FROM SEISMIC SOURCES TO ENGINEERING DEMAND PARAMETERS: AN INTERDISCIPLINARY FRAMEWORK FOR ESTIMATION OF SEISMIC LOSSES IN URBAN REGIONS

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Abstract. Risk mitigation in urban regions starts with identification of potential seismic losses in future earthquakes. Estimation of seismic losses concerns a wide range of authorities varying from geophysical and earthquake engineers, physical and economic planners to insurance companies while the process naturally involves inputs from multiple disciplines. In this study, we present a city-level model where potential seismic losses are expressed in terms of regional seismic hazard, local soil conditions and local building vulnerabilities. The main components of the study are probabilistic and deterministic seismic hazard assessment and estimation of potential ground motions, regional building vulnerability, fragility information, and loss functions. As the study area, Erzincan, a city on the eastern part of the North Anatolian Fault zone is selected. Located within a triple conjunction of major fault systems within a basin structure, and experienced two major events within the last century in 1939 (Ms=8.0) and in 1992 (Mw=6.6), this city has significant hazard potential. We present the results in terms of key components such as construction of a 2D velocity model, ground motion simulations of past earthquakes and scenario events, site-specific probabilistic seismic hazard analyses and fragility functions derived using regional building characteristics along with simulated regional ground motion data. The verification of the model is performed through comparisons of estimated mean damage ratios for the 1992 earthquake with the corresponding observed values. The consistency of the estimated and observed values points out the significance of using locally-derived models for every component of loss estimation process.

Key Words: Seismic Hazard, Ground Motion Simulations, Site Effects, Dynamic Structural Response, Loss Estimation

1. INTRODUCTION

The fundamental step in risk mitigation is the identification of potential seismic losses in future earthquakes. Seismic loss estimation is naturally an interdisciplinary task which involves multiple physical processes and their models. Observations on seismic damages and losses during past major earthquakes show that the damage patterns are dependent on regional seismic hazard, site conditions and local building characteristics ([1]). As a result, multidisciplinary loss estimation models which are built on local data are necessary for accurate loss estimations in urban areas. Recent advances in both computing technologies and engineering databases make such models possible.

This study focuses on developing a new approach for estimating potential seismic losses which relies on entirely local information ranging from regional seismic sources and local site conditions to ground motion simulations and building fragility functions. The proposed model includes four main steps: The first step is the characterization of detailed site conditions at selected locations in the study area. Next, site-specific seismic hazard is estimated by both probabilistic and deterministic approaches. In the third step, buildings in the area are modelled numerically where fragility functions are derived using the local structural characteristics. The fragility curves are derived using the simulated ground motions as inputs which reflect regional seismic properties. Finally, losses are computed in terms of structural damages at selected districts within the study area.

The model is applied in Erzincan city center located in Eastern Turkey, close to several active fault zones including the North Anatolian fault zone. Despite the seismic activity, there is a sparse seismic network in the region. The proposed approach is first validated to estimate the spatial distribution of damage after the 1992 Erzincan earthquake (Mw=6.6). Next, the model is used to predict damage distribution for scenario events. In this paper, a summary of the proposed methodology is presented. Further specific details of this study can be found in [1] and [2].

2. STUDY REGION

The study is conducted in Erzincan (Eastern Turkey), a small city which is among the seismically active cities in Turkey. Erzincan is located at the intersection of North Anatolian, North East Anatolian and Ovacik faults. North Anatolian fault zone displays a right lateral strike slip character while the latter two are left lateral strike slip faults. The city center is built upon a pull-apart basin which is formed due to mechanical interactions between the nearby faults. Deep alluvial deposits exist in the center of the basin with relatively shallow and stiffer soil media close to the neighboring mountains. This city has experienced two major events in the last century: the 1939 (Ms~8) and the 1992 (Mw=6.6) earthquakes both causing major structural damage and significant number of mortalities. Figure 1 shows the major fault systems and past large earthquakes that occurred on the Anatolian plate and around the study region.

