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Assessing the impact of ground-motion variability and uncertainty on empirical fragility curves

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ABSTRACT

Empirical fragility curves, constructed from databases of thousands of building-damage observations, are commonly used for earthquake risk assessments, particularly in Europe and Japan, where building stocks are often difficult to model analytically (e.g. old masonry structures or timber dwellings). Curves from different studies, however, display considerable differences, which lead to high uncertainty in the assessed seismic risk. One potential reason for this dispersion is the almost universal neglect of the spatial variability in ground motions and the epistemic uncertainty in ground-motion prediction. In this paper, databases of building damage are simulated using ground-motion fields that take account of spatial variability and a known fragility curve. These databases are then inverted, applying a standard approach for the derivation of empirical fragility curves, and the difference with the known curve is studied. A parametric analysis is conducted to investigate the impact of various assumptions on the results. By this approach, it is concluded that ground-motion variability leads to flatter fragility curves and that the epistemic uncertainty in the ground-motion prediction equation used can have a dramatic impact on the derived curves. Without dense ground-motion recording networks in the epicentral area empirical curves will remain highly uncertain. Moreover, the use of aggregated damage observations appears to substantially increase uncertainty in the empirical fragility assessment. In contrast, the use of limited randomly-chosen un-aggregated samples in the affected area can result in good predictions of fragility.

1. Introduction

Fragility curves of buildings exposed to earthquakes express the likelihood of damage to these assets from future seismic events. Empirical fragility curves are based on the statistical analysis of post-earthquake observations of the damage sustained by the exposed buildings and the corresponding ground-motion intensity level at the building locations. Currently at least 119 empirical fragility curves have been published [1]. These curves have generally been constructed assuming that the measurement error in the intensity-measure levels (IMLs) is negligible. However, given the general lack of a dense strong-motion network in the areas of damaging earthquakes, the intensity levels are typically estimated though ground motion prediction equations (GMPEs) or, more recently, ShakeMaps. Hence, the IMLs are associated with high measurement error. In recent years, a handful of studies have proposed undertaking a Bayesian regression analysis to explicitly model this error [2–4]. Nonetheless, the impact of this measurement error on empirical fragility curves is not well understood.

This study aims to examine the impact of the measurement error in the IMLs on empirical fragility curves. A simulation study is undertaken to investigate this issue, following a similar philosophy to Gehl et al. [5], who studied the influence of the number of dynamic runs on the accuracy of fragility curves. In the next section the method of simulation is introduced. This approach is applied in the subsequent section to undertake a parametric analysis to study the influence of different assumptions on the empirical fragility curves. The paper finishes with some discussion of the results, the limitations of existing empirical fragility curves, implications for the development of future empirical fragility functions as well as possible ways forward.

2. Method

The impact of ground-motion variability and uncertainty on empirical fragility curves is studied here by undertaking a series of experiments. In these, an earthquake with specified characteristics

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(i.e. magnitude, location and faulting mechanism) affects a number of buildings ($N_{Buildings}$) located in a number of towns (N_{Towns}).

The construction of empirical fragility curves requires observations of two variables, namely: the damage sustained by the considered buildings and their corresponding IMLs. IMLs are generated assuming the absence or the presence of ground-motion observations.

2.1. Seismic damage

In this study, the damage experienced by each building in the affected area is considered random due to the uncertainty in its IML as well as the uncertainty in its structural performance given this IML. Therefore, seismic damage for each building is determined here by modelling these two uncertainties through a Monte Carlo analysis. The procedure adopted is an extension of the procedure used by Douglas [6] in order to study the density of seismic networks required to monitor ground motions from induced seismicity. According to this analysis, a large number, $N_{Realisations}$, of IMLs and subsequent damage states are generated.

