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THE USE OF INSURANCE AND OTHER POLICY INSTRUMENTS IN MANAGING CATASTROPHIC RISK

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SUMMARY

The purpose of this research is to examine the role of the public and private sectors in managing catastrophic risks from natural hazards. Using the study region of Oakland, California, residential structures in the community are subject to a series of earthquake events. Losses are generated using the HAZUS software issued by the Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS) of the United States. The effects of insurance deductibles and limits, the role of mitigation for the hazard, and the uncertainty in the earthquake loss estimation process are all evaluated in understanding and potentially reducing losses.

INTRODUCTION

The on-going work presented in this paper utilizes the methodology of the HAZUS software [NIBS, 1997] with additional software modules and a logic tree approach to systematically look at the impact of varying parameters and models on the final estimates of loss to portfolios of residential structures. Losses are defined in terms of an exceedance probability (EP) curve (*i.e.* probability that economic loss is greater than or equal to a particular value, *L*). Specifically, the frequency of earthquake events, attenuation models for ground shaking, soil parameters, and exposure and vulnerability of residential structures are all considered in the large-scale sensitivity analysis. Additionally, a methodology to incorporate expert opinion on the costs and benefits of structural mitigation into the seismic risk assessment is introduced. The goal is to ascertain the parameters and models that are most influential in the catastrophic loss estimation process. Both the homeowner and the insurer perspectives are considered in generating results from the analysis.

The paper is broken down into the following sections. First, the HAZUS methodology and pre-processing and post-processing software modules used for analysis are discussed. Next, the study region of Oakland, California, is defined, including the residential building stock and structure type considered for mitigation. Third, the sensitivity analysis parameters are summarized, including the methodology used to incorporate the use of structural mitigation into the analysis. Finally, some preliminary results on the effects of uncertainty on losses to homeowners and insurers for various deductible and limit levels are offered and conclusions are drawn.

EARTHQUAKE MODEL

The earthquake loss estimation (ELE) methodology can be discretized into four basic stages: (1) *define the earthquake hazard*, including seismic sources, earthquake recurrence and attenuation; (2) *define the inventory characteristics*, such as structure location, value, year built, and occupancy class; (3) *estimate the inventory damage*, through historical loss data, engineering data, and/or expert opinion; and (4) *calculate the economic losses*, such as the expected loss or probable maximum loss (PML) to the homeowner or insurer. The ELE software used for this residential structure portfolio analysis is HAZUS ("Hazards U.S.") with a pre-processor (Scenario Builder) and a post-processor (EP Maker) to generate a series of losses for various scenario-based earthquake events (Figure 1). In this way, a large number of earthquakes believed to be capable of affecting the model city are incorporated into the analysis in the form of a *probabilistic seismic hazard analysis.*

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In defining the earthquake hazard, seismic source determination and the associated earthquake occurrence are established using the pre-processor, Scenario Builder. Sources include a number of strike-slip faults in the Northern California region and events on these fault sources are defined by a Moment Magnitude, event duration, epicenter location and rupture length, based on Wells and Coppersmith [1994]. Two density functions are considered for earthquake magnitude-distribution: a truncated Gutenberg-Richter relation and a characteristic earthquake model, similar to the approach used in previous studies [Peterson et al., 1996a]. The Gutenberg-Richter or exponential magnitude distribution partitions the rate of seismic release on the fault into events between a minimum and maximum magnitude considered damaging to the building stock of the region [*eg.* Anderson and Luco, 1983]. In contrast, the characteristic earthquake model assumes a characteristic or "same-size" earthquake frequency density, banded at or near the maximum magnitude event considered on the fault source [*eg.* Schwartz and Coppersmith, 1984]. Gutenberg-Richter b-values are dependent on the fault source and are developed by members of the research group from Risk Management Solutions, Inc. Occurrence rates for the characteristic model are based on published reports by the USGS [Peterson et al., 1996b].