The western segments of North Anatolian fault zone which include higher population and industrial facilities are continuously focused on. However, the eastern sections are not as densely monitored despite the significant seismic activity. Thus, in this study, Erzincan is particularly selected in order to apply the proposed model which involves simulated ground motions and locally-derived fragility functions. The objective is to bring attention to this hazardous region as well as to validate our city-level loss model in a relatively smaller city.

3. ESTIMATION OF SITE CONDITIONS: LOCAL VELOCITY MODELS

In this study, a passive seismic method is employed in order to construct one-dimensional S-wave velocity models within Erzincan basin. Particularly, Multi-mode Spatial Auto Correlation method (MMSPAC) is used as outlined in [3-5]. MMSPAC is developed from the original Spatial Auto Correlation (SPAC) method proposed by Aki ([6]), in order to include effect of higher modes.

(a)

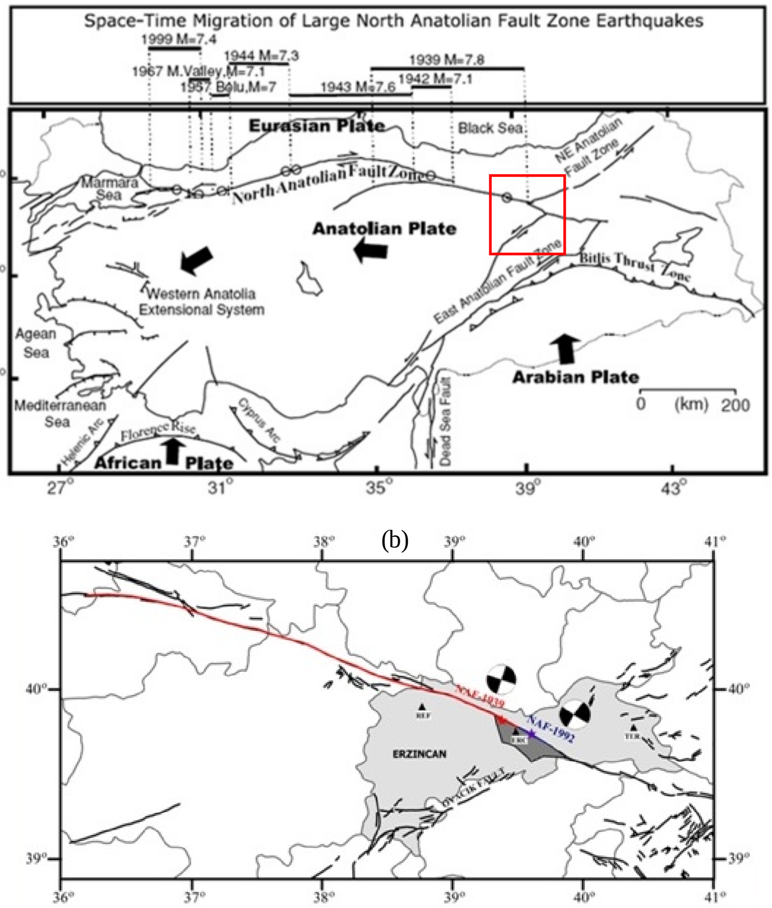

FIG. 1 (a) Major fault zones on the Anatolian plate and large earthquakes that occurred on the North Anatolian Fault Zone in the last century (Figure is adapted from [7]), (b) Faults in the Erzincan region (shown as the red square in the top panel) along with the source mechanisms and epicenters of the 1939 and 1992 earthquakes (Figure is adapted from [8])

Traditionally, SPAC method uses vertical geophones within circular arrays. Asten ([3]) proposed and validated MMSPAC technique with 3D seismometers and non-circular arrays. In this study, instead of a formal inversion of the dispersion curves, direct fitting of observed and modeled SPAC is used. This approach eliminates the necessity of computing observed phase velocities which is a nonlinear and non-unique problem. Additional details of the methodology and microtremor dataset can be found in [2].

