A New Approach to Building Stock Vulnerability Modeling based on Bayesian Analysis

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SUMMARY:
Accurate estimation of the vulnerability of the structural portfolio is critical for effective management of earthquake risks. Vulnerability models are used for estimating the losses that are expected to occur when a given set of buildings is subjected to a specific level ground motion. In this proceeding, a new method for developing vulnerability models is presented. The method is based on establishing empirical vulnerability models by considering post-earthquake damage distributions. It is particularly suited for the building types (e.g. non-engineered or non-seismically designed) which impose difficulties in numerical modeling. An important novelty of the model is the explicit consideration of geospatial variability of the ground motion intensity. As an example case, the method was used in establishing vulnerability models for reinforced concrete moment resisting frame buildings. The damage data from M7.2 Duzce 1999 earthquake was considered in the application. The results confirmed that the using the proposed method vulnerability models for building stocks can be developed by explicitly considering the uncertainties associated with the utilized damage observations.

Keywords: vulnerability modeling, geospatial variability, Bayesian analysis, loss estimation, stochastic simulation

1. INTRODUCTION

Vulnerability modeling is one of the key components in seismic loss estimation. A vulnerability model is a relationship between the ground motion intensity and the level of damage sustained by the set of affected buildings that belong to a specific class. Potential losses can only be accurately estimated if the adopted vulnerability relationships are capable of effectively capturing the actual vulnerability of the considered building stock. Intensity of the ground motion is measured in terms of pseudo-spectral acceleration, peak ground acceleration, peak ground velocity or Modified Mercalli Inentisty (see e.g. Whitman et al. 1973, Singhal and Kiremidjian, 1996, Mosalam, et al. 1997; Akkar et al., 2005; Kırçıl and Polat 2006; Erberik, 2008). The level damage is defined in terms of the parameter that is used in the evaluation of the losses. Damage ratio, structural damage index functions (e.g. Park and Ang, 1985; DiPasquale and Cakmak, 1987) and the duration of loss of functionality, are some of the common damage ratio measures.

In the vulnerability estimation for buildings stocks, vulnerability models are developed for specific classes of buildings. These classes are often defined in general terms of the type of structural system, number of stories, design year, etc. The entire set of possible variations within a specific class of buildings is modeled by introducing a set of random variables. These random variables represent the epistemic uncertainties and aleatory variability related to structural properties, site conditions, as well as characteristics of the ground shaking at the site.

The alternatives for developing vulnerability models may be grouped as: (1) analytical methods (e.g. Singhal and Kiremidjian, 1996), (2) empirical methods (e.g. Rossetto and Elnashai, 2003), (3) expert-opinion based methods (e.g. ATC-13, 1985) and (4) hybrid methods (e.g. Singhal and Kiremidjian, 1998). An overview of these approaches is presented by Porter (2003). The new method proposed in this proceeding can be considered as an empirical method. However, it is important to note that the method can be conveniently extended to be used as a hybrid method without much difficulty. If the base vulnerability models (defined in the next section) are established by means of analytical investigations the approach would directly yield hybrid vulnerability estimates.

The primary advantage of empirical methods compared to other approaches is the fact that they do not rely on assumptions related to analytical modeling of seismic response of the considered structures. Particularly, in the case of non-engineered or non-code conforming structures establishing reliable numerical models is a challenging problem. Empirical approaches on the hand have the limitation of requiring sufficient number of damage data from past earthquakes. This limitation becomes important if a relatively uncommon structural class is of interest in the analysis. Otherwise, past damage observations can be found for the structural class and these can be utilized in the analysis.

A critical issue in the utilization of empirical models is the proper handling of the uncertainties related to damage observations. The actual levels of ground motion intensity that affected the damaged buildings are unknown unless a dense strong ground motion station array is located in the region. In most of the existing approaches, the ground motion intensity that had taken place in the affected sites are assumed to be equal to specific deterministic estimates (e.g. Singhal and Kiremidjian, 1998; Rossetto and Elnashai, 2003). These deterministic values are assumed either by considering the few ground motion stations in the region or by utilizing ground motion prediction models. Due to the utilization of such deterministic estimates, the uncertainty associated with the level ground motion shaking at the site cannot be reflected to the resulting vulnerability models.

