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A CLOSER LOOK AT GIS-EARTHQUAKE LOSS ESTIMATION METHODOLOGY TO IMPROVE CRISIS MANAGEMENT CAPABILITY

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Abstract

This paper uses HAZUS[1] for sensitivity analysis for earthquake scenarios for San Francisco County. In addition, in the paper, we suggest guidelines that could be used in response to earthquake catastrophe in the San Francisco Bay Area (SFBA), and for other regions. This analysis will help emergency mangers and decision-makers to understand the potential risk in their jurisdictions from an earthquake, which will help them in preparedness and planning for future catastrophes. Urbanization compounds the problems associated with earthquake disasters in large cities. Furthermore, forecasting of unknown accuracy of earthquake loss estimation is of limited use, and can be very misleading to stakeholders. The parameters that are used in the sensitivity analysis are: 1) site effect, 2) attenuation relationships, 3) ground failure effects, and 4) building inventory. In this analysis, we used hypothetical earthquake scenarios to test the number of people who would be killed, the number of people who would need hospitalization, the number of people who would seek shelter, and the total economic losses that would result from residential building damage. It is apparent that Potential Earth Science Hazards parameters (items 1-3 above) are more sensitive to earthquake magnitude than the Direct Physical Damage parameter (item 4 above). Ground failure effect, from no liquefaction susceptibility to detailed liquefaction susceptibility, is the most sensitive parameter in earthquake loss estimation, followed by choosing the attenuation function, subsequently, site effect parameters, from soil type D to detailed soil type map of the region, and lastly effects of building construction parameters, high code standards to moderate code standards. The building construction sensitivity on the economic losses is relatively stable. For the other loss estimations—number of people who would be killed, number of people who would be hospitalized, and number of people who would be sheltered—the sensitivity of the other analysis parameters, either enlarged or diminished with the increasing in earthquake magnitude.

Introduction

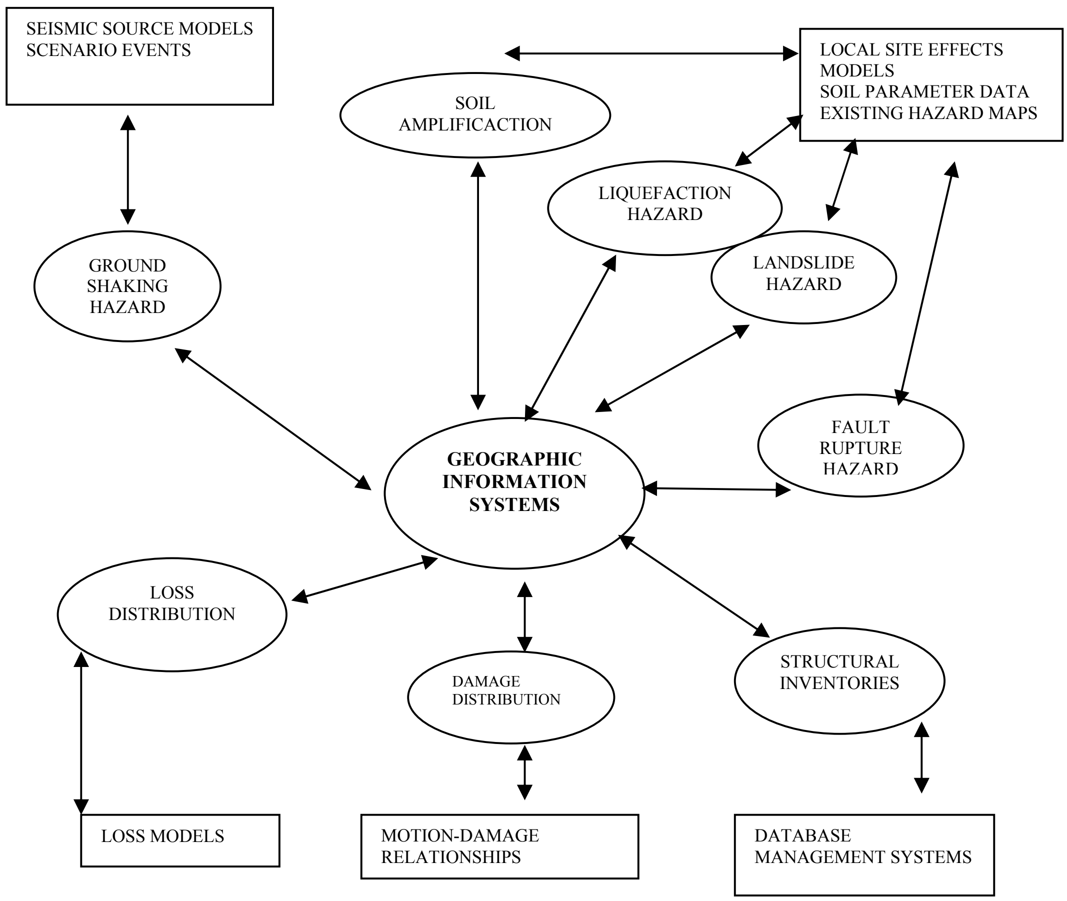
Earthquakes are both physically and emotionally devastating to the population and detrimental to a country's assets. For example, the world experienced two large earthquakes that hit hard two of the most advanced countries in earthquake science, the United States and Japan. The Northridge

[1] An earthquake loss estimation methodology developed in 1997 for FEMA by the U.S. National Institute of Building Science (NIBS)

Earthquake in the United States and The Kobe Earthquake in Japan resulted in huge impacts in terms of casualties and monetary losses. Engineers, scientists, and other interested groups visited the earthquake-damaged areas hoping to learn lessons from such disaster. Beyond site visit, it is possible to study earthquakes and their associated impacts with models such as HAZUS (Hazards U.S.). We used hypothesized earthquake scenarios and analyses to measure the sensitivity of earthquake loss estimation in order to improve crisis management capability in response to earthquake catastrophe in our study.