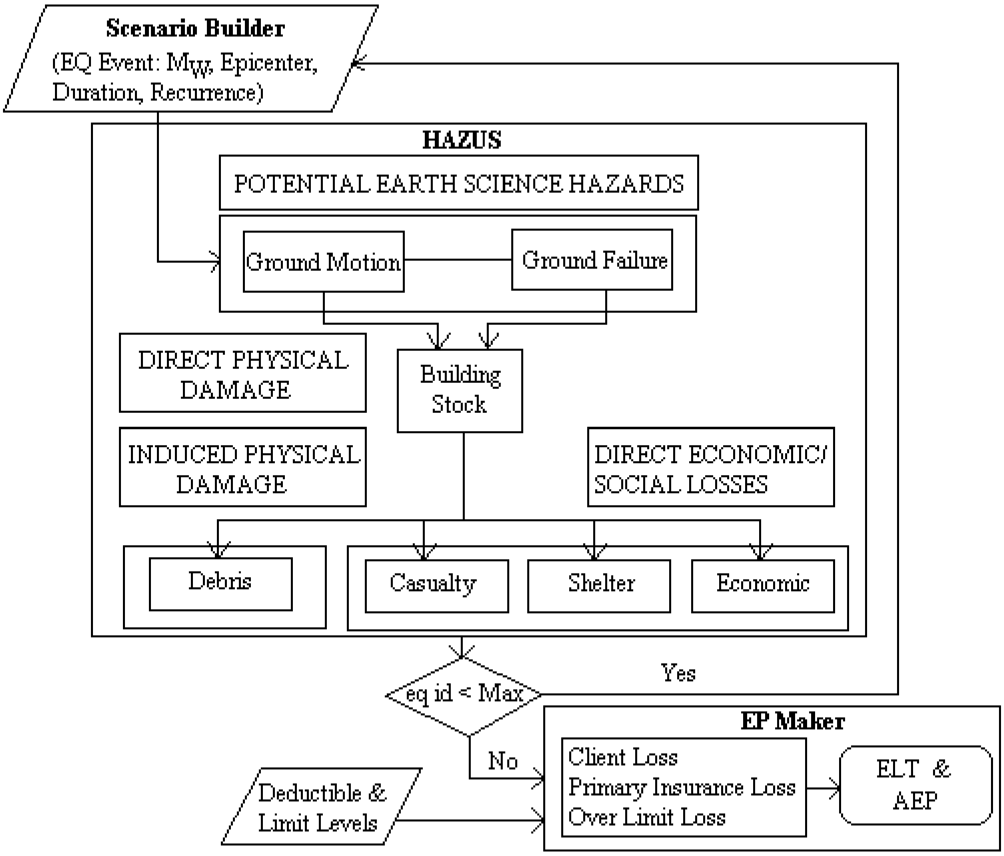

Figure 1: Earthquake Loss Estimation using HAZUS

Attenuation of ground shaking, defining the building stock characteristics of the region, and estimating the physical damage and subsequent losses from the various earthquake events defined in the Scenario Builder are all executed using the HAZUS software. First, the rate at which ground motion decays from fault source to various sites, discretized according to census tracts in HAZUS, can be designated in HAZUS by one of four attenuation relationships for shallow crustal earthquakes (*i.e.* epicenter depth ≤ 10 km) in the Western United States (WUS). These include: Boore, Joyner and Fumal [1993, 1994]; Sadigh et al. [1993]; Campbell and Bozorgnia [1994]; and Project 97, a linear combination of the first three attenuation curves.

The building stock is classified according to its occupancy class (*i.e.* residential, commercial, etc.) and its structure type (*i.e.* wood frame, steel braced frame, etc.). In this way, buildings with similar damage and loss patterns are grouped together in the different census tracts for analysis. Occupancy classifications are used to estimate the typical square footage per structure unit and associated repair and replacement costs per square foot. For example, single family dwellings are assumed to be 1,500 square feet on average and cost approximately $95 per square foot to replace, based on 1999 Means data. Structure type designations are used to estimate the typical building story height and building capacity curve (*i.e.* push-over curve). For a low-rise wood frame structure, the average height is 14 feet and it is assumed to have an elastic period of 0.35 seconds.