A major novelty of the proposed method is the explicit consideration of the uncertainty associated with the ground motion intensities that were experienced by the considered sample buildings. The geospatial correlation in between the ground motion intensities at different sites are also directly taken into account in the proposed method. Another major novelty of the proposed method is its flexibility to allow uncertain damage observations being considered in the analysis. The last important characteristic of the method is its flexibility. Many different types (i.e. functional forms) of vulnerability relationships can be considered using the proposed method. This is achieved by employing discrete random variables in the calculations instead of continuous variables considered in the previous studies (e.g. Singhal and Kiremidjian, 1998).

2. PROPOSED METHOD

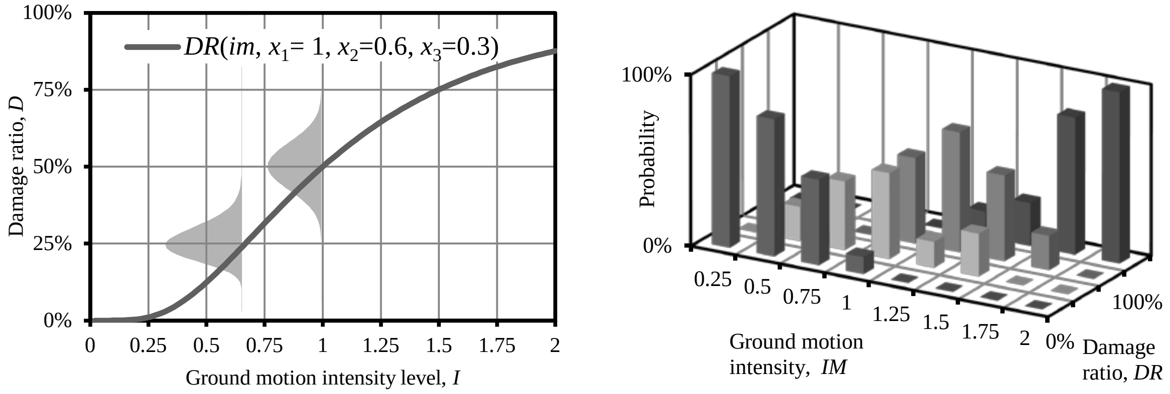
The aim of the proposed methodology is to establish a vulnerability model for a specific class of buildings based on the observed damages to such buildings during past earthquakes. In the context of this method, a vulnerability model is a relationship between the ground motion intensity experienced at the site of the considered building and the damage ratio of the building. Damage ratio is defined as the cost of repairing the damage to the structure divided by the total replacement cost. By definition, this ratio is bounded in the interval from 0% to 100%. Proposed method utilizes the Bayesian analysis approach (Ang and Tang, 1984). First, a set of alternative basis vulnerability models are established. For each model, a prior likelihood is assumed. These prior likelihoods represent the degrees of beliefs assigned to each model. Subsequently, these likelihoods (or degrees of beliefs) are updated based on the damage observations from past earthquakes. Basically, a set of conditional likelihoods are calculated for each basis vulnerability model. *Bayes' Theorem* is utilized in the calculation of these conditioned likelihoods.

2.1 Prior Vulnerability Models

The method is highly flexible in terms of utilizing different prior vulnerability models. In the following, a sample functional form with a relatively simple model representation is presented as a sample case. However, it should be noted that the method is capable of utilizing other functional forms and relationships as well. In this proceeding, the damage ratio DR is assumed to be a random variable represented by a 'logit-normal' distribution model. The mean value of DR is referred to as the mean damage ratio MDR.. The mean damage ratio MDR is assumed to be related to the ground motion intensity level as follows:

