QUANTIFYING THE UNCERTAINTY IN SEISMIC RISK AND LOSS ESTIMATION

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ABSTRACT

The work presented in this paper is an outgrowth of a joint NSF-funded project between Risk Management Solutions, Inc. and the Wharton School of the University of Pennsylvania. Entitled *The Use of Insurance and Other Policy Instruments in Managing Catastrophic Risks*, the primary research goal examined the role of the private and public sectors in managing catastrophic risks. The effects of residential earthquake insurance and structural mitigation techniques were studied in depth through loss exceedance probability (EP) curves. The research expanded to include a sensitivity analysis of the HAZUS earthquake loss estimation methodology [8] and the interaction of uncertainty with the effects of mitigation and insurance. The ultimate goal is to promote understanding of the uncertainty in earthquake risk and loss estimation, as well as to advance the state-of-the-art in catastrophic risk modeling. Parameters considered in the sensitivity analysis include earthquake recurrence, ground motion attenuation, soil classification, and the exposure and fragility of residential structures. The effects of these models and parameters on the final estimates of loss are presented here. For the Oakland, California region considered in the analysis, results indicate that the earthquake hazard parameters are most influential in estimating losses and the soil classification scheme is the least influential.

1. INTRODUCTION

In 1989, two events occurred that had a drastic impact on both the insurance industry and the political climate in the United States. Late on September 21, 1989, Hurricane Hugo hit the coast of South Carolina, devastating the towns of Charleston and Myrtle Beach. Insured loss estimates totaled $4.5 billion before the storm moved through North Carolina the next day. Less than a month later, on October 17, 1989, the Loma Prieta Earthquake hit with a Richter Magnitude of 7.1 near the town of Santa Cruz, California. Property damage was estimated between $6 and $7 billion to the surrounding Bay Area. In order to remain solvent, the insurance industry realized that it needed a better way to estimate and manage the losses associated with such natural disasters. Moreover, the Federal Emergency Management Agency (FEMA) recognized a need for better catastrophic loss estimates for both mitigation and emergency planning purposes.

As a result, over the course of the past decade, *advanced* tools have emerged that allow both insurance companies and agencies of the government to more accurately assess their catastrophic risk exposures. These software tools, known as catastrophic risk models, utilize advances in Information Technology (IT) and Geographic Information Systems (GIS). They were developed in two separate arenas. First, private companies developed models for insurance companies to estimate their portfolio losses and individuals to estimate their site-specific losses from either a probabilistic seismic hazard analysis (PSHA) or a deterministic earthquake scenario. Second, the federal government developed a regional loss estimation model (HAZUS) to estimate monetary losses as well as other types of losses (*eg.* casualties and shelter requirements) from an earthquake event.

While the private industry's software and the HAZUS software are intended for different audiences, each utilizes the same general methodology to analyze catastrophic earthquake losses. The earthquake loss estimation (ELE) methodology is comprised of four basic stages: (1) define the earthquake hazard, (2) define the inventory characteristics, (3) estimate the inventory damage, and (4) calculate the economic losses. For the four-stage earthquake loss estimation process, there is uncertainty in the seismological data used to define the earthquake hazard, in the exposure data and vulnerability functions used for damage estimation, and in the estimated costs in determining losses. In general, limited scientific information, lower quality data, or limited engineering information results in greater variability of expected losses.

This paper presents an approach to quantify the uncertainty in the ELE methodology used in the HAZUS software. Due to the proprietary nature of the private companies' software packages, the "public domain" HAZUS software and methodology is utilized. The approach is to determine the Range of Uncertainty (RU) of the Loss, defined as the absolute difference between the monetary loss in an updated information state, x_1, at the time of the decision and the loss in the default information state, x_0. In this framework, the sensitivity analysis completed will offer insight into the susceptibility of losses to changes in the values of uncertain models and parameters. Moreover, some insights into how various parameters interact with each other will be gained. The largest absolute difference or RU value will define the parameter or modeling uncertainty most influential in the earthquake loss estimation process.

Section 2 outlines the scope and goal of this work. Section 3 is an overview of the three software modules (Scenario Builder, HAZUS, and EP Maker) utilized in the analysis. Section 4 presents the Oakland, California region used in the study, including the structural mitigation technique considered in the analysis and the seismic sources in the surrounding region. Section 5 outlines the seismic hazard parameters and inventory, damage, and loss parameters tested for sensitivity. Section 6 describes the relevant findings and section 7 discusses the implications and draws some conclusions.

2. SCOPE AND GOAL OF WORK

In this work, the role of uncertainty in the earthquake loss estimation (ELE) methodology is studied. In order to quantify the uncertainty associated with ELE, a sensitivity analysis is completed, assuming alternative estimates for different parameters in the process, varying the estimates one-by-one and seeing the effects on the calculations of expected and worst case losses. A total of 64 (2^6) runs were completed. This study is unique in that it uses a regional loss estimation model, HAZUS, with pre-processing and post-processing software modules to estimate direct economic losses to residential structures in the Oakland, California region.

