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A COMPARISON OF EARTHQUAKE DAMAGE AND LOSS ESTIMATION METHODOLOGIES

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ABSTRACT

Two earthquake damage and loss estimation methodologies, one with empirically derived motion-damage relationships and the other with analytically derived motion-damage relationships, were implemented for a Magnitude 7.5 scenario event in Salt Lake County, Utah. The analyses were limited to roughly 175,000 residential buildings and to damage caused only by ground shaking. Although the two methodologies differ in many aspects, both produced overall damage factors (percent of value that is damaged) between 25 and 26%. The differences in the models that comprise the two methodologies and the resulting damage and loss estimates for Salt Lake County are discussed in this paper.

KEYWORDS

Seismic hazard analysis; seismic risk analysis; damage estimation; loss estimation; geographic information systems; earthquake scenario.

INTRODUCTION

Numerous earthquake damage and loss estimation methodologies have been developed over the past 20 years for the purpose of assessing seismic hazard and risk in various regions of the world. Most of these methodologies follow the same steps: assessing the hazard, developing an inventory of structures, predicting the damages, and quantifying the economic and social effects. The methodologies typically differ in the models that comprise these steps.

Two regional earthquake damage and loss estimation methodologies with significant modeling differences were selected for comparison. The first methodology was developed by the Applied Technology Council (ATC) of Redwood City, California, a non-profit corporation serving the research needs of several structural engineering practitioners. The ATC methodology, developed with funding from the Federal Emergency Management Agency, involved updating and adapting the ATC-13 methodology (Applied Technology Council, 1985), one of the most widely used damage and loss estimation tools in the United States, for application to the state of Utah. The second methodology was developed by Risk Management Solutions, Inc., of Menlo Park, California for the National Institute of Building Sciences (NIBS), with funding from the Federal Emergency Management Agency. The NIBS methodology is the result of a three and one-half year effort to develop a nationally applicable standardized methodology for estimating potential earthquake losses on a regional basis. The two earthquake damage and loss estimation methodologies are described in more detail in the following sections.

ATC LOSS ESTIMATION METHODOLOGY

The ATC-36 project (Applied Technology Council, in progress) involved the development of an earthquake damage and loss estimation methodology and the associated structural inventory for the region of Salt Lake County, Utah. The widely-used ATC-13 methodology, originally developed for structures located in California, was adapted and modified to form the basis of the ATC-36 methodology. The ATC-36 methodology produces estimates of earthquake damage due to strong ground shaking, collateral hazards (i.e., liquefaction, landslide, inundation, and fault rupture), and fire following earthquake. Three types of loss are considered, including direct loss due to structural damage, loss of function, and casualties. The methodology assumes that a seismic hazard map with Modified Mercalli Intensity (MMI) as the ground motion parameter already exists; therefore, a model for ground shaking estimation is not included in the methodology.

Although the ATC-36 methodology estimates earthquake damage and loss for all building and lifeline structures, only residential buildings (subjected only to damage from ground shaking) are considered in this paper for ease of comparison. In the ATC-36 project, 16 structural model building types were defined for Utah. Motion-damage relationships were developed for these 16 building classes by translating the relationships developed for California buildings in the ATC-13 project. Local structural engineering experts did the translation which resulted in 16 curves that estimate the expected damage factor (damaged value divided by replacement value) and standard deviation (σ) on the expected damage factor (μ) as a function of MMI for each building class. Modification factors were defined for adjusting the curves to account for building height and construction quality. Figure 1 illustrates the ATC-36 expected damage factor curves for light wood frame and unreinforced masonry buildings, the two classes of buildings that make up the residential building stock in Salt Lake County. It is assumed that the building damage includes both structural and non-structural damage.