$$MDR(im) = \Phi\left(\frac{\ln(im/x_1)}{x_2}\right) \tag{2.1}$$

In the equation above, $\Phi(.)$ is the cumulative standard distribution function and, x_1, x_2 are two of the base vulnerability model parameters. The standard deviation of DR is the 3rd base model parameter. Infinitely many different base vulnerability models may be developed by assuming different values for x_1, x_2, and x_3 in Eqn. 2.1. Hence, vulnerabilities of various building classes with different characteristic can be conveniently represented. First model parameter, x_1 represents the ground motion intensity level at which total cost of the damage is equal to 50% of the total repair cost. The second parameter x_2 is related to the smoothness of the transition into higher damage levels with increasing ground motion intensity. A smaller (e.g. 0.1) x_2 value indicates a sharper transition from smaller damage ratios to greater ones. Model parameter, x_3 is related to the dispersion of DR around the mean value at each ground motion intensity level im. It represents the variability of the damage ratios for the considered group of buildings. A sample vulnerability curve that is obtained by assuming $x_1 = 1$, $x_2 = 0.6$ and $x_3 = 0.3$ is presented in Fig 2.1a. It is important to note the proposed methodology can be applied to any functional form defined by any set of parameters. Functional form in Eqn. 2.1 is only utilized as an example case in this proceeding.



(a) **(b)**

Figure 2.1.Sample base vulnerability model: (a) damage ratio and mean damage ratio (MDR) versus ground motion intensity and (b) a sample set of probabilities $\Pr(D_k|I_l|)$

The fundamental approach proposed here is based on establishing a set of alternative base vulnerability models and estimating likelihoods of each base model conditioned on the observed damage evidence. For the purpose, a set of event are defined. A base vulnerability model M is defined by a given combination of the three parameters x_1, x_2 and x_3. Event M_i represents the case for ith model that is obtained by assuming $x_{1,i}$, $x_{2,i}$ and $x_{3,i}$ respectively. Random variable DR and the actual ground motion intensity A are considered as a set of discrete events D_k and I_l which are defined as follows:

$$D_k = \{dr_k < DR \le dr_{k+1}\} \tag{2.2a}$$

$$I_l = \{im_l < A \le im_{l+1}\} \tag{2.2b}$$

In the definitions above dr_k and dr_{k+1} are the upper and lower bounds of the kth damage ratio interval. Likewise, im_l and im_{l+1} are the upper and lower bounds of the lth ground motion intensity interval, respectively. Using a given base vulnerability M_i, the conditional probability $\Pr\left(D_k \middle| M_i, I_l\right)$ of damage ratio *DR* being in the k^{th} interval given that ground motion intensity I_l can be estimated as:

$$\Pr\left(D_k \middle| M_i, I_l\right) \cong \int_{dr(k)}^{dr(k+1)} f_{DR}\left(z; MDR\left(im_l^*\right), x_3\right) dz \tag{2.3a}$$

$$\text{where } im_l^* = \left(im_l + im_{l+1}\right)/2 \tag{2.3b}$$

In the above equation, $f_{DR}(.)$ is the probability (i.e. logit-normal) density function of the damage ratio *DR*, $MDR\left(im_l^*\right)$ is the median damage ratio evaluated at the mean ground motion intensity level m_l^* of the l^{th} intensity interval. The probability $\Pr\left(D_k \middle| M_i, I_l\right)$ is the likelihood of a building to sustain a damage level that corresponds to k^{th} damage interval given that intensity at the site of the building reaches l^{th} interval, based on i^{th} base vulnerability model M_i.

For a given set of base vulnerability model likelihoods $\Pr\left(M_i\right)$, the marginalized vulnerability model is obtained by making use of the *Total Probability Theorem* as follows:

$$\Pr\left(D_k \middle| I_l\right) = \sum \Pr\left(D_k \middle| M_i, I_l\right) \cdot \Pr\left(M_i\right) \tag{2.4a}$$

$$\text{where } \Pr\left(M_i\right) \cong 1/n_m \tag{2.4b}$$

In the equation above, $\Pr\left(M_i\right)$ is the prior likelihood of (or the prior degree of belief in the) i^{th} vulnerability model representing the actual vulnerability behavior of the considered building class, and n_m is the total number of alternative vulnerability models. The prior estimate in Eqn. 2.4b implies that all alternative base models are be assumed to have equal likelihood. However, depending on the specific preferences any set other set of prior likelihood estimates may be employed as well.