The monetary losses to residences in the region are distributed to homeowners and insurers through various deductible and limit level schemes. The average annual loss (AAL) and worst case loss (WCL) are the focus of the sensitivity analysis. The approach is "event-based". In other words, a catalogue of earthquake events is carefully chosen to reflect the overall seismic risk of the region and an event loss table (ELT) is generated using the HAZUS methodology. An ELT is a tabular listing of N scenario events (j = 1,2,…,N) considered in the analysis with associated annual probabilities of occurrence, p_j, and expected losses, L_j. These losses are consolidated into a loss exceedance probability curve (Eq. 1). A loss exceedance probability curve is a graphical representation of the probability that a certain level of loss will be exceeded on an *annual* basis. In Equation 1, *F(L)* denotes the cumulative probability function for the loss or $P(Loss \leq L)$ and the loss exceedance probability curve, *EP(L)*, follows easily.

$$EP(L) = P(Loss > L) = 1 - F(L) \tag{1}$$

Using these EP(L) curves, the Range of Uncertainty on the Loss or *RU[F(X)]* is derived. *RU* is defined as the absolute difference between expected monetary loss in an updated information state, x_1, at the time of a decision and the expected monetary loss in a default information state, x_0 (Eq. 2). For each stakeholder in question (*i.e.* homeowner and insurer), it is the absolute value of the average annual or worst case loss using "updated" information minus the same losses using "default" data. It is important to take the absolute value because, with certain updated knowledge, the losses will reduce. A significant change in either direction from the loss is important to understanding the uncertainty involved in the earthquake loss estimation process.

$$RU[F(X)] = | F(x_1) - F(x_0) | \tag{2}$$

3. EARTHQUAKE LOSS ESTIMATION SOFTWARE

The ELE software used for this analysis is HAZUS with a pre-processor, Scenario Builder, and a post-processor, EP Maker (Fig. 1). The earthquake hazard is defined in Scenario Builder based on the seismic sources and ground motion attenuation relationships defined in HAZUS. The inventory characteristics are defined in HAZUS and the inventory damage and subsequent losses are calculated in HAZUS. EP Maker aggregates the losses and assigns them to each of the stakeholders in the insurance framework.

First, the Scenario Builder input file must be created. An earthquake event in the input file is defined by its epicenter location on a seismic fault source (*i.e.* latitude, longitude, depth), Moment Magnitude (**M**), and the associated rupture length of the fault (surface and subsurface). Additionally, the event duration, the event's annual recurrence, and the *choice* of ground motion attenuation are needed. Then, the series of earthquake events are run through HAZUS.

The rate at which ground motion decays from a source 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. These include: Boore, Joyner and Fumal [1,2]; Sadigh et al. [10]; Campbell and Bozorgnia [3]; and Project97, a linear combination of the first three attenuation curves. Additionally, the building stock is classified in HAZUS according to its occupancy class (*eg.* single family residential or RES1) and its structure type (*eg.* low-rise wood frame or W1). 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 typical repair and replacement costs per square foot. Structure type designations are used to define building capacity curves.

In HAZUS, direct physical damage is described as being in one of five damage states: None, Slight, Moderate, Extensive, or Complete. 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 demand parameter (*eg.* spectral displacement, S_D).

$$P[ds \mid S_D] = \Phi\left[\frac{1}{b_{ds}} \ln\left(\frac{S_D}{\overline{S}_{D,ds}}\right)\right] \qquad (3)$$

In Equation 3, $\overline{S}_{D,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage state, ds; b_{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. These functions are developed to estimate damage to a structure and its drift-sensitive nonstructural components. Similar functions using spectral acceleration, S_A, are used to estimate damage to acceleration-sensitive nonstructural components.

