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EARTHQUAKE RISK MODEL FOR GREATER CAIRO

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ABSTRACT:

This paper describes an assessment methodology to estimate losses resulting from structural damage to the building population in Greater Cairo. The adopted framework is amenable to application in other regions that are typically characterised by low-to-moderate seismicity and where the inadequacy of data hampers the use of systematic and conventional seismic risk modelling approaches. Focus is firstly directed towards developing a ground shaking model. Towards this end, integrating data on the tectonic configuration, seismicity, and previous hazard studies for the region, is used to define the hazard. This is followed by collating data on geological structures and surface soil conditions, using a considerable number of boreholes, to produce a classification of different soil deposits. An inventory database for the existing building stock is then prepared. A general overview of the history of seismic provisions in Egyptian codes, combined with extensive ground surveys and satellite imagery, are used to delineate the area into geographical references of uniform building and soil characteristics. Using this information, the seismic vulnerability of the representative building models, designed according to prevalent codes and construction practices, is evaluated by carrying out extensive static nonlinear analyses. Use is made of capacity-spectrum methods for assessing the structural performance using a multi-level damage scale. Finally, the results are used to build-up an event-based loss model for possible earthquakes in the region.

KEYWORDS: Vulnerability, fragility, loss assessment, seismic risk, Cairo, Egypt

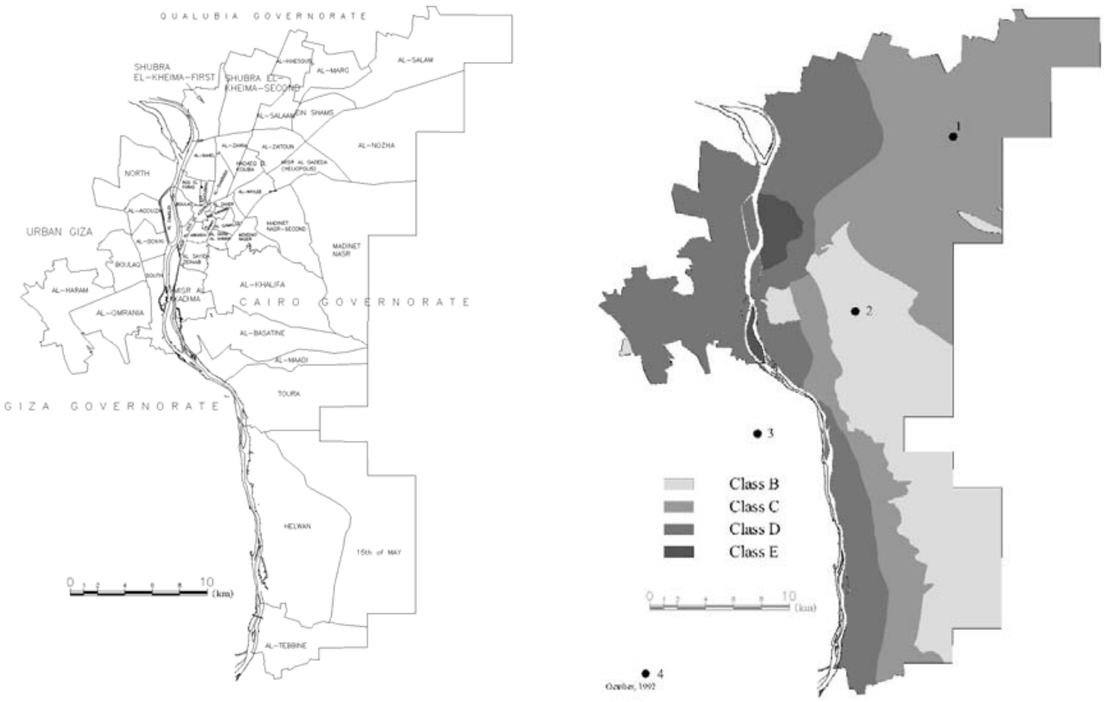
1. INTRODUCTION

This study focuses on Egypt's capital, Greater Cairo, which can be defined as the cities of Cairo and Giza (urban and rural Giza), and part of Qualubiya governorate constituting the district of Shubra El-Kheima (see Figure 1a). Due to the large area of rural Giza which extends some 300 km into the Western Desert, as well as into the eastern bank of the Nile south of Cairo governorate, the Giza portion of the area considered in this study is confined to the urban sector where the majority of the Giza population is concentrated (Figure 1a). Based on recent census data (CAPMAS, 2006), the population of Egypt is about 74 million, the majority of which live along the Nile Valley, Nile Delta, and the Gulf of Suez. Due to economic reasons, there is a high level of migration from rural to urban areas, and Greater Cairo attracts most of those migrants. Consequently, the city is now home to about 17 million inhabitants in addition to an average of 3 million daily influxes from other governorates for work or other purposes, making it one of the most densely populated cities in the world. The historical background, coupled with the rapid growth in urbanisation over the years, has resulted in a diverse building stock. The seismic event that struck Cairo on 12 October 1992 exposed the poor performance of many building types, especially older structures. Existing vulnerabilities, when combined with the steadily increasing population density, clearly emphasise the significance of an earthquake occurring near or within Cairo.