For the mapping of the building stock to the region, both the design and performance levels are used to reflect the capacity of the building to withstand ground motion. Design levels, or seismic zone levels to which the building is designed (*eg.* NEHRP Provisions), are designated Low, Moderate, or High. Performance levels, described as the expected ductility and strength of the structure, are designated as Inferior, Code, and Superior. Therefore, for each occupancy class of buildings, an associated structure type is mapped into one of nine bins describing its capacity (*i.e.* three-by-three matrix of seismic design and performance level).

Once the building stock characteristics are established, the direct and induced physical damages are estimated. Induced physical damage for residential structures includes debris generation. Direct physical damage is described as Slight, Moderate, Extensive, or Complete, thus designating four damage states. Building damage functions are in the form of cumulative lognormal fragility curves that estimate the probability of being in, or exceeding, a damage state of interest for a given Potential Earth Science Hazard (PESH) demand parameter (*i.e.* spectral displacement, S_d). Mathematically, this is given as:

$$P[ds \mid S_d] = \Phi[\frac{1}{\beta_{ds}} \ln(\frac{S_d}{\overline{S}_{d,ds}})] \qquad (1)$$

where $\overline{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage state, *ds*, defined using allowable drift ratios; β_{ds} is the standard deviation of the natural logarithm of spectral displacement of damage state, *ds*; and Φ is the standard normal cumulative distribution function. Damage functions are developed to estimate structural damage, nonstructural acceleration-sensitive damage, and nonstructural drift-sensitive damage to the building stock. With building response characterized by capacity curves, describing the push-over displacement of each building type as a function of laterally-applied earthquake load, and fragility curves driven by the PESH parameter, the Capacity Spectrum Method [Mahaney et al., 1993] is utilized to estimate the *peak building response at the intersection of the building capacity curve and the response spectrum of PESH demand*.

Then, with damage estimates, direct social and economic losses can be calculated. Social losses for the residential building stock include casualty rates and short-term shelter needs due to loss of housing habitability. Direct economic losses are classified according to estimated building repair and replacement costs for structural, nonstructural acceleration-sensitive, and nonstructural drift-sensitive components; building contents loss; relocation expenses; and rental income losses for renter-occupied dwellings. These direct economic losses are used for input in the EP Maker, known as HAZUS-EP, which performs four functions. First, it aggregates the direct economic dollar loss of various occupancy classes of buildings per census tract, as well as business interruption losses for commercial, industrial, and agriculture buildings. Second, with insurance deductibles and limits defined by the user, total dollar losses are broken down into client (*eg.* homeowner) loss, primary insurance loss, and over limit loss. Next, these three types of losses can be consolidated to form an event loss table (ELT), associating the earthquake event with an expected loss. Finally, based on the ELT, an annual exceedance probability (AEP) curve is generated, representing the annual probability that the loss will exceed a threshold level amount. In this way, the area under the AEP curve is equivalent to the average annual loss (AAL) expected for the building stock.

OAKLAND STUDY REGION

For this analysis, the city of Oakland, California was chosen as the study region. Possessing familiarity with the residential building stock of this area [Grossi et al., 1999], aware of the Bay Area HAZUS Risk Assessment Capabilities Project as part of FEMA's Project Impact (See http://www.hazus.org), and cognisant of new USGS studies on the seismic potential on the Hayward fault [Lienkaemper and Galehouse, 1998], the choice became clear. The study region is comprised of 108 census tracts, including the city of Piedmont, California, situated in the center of the region (Figure 2).

