Sensitivity of Earthquake Risk Models to Uncertainties in Hazard, Exposure and Vulnerability Models

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ABSTRACT

Sensitivity of earthquake risk models to the uncertainties in hazard, exposure and vulnerability models has been investigated. Zeytinburnu district of Istanbul, Turkey with a building stock of 14,482 buildings has been selected as the test-bed. A 7.1 magnitude earthquake on the North Anatolia Fault has been used as the scenario earthquake. The distribution of damage estimates showed that the selected ground motion prediction equation and the vulnerability functions significantly affect the earthquake risk models. On the other hand, the building exposure database seems to have a lesser affect than the hazard and vulnerability modules. Further, the equivalent single degree of freedom method used to compute the inelastic displacement demand was found to have no major effect on the risk model.

1. INTRODUCTION

In the last year, earthquake risk modelling has taken a big step forward with the initiation of the "Global Earthquake Model" project, which aims to provide a reliable risk assessment tool as well as to publish risk maps on several resolution levels ranging from local to global. The extent of this project is sufficient to display the need for earthquake risk models. This need is driven by the end-users ranging from emergency planners to the reinsurance sector. These models can further be used for cost-effective risk mitigation since they provide information on the most vulnerable building typologies and zones.

Earthquake risk models have three main components: *hazard, exposure database* and *vulnerability information*. All these three components, undoubtedly, introduce uncertainties in the earthquake risk models. To this date, very few studies focused on evaluating the sensitivity of the earthquake risk models to these uncertainties (Crowley et al. 2005, Karaca 2004, Molina and Lindholm 2007). Hence, the quantitative influence of these uncertainties on the final risk estimates remains guesswork.

The main purpose of this study is to systematically evaluate the sensitivity of earthquake risk models to the uncertainties associated with hazard, exposure, and vulnerability components. The uncertainties associated with all three modules are principally epistemic uncertainties that can, in theory, be reduced if sufficient investment is available (Crowley et al. 2005). It is practically not possible to provide resources to reduce the uncertainties in all components to a minimum. The results of the study can therefore be used to identify the components that the risk models are most sensitive to, so that the limited resources can be allocated for optimizing the quality and reliability of the risk models.

2. CASE STUDY ZEYTINBURNU

For the evaluation of sensitivity of earthquake risk estimates to the aforementioned uncertainties, Zeytinburnu, a district of the city of Istanbul (Turkey) has been chosen as the test bed. Zeytinburnu district has an area of 12 km^2 with an estimated population of approximately 290,000 (acc. to census of 2009;TUIK 2010).

2.1 Hazard

A *M* 7.1 event on the North Anatolian Fault (NAF) has been used as a scenario event. The epicentre, which is located in an approximate distance of 20 km from the centre of Zeytinburnu, the fault line and the study area are depicted in Figure 1.

Figure 1. Epicentre of the scenario event and the study area

Five different ground-motion prediction attenuations (GMPE's) that were developed for the Middle East and the European region are used in order to evaluate the effect of the selected GMPE on the earthquake risk model: Ambraseys et al. (1996), Ambraseys et al. (2005), Akkar and Bommer (2007), Schwarz et al. (2002), and Gülkan and Kalkan (2002).

2.2 Exposure Database

The building census data was provided by KOERI (Kandilli Observatory and Earthquake Research Institute; Hancilar, 2009). A total of 14,482 buildings spread over 50 geographical units constitute the building stock. The description of available building typologies is summarized in Table 2.1 along with the corresponding HAZUS (FEMA 2003) typologies.