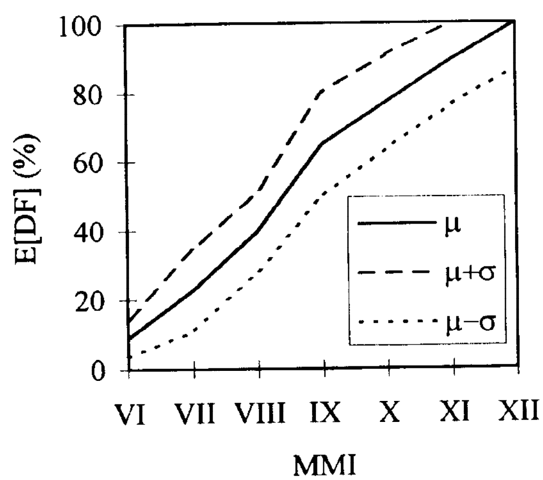

Fig. 1(a). Expected damage factor curve for light wood frame buildings.

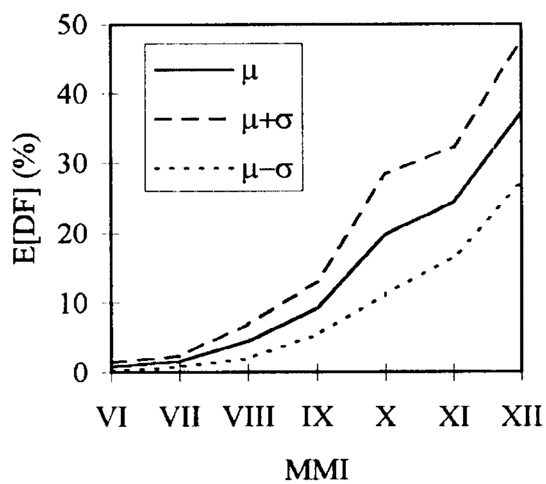

Fig. 1(b). Expected damage factor curve for unreinforced masonry buildings.

The building inventory for Salt Lake County was developed from the County Tax Assessor data file. Buildings were assigned one (or two in a probabilistic manner) of the 16 building classes according to the design date, use, and exterior material data attributes that exist in the Tax Assessor data file. Replacement costs for the buildings were estimated as a function of building use and square footage. Local engineering experts helped to define the classification rules and replacement cost values. Roughly 175,000 of the 200,000 buildings in Salt Lake County are residential and over 60% are of light wood frame construction.

Table 1 presents summary statistics of the residential building inventory developed for Salt Lake County. Note that roughly 21,750 buildings were classified probabilistically, i.e., having probabilities of being either light wood frame (WF1) or unreinforced masonry buildings (URML).

Table 1. Summary statistics of residential building inventory for Salt Lake County, Utah

	All Buildings	Light Wood Frame (WF1)	Unreinforced Masonry (URML)	50% WF1 and 50% URML	75% WF1 and 25% URML
Total Number	176,657	108,789	46,108	18,358	3,402
Total Area (SF)	386,048,485	242,540,822	95,376,794	42,046,386	6,084,483
Area/Building (SF)	2,185	2,229	2,069	2,290	1,789
Avg. Design Date	1960	1969	1941	1963	1922
Total Replacement Cost (ATC-36, $)	17,372,181,825	10,914,336,990	4,291,955,730	1,892,087,370	273,801,735
Cost/Building ($)	98,338	100,326	93,085	103,066	80,483

NIBS LOSS ESTIMATION METHODOLOGY

The NIBS earthquake loss estimation methodology (Risk Management Solutions, Inc., 1995) is the result of a three and one-half year effort undertaken by the National Institute of Building Sciences to develop a nationally applicable standardized methodology for estimating potential earthquake losses on a regional basis. The NIBS methodology includes all of the concepts that are addressed in the ATC-36 methodology, and in addition includes models for estimating ground shaking, hazardous materials release, and indirect economic effects. Similar to the discussion of the ATC-36 methodology given above and for comparative purposes, the description of the NIBS methodology will focus on residential building damage and loss due to strong ground shaking.