The development of the loss assessment model is a multi-phased process which encompasses, in its most general form, constructing a ground-shaking hazard model followed by an estimation of the physical losses to the different building categories. Within this framework, the key points for developing the model involve: (i) developing a model of earthquake occurence in, and within the vicinity of, the study region, including the selection of appropriate ground-motion prediction equations; (ii) consideration of modification characteristics of soil deposits; (iii) establishing the exposure and vulnerability models needed for earthquake loss estimation; (iv) determination of structural response parameters for assessing building damage; (v) development of fragility curves for dominant structural forms; (vi) evaluation of structural damage distributions and the resulting monetary losses. Based on the procedure outlined above, the paper provides a general perspective of the overall risk assessment methodology developed for Greater Cairo in order to estimate the anticipated monetary losses inflicted by possible earthquakes in the study region.

2. SEISMIC HAZARD AND CENSUS TRACTS

An assessment of the tectonic configuration and geological features of the area was firstly carried out. Only a brief discussion of the outcome of this assessment is presented herein, but a detailed description can be found elsewhere (Moharram *et al.*, 2008a). The spatial distribution of significant instrumental and historical seismicity was extracted from several sources, and a review of previous hazard studies conducted for the region was performed. All these sources manifested the seismic threat originating from intra-plate, shallow-crustal, events that are mostly concentrated south-west of the city.



(a) (b)

Figure 1 A map of the study area. Interior lines represent district boundaries (a); and (b) the classification of soil deposits in the study area according to the NEHRP provisions (NEHRP, 2000). Black solid circles indicate the locations of the chosen earthquake scenarios (Moharram *et al.*, 2008a)

The largest known earthquake in the region of Cairo occurred in 1847 and was assigned a magnitude of 5.8 by Ambraseys *et al.* (1994). Published seismic hazard studies for Egypt have generally defined broad seismogenic sources enclosing all of Greater Cairo and the locations of both the 1847 and 1992 Dashour earthquakes, suggesting that it is considered possible for these events to occur anywhere within the city. In accordance with the findings, four M_s 5.8 scenarios were chosen with one of them being located at the origin of the 1992 event and the other three at arbitrarily chosen locations within Greater Cairo, as shown in Figure 1b. From the recurrence relationships derived by Riad *et al.* (2000), with the pertinent seismic zone having '*a*' and '*b*' values of 2.62 and 0.83 respectively, it can be estimated that earthquakes of this size have a recurrence interval of about 156 years.

Using data on geological structures, expert opinion of geotechnical practitioners, geological and historical data, and an extensive data set of borehole logs, the seismic amplification characteristics of the soil deposits were evaluated based on the NEHRP scheme (NEHRP, 2000). The main parameter used was the average standard penetration test (SPT) blow count calibrated over a depth of 30 m. Using the compilation of data obtained for boreholes reaching this depth, empirical relationships were established to enable an extrapolation of data obtained from shallow boreholes to 30 m. Accordingly, a geographical delineation of the different soil deposits based on their NEHRP classification was produced, as shown in Figure 1b.

In the absence of region-specific ground-motion prediction equations for the study area, due to the lack of indigenous strong-motion data, empirically-derived equations for active crustal regions were examined through a comparative study (Moharram, 2006; Moharram *et al.*, 2008a). After carrying out suitable adjustments to the predictions of these equations to account for parameter incompatibilities, a relatively small difference in final estimations was found. However, because of the utilisation of strong-motion data from North African events, the equations of Bommer *et al.* (2003) were employed to develop a ground shaking model for Greater Cairo.