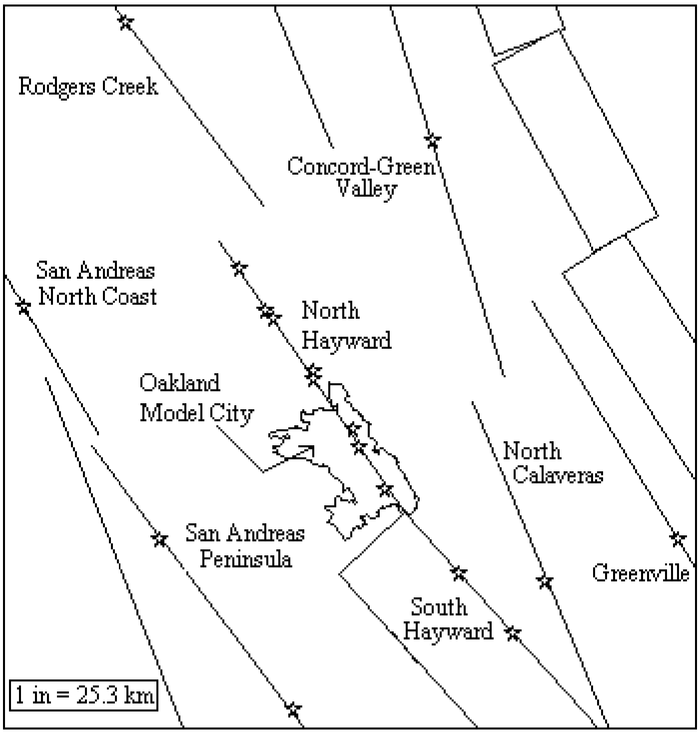

Figure 2: Oakland Model City, Seismic Fault Sources and Representative Scenario Events

With building stock default data based on the 1990 Census, an update to the information was necessary to accurately estimate the number of residential structures in the study region. Through communications with the Oakland Building Department, the Alameda County Tax Assessor's Office, and a few seismic retrofit companies in the Bay Area, it was estimated that over 90% of the total residential building stock are low-rise wood frame single family dwellings. Additionally, approximately 38% of these structures were built prior to World War II.

Based on these inventory characteristics, the structures chosen for mitigation were pre-1940 wood-frame single family residences. These homes ordinarily have cripple walls (*i.e.* the walls between the top of the foundation and the first floor diaphragm). Typically, the structural deficiencies of these homes include a lack of connection between the wood frame and the foundation and a lack of shear bracing at the cripple wall level. Therefore, the structural mitigation for pre-1940 homes in California requires bolting the structure to its foundation and bracing its cripple wall. In the analysis, mitigation is reflected in a change in the intersection of the structure capacity curve and the response spectrum of demand for the four damage states of interest.

SENSITIVITY ANALYSIS PARAMETERS

As indicated, a number of parameters and models are varied as part of a full-scale sensitivity analysis. These choices are grouped as *seismic hazard estimation* parameters or *inventory, damage, and loss estimation* parameters in the earthquake loss estimation process (Figure 3). For seismic hazard estimation, these include the frequency of earthquake events, choice of attenuation relationship, and soil mapping schemes. For inventory, damage, and loss parameters, these include the valuation and fragility of residential structures, the insurance deductibles and limits, and the costs associated with structural mitigation.

The uncertainty in the frequency of earthquake events on the various fault sources is incorporated into HAZUS-EP. For the class A faults (*i.e.* those with well-constrained paleoseismic data), including the San Andreas, Hayward, and Rodgers Creek faults, displacement for characteristic events and slip rates for the faults [Dieterich et al., 1990] are used to estimate the coefficient of variation of the frequency or recurrence rate of particular magnitude events. For class B faults (*i.e.* faults lacking data to constrain recurrence intervals of large events), including the Calaveras, Concord-Green Valley, and Greenville faults, slip rate variations [Peterson et al., 1996b] are used to estimate the recurrence rate variation, assuming similar deviations for both. For the other seismic hazard estimation parameters, attenuation choices include the four relationships defined earlier. And, soil mapping schemes include default maps with a similar site class, liquefaction and landslide potential everywhere (*eg.* site class D, low susceptibility) versus maps with varying site class, liquefaction and landslide potential (*eg.* site classes range from B to E, low to high susceptibility).