The direct fitting of modeled and observed SPAC spectra relies on the following relationship between coherency and phase velocity:

$$C_m(f) = J_0\left(\frac{2\pi f r}{v_p(f)}\right) \tag{1}$$

where $C_m(f)$ is the modeled spatially-averaged coherency, f is frequency, $J_0$is the Bessel function of the first type and zero-order, r is the station separation, and $v_p(f)$ is the modeled phase velocity for a layered earth.

In this study, in addition to the MMSPAC approach, Horizontal-to-Vertical Spectral Ratios (HVSR) method ([9]) is employed in the analyses to include the lower frequencies and obtain the deeper structure as well as the bedrock depth. A total of 9 sites are selected within Erzincan basin (Figure 2) where microtremor field experiments are conducted. The resulting 1D velocity models are obtained as shown in Figure 3. In Figure 3, results from 3 sites are presented in each panel in order to better display the basin structure in the NS and EW directions. The velocity models indicate that the Northern sites (Sites 2 and 8) are on relatively stiffer soil conditions whereas the Southern regions (Site 1) are located on soft soils. A comparison of the profiles along the NS and EW directions reveals the basin structure as well.

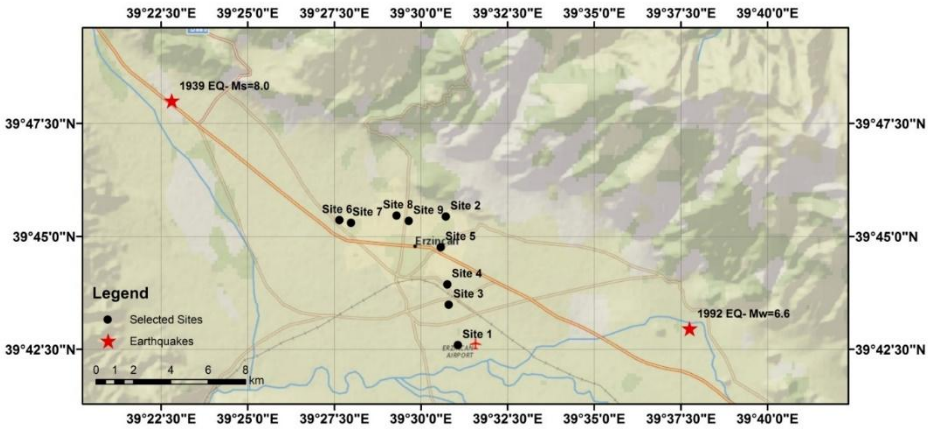

FIG. 2 Nine sites selected within Erzincan basin where velocity models are constructed (Figure is taken from [2])

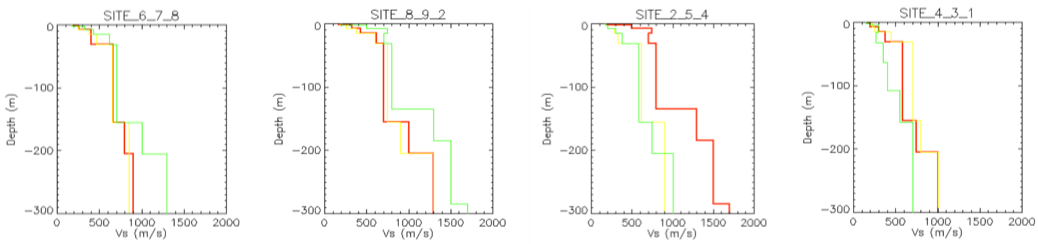

FIG. 3 Wave velocity profiles at the selected sites (Color code order for a sample group of Sites a_b_c: red, yellow, green, for a, b, and c, respectively)

The velocity profiles shown in Figure 3 are employed as input parameters in the seismic hazard analyses described in the next section. Since the site effects influence both the hazard and the resulting risk in an urban region significantly, in this study these local velocity models are used.

4. ESTIMATION OF REGIONAL SEISMIC HAZARD: PROBABILISTIC AND DETERMINISTIC ANALYSES

In the city-level loss model, we employed both probabilistic and deterministic seismic hazard analyses using the local seismic sources and information on the site conditions derived within this study. Herein, a brief summary is presented, further details can be found in [2].