36 structural model building types were identified in the NIBS methodology. Building height is part of the building type definition; therefore, these 36 classes would be very similar to the 16 ATC-36 classes if height (i.e., low-rise, mid-rise, and high-rise) were not considered as part of the building class definitions. In the NIBS methodology, building damage functions are in the form of lognormal fragility curves that relate the probability of being in, or exceeding, a building damage state to a peak spectral response demand parameter (spectral acceleration or displacement). Figure 2 illustrates the NIBS fragility curves for light wood frame (WF1) and low-rise unreinforced masonry (URML) buildings, the two classes of buildings that make up the residential building stock in Salt Lake County. The fragility curves shown in Figure 2 are for structural damage only. Non-structural damage for each building class is expressed in the form of two fragility curves, one in terms of spectral acceleration for those non-structural elements that are sensitive to acceleration, and the other in terms of spectral displacement for those non-structural elements that are sensitive to drift. Figure 3 illustrates the NIBS non-structural acceleration-sensitive and drift-sensitive fragility curves for light wood frame (WF1) buildings.

In the NIBS methodology, peak spectral response parameters (spectral acceleration and displacement) are estimated by the intersection of the capacity curve of the building class of interest with the demand response spectrum corresponding to the geographical location of the building. Building capacity curves were developed for three different levels of seismic design for each of the 36 building classes by means of static non-linear "push-over" analysis. The curves describe the lateral-load-resisting capacity of the model building types as a function of lateral displacement. Figure 4 illustrates the NIBS building capacity curves for light wood frame (WF1) and low-rise unreinforced masonry (URML) buildings located in regions of design for high, moderate (e.g., Salt Lake County), and low seismicity. Demand response spectra are estimated through the use of an attenuation relationship for the given region, and are then modified to account for effects due to local soil conditions. Prior to intersection with the building capacity curve, the demand response spectrum is modified again to account for the increase in damping as the building displaces inelastically and is damaged. Response spectra scaling factors to account for increased damping are given for each of the 36 model building types.

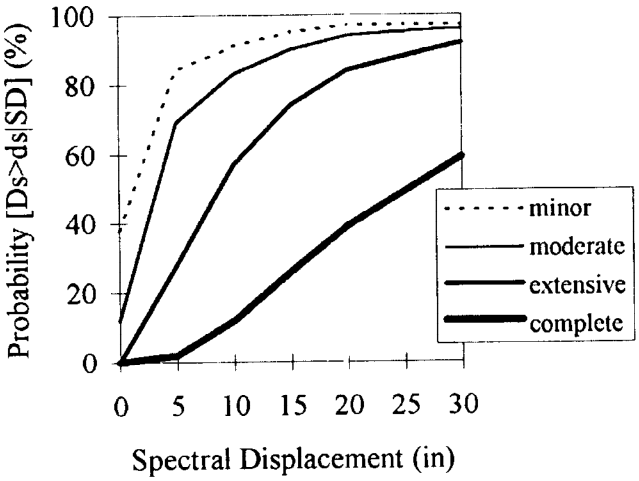

Fig. 2(a). Fragility curve for light wood frame buildings (structural damage).

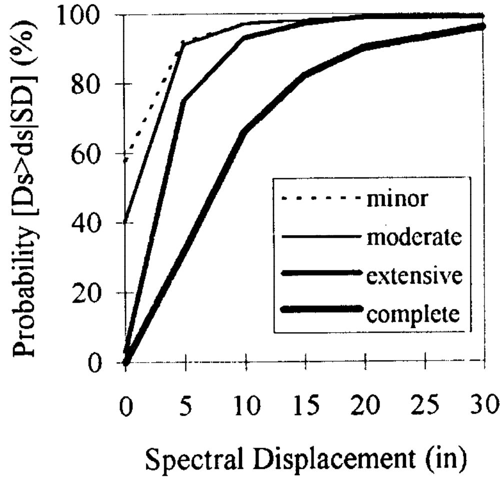

Fig. 2(b). Fragility curve for unreif. masonry buildings (structural damage).