2.2 Damage Observations

In the proposed method, the degrees of belief in the alternative base vulnerability models are estimated on the basis of their agreement with the observed damage evidence. In this proceeding, damage evidence refers to damage distribution information collected for a building stock after an earthquake. Two types of information are considered for each damaged building: (1) ground motion intensity experienced at the site, and (2) the damage ratio for the building. The ground motion intensity is measured in terms of pseudo-spectral acceleration (PSA). Specifically, the PSA for a linear single-degree of freedom oscillator with a natural period of vibration that is in the range of fundamental periods of the considered building stock is considered. The damping of this representative oscillator is assumed to be equal to 5% of critical damping.

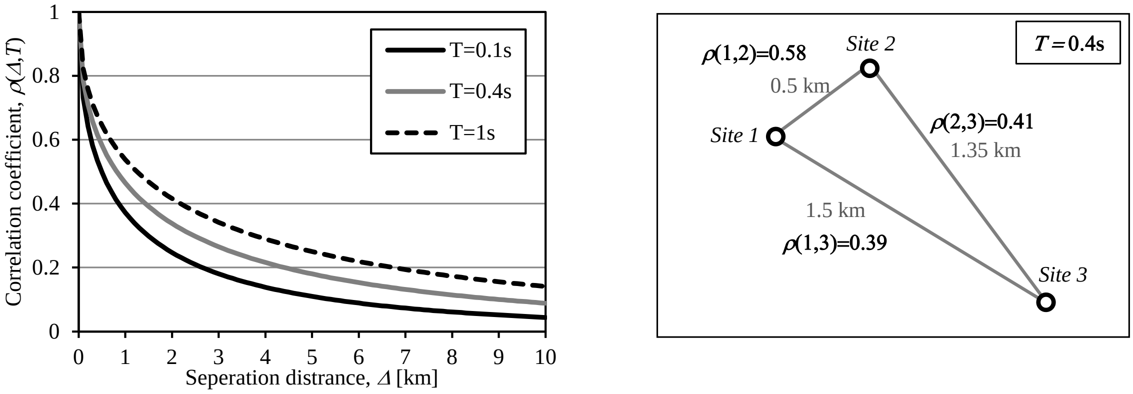
The actual damage ratio of the structure often cannot be precisely estimated easily after an earthquake. The actual cost of repairing a damaged building depends on the optimal repair strategy cost of the adopted strategy, demand surge, etc. However, often a rough estimate of a suitable interval that envelopes the actual ratio (with an error of approximately ±10%) can be obtained relatively easily. In many cases the damage ratios are not reported after damage surveys. Typically a damage grade is reported for each building and this damage grade corresponds to a damage ratio interval. In the proposed method, the damage ratio associated with a considered 'observation' may be represented by a range rather than a specific value. As a result, the uncertainty associated with the actual value of the damage ratio may be directly accounted for in the analysis.

Similarly, the actual level of ground motion experienced at a site during an earthquake may only be estimated probabilistically unless a functioning strong motion station is located at the close vicinity of the site. A known approach for estimating the level of shaking at a site after an earthquake is the ShakeMap approach by Wald *et al.* (2006). In this approach, the ground motion levels experienced at a specific site is estimated by considering the characteristics of the causative seismic event, properties of the site of interest and the accelerations measured at the nearby strong motion stations. The procedure to estimate the ground motion intensities at a group of sites affected by an earthquake is presented by Park *et al.* (2007). The estimates are first made using suitable ground motion prediction models (GMPMs). Subsequently, these estimates are conditioned on the measured accelerations using geospatial variability models such as the model by Goda and Hong (2008) (Fig 2.2). Any of these models may be adopted in the proposed method. Using a GMPM, the acutal ground motion intensity level (i.e. PSA) at a specific (i.e. 'site *j'*) can be estimated using a relationship as followings:

$$\ln\left(A_j\right) = g\left(e, s_j\right) + \tilde{\sigma}\tilde{\varepsilon}_j \qquad (2.5a)$$