Earthquake risk is coupled with local site effects of soil amplification, liquefaction, landslide, and surface fault rupture, and the built environment. These factors are combined with the seismic activities in a region to study the expected damage to the built environment from an earthquake scenario. There have been many hypothesized earthquake scenario studies to understand the potential earthquake risk for human life and monetary investment in a study region. These studies were very data-intensive and time-consuming processes. Nevertheless, with the advances in information technology, especially the Geographic Information System (GIS), it was possible to run different earthquake scenarios for the same study region without extra investment. More importantly, GIS enabled us to do earthquake loss estimation sensitivity analysis. King and Anne (1994) distinguished their research from others by using GIS in regional seismic hazard and risk analysis as shown in figure (1).

Fig. (1) The Role of Geographic Information Systems in Regional Seismic Hazard and Risk Analysis

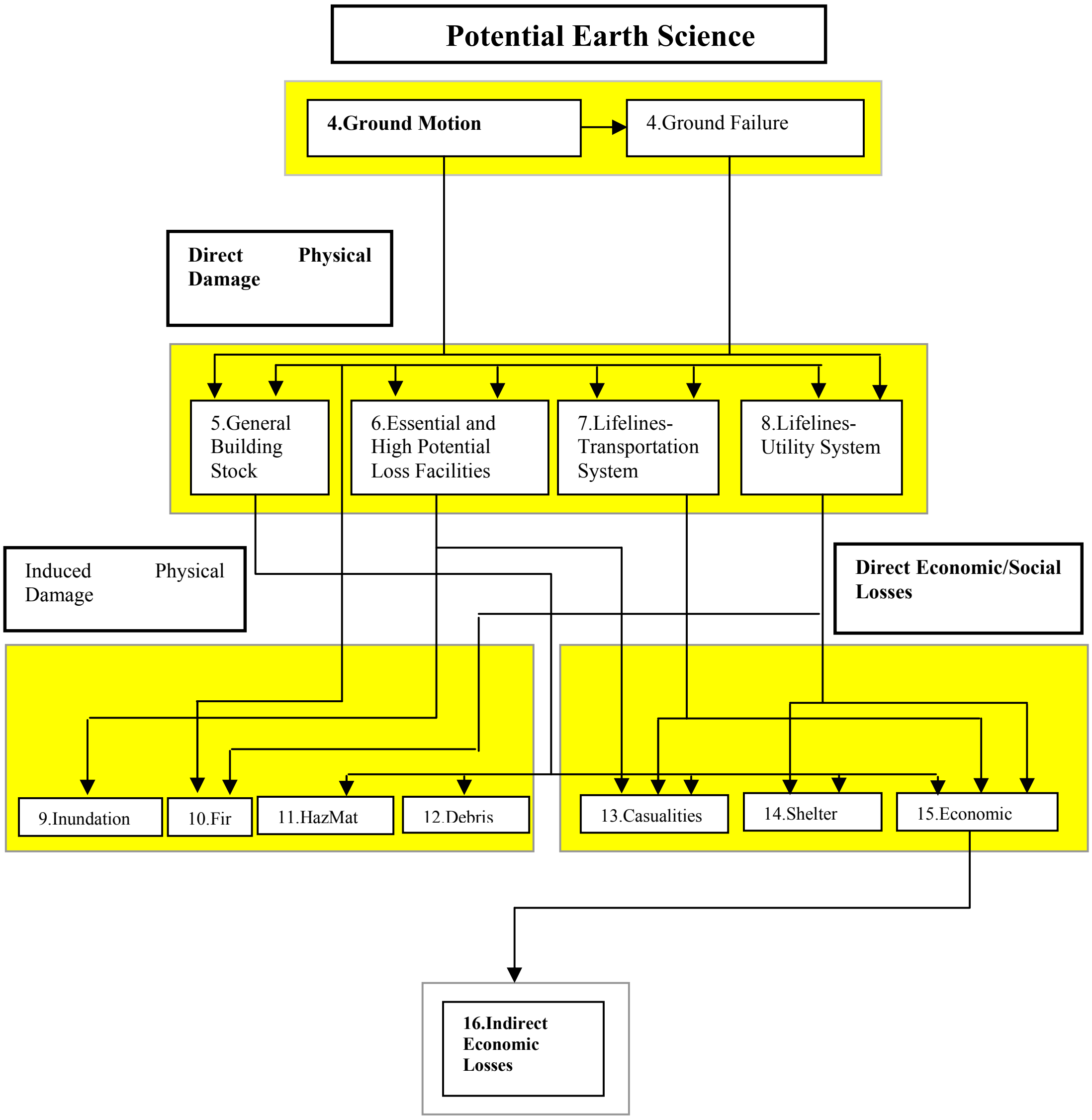


The Federal Emergency Management Agency (FEMA) also tries to capitalize on GIS capability by introducing HAZUS (HAZARD U.S.), an earthquake loss estimation methodology that is intended for local, regional, or state manipulation, for public use in efforts to reduce damage and social and economic impacts from earthquakes. This GIS-based earthquake loss estimation methodology is an improvement over existing regional loss estimation methodologies, and it is in public domain

GIS Earthquake Loss Estimation Methodology

HAZUS is an earthquake loss estimation methodology that is intended for local, regional, or state manipulation. The methodology has been developed for the Federal Emergency Management Agency (FEMA) by the National Institute of Building Science (NIBS) to provide a tool for developing earthquake loss estimates. The Earthquake Loss Estimation methodology, as shown in figure (2), capitalizes on the GIS capabilities to manipulate large multidisciplinary database with different quality and to provide maps that are used in earthquake loss estimation

Fig. (2) HAZUS Loss Estimation Methodology



The framework of the methodology consists of Potential Earth Science Hazard (PESH), Inventory Data (ID), Direct Physical Damage (DPD), Induced Physical Damage (IPD), Direct Economic/Social Loss (DSEL), and Indirect Economic Loss (IEL) models as shown in figure (2). These models are interdependent with the output of some models acting as input for other models.

The Potential Earth Science Hazard (PESH) model consists of earthquake-related hazards that are considered in evaluating casualties, damage, and resultant losses from an earthquake. These hazards are: fault rupture, liquefaction, and landslide.