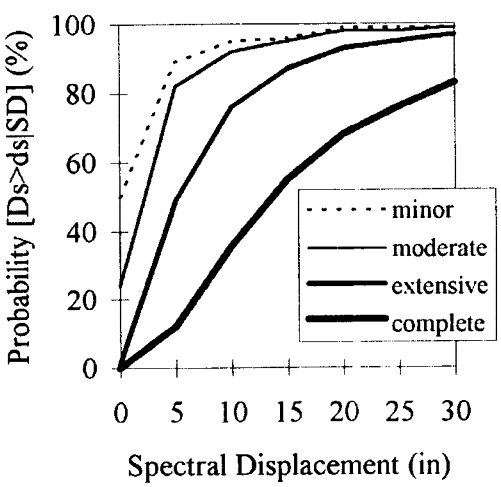

Fig. 3(a). Fragility curve for drift-sensitive non-structural damage (W1 buildings).

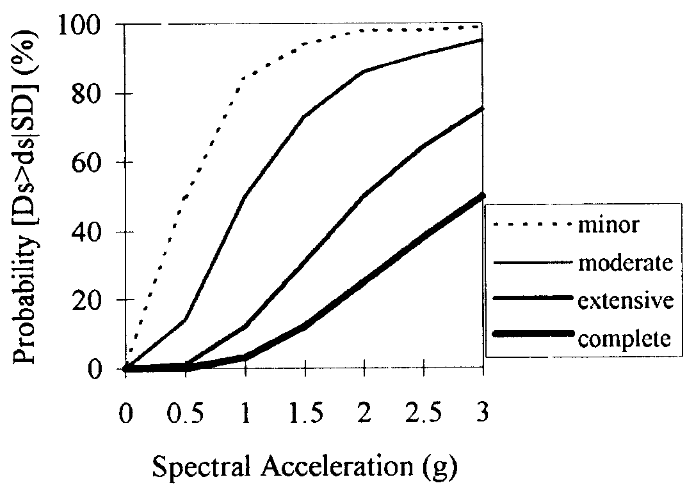

Fig. 3(b). Fragility curve for acceleration-sensitive non-structural damage (W1 buildings).

The peak spectral response parameters that are found by intersecting the building capacity curves with the response spectra demand curves are used with the fragility curves to estimate the probability of being in each of the four damage states. These probabilities are converted to dollar loss through the use of tables that give dollar loss values corresponding to each damage state for each use class of the 36 model building types. Values for the damage state corresponding to complete damage are assumed to be the replacement values. In the NIBS methodology, national dollar values for construction costs were used to develop the replacement values with modification factors corresponding to various regions of the country. The replacement value for the residential building stock in Salt Lake County is estimated at about 22.1 billion dollars, higher than the roughly 17.4 billion dollars estimated with the ATC-36 methodology as shown in Table 1. This difference in replacement values results in differences in total loss estimates, but not necessarily average damage factors (the ratio of damaged value to replacement value) as discussed in the next section.

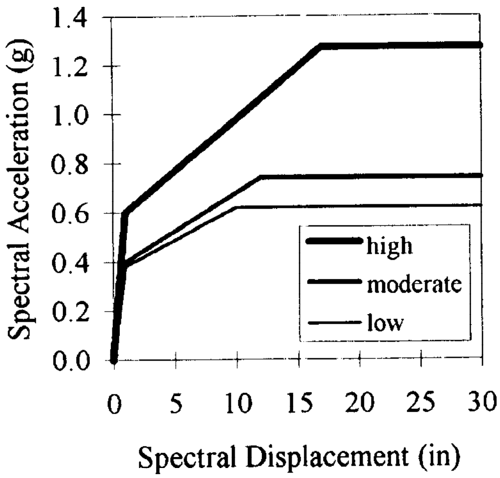

Fig. 4(a). Building capacity curve for light wood frame buildings.

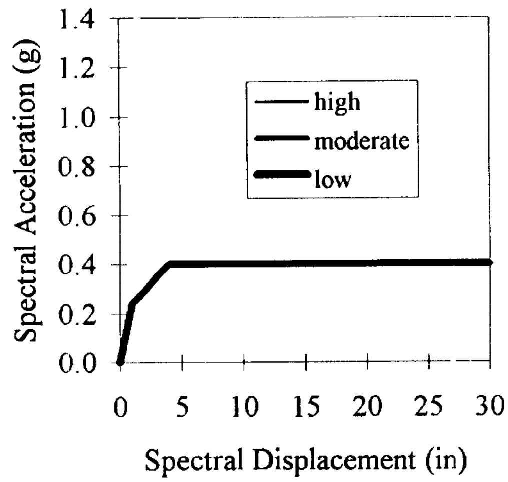

Fig. 4(b). Building capacity curve for unreinforced masonry buildings.