$$\text{where } \tilde{\sigma} = \sqrt{\sigma^2 + \tau^2} \qquad (2.5b)$$

In the relationship above, A_j represents the ground motion intensity level (i.e. PSA) experienced at the site-*j*, $g(.)$ is the GMPM function that is used to estimate the natural logarithm of the median $A_{j,}$ at the j^{th} site, e represents GPMPM model parameters related to the causative seismic event, s_j represents GMPM model parameters for 'site j', $\tilde{\sigma}$ is the total logarithmic standard deviation of the estimated PSA estimated at the site, $\tilde{\varepsilon}_j$ is the standard normal random variable representing the total error associated with the estimated PSA, σ and τ are the standard deviations associated with the intra-event and inter-event variability of the error, respectively. Inter-event variability of error associated with the estimated PSA is due to the intrinsic differences in between different seismic events. On the other hand, the intra-event variability represents the variability of the errors in the estimated PSA at different sites during a given earthquake.



(a) (b)

Figure 2.2 Geospatical PSA variability: (a) model by Goda and Hong (2008), (b) sample intra-event residual correlation coefficients for T=0.4s

Actual level of shaking at a set of sites can be probabilistically modeled as a set of jointly distributed normal random variables ($\ln(A_1)$, $\ln(A_2)$, …, $\ln(A_n)$). Means, standard deviations and correlation structures of these random variables can be conditioned on the ground motions measured by the strong motion stations in the region (see Park *et al.*, 2007). Using these parameters, sets of stochastic simulations are made using these mean, standard deviation and correlation matrices (see Sokolov and Wenzel, 2011). Each stochastic simulation S results in a set of randomly generated acceleration realizations (a_1, a_2, .. ,a_n) for the sites of observation. For a given simulation S_r, The probability $\Pr\left(I_l \middle| O_j, S_r\right)$ of ground motion intensity level at site O_j being in the intensity interval I_l is simply identified as follows:

$$\Pr\left(I_l \middle| O_j, S_r\right) = \begin{cases} 1 & \text{if } im_l < a_j \leq \ im_{l+1} \\ 0 & \text{elsewhere} \end{cases} \tag{2.6}$$

In the relationship above, im_l and im_{l+1} are the upper and lower bounds of the 'intensity interval *l*', a_j is the randomly simulated acceleration value at site-*j* based on the probability distribution estimated for the random variable A_j and the stochastic simulation S_r.

The probability distribution the damage ratio is assigned for each observation based on the extent of structural damage in proportion to the total replacement cost. If the specific interval of the damage ratio can be identified, a likelihood of one is assigned to the corresponding event (i.e. $\Pr\left(D_x \middle| O_j\right) = 1$) and zero likelihood is assigned to all the other events (i.e. $\Pr\left(\overline{D_x} \middle| O_j\right) = 0$). Otherwise, any suitable distribution (e.g. uniform, log-normal) model that captures the uncertainty associated with the actual damage ratio may be adopted.

2.3 Updated Vulnerability Model

The base vulnerability model likelihood $\Pr\left(M_i \middle| O_j\right)$ that is conditioned on a specific damage observation O_j at the affected 'site j' are calculated using the *Bayes' Theorem* as follows:

$$\Pr\left(M_i \middle| O_j\right) = \sum_r \sum_k \sum_l \frac{\Pr\left(D_k \middle| M_i, I_l\right) \cdot \Pr\left(M_i\right)}{\Pr\left(D_k \middle| I_l\right)} \Pr\left(D_k \middle| O_j\right) \cdot \Pr\left(I_l \middle| O_j, S_r\right) \Pr\left(S_r\right) \tag{2.7a}$$

$$\text{where} \quad \Pr\left(D_k \middle| I_l\right) = \sum_n \Pr\left(D_k \middle| M_n, I_l\right) \Pr\left(M_n\right) \tag{2.7b}$$

$$\Pr\left(S_r\right) \cong 1/n_s \tag{2.7c}$$

In the equation above $\Pr\left(M_i \middle| O_j\right)$ is the likelihood of M_i conditioned on evidence O_j, $\Pr\left(M_i\right)$ and $\Pr\left(M_n\right)$ are the prior likelihoods assigned for the base vulnerability models M_i and M_n, $\Pr\left(D_k \middle| O_j\right)$ and $\Pr\left(D_k \middle| O_j, S_r\right)$ are the probability distributions defined in the previous sub-section, $\Pr\left(S_r\right)$ is the likelihood assigned to stochastically simulated ground motion intensity realization S_r, and n_s is the total number of stochastic simulations.