Greater Cairo is a very old city and hence encloses a wide range of structures varying according to age, construction material, structural system, and design concepts. The geographical distribution of the different types of buildings is highly random. Modern high-rise buildings may be found in very close proximity to informally-built non-engineered buildings. Accordingly, dividing the study area into a number of geographical references (or geocodes) of uniform soil and building characteristics is an intricate task. In this context, an extensive investigation was conducted which utilised official building surveys available in the literature, knowledge of the history of seismic provisions in Egyptian codes, satellite imagery, expert opinion, additional field surveys performed for representative samples, as well as the soil configuration map described previously. The result is a geographic division of the study area into 191 census-tracts, or geocodes, of classified building and soil characteristics (Moharram *et al.*, 2008a; Moharram *et al.*, 2008b).

3. FRAGILITY CURVES FOR RC AND MASONRY BUILDINGS

Within the study area of Greater Cairo, it was found that a typical building type is represented by non-seismically designed, non-ductile, masonry-infilled reinforced concrete buildings designed exclusively to resist gravity loads according to obsolete codes. Together with unreinforced masonry buildings, this type of construction appears to dominate the building population as indicated in recent studies which provide a statistical breakdown of inventory data (Moharram, 2006; Moharram *et al.*, 2008a). Non-seismically designed RC skeletal structures, with their height subdivisions, amount to between 36 and 59% of the total population of buildings within various age groups.

Three representative buildings of low-rise, medium-rise and high-rise RC masonry-infilled buildings were designed and modelled as part of a detailed analytical study (Moharram, 2006). The study implemented the structural characteristics typical of the design and construction practices in use prior to the 1989 code of practice (RCC, 1989), which was the first code to consider seismic loading explicitly. The buildings were then subjected to inelastic analysis procedures to capture the global and local deformation, strength and stiffness characteristics of the whole structure as well as its structural and non-structural components. Static inelastic (pushover) analyses were performed to produce capacity curves and distinct damage states in terms of global and local response criteria (Moharram, 2006). These results served as the basis for the derivation of vulnerability curves and the assessment of seismic performance within the capacity spectrum framework.

The analytical derivation of fragility curves for a class of buildings involves an extensive assessment for a population of structures subjected to characteristic seismic loading. This implies that the inherent uncertainty in exceeding a certain damage limit state (represented by the fragility curves) is primarily related to the variability in ground motion and material behaviour. Ideally, the variability should include changes in the geometrical configuration of buildings. However, these changes are not commonly incorporated due to the complexity associated with their inclusion and are hence usually treated deterministically by assuming representative layouts. On the other hand, height variability was captured to some extent by deriving distinct fragility functions for the three height sub-groups comprising the pre-code non-ductile class (EC1) (Moharram *et al.*, 2008b). A further simplification was incorporated by signifying each of these sub-groups through their assigned median number of storeys. These were obtained from the field surveys carried out on the building stock (Moharram *et al.*, 2008a).

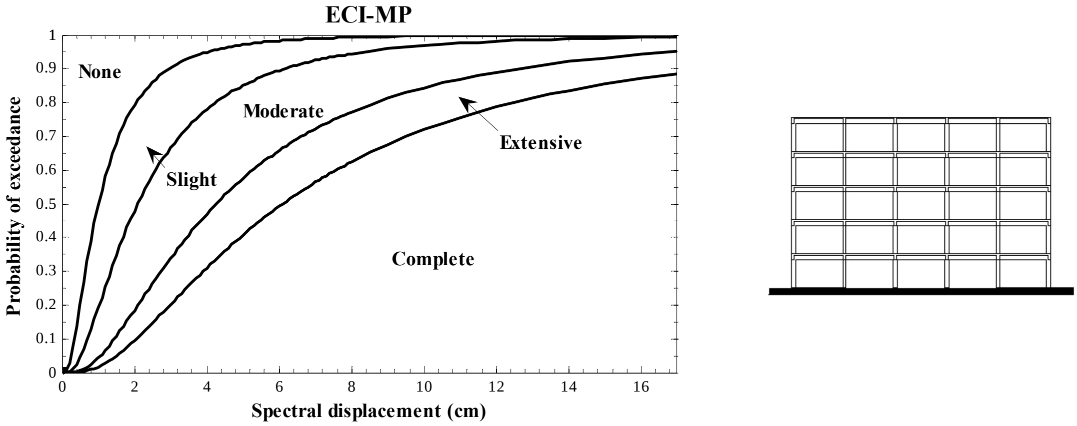


Figure 2 Fragility curves for a typical mid-height RC building model in Greater Cairo