Table 2.1. Description of building typologies

#	Index	HAZUS mbt	Story #	Comments
1	RC1-L	C3L	1-3	Concrete frames with unreinforced masonry infills
2	RC1-M	C3M	4-7	
3	RC1-H	C3H	8+	
4	RC2-L	C1L	1-4	Concrete moment frames without infills
5	RC2-M	C1M	4-8	
6	RC2-H	C1H	8+	
7	RC3-L	C2L	1-3	Concrete shear walls
8	RC3-H	C2H	8+	
9	URM-L	URML	1-3	Unreinforced masonry
10	URM-M	URMM	1-3	
11	PC-L	PC1	1-3	Precast concrete
12	W2	W2	1-3	Wood frame with heavy members

In addition to the local KOERI database, a global database provided by USGS through the PAGER project has been used in the earthquake risk estimations to assess the sensitivity to the exposure databases. The PAGER database (Jaiswal 2008) provides information about the percentage distribution of building typologies in each country subdivided by rural and urban settlements. For this study, the distribution numbers for urban areas have been used. To adopt the ratios given by the PAGER database to the conditions of the Zeytinburnu test bed, the total number of buildings in each geounit has been multiplied by the percental distribution of the respective building typology. Figure 2 presents the overall percentage distribution of available building typologies as represented by the two databases. It should be noted that, for the PAGER database, the distribution shown in Figure 2 is constant for all the geounits whereas, for the KOERI database the percentage distribution varies from geounit to geounit. Figure 2 presents the cumulative numbers over all geounits.

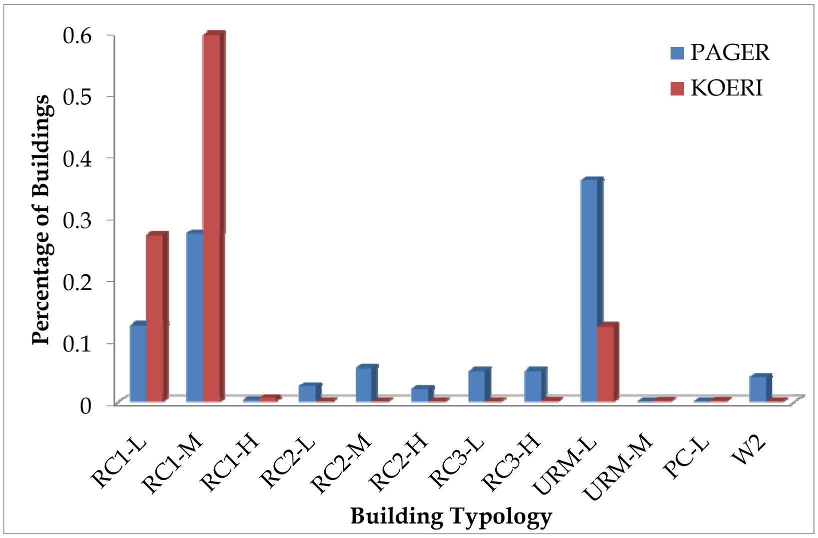

Figure 2. Percentage distribution of building typologies in the Zeytinburnu district

2.3 Vulnerability Functions

The open source earthquake risk package SELENA–RISe (Molina et al. 2010; Lang and Gutiérrez 2010) has been used in the study. The SELENA–RISe risk package uses the HAZUS methodology (ref), where physical building vulnerability is represented by a set of capacity curves and fragility functions for each building typology. The spectral displacement demand, computed using one of the three built-in equivalent single-degree-of-freedom methods, i.e., traditional Capacity Spectrum Method, *CSM*, of ATC-40 (ATC 1996), Modified Acceleration Displacement Response Spectrum, *MADRS*¸ of FEMA-440 (ATC 2005), and Improved Displacement Coefficient Method, DCM, of FEMA-440 (ATC 2005), is used to compute the probability of being in one of the five discrete damage states (none, slight, moderate, extensive, complete) via the provided fragility functions.

Three sets of vulnerability functions (capacity curves and fragility functions) have been used in the risk assessment to evaluate the sensitivity of the risk models to the uncertainties in this component. The first set has been provided by KOERI together with the local exposure database (Hancilar 2009). For the second and third sets, the capacity curves and fragility functions provided by HAZUS (FEMA 2003) have been used. To replicate the non-ductile behaviour of Turkish building stock, HAZUS vulnerability functions that represent the pre-code and low-code design levels have been selected. Figure 3 compares both capacity curves and fragility functions as provided by KOERI and HAZUS for a single typology (RC1-M).