Conditioning of the vulnerability model likelihoods only one observation O_1 (i.e. related to a single damaged building) would not yield sufficiently reliable estimates since the result would be biased by the specific details of that particular building. In order to prevent such a bias, it is always desirable to consider large numbers of damage observations. For calculating model likelihoods by jointly considering multiple observations (i.e. O_1, O_2,…, O_n.), Eqn. 2.7 can be used recursively. In other words, first the probability $\Pr\left(M_i \middle| O_1\right)$ conditioned on observation O_1 at 'site 1' is obtained using Eqn. 2.7. After that, the same equation is used again but this time the prior likelihoods $\Pr\left(M_i\right)$ are replaced with the conditional likelihoods $\Pr\left(M_i \middle| O_1\right)$ both in the nominator and the denominator. As a result, the set of likelihoods $\Pr\left(M_i \middle| O_1, O_2\right)$ conditioned on the two observations from the two sites are obtained. This process can be repeated for the entire set of available damage observations (O_1, O_2, …, O_n). Event O represents the joint set of all considered damage observations related to the considered building class:

$$O = \left\{O_1 \cap O_2 \cap \ldots \cap O_n\right\} \tag{2.8}$$

The vulnerability model for the building class conditioned on this joint set of observations O is obtained as follows:

$$\Pr\left(D_k \middle| I_l, O\right) = \sum_i \Pr\left(D_k \middle| M_i, I_l\right) \cdot \Pr\left(M_i \middle| O\right) \tag{2.9}$$

In the equation above, $\Pr\left(D_k \middle| I_l, O\right)$ is the likelihood of a building sustaining a damage ratio that is in the k^{th} damage interval given that ground motion intensity is in the l^{th} intensity range, and $\Pr\left(M_i \middle| O\right)$. This final vulnerability model can be used as the best-estimate for the vulnerability of the building stock.

3. APPLICATION OF THE METHOD

Proposed procedure was utilized in developing a vulnerability model for 4 story reinforced concrtete (RC) moment resisting frame buildings in Duzce. A set of 25 buildings that belonged to this class were selected from the building damage database by SERU-METU (2003). In this database, structural properties as well as the damage grades are reported for a large group of RC buildings that were affected by the M7.2 Duzce - Turkey 1999 earthquake. The buildings from this database are considered as the ‘damage observations’ in this sample application. The geographic coordinates and damage grades of the buildings were identified from the database. Reported damage grades were converted into damage ratios based on the assumed approximate intervals listed in Table 3.1. For each observation, the actual damage ratio value *DR* was assumed to be uniformly random variable in the damage ratio range depending on the damage grade of the building. The entire range of damage ratios *DR* from 0 to 100% was discretized into intervals with 5% increments in order to define the discrete D_k intervals. As a result, the set of probabilities $\Pr\left(D_k \middle| O_j\right)$ were obtained for each of the considered buildings.

