MITIGATION STRATEGIES FOR REGIONAL LOSS ASSESSMENT

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Abstract: In recent years, there has been a surge of interest in analyzing seismic impacts on a regional basis. The regional approach is especially apropos in regions of low-to-moderate seismicity, where the risk to individual structures is not sufficient to justify extensive analyses and proactive mitigation in the minds of many stakeholders. However, the aggregate effects across a study region for low-probability, high-consequence events justify investigations and planning at the regional level. The shift toward studying regional effects has also been propelled by the development and integration of tools to address the various aspects of seismic risk and loss within GIS environments. One example of these activities is the Consequence-Based Risk Management approach adopted by the Mid-America Earthquake Center, including the development of refinements for various stages of seismic risk assessment and integration within the open source, GIS-based environment of MAEViz. This paper will address approaches and concerns available to equip and assist decision-makers when assessing loss across large regions by illustrating applications to a regional test bed investigated using MAEViz.

1. INTRODUCTION

In regions of low-to-moderate seismicity, many stakeholders do not find the risk to exposed assets to be sufficient to justify extensive analyses and proactive mitigation efforts. However, in such areas, the potential exists for infrequent but large magnitude events, capable of simultaneously causing extensive damage to buildings, transportation networks, and utilities. Even in regions of high seismicity, the regional response to an unusually strong event has only recently become the focus of large scale investigations.

A number of regional studies have been conducted and reported in published literature for various locations worldwide. In the United States, studies have been documented for six individual cities in the New Madrid Seismic Zone (NMSZ) of Mid-America (CUSEC, 1985). A study was also performed in greater detail specifically for Memphis, TN (Abrams and Shinozuka, 1997). FEMA has developed a loss assessment tool, HAZUS (FEMA, 2006), which has been updated and expanded through multiple releases since 1997. HAZUS has been employed for several documented studies, including commercial studies, such as Charleston, SC (URS, 2001), Northridge, CA (Reis et al., 2001), a repetition of the NMSZ six-city study by CUSEC (2003), Seattle, WA (Ballantyne et al., 2005), and an eight state study of the New Madrid Seismic Zone (Elnashai et al., 2008).

Numerous other commercial studies have been conducted worldwide, some of which have been performed by professional risk assessment firms using proprietary software. Among studies within academic research, notable published studies for losses on a regional scale include papers focusing heavily on western Turkey, as well as other Mediterranean areas such as Italy (e.g., Bal et al., 2008; Erdik et al., 2008; Teramo et al., 2008; Spence et al., 2008). Much of this work serves to form background and establish general guidelines of good practice when performing regional loss assessment. Strategies for decision-making and prioritizing mitigation efforts are not yet uniformly well established. This paper outlines a comprehensive procedure for regional loss assessment and decision support based on integration of several new algorithms within the open source, GIS-based environment of MAEViz (MAEViz, 2008), using Shelby County, TN (including Memphis, TN) in the USA as a case study.

2. INITIAL RISK ASSESSMENT

2.1 General Approach

The core components of the regional seismic risk assessment in this work include: inventory collection, hazard definition, vulnerability assessment, and estimation of social and economic consequences. Each step as established within this work will be described in greater detail in the following sections.

2.2 Inventory Collection

Inventory information for Shelby County, TN was collected for buildings and bridges in the study region from several sources. Building-by-building data was acquired specifically for this study by extrapolating from tax record data through a neural network model, calibrated by surveys of sample buildings in the study region (French and

Muthukumar, 2006). Demographic information was extracted on a census track-basis, and disaggregated as required for algorithms that mesh with demographic data. Example statistics for buildings within the study region are shown in Tables 1 and 2 (French and Muthukumar, 2006). The Tables show concentrations of exposure (replacement value) for combinations of general structure types and general occupancies. C, M, S, and W represent concrete, masonry, steel, and wood, respectively. Likewise, RES, COM, and IND indicate residential, commercial, and industrial occupancies. Agricultural, religious, government, and educational buildings are not shown; even excluding single-family structures, those occupancies only account for about 0.4% of the study region exposure according to the dataset. Bridge data for the study region was obtained from the National Bridge Inventory (FHWA, 2007).