The Inventory Data (ID) model contains the collection and classification of different buildings and utility systems, data and attributes required for performing damage and loss estimation. These data include: buildings and facilities, transportation systems, utility systems, hazardous material facilities, census data, county business patterns, and indirect economic data for the study region.

The Direct Physical Damage (DPD) model, as shown in figure (2) above, determines the probability of slight, moderate, extensive, and complete damage to general building stock. The extent and severity of damage to structural and non-structural components of buildings is described by one of five damage states (none, slight, moderate, extensive, and complete) based on functions for estimating building damage due to ground shaking. These building damage functions include fragility curves, which describe the probability of reaching or exceeding different states of damage given the peak building response, and building capacity curves, which are used to determine peak building response.

Induced Physical Damage (IPD) model, as shown in figure (2), estimates induced physical damages which include: inundation, fire, debris generation

Direct Economic /Social Losses (DESL) model, as shown in figure (2), estimates direct economic and social losses from an earthquake. These types of losses are:

Economic Losses. HAZUS estimates the direct economic losses results from earthquake. These losses consist of building related losses and transportation and utility lifeline losses.

Casualties. HAZUS estimates the number of people who will be injured and killed by the earthquake. The casualties are broken down into four severity levels that describe the extent of the injuries. The levels are described as follow:

Severity Level 1. Injuries will require medical attention, but hospitalization is not needed.

Severity Level 2. Injuries will require hospitalization but are not considered life threatening.

Severity Level 3. Injuries will require hospitalization and can become life threatening if not promptly treated.

Severity Level 4. Victims are killed by the earthquake

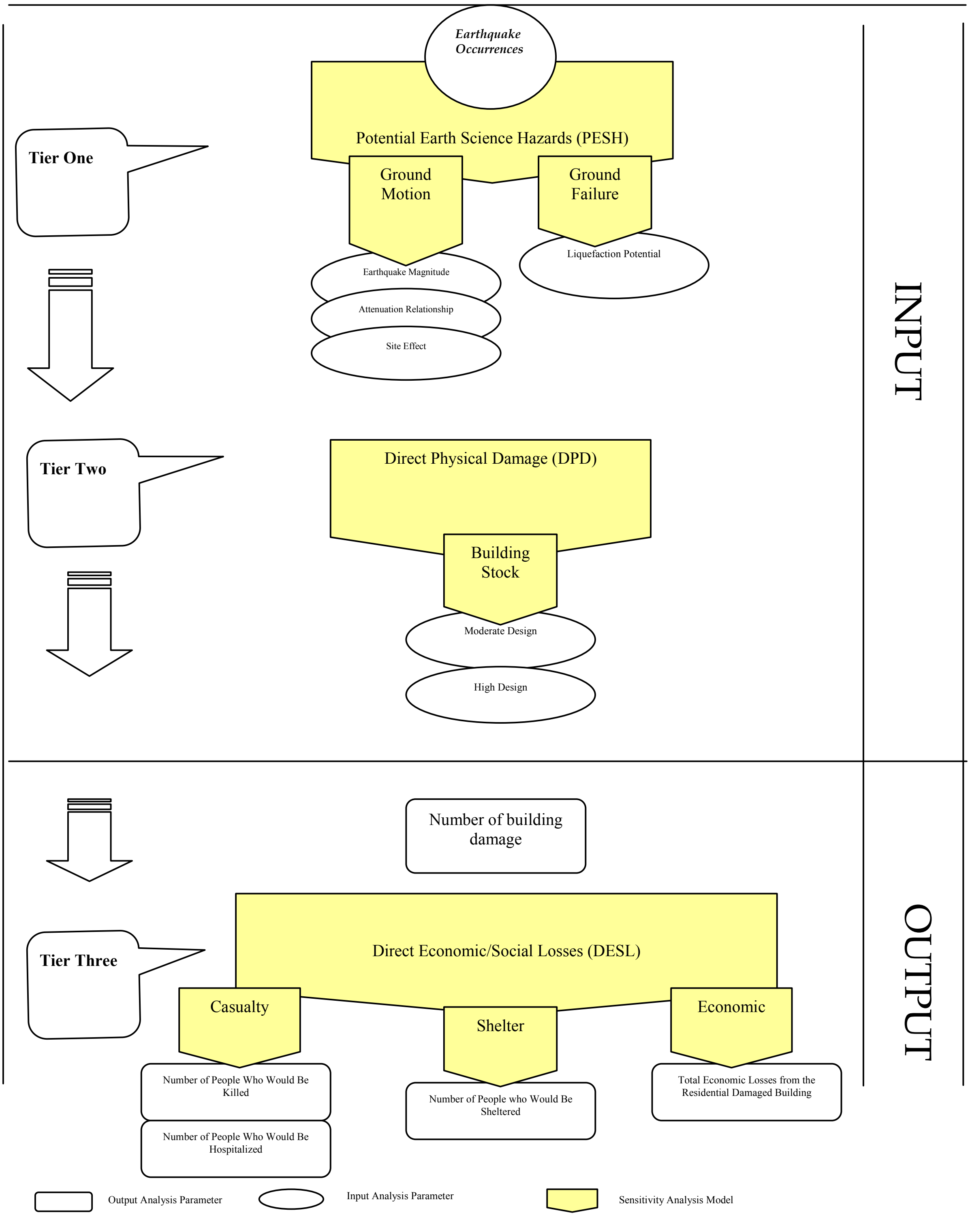
Shelter requirement. HAZUS estimates the number of households that are expected to be displaced from their homes due to the earthquake and the number of displaced people who will require accommodations in temporary public shelters.

The Indirect Economic Loss (IEL) model, in comparison, estimates the long-term economic impacts to the region for 15 years after the earthquake. The model quantifies this information in terms of income and employment changes within the study region.

Scope of Analysis

In this analysis, we worked on three tiers of models, as shown in figure (3) below. The first two tiers of models were used to select the parameters that were used in the sensitivity analysis, and the third tier was used to measure the HAZUS methodology output sensitivity for the selected parameters.