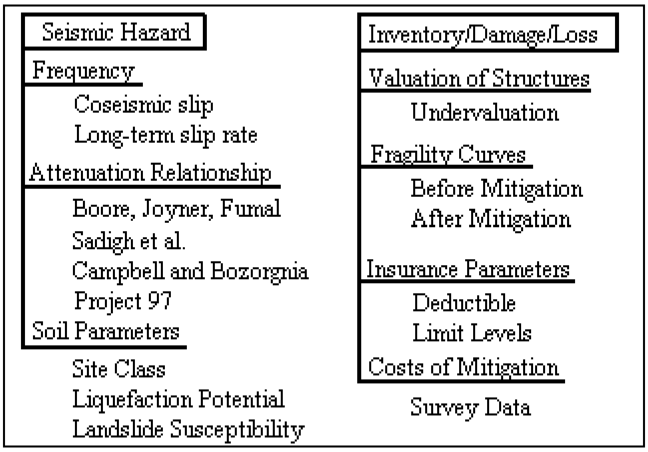

Figure 3: Scope of Sensitivity Analysis

Uncertainty in the exposure value of the structure is incorporated to reflect the tendency of the insurance industry to undervalue structures. With policy deductibles and limits written and fixed, if the building is undervalued, there is a higher chance the loss will exceed the deductible, resulting in a higher loss to the homeowner. Uncertainty in the fragility curves are reflected in HAZUS and carried over into HAZUS-EP via the β_{ds} parameter mentioned previously, which combines the variability of the capacity curve, the demand spectrum, and the uncertainty in the estimate of damage-state threshold to estimate total variability. Finally, the sensitivity analysis of the insurance parameters is incorporated through direct input into HAZUS-EP and costs of mitigation are incorporated through statistical manipulation of expert opinion surveys to contractors proficient in seismically retrofitting wood frame residential structures [Grossi, 1998].

INCORPORATION OF STRUCTURAL MITIGATION

An important part of this study is the inclusion of expert opinion survey data collected from registered structural engineers in California experienced in post-earthquake damage evaluation [Grossi, 1998]. With estimates of mean damage (MDF) for various levels of Modified Mercalli Intensity (MMI) for pre-1940 wood frame residential construction, the damage before and after mitigation is converted to a demand reference spectrum, which intersects the building capacity curve at the spectral displacement of the median value of the damage state of interest. The process for conversion of this data is an involved, five-step process, combining techniques from a number of previous studies on estimates of earthquake damage [ATC-13, 1985; Anagnos et al., 1995; Newmark and Hall, 1982]. This method is too considerable to explain in detail here and is the subject of a forthcoming paper. A brief synopsis, however, is offered for completeness.

First, the raw data of MDF versus MMI is fit to over twenty types of distributions, using a variety of goodness-of-fit tests. After a number of iterations, a set of distributions was settled upon that fit the data best. Second, once the data is fit to curves, damage state probability matrices are developed which reflect the probability of being in the Slight (S), Moderate (M), Extensive (E), and Complete (C) damage states. These matrices are developed by integrating under the curves fit in step one and assuming limits of integration between (0.01, 0.1), (0.1, 0.3), (0.3, 0.6), and (0.6, 1.0) for Slight, Moderate, Extensive, and Complete damage states, respectively.

Third, from these probabilities, cumulative probability damage matrices are developed that reflect the probability that the mean damage factor meets or exceeds the various damage states, and a lognormal curve is fit to these data points. Mathematically, this is given in equation (2), where *y* represents MMI and *x* represents *ln*(MMI). In this way, eight cumulative lognormal distribution functions are defined, which estimate the median value of *ln*(MMI) for Slight, Moderate, Extensive, and Complete damage states before and after mitigation.

$$P[Y \le y] = F_Y(y) = \int_0^y \frac{1}{y\sigma_x\sqrt{2\pi}} \exp[-\frac{1}{2}(\frac{\ln y - m_x}{\sigma_x})^2]dy \qquad (2)$$

With this information, the fourth step is to convert the *ln*(MMI) values to peak ground acceleration (PGA) using various empirical relationships [*eg.* Trifunac and Brady, 1975]. And, finally, these median PGA values of the various damage states are transformed into equivalent spectral displacement demand through an assumed demand spectrum shape. This elastic reference spectrum shape represents ground shaking of a large-magnitude (M $\cong$ 7.0) western United States earthquake for soil Site Class D, and site-to-source distances of 15 km or greater for buildings with elastic damping equal to 5% of critical. The spectrum is scaled downward to reflect 15% elastic damping of low-rise wood frame structures and hysteretic energy dissipated by these structures "pushed" beyond their elastic limits. An example of the intersection of the building capacity curve and the demand spectra for the four damage states, via the Capacity Spectrum Method (CSM), is shown in Figure 4.

