Using GIS for Assessing Earthquake Hazards of San Francisco Bay, California, USA

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Abstract

The U.S. Geological Survey estimates a 62 percent probability of a damaging earthquake in the San Francisco Bay Area (USA) within the next 30 years (Field and Milner, 2007). The Federal Emergency Management Agency (FEMA, 2008) estimates that a 7.5 to 8.3 Richter magnitude earthquake in an urban area could cause up to $60 billion in damage. The analysis of expected ground motion and the effect of earthquakes is critical for emergency responders, utilities, city planners, insurance companies, and many other agencies. This research application describes how GIS can aid in evaluating risks and support earthquake management by creating thematic maps. The results of modeled earthquake scenarios are utilized to understand the magnitude of losses and to help mitigate the effects of future earthquakes.

Introduction

According to Perkins and Boatwright 2010), an average of one earthquake occurs every seven years in the San Francisco Bay, California, USA area. Many moderate and earthquakes larger than a 6.0 magnitude affect the Bay area. One of the largest was a 7.8 magnitude earthquake in 1906 which caused massive damage in Oakland, Santa Rosa and San Jose (Ellsworth, 1990). A more recent earthquake occurred in 1989 (Loma Prieta) with magnitude of 6.9 which affected the Santa Cruz mountain, San Francisco and Oakland. The 1989 Loma Prieta earthquake caused a total of over 16,700 housing units to be uninhabitable throughout the Monterey and San Francisco Bay Areas with almost 13,000 of these in the Bay Area alone (Association of Bay Area Governments, 2010).

A working group consisting of the United States Geological Survey (USGS), the California Office of Emergency Service, the California Geological Survey (CGS), and the Association of Bay Area Governments (ABAG) conducted a future loss estimation study for the Bay region. Based on their findings, the east bay along the Hayward Fault would experience the most property damage. This part of the Bay includes Alameda and Contra Costa County (USGS, 2012).

Earthquakes are significant threats to the population, properties, and infrastructures of the region and all prompt for more studies and effort to help mitigate the effects of another large earthquake.

Site Location

The San Andreas Source-Characterization Group divided the San Andreas Fault into major segments: Offshore (SAO), North Coast (SAN), Peninsula (SAP), and Santa Cruz Mountains (SAS). The East Bay Source-Characterization Group defines

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three segments for the Hayward-Rodgers Creek Fault: the south Hayward (HS), north Hayward (HN), and Rodgers Creek (RC) segments. Segment names and their acronyms are listed in Table 1.

In Figure 1, the study area is within the SAP segment of the San Andreas Fault and HS segment of the Hayward Fault. The area examined included the following counties: Contra Costa, Alameda, Santa Clara, San Mateo, and San Francisco.

Table 1. San Andreas and Hayward Fault segment and acronyms.

Fault	Segment	Name
San Andreas	SAO	Offshore
	SAN	North Coast
	SAP	Peninsula
	SAS	Santa Cruz Mountains
Hayward	RC	Rodger Creek
	HN	Northern Hayward
	HS	Southern Hayward

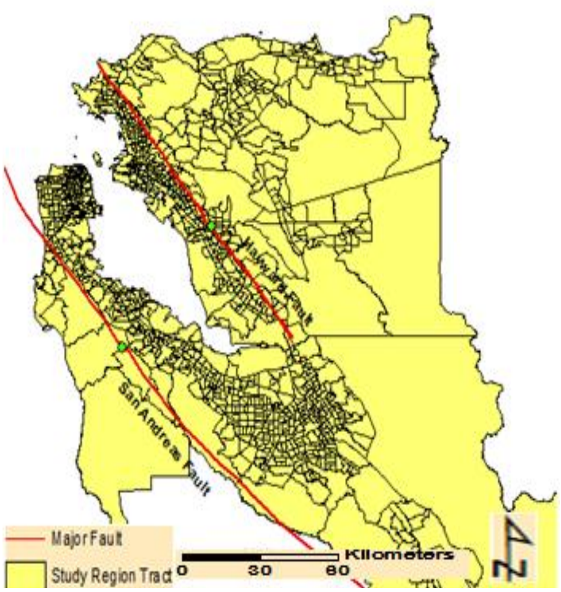

Figure 1. Site location with county boundaries, highlighting the Hayward and San Andreas faults location, and specified epicenters.