In addition to the vulnerability functions selected, the effect of the equivalent SDOF method used to compute the displacement demands on the earthquake risk models has also been evaluated.

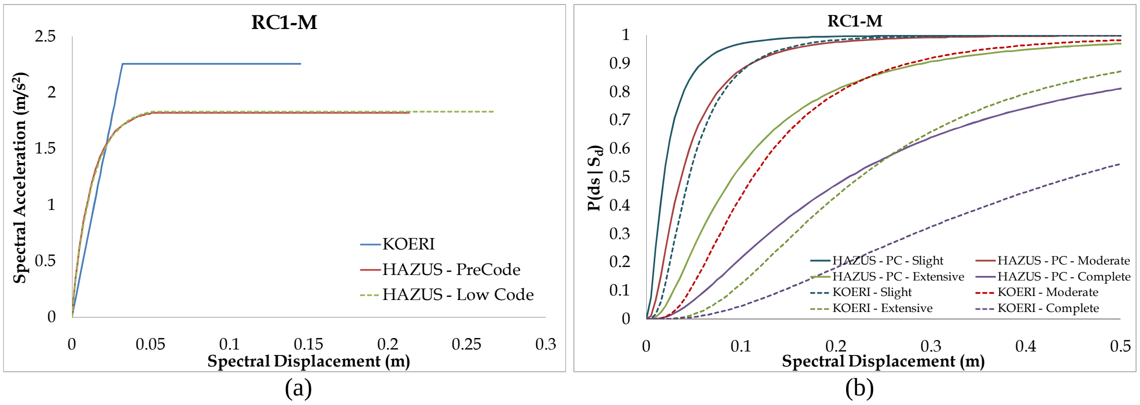

Figure 3. (a) Capacity curves and (b) fragility functions for RC1-M provided by KOERI and HAZUS

3. RESULTS

In the current study, the earthquake risk model has been limited to the estimation of the damage distribution. Economic as well as social losses have not been considered.

3.1 Sensitivity of the Earthquake Risk Model to the selected GMPE

The risk assessment for the Zeytinburnu region has been conducted using the aforementioned five GMPE's. Thereby; it was concentrated on the predicted median ground motion values without considering their aleatoric uncertainties. During this assessment, all other parameters have been kept constant: the KOERI building database was used along with the HAZUS pre-code vulnerability functions. MADRS method was selected as the base method to compute the spectral displacement demands. Figure 4 shows the damage estimates obtained using each GMPE together with the median value for the five equations.

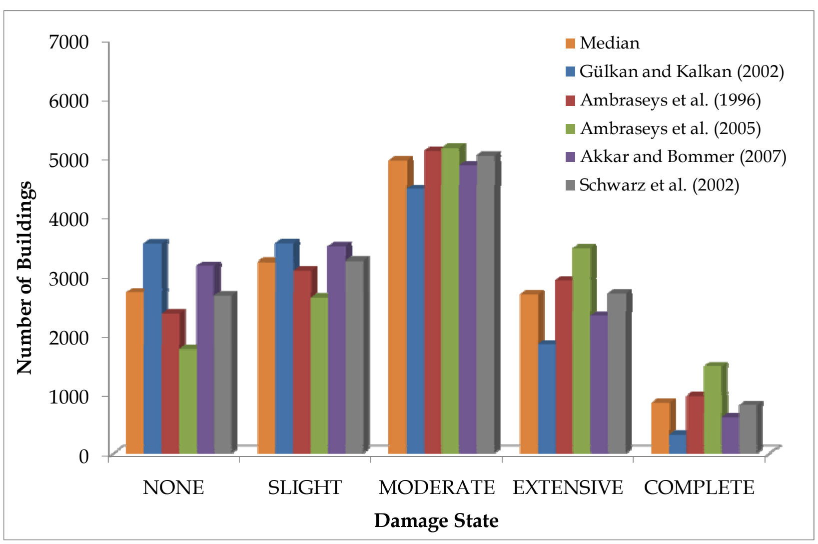

Figure 4. Damage distribution of Zeytinburnu building stock estimated using five different GMPEs