4.1 Probabilistic Seismic Hazard Analyses

The main steps of Probabilistic Seismic Hazard Analyses (PSHA) are as follows ([10]): Defining the seismic sources in the study area; construction of a magnitude-frequency model for every source; modeling the temporal occurrence of the earthquakes; choosing a ground motion parameter to express the seismic hazard; selecting a ground motion prediction model and finally computing the probabilities of exceedance for various levels of the chosen ground motion parameter by considering the contributions of all seismic sources within the study area. In this study, classical PSHA analyses are carried out in Erzincan city center: The step-by-step computation of the probabilities is performed based on the regional seismic activity, seismic sources, local soil models described previously and a suitable ground motion prediction model. Site-specific PSHA is conducted at 123 nodes within Erzincan city center in terms of selected ground motion parameters such as PGA and Spectral accelerations for several return periods. Due to space reasons, we show the seismic hazard maps in Figure 4 in terms of PGA and SA only for one return period. The PSHA results for all ground motion parameters and return periods reveal the noticeable seismic hazard in the study area.

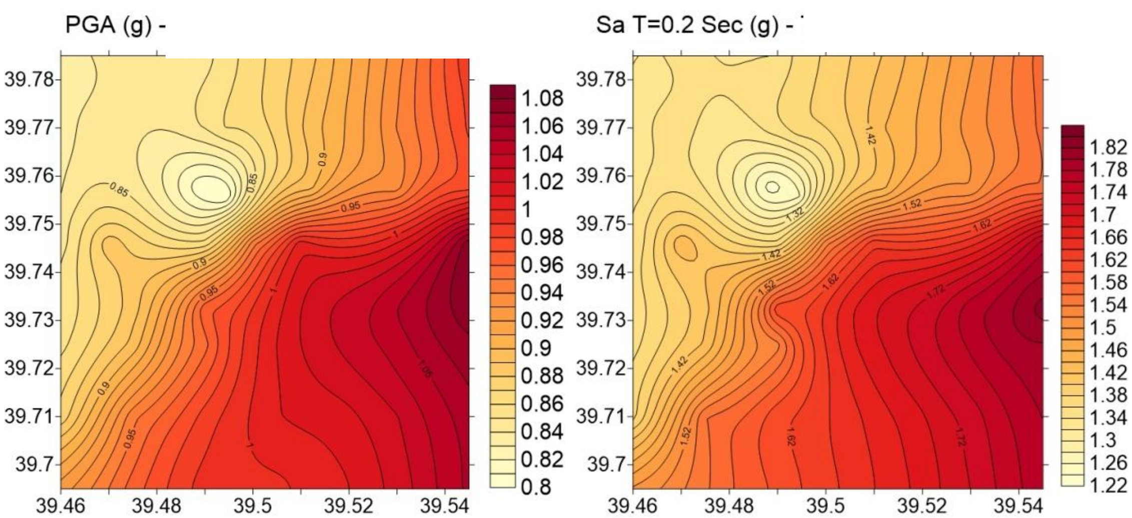

FIG. 4 Probabilistic seismic hazard maps in Erzincan in terms of PGA and SA (T=0.2 sec) for a return period of 475 years

4.2 Deterministic Seismic Hazard Analyses

Deterministic Seismic Hazard Analysis (DSHA) is performed to assess the anticipated ground motion levels due to specific earthquake scenarios. Similarly ground motions from a past event can also be modeled with DSHA.

In this study, stochastic finite-fault simulation method is employed as described in [11]. Ground motions are assumed to radiate from a rectangular finite-fault which is divided into subfaults, each of which is modeled as a stochastic point source with an w^{-2} spectrum. The stochastic point source model relies on a deterministic target spectrum that is expressed as a multiplication of source, path and site filters ([12]). In the finite-fault model, the hypocenter of the earthquake is located on one of the subfaults, and the rupture propagates radially from the hypocenter. The contribution of all subfaults is summed with corresponding time delays in order to obtain the entire contribution of the fault plane to the seismic field, at any observation point ([11]).