Table 1 Example Exposure Data for Study Region, Including Single-Family Residences

		GENERAL OCCUPANCY			
		RES	COM	IND	Grand Total
GENERAL STRUCTUR TYPE	C	0.8%	6.7%	2.8%	10.4%
	M	2.4%	3.9%	0.5%	6.8%
	S	1.0%	6.5%	1.0%	8.5%
	W	73.8%	0.5%	0.0%	74.3%
	Total	78.0%	17.6%	4.3%	100.0%

Table 2 Example Exposure Data for Study Region, Excluding Single-Family Residences

		GENERAL OCCUPANCY			
		RES	COM	IND	Grand Total
GENERAL STRUCTUR TYPE	C	2.7%	23.0%	9.6%	35.4%
	M	8.1%	13.4%	1.8%	23.4%
	S	3.4%	22.2%	3.3%	29.1%
	W	10.3%	1.8%	0.0%	12.2%
	Total	24.5%	60.4%	14.7%	100.0%

2.3 Hazard Definition

The study region under consideration is subject to a potentially large seismic hazard with a long recurrence interval. To appreciate the consequences of such hazards, a probabilistic hazard approach is not likely to provide a fair representation. The probabilistic hazard will provide a long-term view of seismic hazard, taken over a time interval that may span hundreds or thousands of years, but the approach effectively smoothes the spike of activity that potentially characterizes this region.

To capture the true nature of a low-probability, high-consequence event, a seismic source was selected consistent with the historical seismology of the region. The magnitudes of the 1811-1812 earthquakes are generally estimated to be ranging from moment magnitude 7.0 to 8.1 (Petersen et al., 2008). For this study, a moment magnitude of 7.9 was selected and located at Blytheville, AR, based on guidance provided by geotechnical experts within the Mid-America Earthquake Center. Appropriate formulae were then employed to predict the effects of the seismic source throughout the study region. Attenuation equations developed by Fernandez and Rix (2006) were selected to account for the particular seismological characteristics of this region.

When smoothed spectra based on the USGS attenuation functions and soil adjustment coefficients recommended by the U.S. National Earthquake Hazard Reduction Program (NEHRP) are compared with spectra associated with the two representative soil profiles (“Uplands” and “Lowlands”) in the study region considered by Fernandez and Rix (2006), the most significant difference between the two sets of curves is that the NEHRP coefficients generally assume that soil deposits will amplify ground accelerations, whereas the Fernandez and Rix equations implicitly account for nonlinearity in deep soil deposits, such as the 1000 m thick layer underlying Memphis, TN, thus leading to lower acceleration and higher displacement response of surface soils.

2.4 Vulnerability Assessment

There are a number of ways that vulnerability may be assessed for buildings in a study region. The methodologies employed in the various studies mentioned previously vary widely in their vulnerability assessment. HAZUS uses an overdamped capacity spectrum method (CSM) approach (FEMA, 2006), in which a linear elastic acceleration-displacement spectrum is adjusted to account for hysteretic response of a structure by adding “effective hysteretic damping” to elastic damping. Plotting the adjusted hazard spectrum superimposed with a capacity curve and finding the point of intersection, termed the performance point, is expected to yield a reliable prediction of building displacement response when subjected to an earthquake. The methodology has remained unchanged in every release of HAZUS, however, Fajfar (1999) cites discussions in which key assumptions of the overdamped CSM are called into question, most notably including the lack of a “physical principle that justifies the existence of a stable relationship between the hysteretic energy dissipation of the maximum excursion and equivalent viscous damping.”

The risk assessment for the study region in this work was based on nonlinear time history analyses of various structure types. Several structure types were studied by constructing detailed models to capture the numerous complicated aspects inherent in nonlinear seismic response. Fragility functions have been developed for light wood frame construction, both 1- and 2-story structures, and considering both slab-on-grade construction and frames constructed with crawl spaces (Ellingwood, 2006; Ellingwood et al., 2008). Fragility functions have also been developed to represent 2-story and 4-story partially restrained steel moment frames, 3-story fully restrained steel moment frames, and 6-story X-braced steel frames (Ellingwood, 2006). Extensive studies of concrete frames have also been conducted (Bai and Hueste, 2006; Erberik and Elnashai, 2006; Hueste and Bai, 2003; Ramamoorthy et al., 2006).