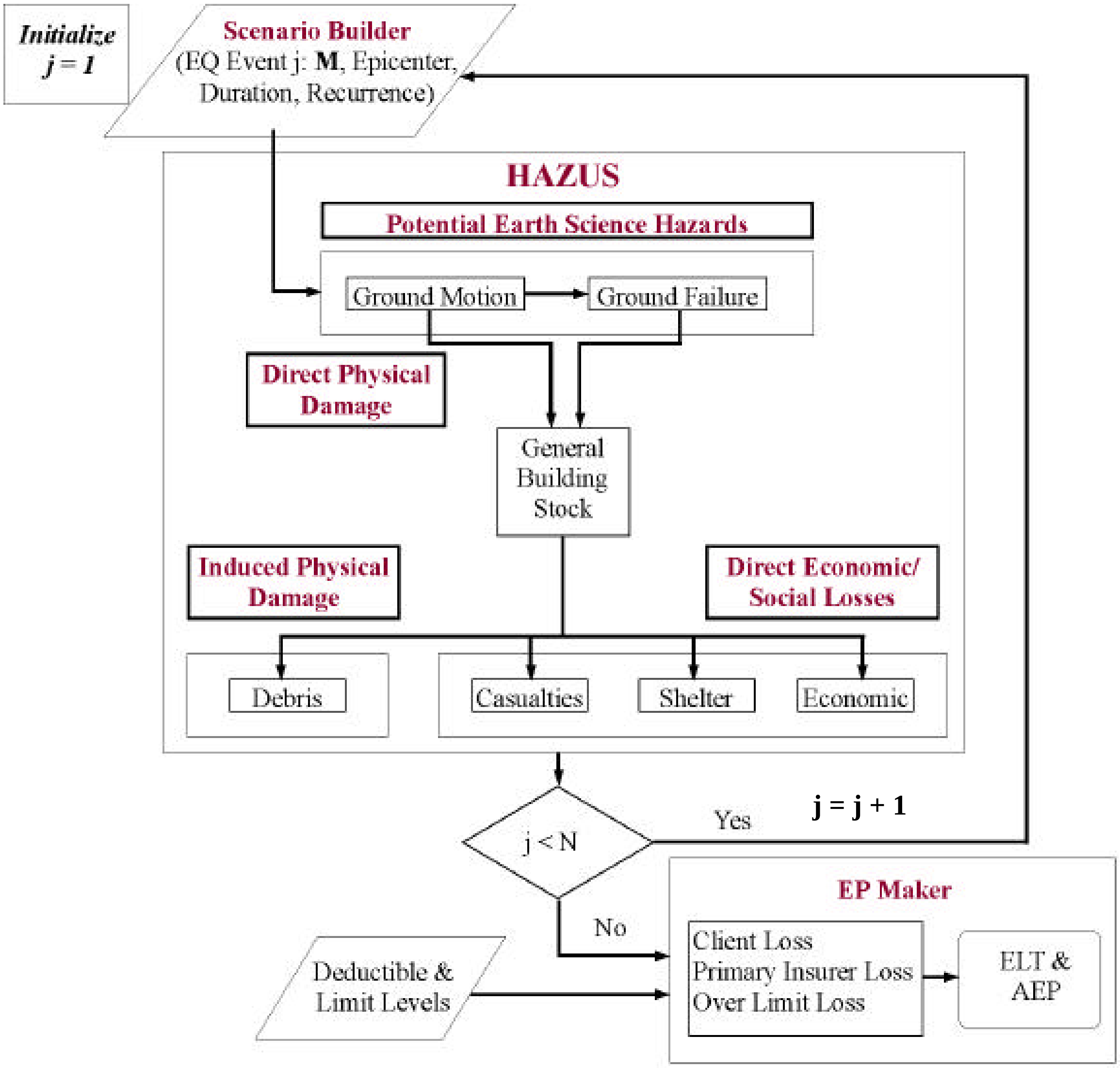

FIGURE 1. Flowchart of earthquake loss estimation methodology

With these damage estimates, direct economic losses are calculated. Direct economic losses input into EP Maker include repair and replacement costs for structural, nonstructural acceleration-sensitive, and nonstructural drift-sensitive components, as well as building content losses. With these losses, EP Maker performs four functions. First, it aggregates the net economic dollar loss to the different occupancy classes of buildings by census tract. Second, with insurance deductibles and limits defined by the user, the net losses are broken down into client (*eg.* homeowner) loss, primary insurer loss, and over limit loss. Third, these three types of losses can be taken separately or consolidated to form an event loss table (ELT). Finally, based on the ELT, an annual exceedance probability (AEP) curve is generated, representing the annual probability that a loss will exceed a threshold level amount. In this way, the area under the AEP curve is equivalent to the average annual loss (AAL).

4. OAKLAND, CALIFORNIA REGION

For this analysis, the study region is the Oakland, California area. It is comprised of 108 census tracts, including the city of Piedmont, California, situated in the center of the region (Fig. 2). In order to accurately estimate the number of residential structures in the region and choose a mitigation technique, the Oakland Building Department, the Alameda County Tax Assessor's Office, and a few seismic retrofit companies in the Bay Area were contacted. Through these communications, it was estimated that over ninety percent of the total residential building stock are low-rise wood frame single family residences. Additionally, approximately thirty-eight percent of these structures were built before 1940.