In this study, initially the 1992 (Mw=6.6) Erzincan event is simulated with regional source, path and site parameters. The regional source and path parameters are obtained from the literature ([8]) while the site amplifications are computed using the velocity profiles derived in this study. After the validation in terms of comparisons of available observed and simulated ground motions of the 1992 event, blind simulations are performed for a set of scenario events in Erzincan city center with magnitudes of Mw=5.0, Mw=5.5, Mw=6.0, Mw=6.5, Mw=7.0 and Mw=7.5 on the same fault which caused the 1992 event. The epicenter of the scenario events are assumed to be at the same location with the epicenter of the 1992 earthquake. For every scenario earthquake, full waveforms are obtained at the 123 nodes in the city center mentioned previously. The spatial distribution of simulated peak ground acceleration and peak ground velocity values are displayed for the 1992 Erzincan earthquake and a selected scenario event (Mw=7.0) in Figure 5.

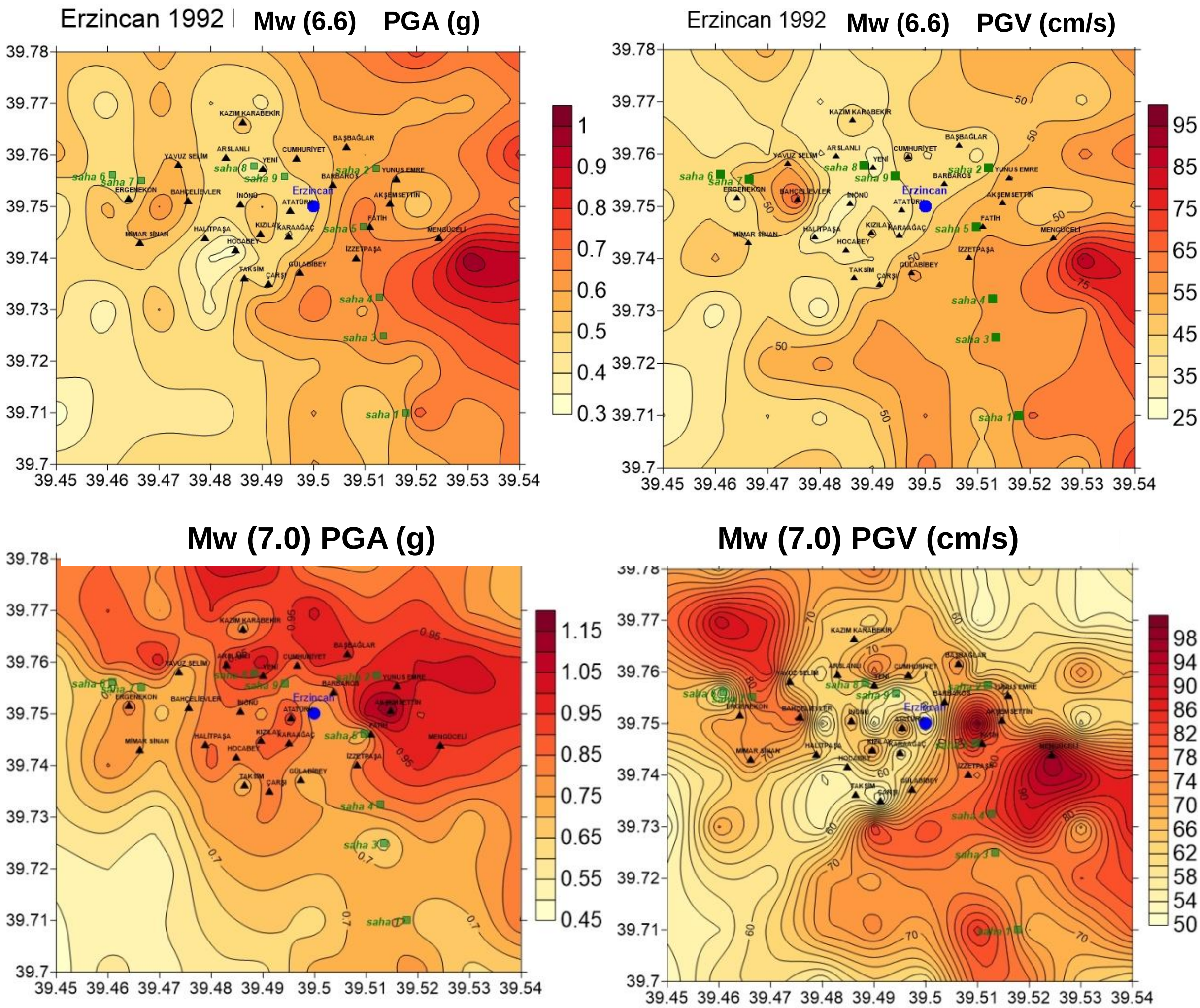

FIG. 5 The spatial distribution of simulated ground motions in terms of PGA and PGV for the 1992 Erzincan earthquake (top panel) and the scenario event with Mw=7.0 (bottom panel)

Figure 5 shows that the anticipated ground motions of the 1992 Erzincan earthquake (Mw=6.6) yield PGA values which reach almost 1 g around the city center. The corresponding PGV values reach 90 cm/sec. These amplitudes explain the widespread damage observed in the residential buildings in the city center during the earthquake despite its moderate magnitude ([13]). For the scenario earthquake with Mw = 7.0, significantly high peak ground motion acceleration as well as spectral acceleration levels (exceeding 1*g* at several locations) are simulated. These ground-motion amplitudes are attributed to close distances from the fault plane and the soft soil conditions. High seismic hazard coupled with the building vulnerability in the region explain the severity of the observed damage during the 1992 event and point to the significant seismic risk in Erzincan area.

The ground motions simulated for the mentioned scenario events with Mw=5.0-7.5 are used in the derivation the regional fragility curves which is explained next.

5. DERIVATION OF LOCAL FRAGILITY CURVES

Fragility curves express the probability of exceeding a predefined damage level under specific levels of ground motion intensity for a given structural type. In this study, fragility curves are derived considering the local building characteristics and the simulated ground motion dataset. Since it is not possible to find real ground motion data for all intensity levels from the region, the simulated dataset are employed to reflect the local seismological properties.