Methods

When it comes to modeling earthquake risk assessment, disaster managers and researchers must conduct an evaluation of seismic hazard, vulnerability, and a loss estimation. The easiest way to explain the dimensions of a disaster is with an earthquake scenario that defines the earthquake hazard losses associated with a defined epicenter, magnitude, and depth.

Seismic Hazard Analysis

Seismic hazard relates directly to the ground motion associated with an earthquake in terms of peak ground acceleration. There are several elements needed to compute the seismic hazards including source and site characterization.

Historic Earthquake

The region surrounding the Hayward and Peninsula rupture zone includes the seismicity associated with the major 1838 San Francisco peninsula earthquake, (M ~ 6.8), 1868 Hayward earthquake, (M ~ 7), 1906 San Andreas earthquake, (M ~ 7.8), and the 1989 Loma Prieta earthquakes (M ~ 6.9). However, a number of moderate ($M \geq 5$) to large earthquakes have also occurred on faults situated well away from the San Andreas Fault (Figure 2). The seismicity was high in the years before and remarkably low in the years after each of these four major earthquakes (Toppozada, Branum, Reichle, and Hallstrom, 2002).

There were 18 earthquakes in the Bay Area of magnitude 6 or larger between 1836 and 1911 (75 years) yet there were no events of this magnitude during the 68 years between 1911 and 1979. Since 1979 however there have been four earthquakes of magnitude 6 or greater including the recent Loma Prieta earthquake. It may be a new era of major earthquake activity similar to the era before 1911. According to the Risk Management Solutions Report (2008), the South Hayward Fault has generated twelve major earthquakes in the last 1900 years; one on average every 160 ± 65 years. The last five earthquakes have occurred more frequently, at an average interval of about 140 ± 60 years. The probability of a major earthquake (M > 6.7) on the Hayward within the next thirty years is estimated at nearly 30 percent, compared to about 20 percent for the San Andreas Fault.

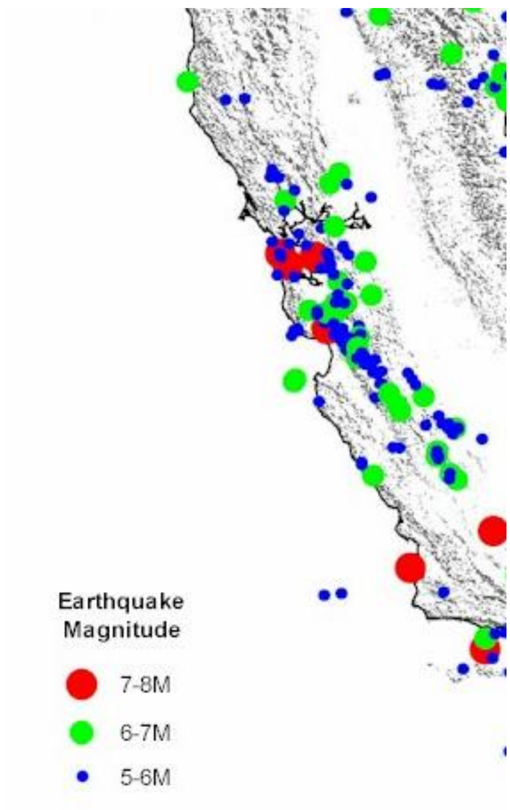

Figure 2. Historic Earthquakes (1800-1994) with Magnitudes 5 and Greater from California Geological Survey. This map is showing the distance of approximately 850 kilometers from the top of the map to the bottom.

Slip Rate of Fault Segment

Slip rates are typically averaged over time periods of hundreds to several tens of thousands of years. They are estimated primarily from observations of offsets of geological or cultural features. Large size faults have larger earthquakes. Also faults with higher slip rates often have more frequent earthquakes. Thus considering slip rates of faults are is an important factor to consider when modeling an earthquake.