The variability in material properties and ground motion characteristics were considered in this study to derive fragility functions for typical RC buildings in Greater Cairo. Three sets of building populations with different height ranges were generated for representative RC models. Samples of material values were generated from their probability distributions using the Latin Hypercube Sampling technique and combinations of these parameters were obtained to produce sets of buildings with different material characteristics. Ground-motion variability was incorporated into fragility functions through a simplified approach which reduces computational requirements to practical levels (Bommer and Crowley, 2006). Figure 2 shows the fragility functions derived for the 5-storey building model used to characterise typical mid-height RC buildings designed to obsolete building codes. A more comprehensive description of the derivation procedure as well as the fragility functions for the different building models representing the typical building population can be found elsewhere (Moharram *et al.*, 2008b).

Based on observations from the field surveys (Moharram, 2006; Moharram *et al.*, 2008a), it was concluded that unreinforced masonry (URM) construction constitutes between 28% and 51% of the building population among the various age groups within Greater Cairo. This is typically the case in many regions of the world including seismically active areas, where older buildings are mostly constructed from URM. Detailed rules for the construction of standard capacity curves and fragility functions are provided by the HAZUS methodology (FEMA, 1999; Kircher *et al.*, 1997) for a number of US building types which amount to a total of 36 models. Among these is the ‘unreinforced masonry bearing wall model’ which encompasses old URM buildings and newer ones having various forms of diaphragms that depend on the age and height of the building. Hence, based on the field survey data and other reasons (Moharram, 2006; Moharram *et al.*, 2008b), it was decided to use the functions for the HAZUS model for mid-rise URM structures (URM-M) to derive fragility functions for typical low- and medium-rise URM construction in the study area.

4. SEISMIC PERFORMANCE EVALUATION

A fundamental element of the loss estimation process is the evaluation of seismic performance of the building stock due to the ground-shaking model considered. In this respect, the capacity spectrum method (CSM) is an attractive and practical tool due to its reasonable accuracy and simple visual interpretation. In its most general form, the CSM involves carrying out a comparison between a reduced elastic response spectrum representing the seismic demand, and a transformed capacity curve of the structure. This transformation is performed to convert the top displacement-base shear format of the pushover curve into the spectral displacement-spectral acceleration domain (Acceleration-Displacement Response Spectrum- ADRS format), referred to as the capacity spectrum. The point of intersection of the capacity spectrum and the reduced seismic demand defines the maximum response of the structure under the given earthquake, known as the performance point. In this study, the N2 modified CSM (Fajfar, 1999), which provides a simple and reasonably accurate procedure to represent the seismic demand in the CSM by inelastic spectra, was employed to assess the seismic performance of the selected building models for Greater Cairo. Accordingly, the elastic spectra developed at the centroid of each geocode were compared to the capacity plots to determine performance points. For the four chosen scenarios, the 191 defined geocodes, and the building models dominating the building stock, the process was repeated 3056 times. The spectral response (S_d) at the performance points were then used as input to the assigned fragility functions. Discrete damage probabilities were calculated as the difference of the cumulative probabilities of reaching or exceeding successive damage states. Illustrative examples for the application of the process are shown in Moharram (2006) and Moharram *et al.* (2008b). These discrete probabilities were then used to calculate structural damage-related losses for buildings in the study region.

5. ESTIMATION AND INTEGRATION OF LOSSES

The adopted loss formulations utilise the previously calibrated discrete damage probabilities (DDP), inventory information and economic data to estimate losses. The discrete damage probabilities evaluated in the previous section for each building class and geocode, indicate the proportion of the total number of buildings belonging to each damage state. To provide a more general evaluation of damage, a ratio (MDR) is calculated by combining these probabilities into one average index that defines the mean damage ratio of each building class in each geocode. This is performed using the following equation:

$$MDR = \sum DDP_i \cdot d_{ri} \tag{5.1}$$

where *MDR* is calibrated for each building class within each geocode and for each scenario considered; DDP_i is the discrete damage probability of experiencing damage of state *i*; d_{ri} is the damage ratio which signifies an estimate of the repair costs required in the case of experiencing damage state *i*, as a ratio of the total replacement cost of the building class considered.

