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Empirical seismic fragility assessment with explicit modeling of spatial ground motion variability

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ABSTRACT

The earthquake risk to a group of structures can be managed effectively only if accurate fragility models are available. Fragility models are utilized for estimating the likelihood of specific damage states being sustained by the structures given that they are subjected to a specific ground motion intensity. In this study, a new framework is proposed for establishing empirical fragility models for groups of structures based on observed damage distribution. The novelty of the proposed framework method is that it explicitly takes into account the uncertainty arising from the absence of instrumental recordings of the peak motion intensities that had affected the considered structures. Correlation structure of the unknown peak motion intensities experienced by the affected structures and the known peak motions measured at the strong motion stations sites are utilized for this purpose. This correlation structure is established using geospatial ground motion variability models. As an example of the application of the proposed framework, fragility models for multi-story reinforced concrete moment resisting frame buildings are presented. In this application, the damage observations made after the November 17th, 1999 M7.1 Düzce and the May 1st, 2003 M6.4 Bingöl earthquakes that occurred in Turkey are considered. The results from the example application demonstrate the effectiveness of the method in establishing fragility models.

1. Introduction

Seismic fragility models are critical components of the risk assessment framework in regions subjected to seismic hazard. A fragility model is a relationship between the ground motion intensity that excites a structure, and the probability of damage to the structure exceeding a specific limit state. In the assessment of seismic risk associated with a group of structures, the expected damage states of the structures can be estimated reliably only if the fragility models that are adopted are able to represent the actual vulnerability characteristics of the considered structures accurately. A large variety of fragility and vulnerability models have been proposed in the literature (e.g. [1–11]). In these models, the intensity of the ground motion is typically represented in terms of instrumental measures (e.g. peak ground acceleration, spectral acceleration) or the macroseismic scale (e.g. Modified Mercalli Intensity). In fragility models, the damage grades are typically defined in terms of discrete classes such as light, moderate, and severe. These categories typically correspond to possible states of post-earthquake safety (i.e. safe/unsafe), cost-effectiveness of repairing the damage (i.e. repairable/unrepairable), or in terms of structural integrity (i.e. standing/collapsed).

Fragility models are established by considering certain classes of structures that are expected to have common seismic response characteristics. These classes are often defined in terms of key structural properties such as type of structural system, number of stories, and seismic design level. The aim of this classification is to group together the structures that are expected to sustain the same or similar damage grades at similar ground motion intensity levels. Such grouping of structures makes it possible to estimate the combined risk related to the group of structures by avoiding detailed data collection and extensive analysis efforts for each structure.

Existing approaches for establishing vulnerability models can be broadly classified into four: (1) analytical approaches, (2) empirical approaches, (3) expert opinion based methods and (4) hybrid methods. The key principles underlying these approaches are summarized by Porter [12].

The method proposed in this study can be categorized as an empirical or a hybrid approach. In the empirical approach, actual damage statistics from post-earthquake reconnaissance surveys are utilized for developing fragility models (e.g. [13]). In the hybrid approach, the fragility is first estimated using analytical models for predicting the seismic response. After that, the resulting fragility

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model is calibrated to match the damage observations from actual earthquakes (e.g. [14]). The common characteristic of the both methods is that the damage statistics from actual earthquakes are considered in the development of fragility models.

Empirical fragility assessment methods are particularly suitable for the structures which are difficult to model analytically. Even though promising analytical models (e.g. [15,16]) have been developed for the assessment of RC structures with poor seismic detailing, for the case of non-code conforming buildings with severe deficiencies (low concrete strength, corrosion of reinforcement, insufficient foundation capacity, etc.) accurate prediction of seismic response remains to be a major challenge. For this reason, empirical fragility models are particularly suited for non-code conforming structures with severe deficiencies. For the uncommon types of structures, a limitation of the empirical approach is the lack of sufficient number of damage observations. However for the case of non-code conforming structures, at present there exists a wealth of damage observations. Therefore, the lack of damage observations is typically not a drawback for these structures.

The analytical and the expert opinion-based approaches are not utilized in the proposed framework due to their limitations. Fragility models derived by means of analytical response predictions strongly depend on the specific modeling approach utilized [17–19]. This is a critical limitation for the case of non-code conforming structures with complex failure mechanisms. In the expert opinion-based approaches, the selection of the participating experts and the adopted elicitation process influence the resulting fragility estimates. For this reason an empirical approach is utilized in the proposed framework, rather than an expert opinion-based one.