CASE STUDY IMPLEMENTATION OF LOSS ESTIMATION METHODOLOGIES

Ground Shaking Distribution

The ATC-36 and NIBS earthquake damage and loss estimation methodologies were implemented for a Magnitude 7.5 scenario earthquake on the Wasatch Fault Zone in Salt Lake County, Utah. Both methodologies are designed for implementation in a geographic information system (GIS) and the commercial GIS software Arc/Info™ was used for this purpose. Figure 5 shows the location of the Wasatch Fault Zone superimposed on a map showing the density of residential buildings by census tract in Salt Lake County. Ground shaking in the region was estimated using the Boore, Joyner, and Fumal (1992) attenuation relationships for moderately stiff soil conditions for peak ground acceleration (PGA) in cm/sec^2 and for 5% damped spectral velocity (S_v) in cm/sec as follows:

$$\log(PGA or S_v) = a + b(M_w - 6) + c(M_w - 6)^2 + d(\sqrt{r^2 + h^2}) + e[\log(\sqrt{r^2 + h^2})] + f \quad (1)$$

where a, b, c, d, e, f, and h are regression coefficients (period dependent for S_v), M_w is the moment magnitude, and r is the distance to fault in kilometers.

The ATC-36 methodology requires the distribution of ground shaking in the region to be expressed in terms of MMI. MMI shaking intensities were computed by first using equation (1) to calculate PGA and then converting PGA to MMI using the relationship developed by Trifunac and Brady (1975). A map giving the distribution of MMI within Salt Lake County was created in the GIS by using equidistant buffer zones surrounding the Wasatch Fault, applying the attenuation relationship in equation (1), and overlaying a map of surface geology. Figure 6 shows the resultant MMI map for Salt Lake County.

The NIBS methodology requires ground shaking spectral demand curves in terms of spectral acceleration (S_a) and spectral displacement (S_d) at each building location or at the centroid of each census tract in the region. S_v values were computed for eight different periods using equation (1) at the centroid of each of the 156 census tracts in Salt Lake County and were converted to S_a and S_d values. Because the attenuation relationship shown in equation (1) is for moderately stiff soil conditions, the resulting S_a and S_d values were modified to account for the effects of local site conditions. In addition, the spectral demand values were modified to account for increased damping (greater than 5%) that occurs as the building displaces and become damaged.. Figure 7 illustrates three spectral demand curves (modified for damping for light wood frame buildings) for census tracts located at various distances from the Wasatch Fault Zone. Figure 8 illustrates the distribution of spectral acceleration in Salt Lake County for a period of 0.3 seconds.

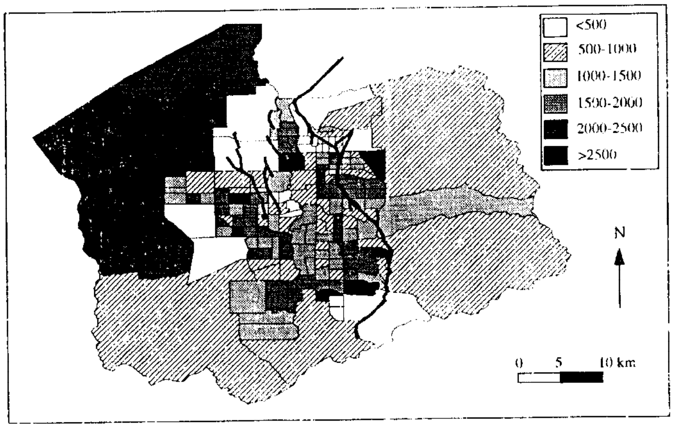

Fig. 5. Wasatch Fault Zone with number of houses per census tract.