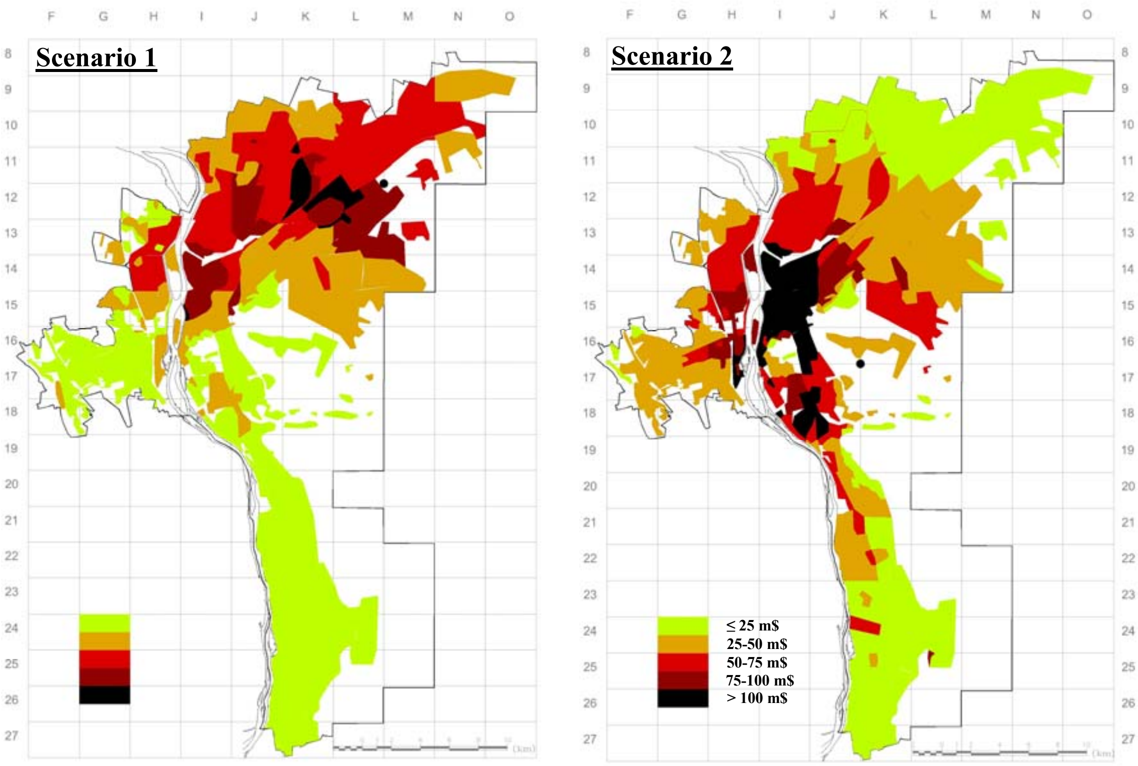
The HAZUS methodology proposes a set of damage ratios that have been used in subsequent risk models. This involves using a value of 2% for slight damage, 10% for moderate damage, 50% for extensive damage and 100% for complete damage. It was decided to adopt the HAZUS values for damage ratios and for each earthquake scenario, the mean damage ratios were computed for each building class, within each of the 191 geocodes.

For calculating losses in each geocode, an integration of losses relevant to each building class is carried out using the following formulation:

$$L = \sum RC_i \cdot (N_i \cdot P_i) \cdot MDR_i \tag{5.2}$$

where *L* is the monetary value of the loss caused by structural damage to the building in the geocode considered; RC_i is the typical value of the total reconstruction cost per building of Class *i*; P_i is the proportion of buildings of Class *i* experiencing damage of any kind and MDR_i is the mean damage ratio for Building Class *i*; the product

($N_i \cdot P_i$) signifies the number of buildings affected.



(a) (b)

Figure 3 Estimated monetary losses in Greater Cairo per unit area (million US Dollars per square kilometre) due to structural damage to buildings, caused by Scenarios 1 and 2 as examples

The resulting losses are integrated over the entire number of geocodes to obtain monetary loss scenarios relevant to structural damage to buildings caused by each of the four reference earthquakes. The losses per unit area are also evaluated on the geocode level and geographically presented, as shown in Figure 3 (for Scenarios 1 and 2 only).