Existing empirical fragility assessment methods share some common limitations regarding the treatment of uncertainty associated with the ground motion intensities (e.g. peak ground acceleration, spectral acceleration) experienced by the considered damaged structures. This uncertainty is known as the intra-event variability and it arises from the spatial variability of the ground motion intensity (see e.g. [20–23]). The variability of ground motion intensity is often attributed to the complexity of the reflections, refractions and scattering of the waves in the near-source region as well as the variability of local site properties [24]. Due to the variability of peak motions, the motions recorded by the strong motion stations only represents the peak motions experienced by the structures located within the close proximity (approx. <0.5 km) of the station. For the structures that are located further away, the peak motions can only be estimated with considerable uncertainty [21]. When the damage data is collected from regions of very low density of strong motion stations, the resulting uncertainty becomes significant. Moreover, the spatial variability characteristics of peak intensities also lead to peak motions exhibited at damage observation sites being correlated. For a group of damage observation sites that are clustered into a small area, the peak motions for the sites tend to be highly correlated. On the other hand for the sites that are spread around over a large region, this correlation becomes insignificant.

In the existing empirical fragility assessment approaches, the ground motion intensities at the sites of damage observation are considered as deterministic quantities. As a result, neither the variability nor the correlation characteristics of the peak motions are taken into account in the analysis. In the existing approaches, the peak motion intensities are typically obtained through interpolation or extrapolation of the values measured at the strong motion stations (e.g. [14,13]). When there is no measurement available, the median estimate obtained using an appropriate ground motion prediction model is utilized in the analysis. Typically, the uncertainty associated with the utilized ground motion intensities is neglected in the calculations. This issue been noted as an important limitation of the existing empirical approaches [25].

A new improved empirical fragility assessment method that enables taking into account the uncertainty due to spatial variability of motion intensities at the sites of damage observation, is proposed here. The spatial variability of ground motion is explicitly taken into account in the proposed method through stochastic simulation of conditional peak ground motion intensities. In these simulations, the probabilistic character of the unknown intensity level is estimated using the existing spatial correlation models. When instrumental measurements of ground motion intensity are available, these measurements are taken into account in the estimation of the probabilistic character of the unknown intensities for the neighboring sites where the damage data are collected. Since the unknown intensities are considered as stochastic variables, —unlike the existing methods– the uncertainty associated with their variability is accounted for in the fragility estimates obtained using the proposed method.

The paper has two main objectives. First objective is to explain the derivation of the formulation of the Bayesian approach that forms the basis of the proposed framework. Second objective is to investigate the sensitivity of the resulting fragility estimates to some of the key assumptions (e.g. prior likelihoods, number of simulations). In this investigation, the results obtained from an example application are utilized. In this application, sets of fragility curves are developed for non-code conforming Turkish residential RC frame buildings using damage information collected after November 17th, 1999 M7.1 Düzce and the May 1st, 2003 M6.4 Bingöl earthquakes that occurred in Turkey.

A method based on a similar approach has been briefly presented by Yazgan [26,27] for establishing vulnerability models. The vulnerability models derived in those earlier investigations and the fragility models that are considered in this study, are suited for different purposes. Vulnerability models are used for estimating of damage ratios for RC frame buildings and they are particularly useful in the estimation of potential financial losses for a portfolio of structures [28]. Fragility models provide estimates of the likelihood of onset of discrete damage states (moderate damage, collapse, etc.) as a function of ground motion intensity. Fragility models are more suitable for estimating the likely numbers of buildings that are expected to be collapsed or to remain habitable after an earthquake. Reliable estimation of these numbers are crucial in planning of disaster mitigation efforts, emergency response operations as well as drafting of recovery strategies for improving the earthquake resilience.

2. Proposed method

The empirical fragility modeling method proposed here aims at establishing fragility models for classes of structures. In the context of this study, a fragility model is a mathematical model for estimating the conditional likelihood of the damage to a group of buildings exceeding a specific damage state given that they are subject to a specific shaking intensity level. First, a set of alternative fragility models is established. Subsequently, the performance of each fragility model in terms of capturing the observed damage distribution is investigated. The Bayesian analysis is utilized for this purpose [29]. The steps of the proposed method are presented below. For the sake of simplicity, the procedure is presented for only one damage state *ds*. To obtain fragility models corresponding to a set of different damage states, the same procedure needs to be repeated for each damage state. In the presentation below, proposed approach is presented for the case of pseudo-spectral acceleration being the ground motion intensity parameter. However, other intensity measures can be utilized in the proposed framework as well. The only requirement is that models must be available for capturing the spatial variability characteristics of the