If a structure type occurred in the inventory for which a fragility set was not available (e.g., reinforced masonry), then a fragility set obtained from the parameterized fragility method (Jeong and Elnashai, 2007) was substituted, which incorporated the expected characteristics for the local ground motion in the study region (Fernandez, 2007). The parameterized fragility method was expanded to consider degradation models, as well as provide nonstructural fragilities in addition to structural fragilities, as described in Steelman and Hajjar (2008). In addition to the adjustments made in that paper, several parameters were adjusted prior to invoking the parameterized fragility engine for this study. Elastic damping ratios were generally reduced to reflect common estimates found in the literature. Also, uncertainty parameters were calculated as a combination of modeling and capacity uncertainty terms obtained from the HAZUS Technical Manual (FEMA, 2006), and demand uncertainties arising from variability in response to ground motion records. Finally, appropriate bridge fragilities were also implemented to represent bridge construction typical of the Central and Eastern US (Choi et al., 2004; DesRoches et al., 2003; DesRoches et al., 2006). The required hazard input for each fragility set was determined by the researcher who originally performed each study. All fragilities took the form of a lognormal distribution.

2.5 Social and Economic Loss Estimation

This final component of loss assessment includes consideration of a range of individual metrics related to social and economic loss (Bai et al., 2007; Green and Feser, 2007; Peacock, 2007; Padgett and DesRoches, 2007). Examples include repair and replacement costs of buildings and bridges, injuries requiring hospitalization, fatalities, business losses due to disruption of normal operations, and population dislocation. In each case, probabilities of discrete damage states from the vulnerability assessment are combined with coefficients and demographic data as appropriate to provide estimates of losses. Sample aggregated results for the case study scenario are given in Table 3.

Table 3 Initial Risk Assessment Summary

Buildings Repair / Replacement	$4.80 x10^9$
Bridges Repair / Replacement	$10.6 x10^6$
Hospitalizations	984
Fatalities	188
Business Interruption	$964 x10^6$
Business Inventory Damage	$83.8 x10^6$
Displaced Households	14,900
Displaced Persons	37,900
% Requiring Short Term Shelter	27.1
Loss of Property Tax Revenue	$42.4 x10^6$

Bridge functionality was also investigated, yielding the results shown in Figure 1. The figure shows that the transportation system is severely impacted by the earthquake, with only 2% of bridges fully operational immediately after the earthquake. Current predictions estimate, however, that many of the bridges that are damaged can be repaired within several days if adequate materials and personnel are available. Similarly to the results shown in Table 3, functionality estimates for the bridges are based on direct correlation from damage output of the vulnerability assessment.

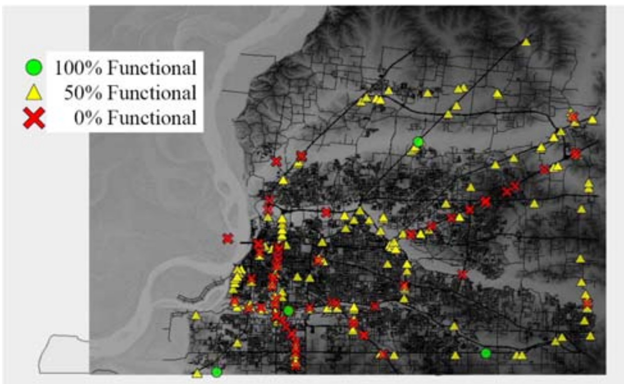

Figure 1 Bridge Functionality Immediately Following Earthquake (28% Non-Functional, 70% @ 50% Functional)

3. MITIGATION PLANNING

3.1 Planning Based on Direct Effects

For the case study region, two methods of mitigation planning and prioritization (i.e., decision support) were employed: Comparative Equivalent Cost Analysis (ECA) and Multi-Attribute Utility Analysis (MAUA). Applications of each framework were carried out as described in Park (2004). The ECA is a relatively simple technique, where the primary calibration involves assigning dollar values to certain key commodities that do not inherently have a dollar value associated with them, such as a human casualty. For this study, estimates were developed based on forensic economic literature (Dillingham, 1985; Hahn, 1996; Karels, 2003; Miller, 1990; Viscusi, 1993), so that a death was estimated to be worth approximately $8.5 million, and an injury was estimated to be worth $1 million.

Additional required data to perform the ECA include vulnerability data for retrofit options and some method of estimating costs to install retrofits. The approach used for these scenarios was to develop additional fragility sets using the parameterized fragility method, as described previously, including implementing parameters (e.g., strength ratio, period) tabulated for higher (i.e., improved) “code levels” in the HAZUS documentation. Costs were estimated for these retrofits based on FEMA 156/157 (FEMA, 1994; FEMA, 1995) as described in Steelman and Hajjar (2008). The optimum retrofit assignments were calculated for each building in the study region, based on maximizing the cost-benefit ratio and ensuring that only ratios greater than one were acceptable.