Figure 4 indicates that the damage estimates obtained using different GMPEs may differ significantly from one another. Gülkan and Kalkan (2002) and Ambraseys et al. (2005) GMPEs result in the two extreme damage estimations and show significant discrepancy from the median damage estimates. For instance, the former leads to a collapse rate estimate, defined as the ratio of the buildings in the complete damage state to the total number of buildings, of 2.2%; approximately 63% less than its median counterpart (5.9%). On the other hand, the damage assessment using Ambraseys et al. (2005) yields a collapse rate of 10.1%; approximately 70% higher than the median collapse rate. In other words, the GMPE by Gülkan and Kalkan results in an estimate that one in every 45 buildings will suffer collapse under the scenario earthquake whereas the GMPE of Ambraseys et al. leads to an estimate that one in every 10 buildings will collapse under the same event and with all the other parameters kept constant.

The discrepancy between the damage estimates obtained using different GMPE's decreases when the extensive and complete damage states are evaluated together. Combining these two damage states may be a better indicator of the economic losses than the complete damage state alone, since this combined damage state can be assumed to give an estimate of the buildings that are expected to be damaged beyond repair. According to the damage assessment conducted using Gülkan and Kalkan (2002) GMPE, 15.6% of the buildings are expected to suffer at least extensive damage. This value is 36% lower than its median counterpart, which stands at 24.5%. Similarly, the discrepancy between the damage estimates between the Ambraseys et al. (2005) GMPE and the median decreases when the combined extensive and complete damage states are considered. Ambraseys et al. GMPE leads to 39% higher estimates of the number of buildings that will suffer at least extensive damage compared to the median value: 34.1% compared to 24.5%.

Although it was not possible to accurately estimate the economic and social losses (casualties) with the data at hand, the results and the ensuing discussion presented above suggest that using one GMPE instead of the other one can result in significantly different estimates of casualties and economic losses, as evidenced by the discrepancy in collapse rate estimate and the estimate of the number of buildings that are expected to suffer damage beyond repair, respectively.

3.2 Sensitivity of the Earthquake Risk Model to the Exposure Database

The distribution of building typologies from KOERI and PAGER databases is depicted in Figure 2. This figure indicates that the PAGER and KOERI databases have some discrepancies amongst the percentage of the prevalent building typologies: KOERI database indicates that 87% of the buildings in Zeytinburnu are low-rise or mid-rise reinforced concrete (RC) frames with infill walls whereas, according to the PAGER database, these typologies constitute 40% of the total building stock. On the other hand, unreinforced masonry buildings are much more common according to the PAGER database compared to the local (KOERI) database. This difference in the building distribution should not be surprising since PAGER database considers all the urban areas in Turkey, whereas KOERI database is very specific to the case study area, hence more reliable.

To evaluate the effect of this discrepancy in the exposure database on the earthquake risk model, the damage assessment of the Zeytinburnu region has been conducted twice: once using the KOERI database and once using the PAGER database. To enable a direct comparison, all the other parameters are kept constant: all five GMPEs were included in the analysis in a logic tree computation scheme with an equal weight of 20%; HAZUS pre-code vulnerability functions were used along with the MADRS method. Figure 5 presents the damage estimates obtained using the two exposure databases. Figure 5 suggests that using one exposure database instead of the other results in a change that can be deemed to be rather insignificant in the estimated damage distribution. The collapse rate estimate of 5.9% obtained from KOERI database decreases to 4.9% when PAGER database is used. Similarly, the damage assessment using KOERI database estimates that 24.5% of the buildings will be damaged beyond repair while the estimate from the PAGER database is 20.8%; a decrease of 18% from the KOERI database estimate.