Fig.(3) Scope of Sensitivity Analysis Models and Parameters



earthquake magnitude, attenuation relationships, site effect, and liquefaction potential effects. In the second tier models, we considered the general building stock from the Direct Physical Damage (DPD) model. In the third tier models, we considered casualties, shelter, and economic models from the Direct Economic/Social Losses (DESL) model. We examined 240 earthquake scenarios for the analysis. In each scenario, we kept one factor stable and changed the others.

Analysis Parameters

Earthquake risk is coupled with local site effect of soil amplification, liquefaction, landslide, and surface fault rupture, as well as the built environment. These factors are combined with the seismic activities in a region to study the expected damage to the built environment from an earthquake scenario. In the following sections, we will discuss the models that were used in the HAZUS ELE sensitivity analysis.

Potential Earth Science Hazard (PESH) Model

The Potential Earth Science Hazard (PESH) model is the main model in the HAZUS loss estimation methodology. Moreover, as shown in figure (2), the model output is used in evaluating casualties, damage, and resultant losses from an earthquake scenario. Most damage and losses caused by an earthquake are the direct result of the ground shaking. This shaking strength mainly depends on the earthquake magnitude and how the shaking waves move from the earthquake hypocenter to the impacted area, and, lastly, the site effects. Therefore, in our study we considered the earthquake magnitude and the attenuation function—which shows how the earthquake shaking attenuates with distance—as well as the soil types that could amplify or reduce the shaking intensity below the building environment based on different soil types at the site of interest.

Earthquake Magnitude

Earthquake magnitude is the key factor that was used to direct our analyses, as shown in figure (3) above. In order to understand the variety of the HAZUS methodological output in different earthquake scenarios, we chose the earthquake range from 5.5 to 7.5 for the sensitivity analysis. It is important to remember that an earthquake with magnitude less than 5.5 will not cause significant damage. Therefore, we were not able to measure the sensitivity of earthquake damage below this range. An earthquake with magnitude larger than 7.5, furthermore, is unlikely to happen. In addition, the attenuation relationships that were used in the analysis are applicable to earthquake magnitude within this range.

Attenuation Relationship

The HAZUS methodology provides five different attenuation functions that are used for the Western United States (WUS) region. In our analysis, we used Boor, Joyner & Fumal (hereafter BJF94); Sadigh, and Chang, Abrahmson, Chiou, and Power (hereafter Sadigh93), as well as the Project 97 attenuation function, which is a linear combination of the WUS attenuation functions that are based on the theory developed by the United State Geological Survey (USGS). The Project 97 attenuation function is used as a default attenuation function in the HAZUS methodology. These different attenuation functions predict different peak ground acceleration (PGA) values, which will further be used to measure the earthquake losses for the study region.

Site Effect

HAZUS methodology uses soil amplification functions to account for the local site condition of the earthquake scenario area. Soft soil tends to amplify certain frequencies within the ground shaking, resulting in greater damage. HAZUS uses six different soil classification types based on The National Earthquake Hazards Reduction Program (NEHRP) 1997 provision, which classifies the soil types based on their shear-wave velocity (Vs).

The default soil class for HAZUS is soil class D. It is described as stiff soils with a shear wave velocity between 180 m/s and 360 m/s. In our sensitivity analysis, we used the default soil class as well as an updated soil class map, a detailed map contains soil types B, C, D, and E, for the study region.

Liquefaction Potential

In addition to the damage that results from ground motion, HAZUS considers three features of earthquakes that can cause permanent ground failure. These features are fault rupture, liquefaction, and landslide. HAZUS assumes no liquefaction potential for our study region. In our research, we used an updated liquefaction map in the HAZUS sensitivity analysis. Seed et al. (1983) described the Liquefaction phenomenon in which "if a saturated sand is subjected to ground variations, it tends to compact and decrease in volume that results in an increase in pore water pressure, and if the pore water pressure builds up to the point at which it is equal to overburden pressure, the effective stress becomes zero, the sand loses its strength completely, and it develops a liquefaction state. The phenomenon of liquefaction could cause damage to the built environment if the earthquake magnitude triggers the liquefaction effect.

Direct Physical Damage (DPD) Model

The Direct Physical Damage model determines the probability of slight, moderate, extensive, and complete damage to the general building stock based on functions for estimating building damage due to ground shaking.

General Building Stock

HAZUS provides the number of buildings that will be damaged within different damage classes. HAZUS provides a description for these states of damage for each model building type (e.g., descriptions for extensive damage wood structures are: toppling of most brick chimneys; cracks in foundations; partial collapse of room-over-garage or other soft-story configurations; small foundations cracks). Buildings classified as complete or extensive are unsafe to enter and should be inspected for possible evacuation.

HAZUS provides different default occupancy to building type mapping based upon a default mix of ages (i.e., pre 1950, 1950-1970, and post 1970) and heights (i.e., low rise [1-3 stories], medium rise [4-7], and high-rise [more than 8 stories]). This mapping scheme varies by state, and it is possible that different census tracts within the study region will have different age and height mixes. In addition, HAZUS provides a mapping scheme to reflect different design levels. In this mapping scheme, buildings are classified, as structures that are built to code, are superior to the code or inferior. In addition, HAZUS provides a mapping scheme to reflect the design level. For example, the design level is high in California, moderate and low in Florida. HAZUS provides three different mapping scheme combinations of the above mapping classifications for our study region. Those are high, moderate, and low. We used the default high and default medium in our analysis.

Casualties

HAZUS provides casualty estimates for each census tract at three times of the day (2 AM, 2 PM and 5 PM). We used HAZUS default parameters, which are based on previous earthquake experience and expert judgment, to measure these estimates. The output from this model consists of a casualty breakdown by injury severity, defined by four severity scales, as we discussed above. In our analysis, we measured the casualties in residential buildings that would result from an earthquake at 2 AM. Casualties in the residential buildings at this time of day would be greatest. In our analysis, we measured the number of people who would be killed and the number of people who would need hospitalization.