The cost to install all optimum retrofits is $602 million. However, when reviewing the results at the building level, a subset of buildings is found to provide exceptionally high benefit in return for the required investment. A group of eight hospitals provide benefit-cost ratios in excess of 40. The selected hospital locations are indicated in Figure 2 as white circles overlaying a map of hospitalizations by tract. The total cost to retrofit this subset is estimated at $10.5 million, but the total projected benefit is $555.6 million. This subset of buildings also happens to share the same structure type: steel frame. Although not explicitly considered algorithmically, the selected subset may potentially permit the use of similar retrofit designs and details for multiple buildings.

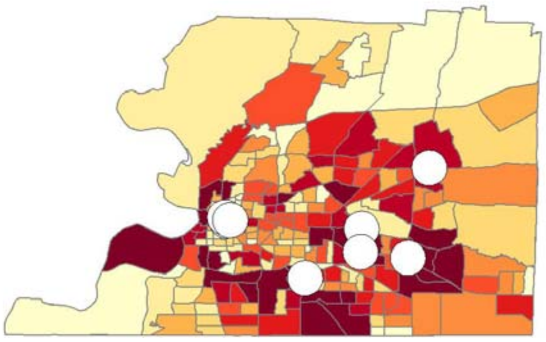

Figure 2 Selected Retrofits according to ECA

The MAUA , in turn, seeks to quantify performance parameters of the region in a relative "utility" sense. In this context, utility may be viewed as an indicator of satisfaction. The maximum value is 1, and this is assumed to be the value for the study region prior to the earthquake. As repair costs increase and casualties mount, the utility drops. The utility function can be any non-increasing function desired by a decision-maker. For this case study, two functions were implemented to reflect two risk attitudes: a cubic function to represent a risk-averse attitude, and an exponential to represent a risk-seeking attitude. Both curves satisfy the requirements of bounding utility by 0 (0.001 for Risk-Seeking) and 1. The Risk-Averse attitude is characterized by a desire to avoid high-risk, defined as scenarios for which utility is near zero. Thus, the maximum gradient of utility perceived by a Risk-Averse decision-maker occurs as the estimated losses near low utility values. The Risk-Seeker, in turn, would perceive little difference between alternatives or low utility values. Utility functions for each attitude are shown in Figure 3.

The limit parameters for the analyses were determined by scaling and calibrating from published losses for the 1994 Northridge earthquake. Limits of 621 persons killed, 3249 persons injured, and a total economic loss of $4.8 billion were used to establish thresholds of zero utility. Optimum retrofits were established for these cases by computing a change in utility for the region resulting from installation of a retrofit, and then normalizing that change in utility for the study region by the cost of the retrofit. The decision-making influences were also varied as part of the study by considering four cases. To calculate utility for a region, the individual utility values are weighted and summed, so the relative influences of various concerns can be incorporated by scaling weighting factors. The four cases considered, with values established in this work, were: (1) 0.25 weight for economic loss, injuries, fatalities, and loss of essential facility functionality, (2) 0.85 weight on economic loss, (3) 0.45 weight on each of injuries and fatalities, and (4) 0.85 weight on essential facility functionality. Figures 4 and 5 show optimum retrofits based on utility gradient for cases 2 and 3, respectively.