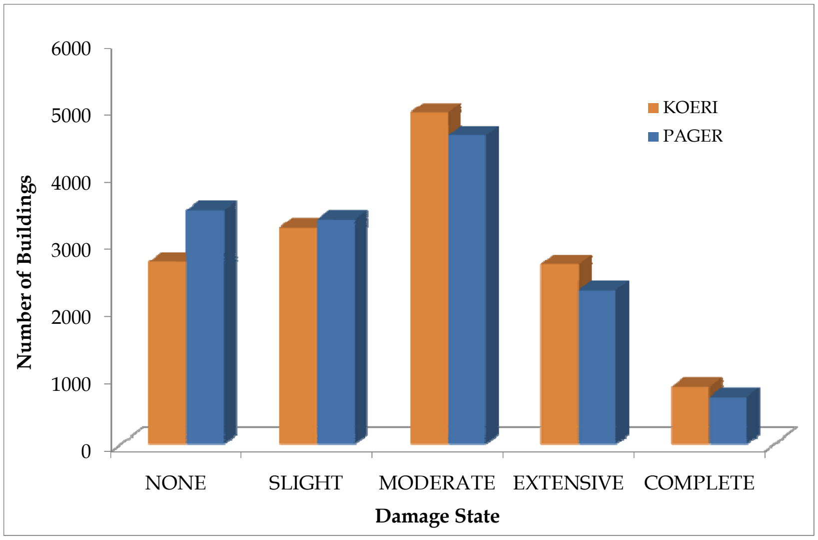

Figure 5. Damage distribution of Zeytinburnu building stock estimated using local and global exposure databases

3.3 Sensitivity of the Earthquake Risk Model to the Vulnerability Functions

Figure 6 presents the damage estimates obtained using different sets of vulnerability functions. It should be noted that all three sets of vulnerability functions have been selected due to their compatibility with the Turkish building stock and construction practice. In other words, all three models are viable models and can be used in the earthquake risk models of Turkey with "*sufficient confidence*". As in the previous cases, all other parameters have been kept constant.

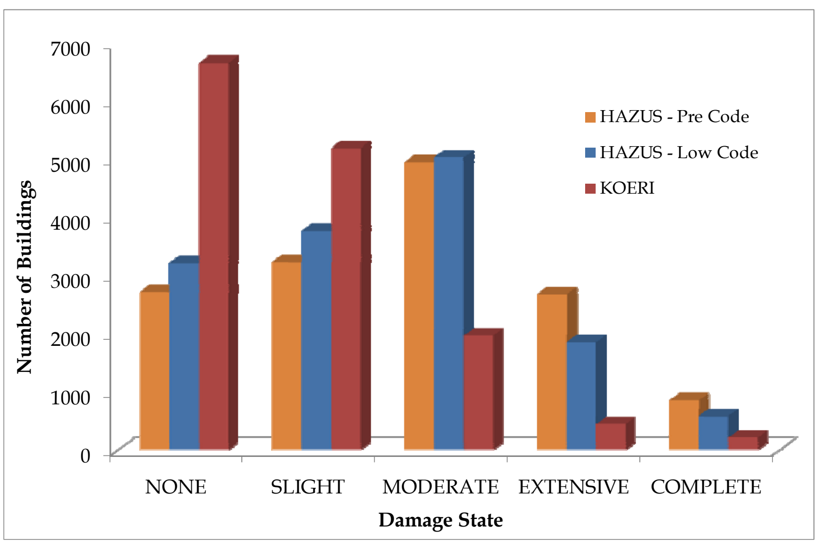

Figure 6. Damage distribution of Zeytinburnu building stock estimated using different sets of vulnerability functions

The discrepancy between the damage estimates obtained using HAZUS pre-code and low-code functions can be regarded as rather limited compared to the discrepancy of these models and the KOERI model. The collapse rate decreases to 4.0% from 5.9% and the percentage of buildings that are expected to suffer at least extensive damage decreases to 16.7% when low-code functions are used instead of pre-code functions, which leads to an estimate of 24.5%. Although, this difference is limited compared to the difference obtained using HAZUS and KOERI databases, it can still be regarded as significant given the fact that the pre-code and low-code vulnerability functions are not significantly different from each other as indicated by Figure 3 (a). Low-code functions exhibit somewhat higher ductility capacity compared to their pre-code counterparts, whereas both low-code and pre-code capacity curves depict the same strength and stiffness. The difference in the damage estimates due to this minimal change in vulnerability functions presented in Figure 6 can be regarded as substantial.