Shelter

HAZUS contains default factors that are based on previous research from earthquake experiences to estimate the shelter needs. We used the default factors in our analysis to calculate the number of people who would seek shelter after an earthquake.

HAZUS provides estimates of displaced households due to loss of housing habitability and short-term shelter needs. Loss of habitability is calculated directly from damage to the residential occupancy inventory and from loss of water and power. The following inputs are required to compute the number of uninhabitable dwelling units and the number of displaced households: fraction of dwelling units likely to be vacated if damaged, probability that the residential units are without power and/or water immediately after the earthquake, and percentage of households affected by utility outages likely to seek alternative shelter.

Economic

HAZUS provides default parameters to estimate the economic losses that result from an earthquake. We used these parameters to estimate the economic losses resulting from residential building damage. These losses are directly derived from building damage that consists of cost of repair and replacement charges for damaged and destroyed buildings, costs of damage to building contents, and losses of inventory contents related to business activities. These are the main contributors to the economic loss resulting from the residential building damage. Moreover, HAZUS provides estimates for additional indirect losses that also contribute to the total (e.g., relocation and building repair time expenses), but they were not included in our study.

Model City Study

HAZUS is the earthquake loss estimation methodology that was developed and calibrated mainly based on the building inventory and previous earthquake experience in California. HAZUS involves different models, parameters, and expert judgment to measure the potential loss from an earthquake.

We chose a study area in California in order to minimize the span of uncertainty from choosing a different study area for the sensitivity analysis.

In this research, HAZUS was used to estimate the Earthquake Loss Estimation (ELE) for earthquake scenarios in San Francisco County. A HAZUS run is a time-consuming operation. In order to facilitate a large combination of earthquake scenarios, a small region, which is very vulnerable in terms of its infrastructure and inventory content value, was used.

In this study, the description of the demographic and the building inventory content for the study region, as provided by the HAZUS Earthquake Event Report for the region, is

The geographical size of the region is 48 square miles and contains 152 census tracts. There are over 306 thousand households in the region and has a total population of 724,000 people (1990 Census Bureau data). . . . There are an estimated 128 thousand buildings in the region with a total building replacement value (excluding contents) of 58,663 million dollars (1994 dollars). Approximately 93% of the buildings (and 67% of the building value) are associated with residential housing . . . . In terms of building construction types in the region, wood frame construction makes up 91% of the building inventory.

Analysis Scenarios

We chose two seismic faults, from the San Francisco Bay Region fault sources. These faults are the San Andreas (SA) fault, Peninsula Segment, which experienced a 7.0 earthquake in 1838, and the Northern Hayward (NH) fault, which experienced a 6.8 earthquake in 1836.The length and slip rate and the probability of earthquake occurrences on these faults as discussed by the working group on California Earthquake Probabilities, are shown in table (2) below.

Table (2). San Francisco Fault Sources for Earthquake Scenarios

Fault	San Andreas (SA) Fault, Peninsula Segment	Northern Hayward (NH) Fault (
Length (Km)	85	35
Seismic Width (Km)	13	12
Slip Rate (mm/yr)	17	9
Significant Earthquakes	1838, M~7.0 37.6 Lat., -122.4 Long.	1836, M~6.8 37.8 Lat. , –122.2 Long.
Probability of M>/= 6.7 earthquake before 2030	15 %	16 %

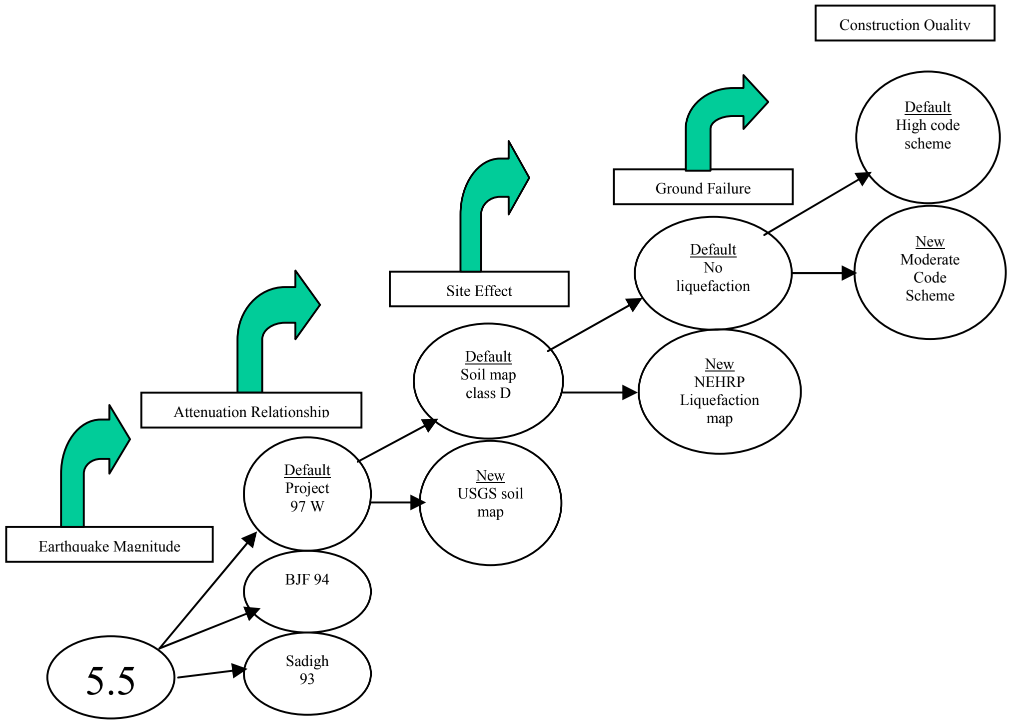
Therefore, we will have two sets of analyses for NH and the SA faults. Any major earthquake on these faults will be a catastrophic event for the San Francisco area. Hayward fault is considered in many previous earthquake scenarios for SFBR. Moreover, the San Andreas Fault was the source for the 1906 Great San Francisco Earthquake, which resulted in catastrophic damage for San Francisco County.