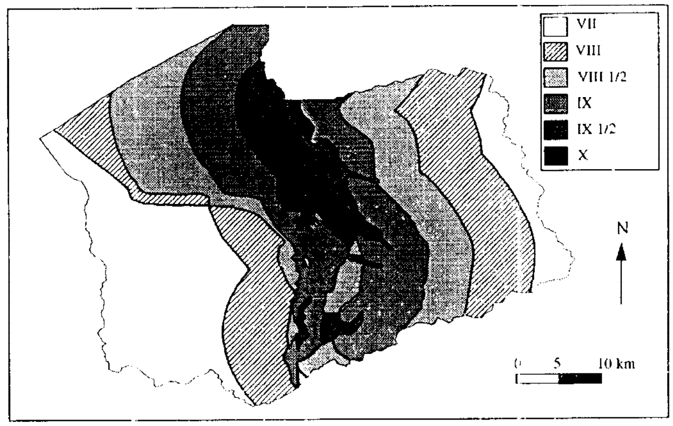

Fig. 6. Distribution of MMI for M 7.5 earthquake in Salt Lake County.

Building Damage and Loss Estimation

Earthquake damage to the roughly 175,000 residential buildings in Salt Lake County was estimated for a Magnitude 7.5 earthquake on the Wasatch Fault Zone. Damage estimation using the ATC-36 methodology was achieved through the use of the expected damage factor curves shown in Figure 1, the MMI distribution map shown in Figure 6, and GIS maps of the residential building stock. Using the NIBS methodology, the damage estimated were made by developing spectral demand curves at the centroid of each census tract, such as those shown in Figure 7. These spectral demand curves were intersected with the building capacity curves shown in Figure 4 to determine the spectral response parameters. The spectral response parameters were used as input to the fragility curves shown in Figures 2 and 3 to estimate the probability of being in, or exceeding, the four damage states.

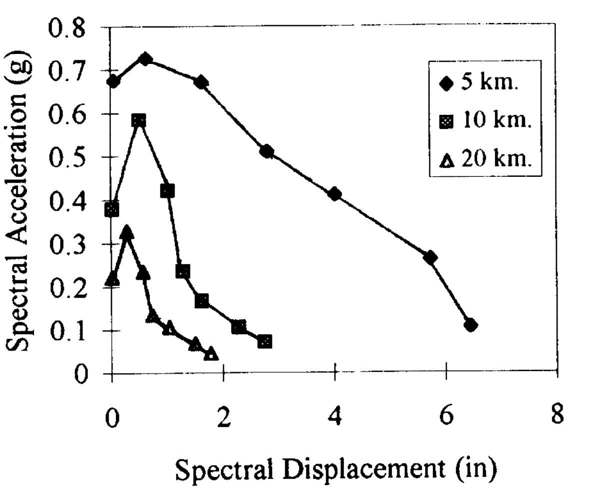

Fig. 7. Spectral demand curves for light wood frame buildings for M 7.5 earthquake.

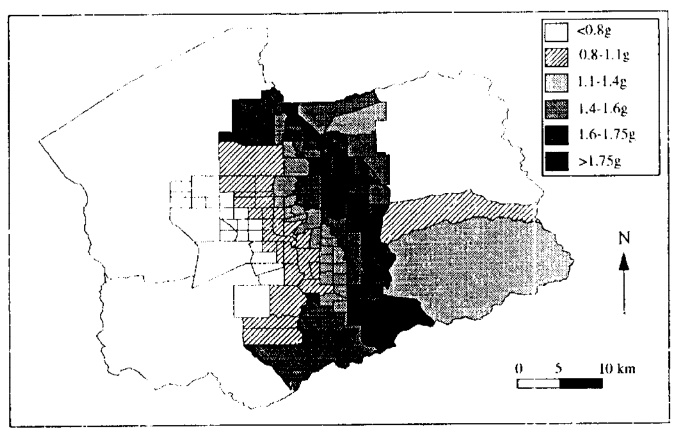

Fig. 8. Spectral acceleration (0.3 sec) for M 7.5 earthquake in Salt Lake County.