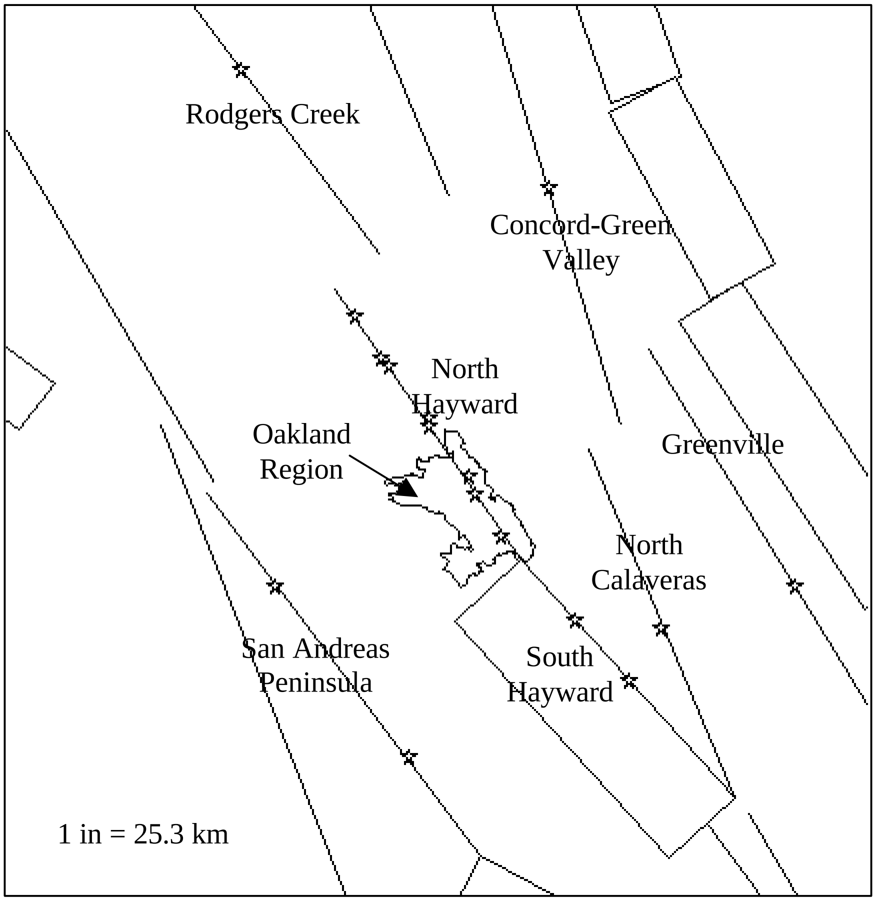

FIGURE 2. Oakland, California region

Based on these inventory characteristics, the structures chosen for mitigation were pre-1940 wood-frame residential structures. 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, structural mitigation for pre-1940 homes in California requires bolting the structure to its foundation and bracing its cripple wall. In this work, mitigation is reflected in a shift in the fragility curves for structural damage (Eq. 3). Furthermore, this shift is based on the expert opinion of structural engineers experienced in post-earthquake damage evaluation [5].

In this study, seismic fault sources include seven right-lateral strike-slip faults in the Northern California region (North Hayward, South Hayward, San Andreas Peninsula, Rodgers Creek, Calaveras, Concord-Green Valley, and Greenville). There are a total of forty-six events considered on these fault sources. Moreover, two density functions are utilized for earthquake magnitude-distribution: a truncated exponential relationship and a characteristic earthquake model, similar to the approach used in previous studies [9]. The 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. 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.

5. SENSITIVITY ANALYSIS

As indicated, a number of parameters and models are "updated" as part of the sensitivity analysis. The default and updated choices are grouped into *seismic hazard estimation parameters* and *inventory, damage, and loss estimation parameters* (Fig. 3). For seismic hazard estimation, the parameters/models include the recurrence of earthquake events, attenuation relationship, and soil classification schemes. For inventory, damage, and loss parameters, the parameters/models include the exposure and fragility of unmitigated and mitigated residential structures.