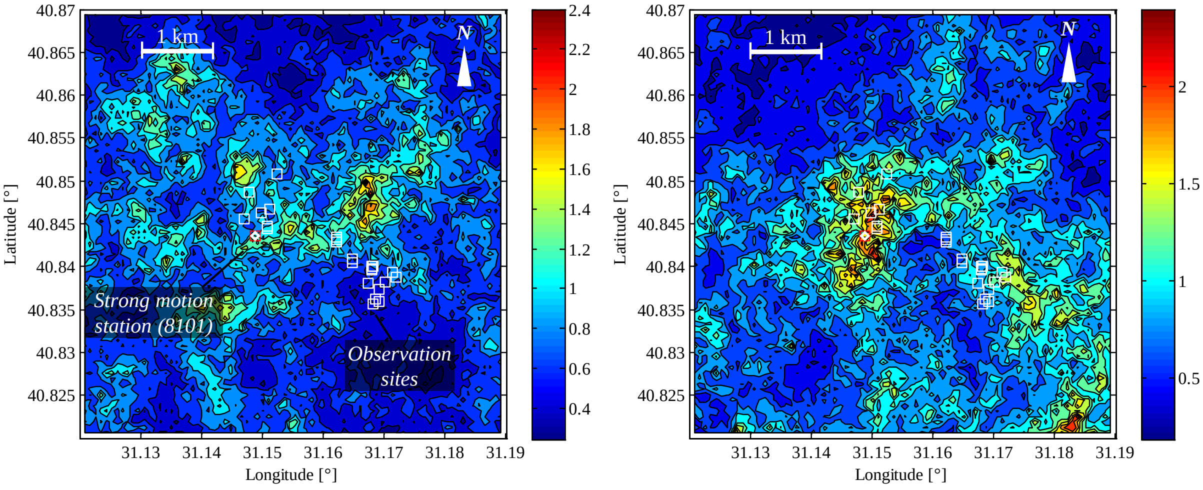
Table 3.1 Intervals of damage ratios assumed for the damage grades in the database

Damage grade	N	N/L	L	L/M	M	M/S	S
Damage ratio	0%-5%	0%-10%	5%-10%	5%-30%	20%-50%	40%-80%	70%-100%

The pseudo-spectral acceleration PSA(T=0.4s, ζ=5%) of a single degree of freedom system with 0.4s natural period of vibration and 5% critical damping considered as the measure of ground motion intensity. The GMPM proposed by Campbell and Bozorgnia (2007) was utilized to estimate the PSAs experienced during M7.2 Duzce earthquake at the sites of the considered buildings. The average shear wave velocities (V_{s30}’s) at the sites were estimated using the data provided in USGS Global Vs30 server (Allen and Wald, 2009). The rupture plane model by Delouis et al. (2004) was used in the calculation of the source-to-site distances to be used in the ground motion intensity estimations.

The geospatial variability of the PSAs over the considered sites in Duzce was modeled using the correlation model proposed by Goda and Hong (2008). The intra event and inter event variability were found to be equal to approximately 0.5 and 0.2, respectively. The site-to-site correlation coefficients were the same with the plot presented in Fig 2.2a (2nd series). The ground motion measurements at the Duzce Meteorological Station – Strong motion station (ID# 8101) were considered as the conditioning measurements (AFAD, 2012). The geometric mean of PSAs for the two horizontal components recorded at this station during the M7.2 Duzce 1992 earthquake is equal to 1.41g. This measurement was used as a conditioning value in the stochastic simulation of the PSAs at the considered sites (see Park et al. 2007). Two of the stochastically generated PSA distributions are plotted in Fig 3.1. In these figures, the locations of the considered observation buildings are marked with white ‘□’ symbol and the location of the strong ground motion station is indicated with a red ‘◊’ symbol. Note that in each simulation the PSA value corresponding to the site of the ground motion station is equal to 1.41g (i.e. value measured during Duzce earthquake). The likelihood $\Pr(I_l|O_j,S_r)$ of PSA at the site of the observation O_j reaching intensity level I_l was identified using Eqn. 2.6. In this sample application, 10 different stochastic realizations $S_1 - S_{10}$ were considered. Each stochastic realization were assumed to be equally likely (i.e. $\Pr(S_r)$=0.1). It is also worthwhile to note that different GMPM and geospatial variability models may be employed in the different if desired.

The proposed method can be utilized by considering large number of alternative base vulnerability models simultaneously. For the sake of brevity however, only 4 alternative models were considered in this sample application. Models parameters x_1, x_2 and x_3 assumed for these alternative models are listed in Table 3.2. The prior likelihoods and the estimated conditioned likelihoods are listed in the same table as well. Each of the considered alternative models are assumed to have equal prior likelihoods (i.e. $\Pr(M_i) = 0.25$).