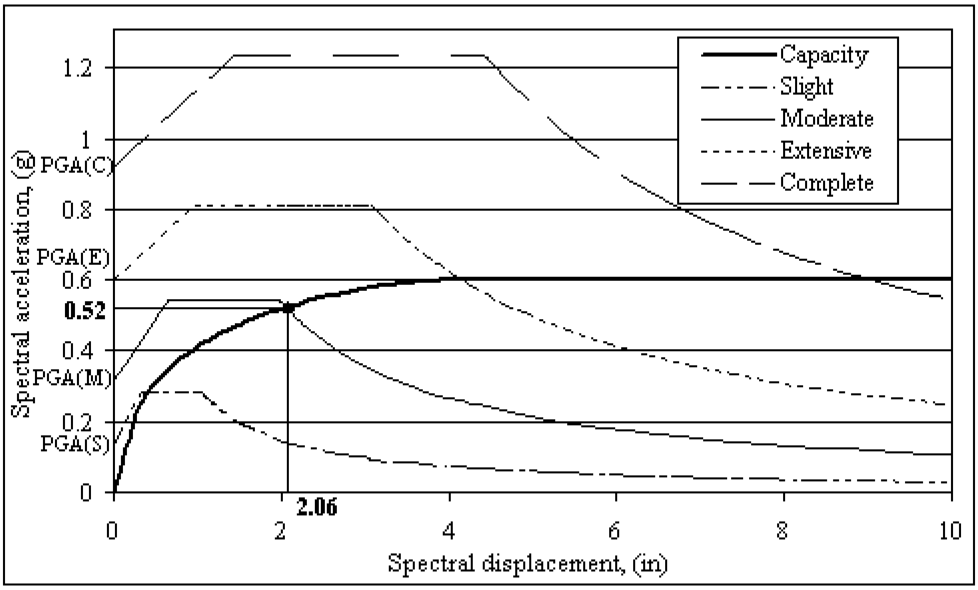

Figure 4: Capacity Spectrum Method

PRELIMINARY RESULTS

Since this project is still on-going at the time of this writing and the paper is limited in length, only preliminary analyses are presented here. Specifically, the effects of uncertainty on the losses under different assumptions of *inventory valuation* and *ground motion attenuation* are presented. First, the average annual losses to the homeowner and the insurer, using a fixed attenuation relationship and soils map, for varying structures' valuations are displayed (Table 1). Undervaluation of a structure is reflected in a lower limit level covered by an insurer (*eg.* 100% vs. 85% coverage), and losses are given in terms of an expected annual loss to *all* residential homeowners. From the results, there is an average total savings of over $3 million to those who mitigate. More importantly, *with a 15% deductible, the homeowner is bearing ≈ 56% of the total loss.*

Table 1:Average Annual Loss (AAL) to Stakeholders for Varying Deductible and Limit Levels

	Before Mitigation		**After Mitigation**	
Total Loss	$203,931,004		$200,726,115	
0% deductible	**Homeowner Loss**	**Insurer Loss**	**Homeowner Loss**	**Insurer Loss**
100% Limit	$0	$203,931,004	$0	$200,726,115
85% Limit	$546,196	$203,384,808	$518,873	$200,207,242
75% Limit	$2,257,688	$201,673,316	$2,136,110	$198,590,005
15% deductible	**Homeowner Loss**	**Insurer Loss**	**Homeowner Loss**	**Insurer Loss**
100% Limit	$112,746,405	$91,184,599	$112,552,756	$88,173,359
85% Limit	$113,292,601	$90,638,403	$113,071,629	$87,654,486
75% Limit	$115,004,093	$88,926,911	$114,688,866	$86,037,249