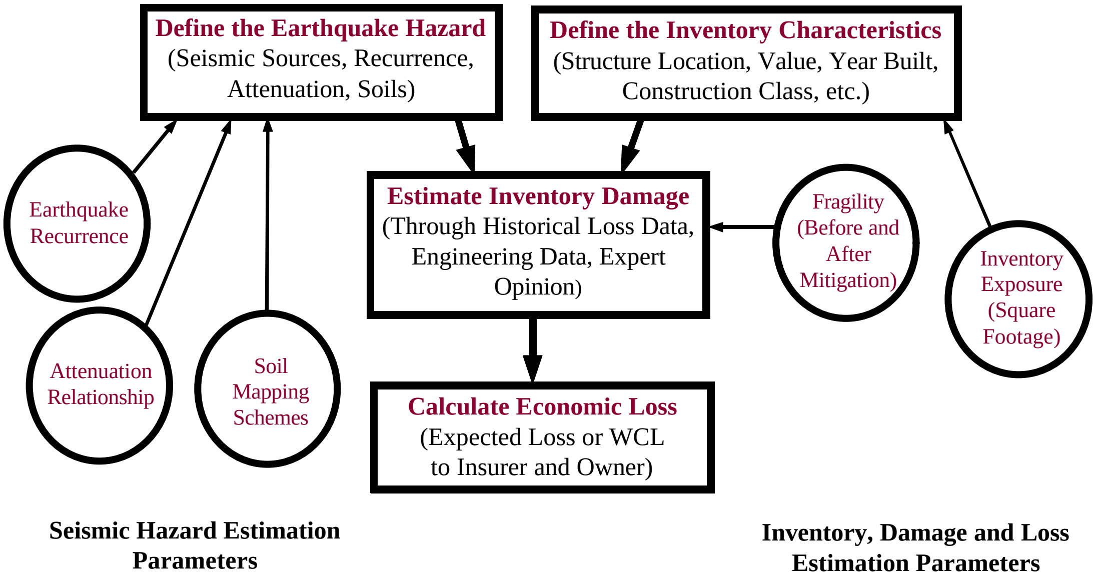

FIGURE 3. Scope of sensitivity analysis

5.1 Seismic hazard parameters

A logic tree approach is used to keep track of the choices in earthquake recurrence, attenuation curves, and soil mapping schemes in the sensitivity analysis (Fig. 4). First, the default frequencies of earthquake events on the faults in the region are developed from USGS data [9]. Specifically, the mean return period of the characteristic event on each of the fault sources is the ratio of the seismic moment of the characteristic earthquake, M_0^e, to the rate that the fault accumulates moment, $\dot{M}_0^g$ (Eq. 4). This simply boils down to the ratio of the average displacement, $\bar{d}$, to the slip rate, $\dot{u}$. Additionally, an exponential distribution is used to estimate the number of events between a minimum magnitude, m_o, and the maximum magnitude, m_u. The earthquake rate is estimated using an incremental a-value (Eq. 5). The constant b is the slope of the exponential distribution and the constants c and d are defined by Hanks and Kanamori [7] as 1.5 and 16.1, respectively. Updated annual earthquake recurrence is developed from proprietary data supplied by Risk Management Solutions, Inc.

$$T = \frac{M_0^e}{\dot{M}_0^g} = \frac{mlw\bar{d}}{mlw\dot{u}} \tag{4}$$

$$a = \log\left(\frac{(c-b)\dot{M}_0^g \ln(10)}{10^d\,(10^{(c-b)m_u} - 10^{(c-b)m_o})}\right) \tag{5}$$

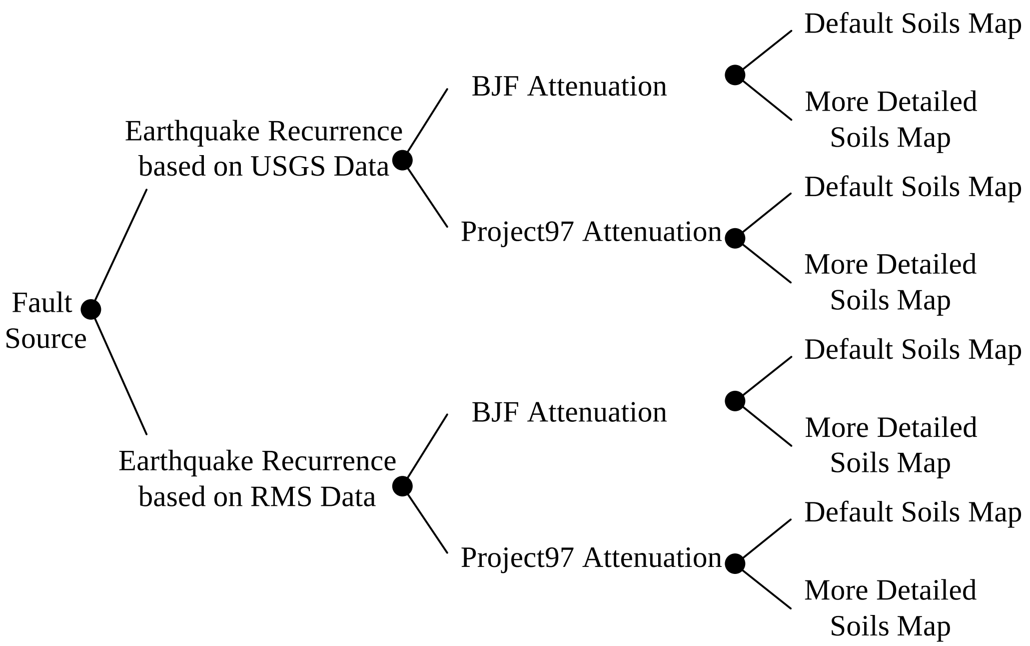

FIGURE 4. Logic tree for seismic hazard parameters

For the other seismic hazard estimation parameters, attenuation relationships include the Boore, Joyner, and Fumal (BJF) relationship as the default choice and the Project97 relationship as the updated choice. The peak ground acceleration (*PGA*) as a function of distance from the source for both empirical relationships is given in Figure 5. In the figure, the "updated" Project97 attenuation curve estimates a higher PGA at distances close to the source. Additionally, two soil mapping schemes are considered in this analysis. The default scheme has the same soil site class, Site Class D, as defined in the NEHRP Provisions [4], and no liquefaction and landslide potential anywhere. The updated scheme has varied site classes throughout the region (site classes B through E) and ranges of liquefaction and landslide potential (low to high susceptibility). In Figure 6, the updates soils map indicates soft soils (site class E) on the San Francisco Bay and rock (site class B) inland.