Paleoseismic findings find slip rates of the San Andreas Fault decreasing from 24 ± 3 mm/yr north of the Golden Gate Bridge to 17 ± 4 mm/yr on the San Francisco Peninsula and southward (Working Group on California Earthquake Probabilities, 1999). This report indicates uniform slip rates of 19 ± 4 mm/yr for San Andreas. A measurement of the slip rate for the Hayward Fault is 9 ± 2 mm/yr based on paleoseismic and fault creep data. A working group on northern California earthquake potentials also used these rates, consistent with new paleoseismic observations of a minimum rate of 7-10 mm/yr for the past 8,400 years on South Hayward (Working Group on California Earthquake Probabilities, 1999).

Surface Geologic Material

Near surface material can change the potential amplification of seismic waves. Soft soil amplify shaking compared to hard rock (Southern California Earthquake Center, 2012). The San Francisco Bay area contains five major surficial geologic units in addition to bedrock: artificial fill, younger San Francisco bay mud, holocene alluvial fan deposits, merritt sand, and pleistocene alluvial fan deposits (Holzer, Bennett, Noce, Padovani, and Tinsley, 2006). These units are classified in Table 2.

The study area considered to be especially dangerous occurs at the border of bay because of poor soil conditions in the alluvial fan. This type of soil runs from the eastern shoreline of the San Francisco Bay to the East Bay Hill. At lower elevations of the region, soil changes to mud because of water saturation and thereby increasing the likelihood to amplify the earthquake wave and produce greater ground motion. Infrastructure on the bay mud will likely experience stronger and longer shaking than those on rock (Perkins and Boatwright, 2010).

Table 2. Unified Soil Classification System (USCS) and estimated ages of geologic units (Holzer *et al.*, 2006).

Geologic Unit	Soil Type	Geologic Age
Artificial fill	Silty Sand (SM)	Modern
Younger bay mud	Clay (CL)	Holocene(<8,000)
Holocene alluvial fan	Clay to Sity Sand (CL,SM)	Holocene(<15,000)
Merritt Sand	Silty Sand (SM)	Pleistocene (80,000-10,000)
Pleistocene alluvial fan	Clay to Sity Sand (CL,SM)	Pleistocene (>116,000)

Hayward Earthquake Scenario Analysis

Figure 3 illustrates ground motion presented at the census tract level by census tract with spectral acceleration at periods of 0.3 second based on a magnitude 7.2 earthquake on the southern segment of the Hayward fault. The epicenter modeled is at 37.693 degrees latitude and 122.097 longitude, along with a depth of 2 kilometers.

The demographic data used for this project was based on 2010 U.S. Census data. The loss estimation was based on the database provided in HAZUS-MH 2.1. The critical facility inventory was updated by gathering input from sources including HAZUS-MH 2.1, San Francisco Bay Counties and the California Geological Survey. Soil map data with San Francisco Bay's National Earthquake Hazard Reduction Program was entered into HAZUS-MH 2.1. HAZUS-MH 2.1 uses the seismic soil type classes recommended by the National Earthquake Hazard Reduction Program (NEHRP). The NEHRP soils classification system ranges from A to E, where A represents hard rock which reduces ground motion from an earthquake and E which represents soft soils which amplifies and magnifies ground shaking and increases building damage and loss.

The geographic extent of the region is 8,497.90 square kilometers and contains 1,161 census tracts. There are over 2,017 thousand households in the region with a total population of 5,559,036 people (2010 Census Bureau). The distribution of population by Census Tract is provided in Figure 4.There are an estimated 1,633 thousand buildings in the region with a total building replacement value (excluding contents) of 555,891 million dollars. Approximately 92 percent of the buildings are associated with residential housing. The replacement value of the transportation and utility lifeline systems is estimated to be $36,150 and $7,353 million dollars, respectively.

Loss Estimation Analysis

This estimation addresses three dimensions of earthquake risk. These are debris accumulation, casualties, and shelter requirements. An earthquake along the southern segment of the fault would cause more damage to the county of Alameda. This is a result of the type of construction which more recently occurred during rapid urbanization as opposed to that of older northern cities.

