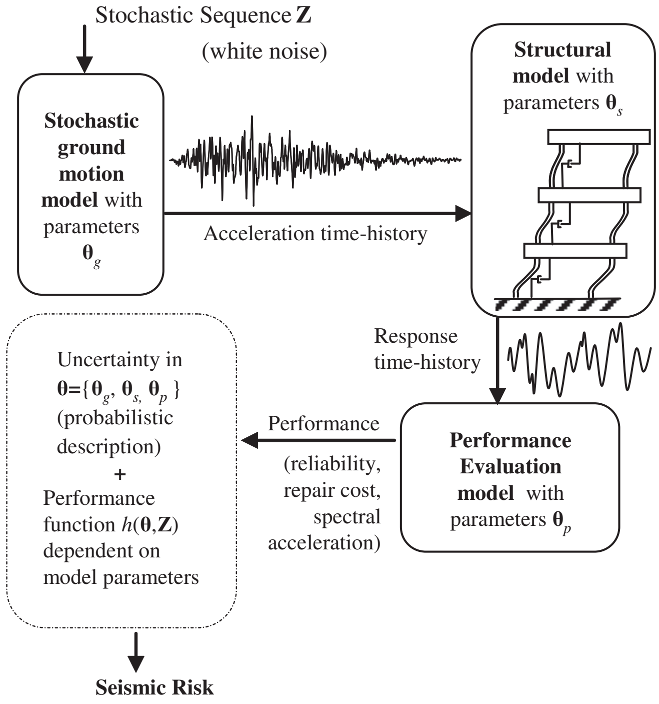

Fig. 1. Augmented model description for seismic risk characterization.