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Weighing the importance of model uncertainty against parameter uncertainty in earthquake loss assessments

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ABSTRACT

Epistemic uncertainties can be classified into two major categories: parameter and model. While the first one stems from the difficulties in estimating the values of input model parameters, the second comes from the difficulties in selecting the appropriate type of model. Investigating their combined effects and ranking each of them in terms of their influence on the predicted losses can be useful in guiding future investigations. In this context, we propose a strategy relying on variance-based global sensitivity analysis, which is demonstrated using an earthquake loss assessment for Pointe-à-Pitre (Guadeloupe, France). For the considered assumptions, we show: that uncertainty of losses would be greatly reduced if all the models could be unambiguously selected; and that the most influential source of uncertainty (whether of parameter or model type) corresponds to the seismic activity group. Finally, a sampling strategy was proposed to test the influence of the experts' weights on models and on the assumed coefficients of variation of parameter uncertainty. The former influenced the sensitivity measures of the model uncertainties, whereas the latter could completely change the importance rank of the uncertainties associated to the vulnerability assessment step.

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1. Introduction

Predicting the consequences (losses) of future earthquakes is of primary importance for risk management. One of the greatest challenges when building such predictive models is the treatment of the multiple sources of uncertainty pervading the different steps of earthquake loss assessment (seismic source, wave propagation, local site effects, exposed inventory, vulnerability assessment, and damage and loss estimation). This issue has been highlighted by numerous authors over the last decades e.g., [1–5]. It is now common to classify uncertainty into randomness (aleatory variability) and knowledge-based uncertainty (epistemic uncertainty) e.g., [6]. Though appearing to be partly a choice of the modeller [7], this categorization can be useful in practice, because decisions motivated by the aleatory variability will be quite different from decisions based on the knowledge-based uncertainty. In the first case, no concrete actions can reduce randomness and only "indirect" actions can be proposed by means of protective or preventive measures. In the second, concrete actions can be undertaken to act directly on the uncertainty reduction and the best solution is to set priorities for data collection/analysis under budget constraints on the basis of the identification of the most influential sources of knowledge-based uncertainties e.g., [8].

To reduce epistemic uncertainties, sensitivity analysis can provide valuable information by addressing the following questions: what sources of uncertainty contribute the most to the uncertainties in the predicted losses? And at what stages of the loss assessment procedure (e.g., hazard, vulnerability or damage evaluation)? How to rank these sources of uncertainties? And how to set priorities for future investigations? The great value of addressing such questions has long been recognized in the field of seismic risk assessments and, more specifically, for probabilistic seismic hazard assessment (PSHA) relying on logic trees [9]. Two main approaches have been followed: a "one-factor-at-a-time" (OAT) approach analysing variations from a base model results by varying, in turn, the input parameters or considering different scenarios [3,10]; and the multi-parameter method based on factorial designs allowing simultaneous changes to parameters on the branches of a logic tree [11]. This approach was applied in an Italian case study by Barani et al. [12].

In the present article, we focus on two types of epistemic uncertainty, which are those most commonly encountered in practice: parameter and model. The first category stems from the difficulties in estimating the input parameters (in a broad sense) of models/analysis due to the limited number, poor representativeness (caused by time, space and financial limitations), and imprecision of observations/data. In addition, models are necessarily

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simplified representations of the phenomena, i.e. they are based on assumptions, and compliance between the model assumptions and the properties of the system being analysed never exist in an absolute sense e.g., [13]. Uncertainty can then appear in the structure/form of the model, which depends on the choice of variables, dependencies, processes and so forth regarded as relevant and prominent for their purpose in the model. Yet, in some cases, a set of different models (e.g. differing in their structure and input variables) are either considered equally adequate (e.g., they equally fit the observations), or they are associated with different confidence levels. This is exemplified by the extensively debated issue of selecting appropriate ground motion prediction equations (GMPEs, e.g., [14]).

In this context, the objective of the present article is to show how recent advances in global sensitivity analysis [15] can provide valuable information to answer the following questions for earthquake loss estimation: What is the contribution of model uncertainty to the uncertainty in predicted losses when simultaneously accounting for parameter uncertainty? How to measure such a contribution? Should future investigations spend effort on the modelling procedure or on parameter estimation? In this view, we propose a strategy based on variance-based sensitivity analysis (VBSA), which can overcome some limitations of the afore-mentioned sensitivity approaches (as discussed in Section 2).