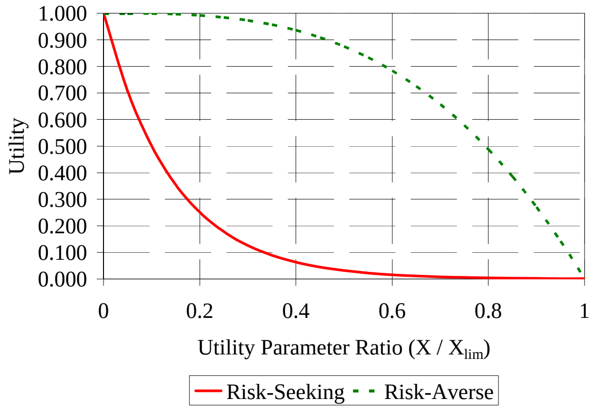

Figure 3 Utility Functions for MAUA

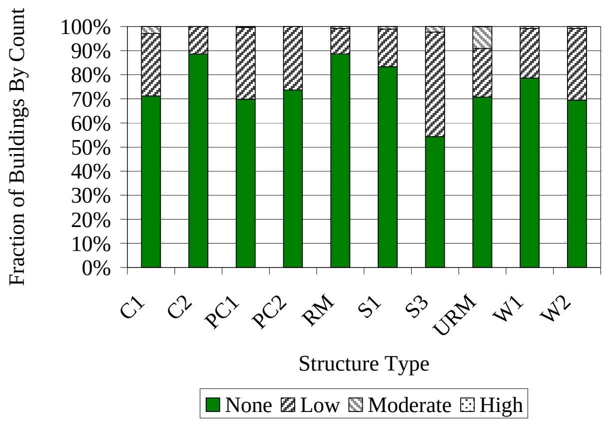

Figure 4 Optimum Retrofit Code Level for MAUA Case 2

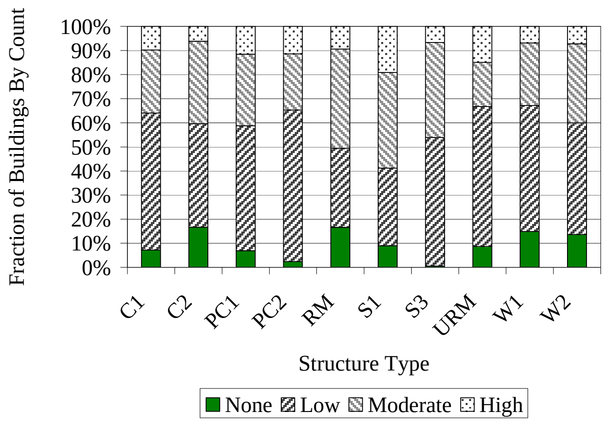

Figure 5 Optimum Retrofit Code Level for MAUA Case 3

The results in Figure 4, in particular, are fairly similar to the ECA result. As shown in Figures 4 and 5, the weight attributed to the value of life by a decision-maker has a pronounced effect on the result of the analysis. The calculations that lead up to the risk assessment, combined with the calculations for the various retrofit options for each structure are computationally intensive, but the final output, in this case, provides direct guidance for the most attractive retrofit options for each structure in the region.

3.2 Planning Based on Multi-Level Interactions

Planning based on multi-level interactions is suited to the current GIS platforms commonly employed for regional seismic risk assessments. One example would be to include consideration of bridge and hospital functionality in casualty estimation. The visual representation of such concerns becomes highly complex and difficult to discern, as in Figure 6, however, the current state-of-the-art is poised to leverage the advantage of GIS to enable these considerations to be considered within the decision framework.

For example, in Figure 6, a primary area of concern would be the northeast region. There is only one hospital nearby, and that hospital is projected to sustain heavier damage than most other hospitals in the region. Decreased functionality of that hospital, combined with extensive damage to the bridges along the primary route providing access to the hospital, leads to a compelling argument to focus mitigation efforts in that geographic region.

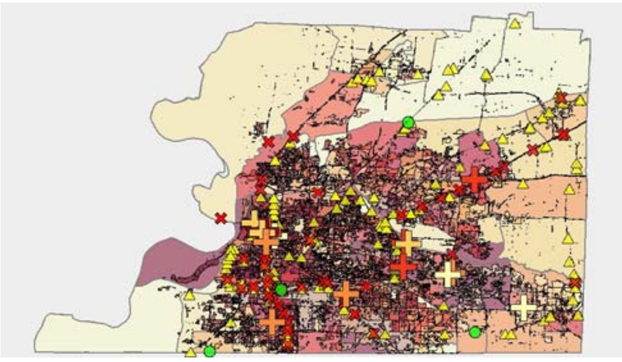

Figure 6 Multi-Level Representation of Injury Risk Factors

4. CONCLUSIONS

Two algorithms suited to evaluating competing retrofit options based on direct effects were presented. The primary consideration for both algorithms is to select suitable decision weights. This presents decision-makers with a conundrum when requiring the assignment of definitive values and influence to considerations of human life, pain, and suffering. However, reasonable values can be estimated from forensic literature and incorporated into regional seismic risk assessments to arrive at justifiable retrofit strategies. Furthermore, the utilization of point-wise inventory allows the prioritization, building-by-building, as a part of the retrofit plan.

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