6. UNCERTAINTY AND SENSITIVITY TESTING

Due to the unpredictable nature of earthquake shaking, coupled with the incomplete nature of available information for constructing a risk model for a region that has not been assessed before, uncertainty is inevitably expected in the final predictions. Uncertainties also arise from the decisions taken at each step of the model, in which many assumptions were unavoidable for such a large area. Hence, further work is required to examine the robustness of the risk model by tracking uncertainties associated with the various decisions and factors employed. This can be partly achieved by comparing the predicted risk with damage surveys from previous events. However, such data is scarce for the study region and the damage reports produced in the aftermath of the 1992 earthquake can only be used to provide very crude guidance. As an essential part of this uncertainty evaluation, the sensitivity of model predictions with respect to variations in the main governing parameters is imperative. These tests can be typically explored by detecting changes in the MDR values for each building model caused by these separate changes, mainly carried out to the input hazard and vulnerability parameters (Crowley *et al.*, 2005). The results of these tests would shed light on the most influential sources of variability and hence assist in allocating further targeted effort towards specific aspects or parameters of the model. Some of these tests have been implicitly considered in various steps of the procedure, as discussed below. However, carrying out a full sensitivity study is prohibitive and entails an extensive research effort in its own right. Hence, the discussion below only highlights the most important aspects of sensitivity testing which needs to be addressed in more detail in future work.

The most important contributors to the overall uncertainty of the model, and for which sensitivity testing is indispensable, are those related to variations in the hazard definition and vulnerability parameters of the building stock. Uncertainty related to the ground-shaking model arises from three main sources: uncertainty in the model for earthquake occurrence, ground-motion prediction equations, and the soil amplification characteristics. An important sensitivity measure is also related to the selected equations (i.e. sensitivity to changing the adopted equations). Again, the discrepancies between the predictions of the different equations were found to largely originate from the different definitions of the predictor variables. It follows that once adjustments have been carried out to achieve consistency between these parameters, closely similar predictions are produced. This reduces the need for carrying out such a sensitivity check at the outset of the process. Another important sensitivity check is to compute the change in the MDR resulting from a change of one site class (for example from Class C to Class D). This is required to examine the importance of improving the accuracy of the procedure by which the soil deposits are seismically classified, for example by carrying out a more elaborate microzonation procedure.

The extent of the influence of the structural vulnerability parameters on the final MDR estimates can be performed by introducing plausible changes to the capacity characteristics of the employed structural models. This may include changes in the extent of infill, material characteristics and the general layout of the building classes. The latter issue involves changes in the number of storeys within the range assigned for each height subgroup as well as changes in plan, for example by using different number of bays, etc. Some of these effects have been examined earlier in this study before choosing a most representative model. However, it is still an important area for further work not only in relation to this study but also to all other available loss models. Finally, as noted before, a key aspect for assessing the accuracy of loss predictions, as well as calibrating and improving any seismic risk model, involves the compilation and examination of damage data in future events.

7. CONCLUSION

A scenario-based loss assessment investigation for the city of Greater Cairo was described in this paper. A seismic risk model for the study region based on geological, hazard and inventory information compiled in previous studies was firstly outlined. Fragility functions for building models representative of the building stock in the city were estimated. Three sets of RC building populations were generated using the Latin Hypercube Sampling technique to produce sets of buildings with different material characteristics. Ground-motion variability was accounted for by introducing the scatter in the adopted ground-motion prediction equations directly into the fragility functions. A modified capacity spectrum approach was used to assess the seismic performance of different building classes based on the developed ground-shaking model. The resulting performance points were then used as input to fragility curves in order to determine the likely distribution of damage across different limit states, for each geocode and earthquake senario. Mean damage ratios were estimated as a combined measure of damage inflicted on each building class and used, together with relative repair-to-replacement cost values and the number of seismically-affected buildings, to calibrate monetary losses due to damage caused by the chosen scenarios. Various levels of refinement can be applied to the model in future studies by considering the inevitable uncertainties associated with the input to any earthquake loss model. To this end, it is important to study the relative influence of these uncertainties through sensitivity testing, such that further effort can focus on addressing the key parameters.

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