The remainder of the present paper is organized as follows. In the next section, we describe the global sensitivity analysis using VBSA and the method for both investigating sensitivity to model and parameter uncertainty. Such a strategy is applied to predictions of direct monetary losses for the city of Pointe-à-Pitre (Guadeloupe, France) using simplified information on uncertainty (but based on real data). The following section describes the earthquake loss model and the case study of Pointe-à-Pitre (context and assumptions for representing the different uncertainty sources). It should be underlined that the application to Pointe-à-Pitre has been chosen for demonstration purposes only and all the presented results should not be interpreted as a definitive uncertainty assessment. The subsequent section shows the results of the VBSA and discusses how results are modified by changing the size of the different sources of uncertainty. The article ends with some brief conclusions and suggestions for future work.

2. Investigating sensitivity to model and parameter uncertainty

In this section we present the technique used here to assess the sensitivity of the results to the two different types of uncertainty.

2.1. Variance-based sensitivity analysis

VBSA is a stochastic method providing a quantitative measure of sensitivity [16,17] assigned to each source of uncertainty (represented by any kind of probabilistic distribution, e.g. uniform, normal or discrete). VBSA presents the advantages of exploring the sensitivity over the whole range of variation (i.e. in a global manner) of the input random variables and of fully accounting for possible interactions between them. This is contrary to the OAT technique, as discussed by Saltelli and Annoni [18]. VBSA allows identification of:

- which input parameters contribute the most to the output variability (within the “factors' prioritisation setting” as described by Saltelli et al. [15]) through the use of the Sobol' indices of first order, also called main effects (see below for a formal description);
- which input parameters interact with one another through the use of the Sobol' indices of higher order;
- which input parameters are insignificant and can be eliminated to “simplify” the model (within a “factors' fixing setting” as described by Saltelli et al. [15]) through the use of total effects (see below for a formal description).

By comparing the main and total effects, this technique improves insight into the nature of the considered model. For instance, the case where main and total effects are of equal importance and the sum of the main effects nearly reach unity indicates that the uncertainty of the output (i.e. the variance) is only due to the sum of the effects of each uncertain parameter taken alone, and not from interactions among them. Thus, the model can be simplified and be represented as a sum of elementary one-dimensional functions of the input parameters. Formally, the model is said to be “additive”. Conversely, if the main effects have low values compared to the total effects, this indicates strong high-order interactions between the parameters, hence a model of high complexity. Thus, VBSA helps to explore the model behaviour in the domain of variation of the input parameters, which can be of great value when using a loss model in a black-box fashion (see discussion provided by Bommer et al. [4]). More recently, the overview of the model complexity brought by VBSA has been better formalized with the notion of effective dimension [19], which can be understood as the number of dominant parameters of the model.

Finally, VBSA is general in the sense that it applicable to any kind of model (linear, non-linear, additive and so forth), i.e. without introducing *a priori* assumptions on its mathematical structure [15]. For instance, simultaneously varying the extreme values of parameters (e.g. using a two-level factorial design as carried out by Rabinowitz and Steinberg [11]) only shows good results for quasi-linear models.

2.2. Brief mathematical description

We introduce here the basic concepts of VBSA. For a more complete introduction and full derivation of the equations, the interested reader is referred to Saltelli et al. [15] and references therein.

Let us define f as the earthquake loss model. Considering the n-dimensional vector $\boldsymbol{X}$ as a random vector of independent random variables X_i ($i=1,2,\ldots,n$), then the output $Y=f(\boldsymbol{X})$ is also a random variable (as a function of a random vector). VBSA aims to determine the part of the total unconditional variance $\mathrm{Var}(Y)$ of the output Y resulting from each input random variable X_i.

In practice, the partial and total variances of Y are determined based on the decomposition of f (i.e. functional analysis of variance decomposition of f as proposed by Sobol' [16]), into summands of increasing dimension (provided that f can be integrated). Each of these terms can be evaluated through multidimensional integrals, which can be approximated through Monte-Carlo-based algorithms (see [20], for a recent review and discussion). For instance, the sequential algorithm of Saltelli et al. [20], using a formula of Jansen [21], requires a total of $N(n+2)$ model evaluations, where N is the number of Monte-Carlo samples and n is the number of input uncertain parameters X_i. This is noteworthy as the quality of the Monte-Carlo-based approach directly depends on the sample size N. The interested reader is referred to Saltelli et al. [15] for a review of other computational procedures.

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