In order to define and classify the local structural properties, a field survey is conducted in the Erzincan city center. As a result, the residential building stock in Erzincan is classified into 21 groups considering three main parameters: Type of construction, number of stories and level of compliance with seismic design principles. Among these 21 classes of structures, 12 are Reinforced Concrete (RC: frame, shear wall or dual type) and 9 are masonry building sub-classes. The local structural characteristics of these building classes in the region are idealized by using Equivalent Single Degree of Freedom (ESDOF) models. The major response parameters of the ESDOF models, which are period (T), strength ratio (η) and ductility factor (μ), are considered as random variables in this study. For sampling of the random variables, Latin Hypercube Sampling (LHS) method is used. The final step is to construct the fragility curve sets of the considered building classes through dynamic analyses of the simplified ESDOF models subjected to a selected set of simulated ground motion records. Hundreds of nonlinear time history analyses are employed to estimate the response of equivalent structural models under each ground motion intensity level.

The structural performance levels expressed in the fragility curves are named as Limit States (LS). In this study, three performance levels are considered: Immediate Occupancy (LS_1), Life Safety (LS_2) and Collapse Prevention (LS_3). From the structural response dataset corresponding to the j^{th} ground motion intensity level, GMI_j; the conditional probability of attainment or exceedance of the i^{th} limit state (LS_i) at the j^{th} ground motion intensity level is computed as follows:

$$P\,(D \geq LS_i \mid GMI_j) = n_A / n_T \tag{2}$$

where n_A is the sum of responses equal or above the i^{th} limit state, and n_T stands for the total number of responses at the j^{th} ground motion intensity level. After repeating this process for different intensity levels, the discrete fragility information for each building class is obtained. Further details on the derivation of the fragility curves mentioned in this study can be found in

[1]. For flexible building types, PGV is used as the main ground motion parameter whereas PGA is used for more rigid structures. Figure 6 demonstrates sample fragility curves for selected RC and masonry structures. Fragility curves for most building classes point at the vulnerable building stock in the study area. The curves generated herein are used in the loss estimation model described in the next section.