When the HAZUS pre-code vulnerability functions are replaced with the KOERI functions, the collapse rate decreases to 1.4%; a 76% decrease. Further, KOERI vulnerability functions lead to an estimate of 4.5% of the total building stock for the number of buildings that are expected to be damaged beyond repair (suffer at least extensive damage). This estimate is only 18% of its counterpart obtained using HAZUS pre-code vulnerability functions, 24.5% of the total building stock. As evidenced by Figure 6 and the discrepancies between the estimated extensive and complete damages states summarized above clearly indicate that vulnerability functions have very significant effect on the earthquake risk models.

Finally, the effect of the equivalent SDOF method to compute the spectral displacement demands on the earthquake risk models have been evaluated using the KOERI database and HAZUS pre-code vulnerability functions. Figure 7 indicates that, CSM, MADRS and DCM methods lead to very similar damage assessments suggesting that anyone of them can be used in the earthquake risk models.

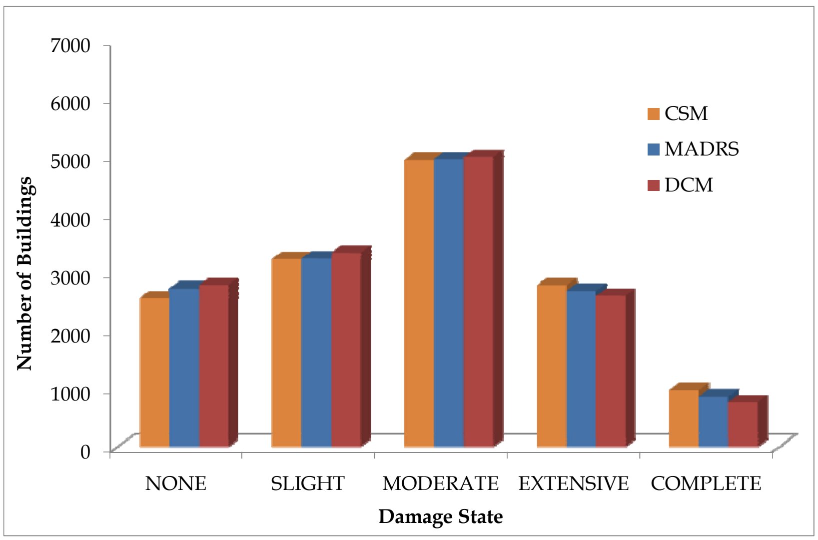

Figure 7. Damage distribution of Zeytinburnu building stock estimated using different equivalent SDOF methods

4. CONCLUDING REMARKS AND FUTURE STUDIES

The following remarks can be drawn based on the results summarized:

- The GMPEs used to estimate the ground-motion parameters may have significant effects on the estimated damage distribution under a scenario earthquake.
- Of the three main components of an earthquake risk model, the exposure database seems to have the least effect on the estimated damage distribution. Despite a significant difference between the local and global exposure databases, the discrepancy in the estimated damage distribution is rather minimal.
- The vulnerability functions seem to have the most significant effect on the estimated damage distribution amongst the three components. Even small differences in the vulnerability functions lead to a significant change in the damage distribution. This difference can be quite substantial once stiffness, capacity and ductility of the building typologies are modified

simultaneously.
- The three equivalent SDOF methods that are used to compute the displacement demands lead to very similar damage distributions.

The results presented in this article are preliminary results from a more comprehensive effort that will consider all aspects of earthquake risk models along with the damage estimates such as economic losses and casualties. Further, the sensitivity study needs to be repeated for different test beds representing different socio-economic regions and construction practices in order to be able to generalize the conclusions summarized above.

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