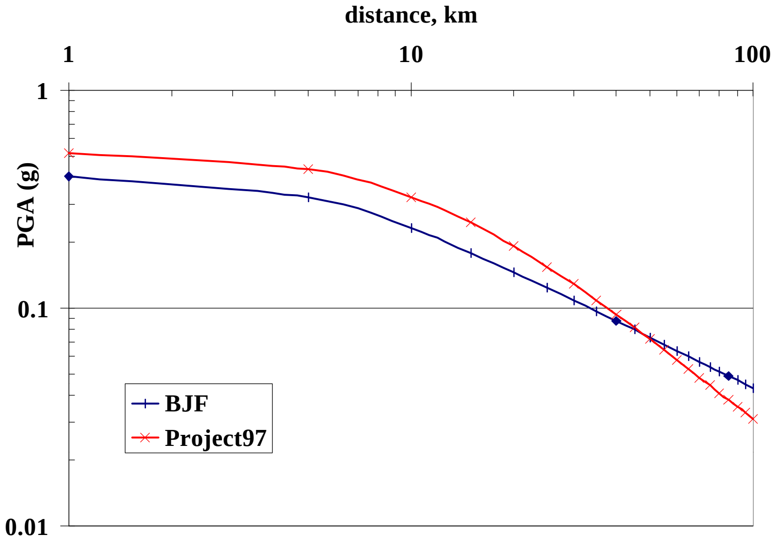

FIGURE 5. Attenuation relationships

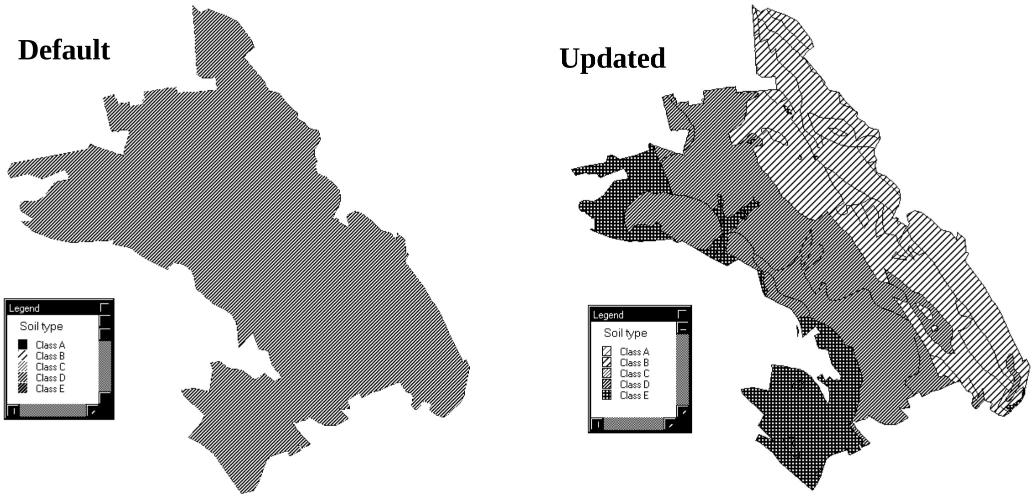

FIGURE 6. Soil mapping schemes

5.2 Inventory, damage, and loss estimation parameters

A logic tree approach is also used to keep track of the choices in exposure data, fragility curves, and mitigation in the sensitivity analysis (Fig. 7). Uncertainty in the exposure value of residential structures is incorporated to reflect the tendency of the insurance industry to misclassify and/or undervalue structures. In HAZUS, the inventory exposure is in terms of total square footage per census tract for each occupancy class. The “default” exposure is from the 1990 Census. There is a total of 123,783 square feet of single family residences (RES1) in the region and 31,358 out of 82,522 structures can be mitigated (*i.e.* 38% of total number of structures, where each structure is 1,500 square feet). The updated exposure is based on tax assessor’s data supplied by Scott McAfee of the California Office of Emergency Services. From this information, there is a total of 110,899 square feet of single family residences in the region and 28,094 out of 73,933 structures can be mitigated.

Uncertainty in the damage to the residential building stock is reflected in a change in the HAZUS fragility curves for *structural* damage to low-rise wood frame structures (W1). Specifically, $\overline{S}_{D,ds}$, the median value of spectral displacement at which the building reaches the threshold of damage, and b_{ds}, the standard deviation of the natural logarithm of spectral displacement, are updated with new knowledge of fragility (Fig. 8). The “default” structural fragility curves are the ones for low-rise wood frame structures currently in HAZUS. Curves to reflect damage before mitigation are those designed “Low-Inferior”; curves to reflect damage after mitigation are those designed for “Moderate-Code”. The “updated” structural fragility curves are based on the expert opinion survey data previously mentioned [5]. For details on these updated curves, see [6].