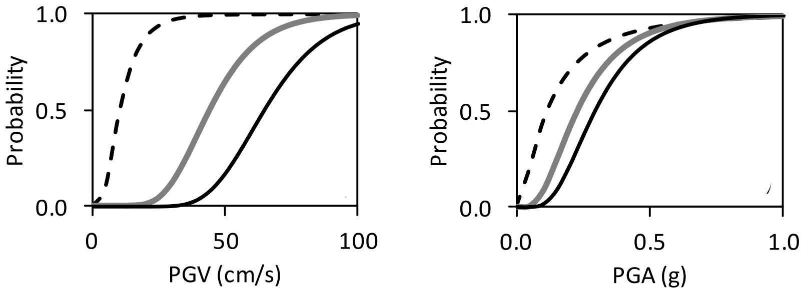

FIG. 6 Fragility curves for mid-rise RC frame buildings (left panel) and 2 story unreinforced masonry buildings (right panel) where the dashed lines correspond to LS_1, the gray solid lines to LS_2, and the black solid lines to LS_3

6. LOSS ESTIMATION: INTEGRATION OF THE MODEL COMPONENTS

In order to estimate the losses in the form of damage distributions, the previously-described components of the proposed model are integrated. The fundamental steps of the regional loss estimation method employed in this study are summarized as follows:

- Among the deterministic earthquake scenario set generated previously in Section 3, the scenario event of interest is selected.

- Spatial distribution of the ground motion intensity parameter of interest (PGA or PGV) within study region is obtained from the simulated ground motion database corresponding to the selected scenario earthquake.

- Damage ratios (DR) for the building sub-classes in the region are calculated with the local fragility curves generated previously.

- A certain value of mean damage ratio (MDR) is calculated for each building sub-class by using the discrete damage state probabilities as follows ([1]):

$$MDR(I) = \sum_{DS} P_k(DS, I).CDR(DS) \quad (3)$$

  where, CDR(DS) represents the central damage ratio corresponding to damage state DS which is a single quantitative value named as central damage ratio (CDR) for each damage state.

- Lastly, a single MDR is calculated for each residential area by considering the percent distributions of building sub-classes in the region.

The validation of the proposed model is performed by comparing the estimated damage distribution in Erzincan and the observed damage distribution just after the 1992 earthquake in terms of MDR values. The comparison is presented in Figure 7. The computed mean damage ratios for a significant percentage of the residential districts match closely with the observed values of the 1992 earthquake. In some districts close to the fault plane, the estimated damage distribution is more severe than the corresponding observations. These discrepancies may be attributed to the subjectivity in the field while collecting the damage data as well as the assumptions and simplifications of the proposed damage estimation model. Despite the small differences, the proposed model is observed to work effectively for regional damage estimation.