(a) (b)

Figure 3.1. Sample stochastically simulated pseudo spectral acceleration PSA(T=0.4s,5%) realizations for Duzce: (a) realization 3, and (b) realization 8 (units in [g])

The conditioned likelihoods that are obtained using the proposed method are listed in the 5th, 6th and 7th columns of Table 3.2. For each model, three conditioned likelihoods $\Pr(M_i|O_{1-3})$, $\Pr(M_i|O_{1-10})$ and $\Pr(M_i|O)$ are listed which are the results obtained considering 3 buildings, 10 buildings and entire set of buildings, respectively. Based on the results, it can be seen that the likelihood assigned to Model 4 for is found to be the highest for the considered sets of observations. Similarly, Model 3 is found to be the second most likely model. The likelihood assigned to Model 1 reduces to zero very rapidly. On the other hand, a more gradual decrease is observed for the case of Model 2.

Table 3.2. Base vulnerability models and the estimated likelihoods

Model	Model parameters			$\Pr(M_i)$	$\Pr(M_i\|O_{1-3})$	$\Pr(M_i\|O_{1-10})$	$\Pr(M_i\|O)$
	x_1	x_2	x_3				
1	0.3	0.4	0.3	0.25	0	0	0
2	0.6	0.45	0.3	0.25	0.040	0.102	0
3	1	0.6	0.3	0.25	0.276	0.357	0.211
4	1.5	0.76	0.3	0.25	0.684	0.541	0.789

In order to establish the updated vulnerability model, the base vulnerability models and the conditional probabilities $\Pr(M_i|O)$ can be inserted into Eqn. 2.9 to establish the 'best estimate' of the vulnerability for the 4-story RC frame buildings in Duzce.

4. SUMMARY AND CONCLUSIONS

A new method to develop vulnerability models for building stocks is presented. The method can be used for establishing probabilistic vulnerability models for buildings by considering past damage observations. The method is based on Bayesian analysis approach. Initially, a set of prior likelihoods are assumed for the considered alternative vulnerability models. After that, these likelihoods are updated based on the damage observations. The uncertainties related to the actual levels of shaking experienced by the affected buildings are directly taken into account in the method through explicit modeling of the geospatial variability of the ground motion intensity. Proposed approach was applied to develop vulnerability curves for reinforced concrete frame buildings damaged during the M7.2 Duzce 1999 earthquake. The results from this sample application confirmed the effectiveness of the method as well.

Following conclusions can be drawn related to the proposed method and its sample application:

- The methodology is very flexible in terms of the basis vulnerability model. Any function can be utilized in the analysis.

- The uncertainty associated with the actual level of ground motion intensity experienced at the site can be explicitly taken into account in the proposed modeling approach. Hence, deterministic assumptions such as assuming all accelerations at entire region to be equal to median GMPM estimates or the measurements from sparsely located strong motion stations.

- The geospatial variability of the acceleration can be explicitly modeled in the proposed method. This allows taking into account both the measured accelerations as well as the cross correlations among the different damage observation sites. Therefore, the potential biases arising from the considered damage observations are all in the close proximity of each other, are prevented.

- The uncertainty associated with the actual level of damage ratio can be explicitly taken into account in the proposed method. As a result, uncertain damage observations may be incorporated in the analysis without introducing any deterministic assumptions related to the actual extent of damage.

- Promising results were obtained from the example application of proposed method to RC frame buildings in Duzce. The results showed that the likelihoods (i.e. degrees of belief) associated with alternative models were updated after the damage evidence was considered. Higher likelihoods were obtained for the 4th base model (*Model 4*) which was found to have a better performance in terms of predicting the damages that were observed in the affected area.

The vulnerability models established using the proposed framework may be implemented into seismic risk assessment tools. This would lead to estimating the level of seismic risk to a considered class of buildings directly by taking into account both the past damage observations and the uncertainty associated with these observations. The loss estimates obtained based on proposed approach are expected to provide more reliable estimates of the actual seismic risk compared to those obtained using conventional vulnerability modeling approaches.

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