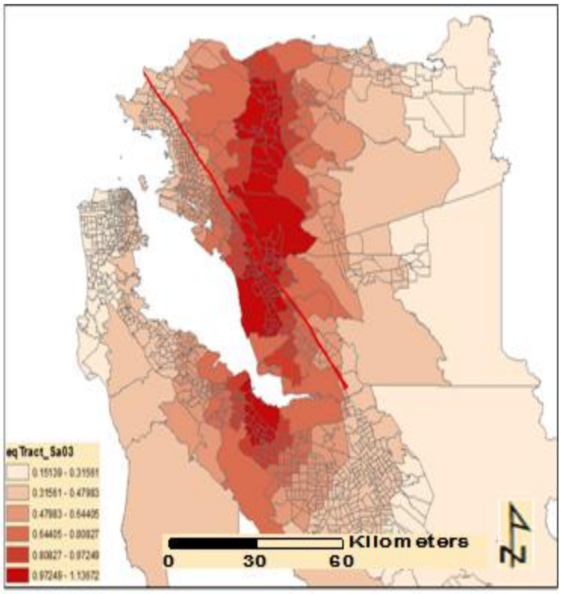

Figure 3. Ground Motion by Census Tract with spectral acceleration at periods of 0.3 second.

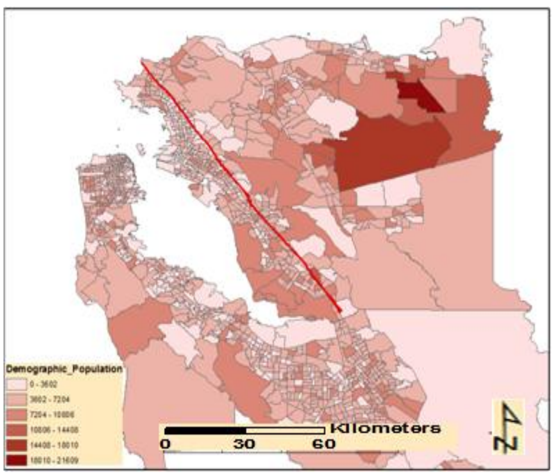

Figure 4. Population distribution in the study area.

Figure 5 shows Hazus estimated amounts of debris generated by the modeled earthquake. The model breaks debris into two categories: a) brick/wood and b) reinforced concrete/steel. This distinction is made because of the different types of material handling equipment required to handle these debris. The model estimates a total of 7.22 million tons of debris would be generated. Of the total amount, brick/wood would comprise 35% with the remainder being reinforced concrete/steel. If the debris tonnage is converted to an estimated number of truckloads, it would require 288,600 truckloads to remove the debris generated by the earthquake.

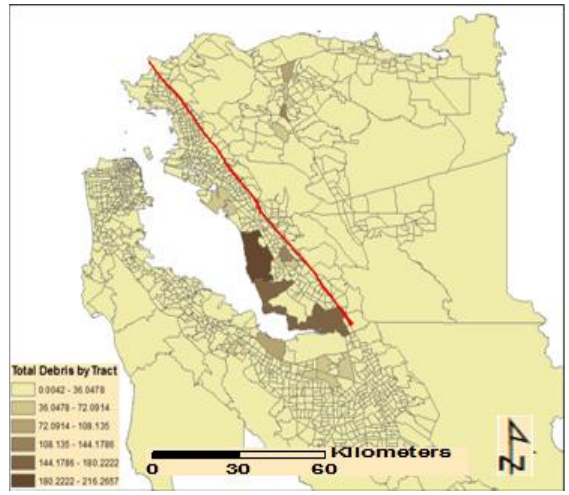

Figure 5. Amount of debris generated by a 7.2 magnitude earthquake.

The casualty estimates are provided for three times: 2:00 AM, 2:00 PM, and 5:00 PM. These represent the periods of the day that different sectors of the community are at their peak occupancy loads. The 2:00 AM estimate considers the residential maximum occupancy load; the 2:00 PM estimate considers the maximum educational, commercial, and industrial sector loads, and 5:00 PM represents the peak commuter times. This study focused on single family casualties. Estimates suggest that approximately 2,646 people may be impacted by the modeled earthquake at 2:00 AM, approximately 473 at 2:00 PM, and approximately 1,020 people at 5:00 PM. Impacts are reflected in Figures 6, 7, and 8.

Hazus estimates the number of households expected to be displaced from their homes due to the modeled earthquake as well as the number of displaced people that would require accommodations in temporary public shelters (Figures 9 and 10).