We examined 120 earthquake scenarios for each fault to measure the sensitivity of each selected parameter in our analysis. The earthquake scenarios for both faults, as shown in figure (8), were as follows:

- San Andreas (SA) fault, Peninsula Segment. The earthquake epicenter was chosen to represent a repeat of the 1838 earthquake that ruptured the SA fault with magnitude of ~ 7.0. The epicenter was 37.6 Latitude and –122.4 Longitude.
- North Hayward (NH) fault. The earthquake epicenter was chosen to represent a repeat of the 1836 earthquake that ruptured the NH fault with a magnitude of ~ 6.8. The epicenter was 37.8 Latitude and –122.2 Longitude.

Therefore, we selected the earthquake epicenter based on the above discussion. Then, for each earthquake magnitude within the range 5.5 to 7.5 we tested the same analysis parameter. An example of the HAZUS scenario for an earthquake with a magnitude of 5.5 is shown in figure (4) illustrated below. Then, for the earthquake scenario, there were three attenuation function relationships guiding each scenario. In each one, we chose the attenuation function and then changed the other parameters, which are for site effect, ground failure, and construction quality. For the attenuation relationship, three attenuation functions were chosen for the analyses; they were Project 97 West (as default attenuation relationship), BJF 94, and Sadigh 93. The site effect in this analysis identifies the capability of the soil to amplify or to reduce the earthquake intensity. The default in our analysis that HAZUS assumes for the San Francisco County is soil class D (stiff soil type). The default ground failure effect with the methodology assumes no liquefaction for the study area. The new liquefaction map, which was developed by the NEHRP, contains different liquefaction susceptibility for the study region. These maps were provided by the HAZUS Working Group for the Bay Area. In the Construction Quality layer, the High Code mapping scheme is considered the default for the study area, and the updated one is for the Moderate Code mapping scheme.

Fig. (4) Example of Choosing the Earthquake Scenarios for Earthquake Magnitude



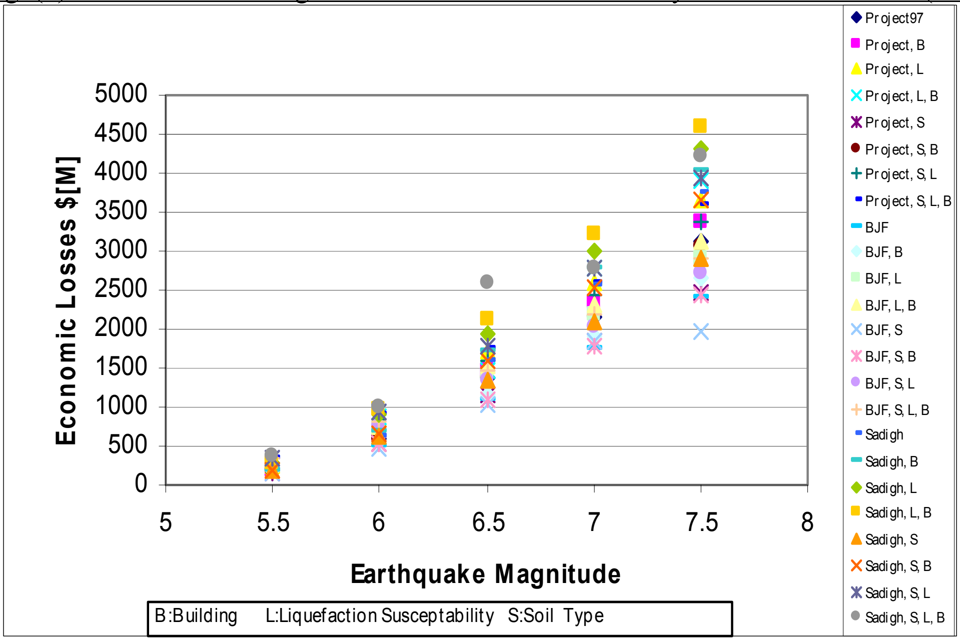
What might be expected from an earthquake with magnitude 5.5 that ruptured through the NH fault? The epicenter, we know, would be 37.8 Latitude and –122.2 Longitude. If we chose the Project 97 West attenuation function, and assumed soil class D (stiff soil) for the Region, as well as there was no liquefaction for the study area, what might be the potential losses from this earthquake for San Francisco County, assuming the buildings for this region are built to high code standards.

We tried to answer this question with different variables, such as earthquake magnitude, attenuation relationship, soil type, liquefaction potential, and building quality through conducting sensitivity analysis (earthquake loss estimation) for San Francisco County.

Results and Analysis

In our analysis, we examined 24 earthquake scenarios for each earthquake magnitude for both the NH and SA faults. The results were then analyzed to understand how these results could be used in emergency response and decision making for the SFBA area and furthermore, be used for different regions. Figure (5) below, shows the millions of dollars in residential economic losses that could result from an earthquake scenario on the NH fault. In the figure below, S refers to the soil type, from soil type D to a detailed soil type map; B refers to the building construction, from high code to low code standards; L refers to liquefaction susceptibility, from no liquefaction susceptibility to detailed liquefaction susceptibility for the study region.

Fig. (5) Residential Buildings Economic Losses in North Hayward Fault Scenario (NH)



The sensitivity analysis of earthquake scenarios illustrated that the Potential Earth Scenic Hazards parameters (earthquake magnitude, attenuation function, ground failure effect) are more sensitive to earthquake magnitude than the Direct Physical Damage parameters (building inventory). Ground failure effects (from no liquefaction susceptibility to detailed liquefaction susceptibility) is the most sensitive parameter in earthquake loss estimation, followed by choosing the attenuation functions, site effect parameters (from soil type D to detailed soil type map of the region) and lastly the effects of building construction parameters (high code standards to moderate code standards). The building construction sensitivity on the economic losses is relatively stable. For other losses estimations— number of people who would be killed, number of people who would be hospitalized, and number of people who would be sheltered—the sensitivity of the other analysis parameters either enlarged or diminished with the increasing in earthquake magnitude. Figure (6) shows an example of the sensitivity of the analysis parameters on the residential economic losses for the Project97 attenuation function that would result from the North Hayward (NH) fault scenario.