Another interesting result is the change in the exceedance probability curve for two different attenuation relationships for fixed structures' valuations and soils map (Figure 5). The Boore, Joyner, and Fumal (BJF) and Project 97 relationships are used to estimate the total loss to the residential building stock. At the 5% probability of exceedance level, *the expected losses using the Project 97 attenuation curve are 30% more than those estimated using the Boore, Joyner, and Fumal curve ($240 Million vs. $170 Million).*

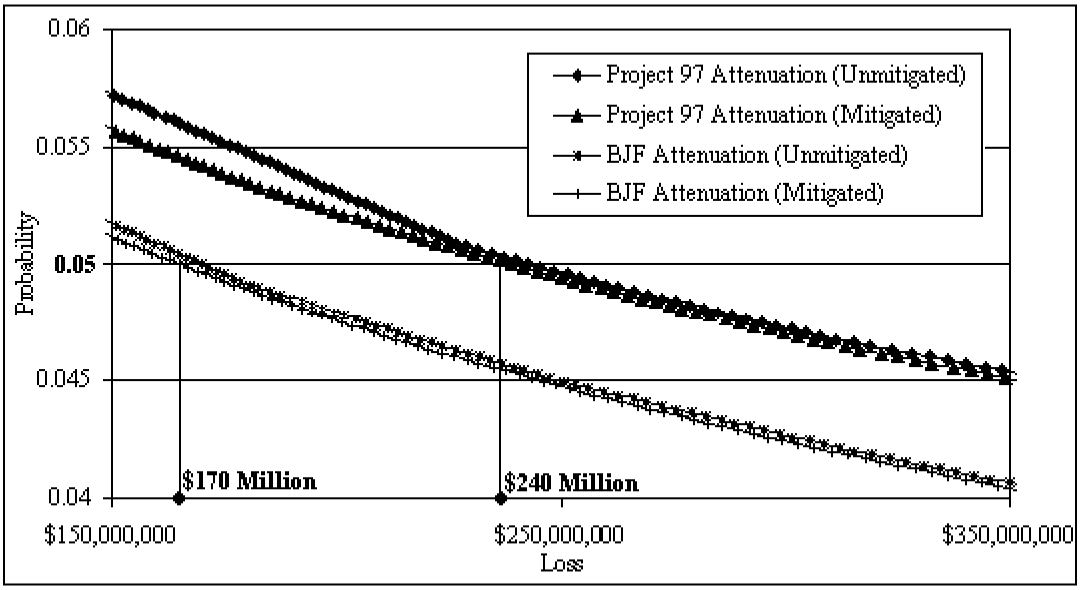

Figure 5: Comparison of EP Curve for Different Attenuation Relationships

CONCLUSIONS

From preliminary results, three main conclusions can be drawn. First, mitigation is much more effective at the higher exceedance probability levels, reducing in effectiveness as the probability of exceedance approaches zero. This is intuitively correct. As the probability of exceedance decreases, the associated magnitude event generally increases, indicating that mitigation will be more effective in moderate earthquakes and less effective at catastrophic (*i.e.* $M_W = 8.0$) events. Second, deductible levels play a major role in which stakeholder bears the brunt of the economic loss. At a 15% deductible level, corresponding to the current terms under the California Earthquake Authority (CEA) residential earthquake insurance policy, the homeowner will have to cover the majority of the loss.

Finally, the choices of parameters and models in the earthquake loss estimation process can be very sensitive to the final estimates of economic loss. For example, alternative estimates of the attenuation of ground motion from source-to-site can give a 10% to 30% difference in economic losses, depending on the exceedance probability level. Future analyses will also estimate the importance of earthquake frequency, soil parameters, and costs of mitigation to final estimates of losses to insurers and homeowners for various exposure and vulnerability levels of the residential building stock.

ACKNOWLEDGMENTS

This work is supported in part by the National Science Foundation under grant CMS97-14401 and in part by a grant from the Lillian Beck Fund in the School of Engineering and Applied Science at the University of Pennsylvania.

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