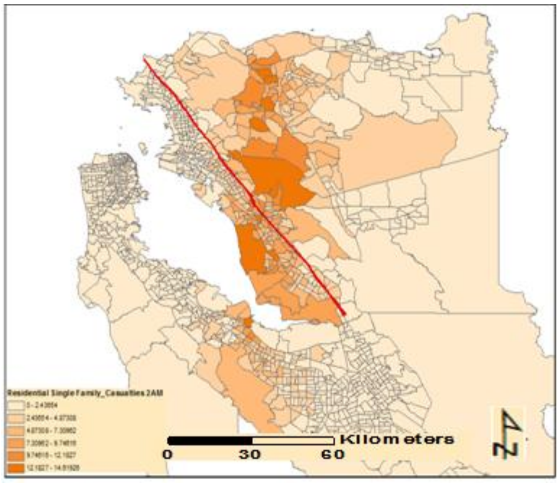

Figure 6. Darker hues of orange indicate greater potential population impacts during 7.2 magnitude earthquake at approximately 2 AM.

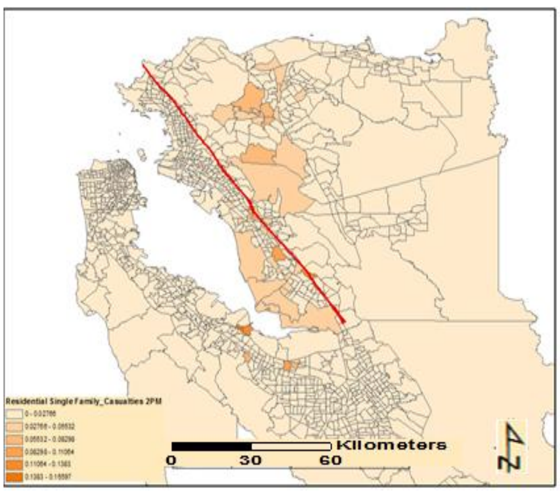

Figure 7. Darker hues of orange indicate greater potential population impacts during 7.2 magnitude earthquake at approximately 2 PM.

The model estimates 25,264 households to be displaced due to a 7.2 magnitude earthquake. Of these, 15,925 people (out of a total population of 5,559,036) may need temporary shelter in public shelters. The number of displaced households and needed shelters in each county are classified in Table 3.

San Andreas Earthquake, Peninsula Segment Scenario Analysis

This earthquake scenario is a magnitude 7.1 modeled earthquake on the Peninsula segment of the San Andreas Fault with an epicenter location of 37.46 degree latitude and -122.31 longitude, and 2 km depth. The HAZUS model estimates a total of 4.67 million tons of debris would be generated. Of the total amount, brick/wood would comprise 35% of the total with the remainder being reinforced concrete/steel. If the debris tonnage is converted to an estimated number of truckloads, it would take approximate 186,840 truckloads.

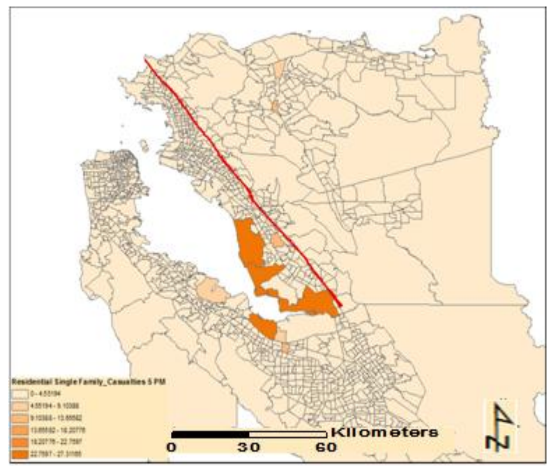

Figure 8. Darker hues of orange indicate greater potential population impacts during 7.2 magnitude earthquake at approximately 5 PM.

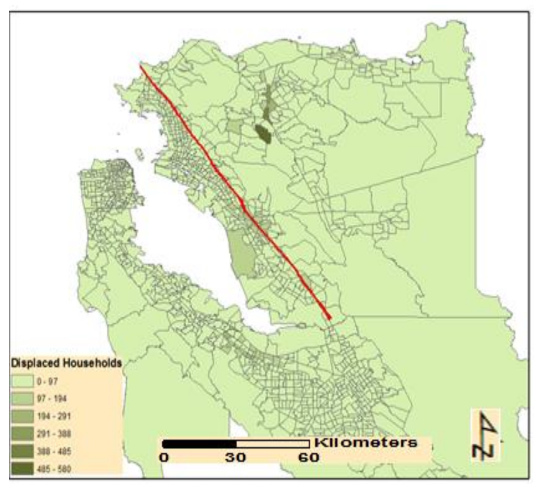

Figure 9. Darker hues of green indicate greater number of displaced households in each census tract.