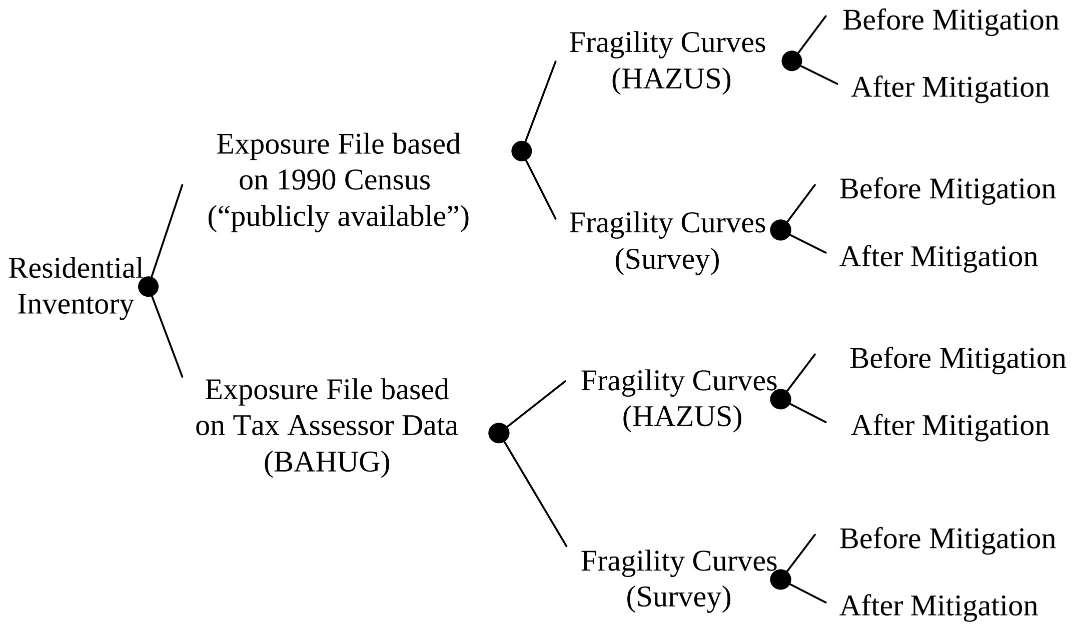

FIGURE 7. Logic tree for inventory, damage, and loss estimation parameters

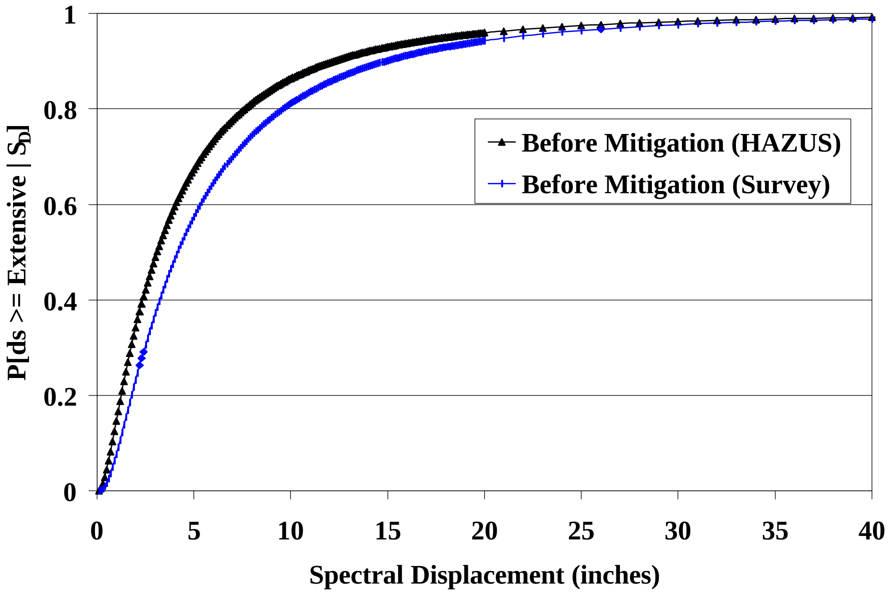

FIGURE 8. Fragility curves for default and updated cases

6. RESULTS

The results presented are the average annual loss (AAL) and worst case loss (WCL) to the low-rise wood frame residential building stock in the Oakland California region. Note that the worst case loss is the loss at the one-percent probability of exceedance level. Five different cases are considered and the Range of Uncertainty (RU) is calculated in each case.

Results for cases 1 through 3 are in Table I. Case 1 compares the use of *all default* parameters/models with *all updated* parameters/models. The RU is $52.4 Million for the AAL and $507.4 Million for the WCL. Case 2 is a calculation of RU using updated knowledge of the seismic hazard parameters (recurrence, attenuation, and soils). With updated recurrence and soil information, losses are lower. With updated ground motion attenuation, losses are higher. Notably, the RU with the updated attenuation is $36.3 Million for AAL and $661 Million for WCL. Case 3 is a calculation of RU with updated knowledge of the inventory, damage and loss estimation parameters (exposure, fragility, and mitigation). With updated exposure and fragility information, losses are lower.