As shown in Fig (7) below, HAZUS losses estimation is within a factor of 10, and a factor of 4 for residential economic losses. For an earthquake magnitude of 7.0, for the NH fault, the maximum value of the residential economic losses are $3229.1 million and the minimum losses are $1496.8 million. Therefore, the ratio between the maximum and the minimum is 2.18. If we assume the factor of economic losses is 3.0, we can use the default parameter values for the sensitivity analysis—soil type, attenuation function, liquefaction susceptibility, and building construction— to get rapid estimates for the potential economic losses from an earthquake scenario.

Fig. (6) Percent Change in Residential Economic Losses for Project 97 Attenuation Function

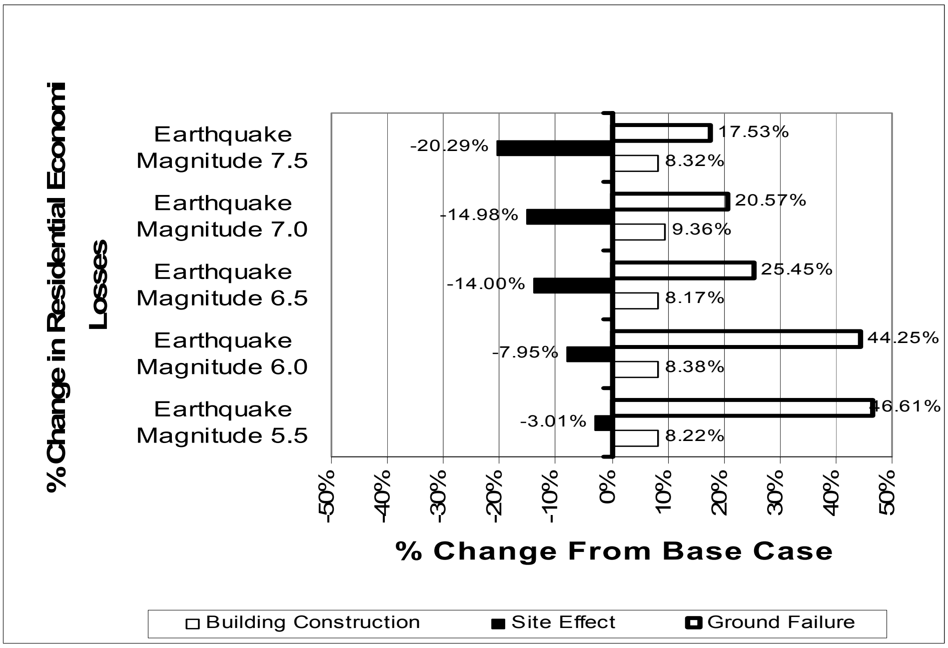
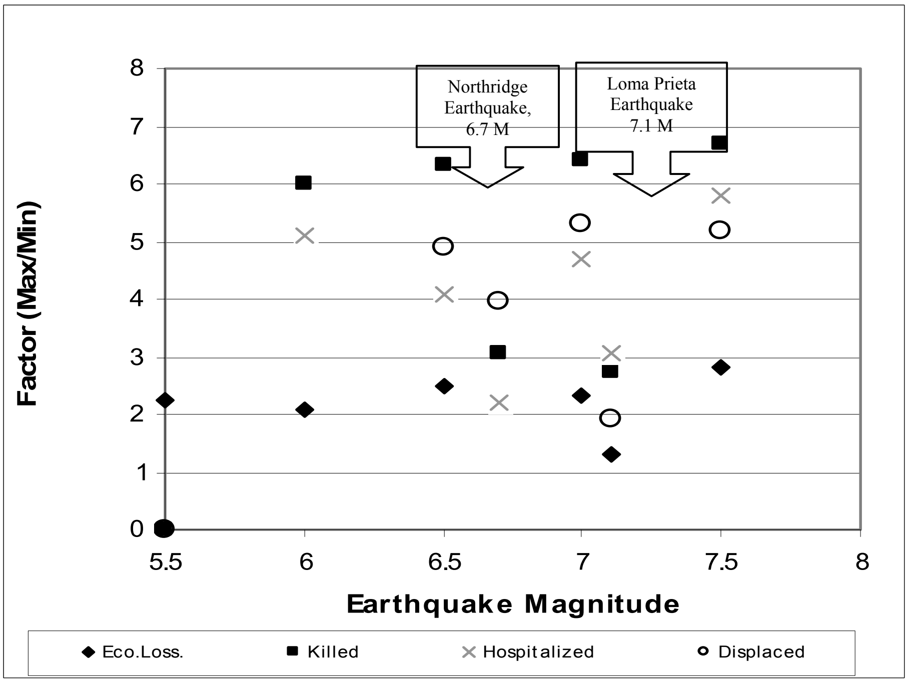


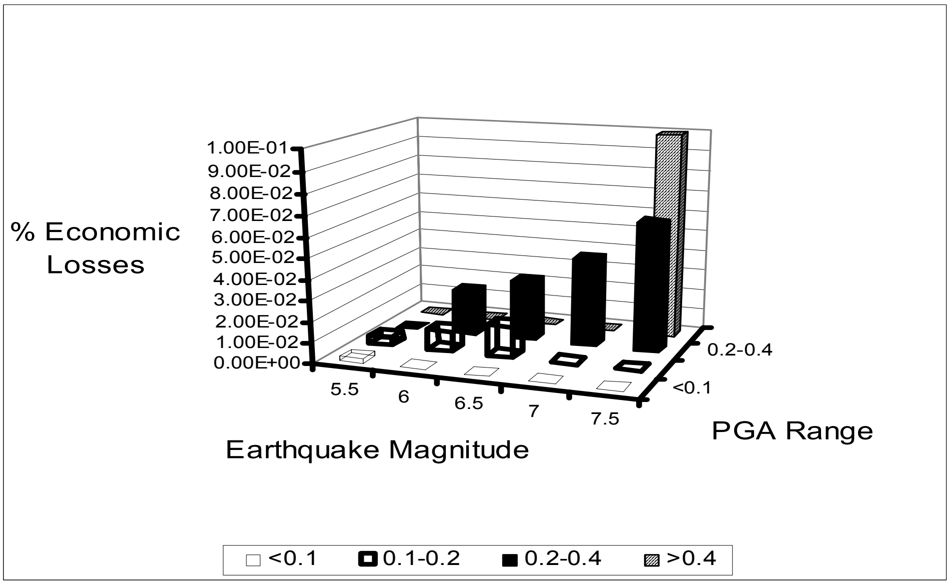
Fig. (7) Ratios of the Maximum and Minimum Losses From Earthquake Scenarios