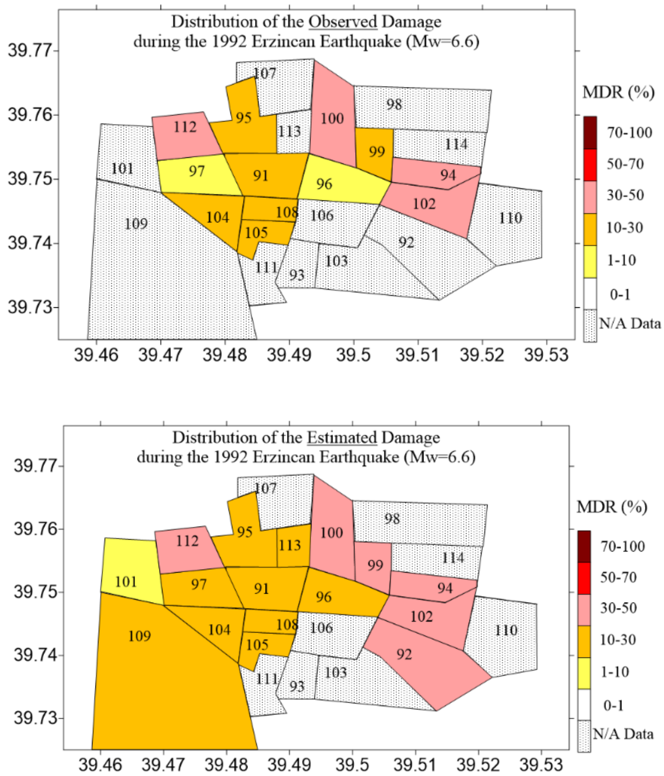

FIG. 7 Distribution of the observed (top panel) and estimated (bottom panel) MDRs in the Erzincan region for the 1992 Erzincan earthquake ("N/A Data" means no building information in those districts where MDR value cannot be calculated. Figure is adapted from [1])

Next, as a prediction exercise, the spatial distribution of damage in the residential districts in Erzincan city center is estimated for a scenario event with Mw=7.0. The result is presented in Figure 8. The epicenter of the 1992 event is kept the same since it creates a critical scenario in terms of damage distribution. As observed in Figure 8, among 16 districts, 6 of them experience severe damage with MDR values between 50% and 100%. The remaining districts are observed to experience moderate damage with MDR values which vary between 10% and 50%. It can be concluded that Erzincan city center is under high seismic risk as a combination of the high regional seismic hazard and vulnerability of the existing building stock.

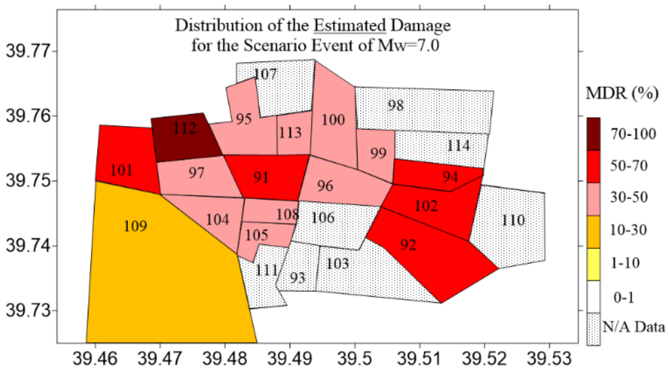

FIG. 8 Distribution of the estimated MDRs in the Erzincan region for a scenario event with Mw=7.0 (Figure is adapted from [1])

7. CONCLUSIONS

In this study, a city-level loss model is presented where potential seismic losses are expressed in terms of regional seismic hazard, local soil conditions and local building vulnerabilities. The verification of the model is performed through comparisons of estimated mean damage ratios for a past major earthquake in the study area with the corresponding observed values. The consistency of the estimated and observed values points out the significance of using locally-derived models for every component of loss estimation process. The predictions for potential scenario events in the region indicate that there is significant seismic threat in Erzincan (Turkey) due to close distances from the nearby active faults, soft soil conditions and vulnerability of existing building stock in the area.

In traditional damage estimation studies, several of the model components (i.e. soil characteristics, ground motions, building vulnerabilities and etc.) are obtained without local data and detailed analysis; or they are directly adapted from other regions with similar seismic or structural properties. The novelty of the proposed damage estimation methodology in this study is that all the ingredients starting from the seismic sources up to the fragility of the structures have been derived within an interdisciplinary framework. In the loss estimation model, only local parameters along with the fundamental principles of engineering seismology and earthquake engineering are employed. Herein, it is tested within a small city center. In the future, it is possible to apply this approach in other seismically active regions. Results of loss estimation studies, when used in practice, can remedy disaster management and risk mitigation.

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