According to the procedure proposed by Douglas [6], each realisation of IMLs for the considered buildings occurs from the generation of a ground-motion field using a given GMPE coupled with models of spatial variability. To simulate the spatially-correlated ground-motion fields the procedure of Strasser and Bommer ([7], pp. 2625–2626) is used. The package geoR [8] of the statistical software R allows such fields to be generated quickly and then manipulated. The between-event and within-event ground-motion variabilities are included within the fields. The deterministic ground-motion field produced by evaluating the considered IMLs for all building locations in the region is perturbed by the addition of a random field derived from a multivariate normal distribution based on a standard deviation equal to the within-event variability of the selected GMPE and an exponential correlation function, $G(h)$, which is found to fit the observed spatial correlation of earthquake ground motions [9,10]:

$$G(h) = \exp\left(-\frac{h}{h_0}\right) \tag{1}$$

where h is the separation distance between locations of interest and h_0 is the correlation range. Because one ground-motion field differs greatly from another, this procedure is repeated many times so that robust conclusions can be drawn from the combined results. The sensitivity of the results on the chosen GMPE, the value of h_0 and other input parameters (e.g. size of the region, density of ground-motion measurements and aggregation level) are investigated in this paper.

In order to simulate earthquake-damage fields, a known fragility curve expressing the fragility of hypothetical buildings in a region is applied. This curve takes as input the simulated ground-motion fields and yields the building damage observations used as the empirical dataset for the study. Consequently, the impact of sparse or uncertain observations on fragility curves can be evaluated by comparing the resulting empirical fragility curves derived from different sampling and assumptions, with the curve used as input in the simulations. The advantage of this approach is that the 'true' fragility of the structures is known and can be compared with the empirical fragility curves resulting from the experiments.

In particular, for a realisation k, resulting in $iml_{realisationk}$, the damage sustained by each building is randomly generated as follows. In order to simplify the analysis, the determination of the exact damage state of each building is not required. Instead, we concentrate on whether the building has reached or not a given damage state, ds_i, assuming an appropriate fragility curve from the literature. In particular, for a realisation k, the building, j, is assigned an indicator, Y_{jk}, where:

$$Y_{jk} = \begin{cases} 1 & DS \geq ds_i \\ 0 & DS < ds_i \end{cases} \tag{2}$$

The indicator is randomly assigned to the building j, by assuming that it follows a special case of the binomial distribution, termed the Bernoulli distribution:

$$Y_{jk}|IM = iml_{realisation_k} \sim \binom{n}{y_{jk}} \mu_{jk}^{y_{jk}} \left[1-\mu_{jk}\right]^{n-y_{jk}}$$
$$\text{where } \mu_{jk} = P(DS \geq ds_i | im_{realisation_k}) = \Phi\left(\frac{\ln(iml_{realisation_k}) - \lambda}{\zeta}\right) \tag{3}$$

where n is the number of buildings for a given intensity measure level, $iml_{realisationk}$, and in this case, $n=1$; μ_j equals the probability that the building is in damage state ds_i or above given $iml_{realisationk}$; μ_{jk} is the mean of the Bernoulli distribution, which is typically expressed in the literature in terms of a cumulative lognormal distribution; Φ is the cumulative standard normal distribution; λ is the lognormal mean; and ζ is the lognormal standard deviation.

2.2. Ground-motion intensity

The determination of the IML at the location of each building is necessary for the construction of empirical fragility curves. These levels are considered known and measured without uncertainty, an assumption commonly made when deriving such curves. The determination of these 'true' IMLs depends on the absence or presence of ground-motion observations.

2.2.1. The absence of ground motion recording stations

In the absence of ground-motion records, empirical fragility curves are derived here by following the common assumption that the IML at the location of each building is equal to the median values obtained from a pre-selected GMPE. It should be noted that the selected equation is not necessarily the same as the one used to generate the damage levels because in practice the appropriate GMPE for an earthquake is not known.

2.2.2. The presence of ground motion recording stations

The random fields of peak ground accelerations (PGAs) are recovered assuming the presence of ground motion recording stations located at a varying number of buildings. This consideration suggests that the IMLs for the buildings at which records are available are known and equal to the corresponding values provided by the random field. The IMLs for the remaining buildings are estimated from these records using a procedure known as kriging. In this study, kriging uses the same correlation model as the one used for the generation of the random fields.

2.3. Empirical fragility curves

The empirical fragility curve is then constructed for the k realisations of IMLs by considering the Y_{jk} indicators generated for all considered buildings, according to the procedure described in Section 2.1, and the corresponding 'true' IMLs as determined in Section 2.2. Their construction follows the procedure proposed in the Global Earthquake Model empirical fragility assessment guidelines [3]:

$$Y_{jk}|IM_{true} = iml_{'true',k} \sim \binom{n}{y_{jk}} \mu_{jk}^{y_{jk}} \left[1-\mu_{jk}\right]^{n-y_{jk}}$$