In the graph above, the factor value of the Northridge and Loma Prieta earthquakes is the ratio between the maximum and the minimum of the reported versus the actual losses that resulted from both earthquakes. The HAZUS earthquake scenario for the Northridge Earthquake resulted in a total economic loss of $4,981.04 billion, 9 people killed, 1095 people hospitalized, and 1116 people displaced from Los Angeles and Ventura Counties. Whereas the reported loss from this earthquake is $20 billion in economic losses, 57 people killed, 9000 injured, and 20,000 people displaced. The Loma Prieta Earthquake resulted in a total economic loss of $10 billion, 62 people killed, 3,700 injured, and 12,000 displaced. A HAZUS scenario for this earthquake resulted in $8.485 billion of total economic losses, 191 people killed, 3077 people hospitalized, and 25,825 people displaced from San Francisco, San Mateo, Alameda, Sant Clara, Contra Costa, and Marin counties.

In order to use our results for the San Francisco Bay Area (SFBA) or other regions, we normalized our estimated losses against exposure in the study region. We measured the potential losses and exposure for each census tract (a parcel of land that contains 2,500 to 8,000 people) in the study region for each of the estimated losses--number of people who would be killed, number of people who would be sheltered, number of people who would be hospitalized, and total residential economic losses. There are 152 census tracts in the study region. We grouped the PGA ranges into four groups, less than 0.1 (slight shaking intensity), 0.1 to 0.2 (moderate shaking intensity), 0.2 to 0.4 (strong shaking intensity), and grater than 0.4 (violent shaking intensity). Figure (8) below, shows the normalized values that resulted from an analysis of the residential economic losses in the NH fault. For example, an earthquake magnitude of 7.0 would result in 0.434% of the building inventory value in economic losses

Fig. (8) Percent of Residential Buildings Economic Losses



This paper introduces a guideline for interpreting the HAZUS earthquake loss estimation output for a given scenario area, which could be used for future catastrophes in a scenario area. This paper helps HAZUS users understand the effects of choosing analysis parameters on the loss estimation results. A ratio of the maximum to the minimum losses of 10 could be used to get a rapid assessment of potential earthquake losses without developing data to be used in the loss estimation. These data are for the liquefaction susceptibility map, the soil type map, and the building inventory. Additionally, this paper shows the sensitivity of analysis parameters on the estimated losses. The sensitivity of the ground failure effects (from no liquefaction susceptibility to detailed liquefaction susceptibility) on the loss estimations, is the largest for a given earthquake scenario. Lastly, this paper presents factors that could be used for different areas in the study region by knowing the earthquake magnitude, the PGA value, and the total exposure for each PGA intensity level in the impacted area. These values need to be validated from future earthquake events. Such interpretation helps in directing the resources needed for the most impacted areas, and if used by agencies, can help in planning and increasing the agency's readiness to meet the expected needs following an earthquake. Additionally, this analysis provides other states and counties that do not have adequate resources for full-scale data collection, but face significant earthquake threats, with information enabling them to invest more significantly in data collection activities and to invest in preparing more accurate data for HAZUS input. Identifying the most significant factors contributing to the earthquake risk provides a maximum benefit from the application of the HAZUS model for a limited data-collection budget.

References

Boore, D. M., Joyner, W. B. and Fumal, T. E. (1993) 'Estimation of Response Spectra and Peak Acceleration from Western North American Earthquakes: An Interim Report', *USGS Open File Report 93-509, United State Geological Survey,* Menlo Park, California.

Boore, D. M., Joyner, W. B. and Fumal, T. E. (1994a) 'Estimation of Response Spectra and Peak Acceleration from Western North American Earthquakes: An Interim Report, Part 2', *USGS Open File Report 94-127, United States Geological Survey*, Menlo Park, California.

Boore, D. M., Joyner, W. B. and Fumal, T. E. (1994b) 'Ground Motion Estimates for Strike- and Reverse-Slip Faults', (preprint)

California Department of Conservation, 2000. An Evaluation of Future Earthquake Losses in California, A White Paper by the California Department of Conservation, Division of Mines and Geology. P14

King, S.A. and Kiremidjian, A.S. (1994) 'Regional Seismic Hazard and Risk Analysis through Geographic Information Systems', Report No.111, June 1994. John A. Blume Earthquake Engineering Center

National Institutes of Building Sciences (1997) HAZUS, Earthquake Loss Estimation Methodology, Prepared for the Federal Emergency Management Agency. Technical and users manuals

Sadigh, K., Chang, C.Y., Abaramson, N.A., Chiou, S.J. and Power, M.S. (1993) 'Specification of Long-Period Ground Motions: Updated Attenuation Relationships for Rock Site Conditions and Adjustment Factors for Near-Fault Effects', *Proceeding of ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control, by the Applied Technology Council*, pp.59-70.

Seed, H.B., Idriss, I.M. (1983) 'Ground motions and soil liquefaction during earthquakes', Engineering Monographs on Earthquake Criteria, Structural Design, and Strong Motion Records, ed. Mihran S. Agbabian, Vol. 5. Okland, California: Earthquake Research Institute.

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