Using the ATC-36 methodology, building loss was estimated by multiplying the expected damage factor for each building by its replacement value. Using the NIBS methodology, building loss was estimated by multiplying the probability of being in each damage state by the dollar loss value for each damage state and summing, including both structural and non-structural damage as discussed earlier in this paper. For comparison purposes, loss values for the buildings were aggregated over each census tract and by structural building class. In addition, damage estimates were expressed in terms of damage factor by dividing the dollar loss values by replacement costs. Table 2 shows the comparison of damage and loss estimates by structural building class made using the ATC-36 and NIBS methodologies. Excluded from this table are damage and loss estimates for contents, which were not considered in this comparison. Figures 9 and 10 illustrate the distribution of average damage factor (DF) by census tract in Salt Lake County resulting from the ATC-36 and NIBS methodologies, respectively. Figures 11 and 12 illustrate the distribution of total loss per census tract in Salt Lake County resulting from the ATC-36 and NIBS methodologies, respectively.

Table 2. Summary statistics of residential building damage and loss for Salt Lake County, Utah

	All Buildings	Light Wood Frame (WF1)	Unreinforce d Masonry (URML)	50% WF1 and 50% URML	75% WF1 and 25% URML
Total Loss (ATC-36, $)	4.482 Billion	961 Million	2.792 Billion	660 Million	69 Million
Total Loss (NIBS, $)	5.608 Billion	2.40 Billion	2.449 Billion	644 Million	119 Million
Loss/Building (ATC-36, $)	25,371	8,832	60,561	35,939	20,318
Loss/Building (NIBS, $)	31,743	22,017	53,124	35,101	34,864
Total Replacement Cost (ATC-36, $)	17.372 Billion	10.91 Billion	4.292 Billion	1.892 Billion	274 Million
Total Replacement Cost (NIBS, $)	22.113 Billion	13.89 Billion	5.463 Billion	2.408 Billion	349 Million
Overall DF (ATC-36,%)	25.80	8.80	65.06	34.87	25.24
Overall DF (NIBS,%)	25.36	17.24	44.84	26.76	34.03
Loss/Sq. Ft. (ATC-36, $)	11.61	3.96	29.28	15.69	11.36
Loss/Sq. Ft. (NIBS,$)	14.53	9.88	25.68	15.33	19.49

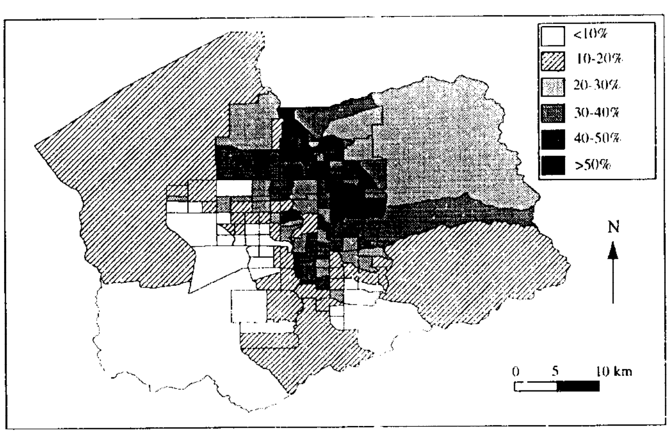

Fig. 9. Average damage factor by census tract in Salt Lake County, ATC-36 methodology.

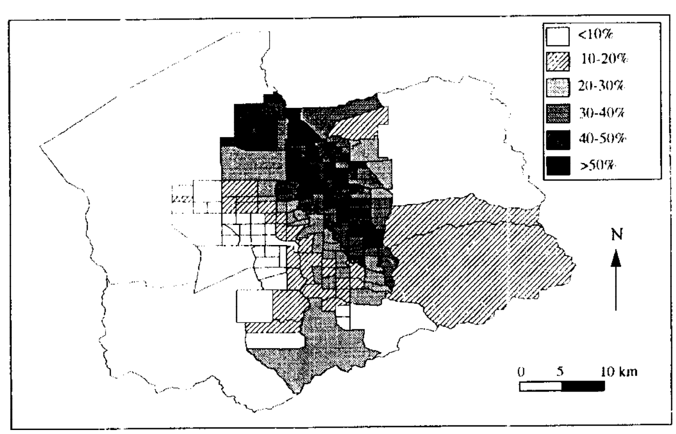

Fig.10. Average damage factor by census tract in Salt Lake County, NIBS methodology.