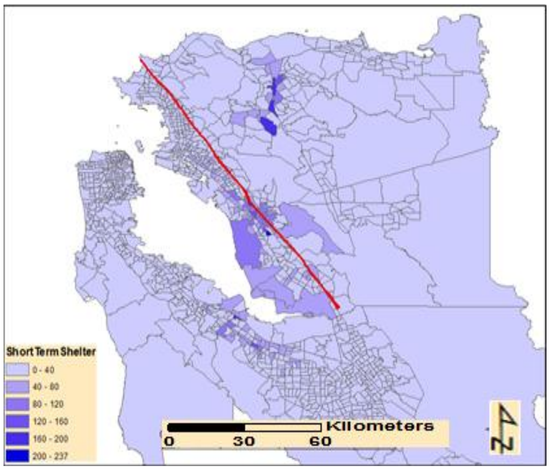

Figure10. Darker hues of blue indicate greater number of short term shelters needs based on each census tract.

Table 3. Number of displaced household and shelter requirement per county.

	# of Displaced Household	# of People Needing Shelter
Alameda	10,412	7,588
Contra Costa	5,186	2,760
San Francisco	1,087	596
San Mateo	1,783	1,197
Santa Clara	6,797	3,784
Total	25,264	15,926

Estimates show 1,679 people based on single family occupancy could be impacted by the modeled earthquake at 2:00 AM, 299 people at 2:00 PM, and 644 people at 5:00 PM. These numbers would be different if commercial, educational, and other residential classifications were included in the analysis. In the case of commercial, educational, and other residential classifications, there is a potential for impact to 5,837 people at 2 AM, 15,295 people at 2 PM, and 11,004 people at 5 PM. The model estimates 17,869 households to be displaced due to the earthquake. Of these, 10,760 people (out of a total population of 5,559,036) would need to seek temporary shelter in public shelters.

Analysis

The damage by census tract vector data of 7.2 Hayward earthquake, and 7.1 San Andreas earthquake scenarios were converted to a raster dataset (Figure 11). Low risk areas were identified that might be candidate areas for future city development. Additionally, emergency managers can get benefit in term of emergency responses in the earthquake events. Alameda, San Mateo, and San Francisco counties need more attention due to their high population and higher debris potential.

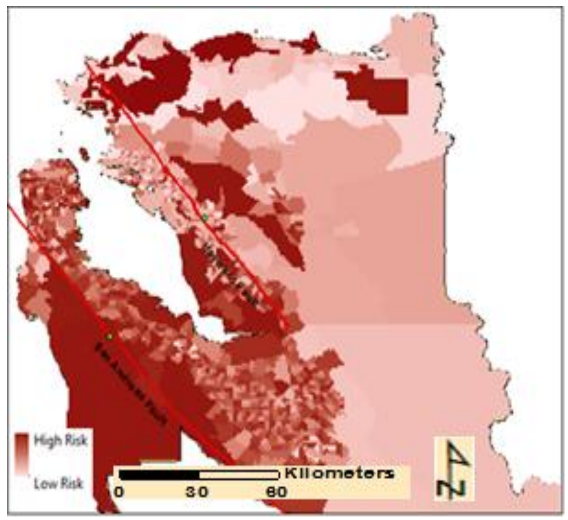

Figure 11. Earthquake risk composite illustrating the total region damage of 7.1, and 7.2 magnitude earthquake scenarios.

Some facilities like transportation may quickly affect potential impacts. Probable damage to transportation systems as a result of the modeled earthquakes is shown in Figure 12. Figure 13 conveys schools and ordinal levels of potential damage noted. Figure 14 illustrates the location of medical centers in the study region relative to earthquake damage probability. Cities are required to evaluate existing hospitals structurally following earthquakes.