Case 4 is a comparison of the effects of mitigation using the default fragility curves to the updated ones. From Table II, mitigation is slightly more effective using the default structural fragility curves. Finally, case 5 compares the largest losses to the smallest losses. In this way, the bounds of AAL and WCL values are established. The maximum losses are obtained using default recurrence, soils, exposure data, and fragility curves before mitigation with the updated attenuation relationship. The minimum losses use default attenuation with updated recurrence, soils, exposure data, and fragility curves after mitigation. The RU is $138.7 for AAL (*i.e.* $219.1 - $80.4) and $2,240 for WCL (*i.e.* $3,810- $1,570). This result is shown via the loss EP curve in Figure 9.

TABLE I. Average annual loss and worse case loss (in $ millions)

LOSS	UPDATED (x_1)	DEFAULT(x_0)	RU
CASE 1 – ALL			
(AAL, WCL)	($130.4, $2,642)	($182.8, $3,149)	($52.4, $507.4)
CASE 2 – SEISMIC HAZARD PARAMETERS			
Frequency (AAL, WCL)	($149.6, $2,769)	($182.8, $3,149)	($33.2, $380)
Attenuation (ALL, WCL)	($219.1, $3,810)	($182.8, $3,149)	($36.3, $661)
Soils (AAL, WCL)	($171.3, $2,914)	($182.8, $3,149)	($11.5, $235)
CASE 3 – INVENTORY, DAMAGE, AND LOSS ESTIMATION PARAMETERS			
Exposure (AAL, WCL)	($166.6, $2,762)	($182.8, $3,149)	($16.2, $387)
Fragility before mitigation (AAL, WCL)	($169.8, $2,979)	($182.8, $3,149)	($13.0, $170)
Fragility after mitigation (AAL, WCL)	($124.7, $2,199)	($127.8, $2,268)	($3.1, $69)

TABLE II. Effects of mitigation (losses in $ millions)

CASE 4 - LOSS	UPDATED (x_1)	DEFAULT (x_1)
AAL(before – after)	$169.8 - $124.7 = $45.1	$182.8 - $127.8 = $55.0

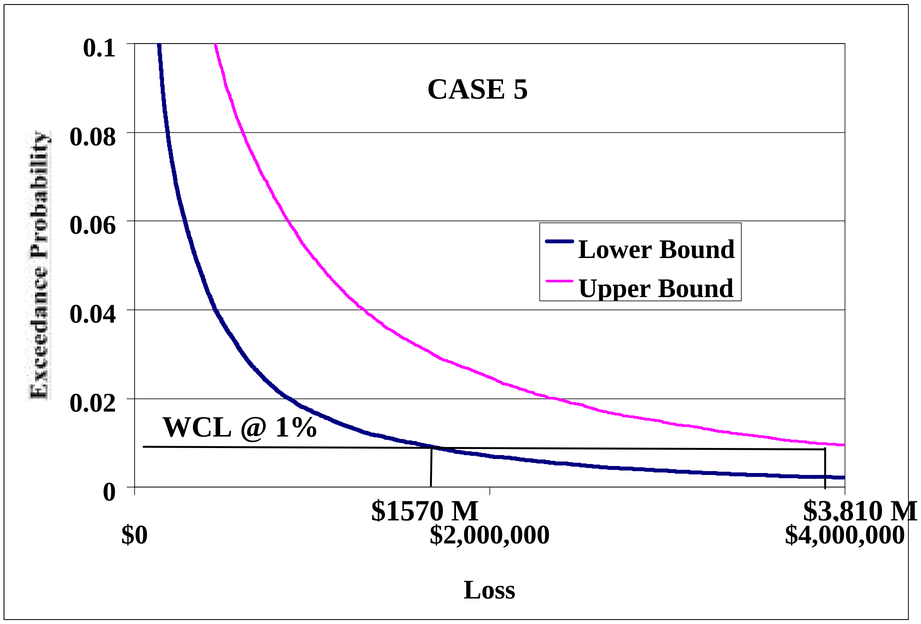

FIGURE 9. Loss exceedance probability curve bounds

7. CONCLUSIONS

From the results, three separate conclusions are drawn. First, the earthquake loss estimation process is *very* uncertain. Depending on which parameters and models are chosen for use in an analysis, there is almost a factor of 3 difference in average annual loss (Case 5). Second, the effects of mitigation are better than expected, and the default fragility curves do a good job reflecting the reduction in damage due to mitigation. The updated fragility curves are a bit more conservative in their estimate.

Finally, using the Range of Uncertainty calculated in the above cases, the parameters/models tested here can be ranked according to their influence on the final estimates of loss. The largest RU calculated is the parameter/model most influential in estimating losses. In the case of the Oakland California region, this ranking, according to the average annual loss estimates, is (1) attenuation, (2) earthquake recurrence, (3) exposure, (4) fragility before mitigation, (5) soils mapping scheme, and (6) fragility after mitigation.

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