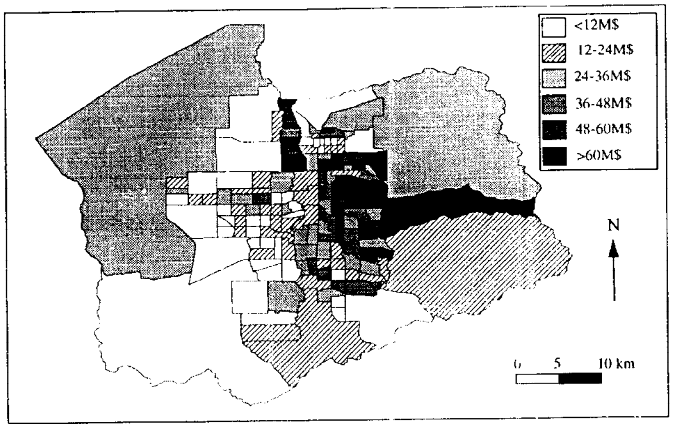

Fig. 11. Total dollar loss by census tract in Salt Lake County, ATC-36 methodology.

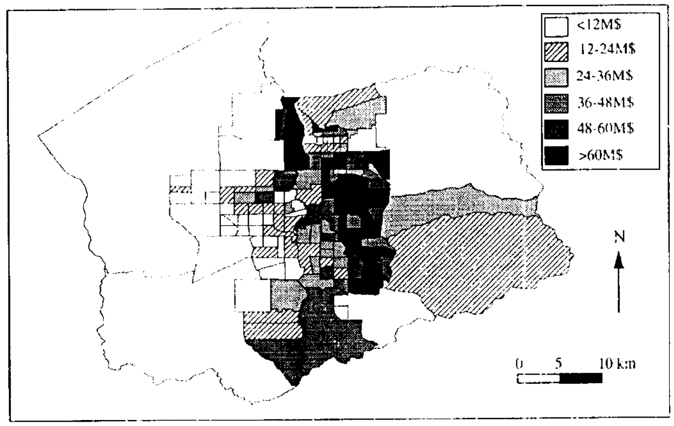

Fig.12. Total dollar loss by census tract in Salt Lake County, NIBS methodology.

CONCLUSIONS

The ATC-36 and NIBS earthquake damage and loss estimation methodologies are different primarily in the characterization of the motion-damage relationships, the choice of ground motion parameters, the treatment of non-structural damage, and the replacement value computation. The ATC-36 motion-damage relationships are heuristically derived and based on MMI, while the NIBS relationships are empirically and analytically derived and based on spectral demand parameters. In ATC-36, one motion-damage relationship is used for both structural and non-structural damage for a given building class, while in NIBS, the two types of damage are treated separately. Finally, the ATC-36 replacement values for buildings result in a lower total replacement value for the Salt Lake County residential building stock than that computed using NIBS.

Despite these methodology differences, the final damage and loss statistics, as shown in Table 2, are not significantly different. The higher replacement values produced by the NIBS methodology result in higher total losses; however, when the dollar values are removed by comparing damage factors, the results are very similar, in the range of 25 to 26% damage. When broken up by structural type, i.e., wood frame and unreinforced masonry, the results from each methodology are less similar. Wood frame building damage is 8.8% with ATC-36 and 17.2% with NIBS, while unreinforced masonry building damage is 65.1% with ATC-36 and 44.8% with NIBS. As shown in Figures 9 through 12, the distribution of damage and loss throughout the county differs between the two methodologies. The ATC-36 results are more widespread throughout the county, while the NIBS results tend to be concentrated near the fault zone. To more thoroughly compare these two methodologies, all structural types, as well as earthquake damage and loss due to collateral hazards, should be included. In addition, other losses due to socio-economic effects should be considered.

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