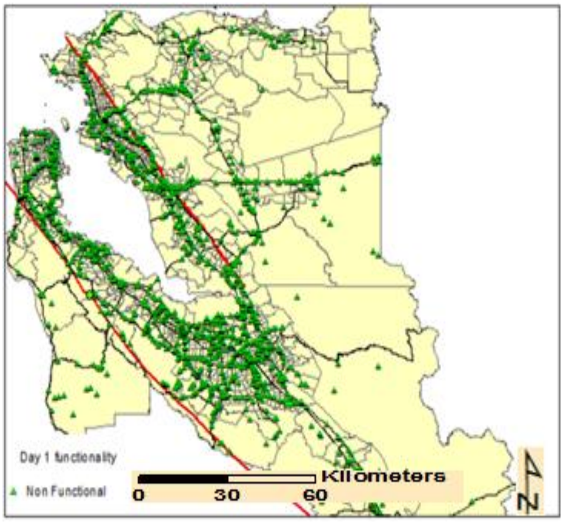

Figure 12. Highway infrastructure impairments during 7.1 and 7.2 magnitude earthquake scenarios.

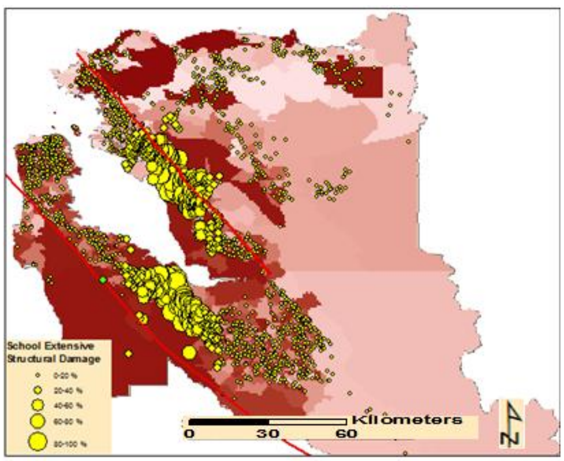

Figure 13. Percentage of school potential structural damage during 7.1 and 7.2 magnitude earthquake scenarios.

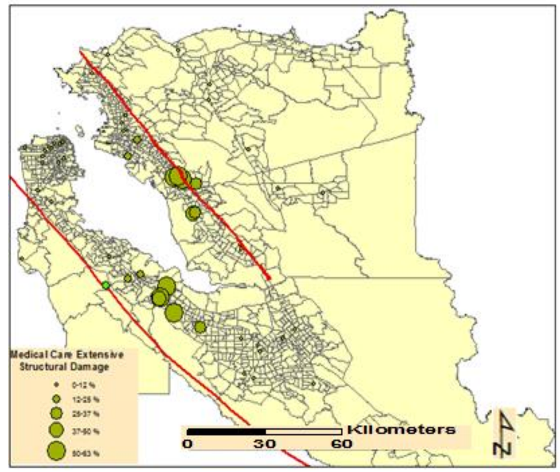

Figure 14. Percentage of hospital structural damage during a 7.1 and 7.2 magnitude earthquake scenarios.

Conclusions

The San Francisco Bay region sits on the tectonic boundary between the Pacific and North American Plates. The region experienced major and destructive earthquakes in 1838, 1868, 1906, and 1989. Future large earthquakes are almost a certainty. The ability to prepare for large earthquakes is critical to saving lives and reducing damage to property and infrastructure. An increased understanding of the timing, size, location, and effects of these likely earthquakes is a necessary component in any effective program of preparedness.

The analysis of the San Francisco Bay region earthquake risk and hazard helps to propose situational events to better plan for the areas requiring greater attention in terms of mitigation. The essential form of mitigation is identifying portions of damages and losses. Damages and losses mapped by census tracts can be used to direct future studies to identify problems and develop mitigation measures. Estimates of debris on a return period basis are useful for planning and preparing risk reduction strategies, particularly in urban areas (FEMA, 2008). Casualty estimates help to plan for medical response. Shelter requirement estimation is needed for post disaster shelters. Each community should determine the anticipated damages as well as assess the availability of shelters. They should consider fund availability to replace buildings due to structural damage mitigation. Those counties with higher earthquake damage might need to identify emergency shelters in addition to the use of schools.

In the study region, Alameda, San Mateo, and San Francisco counties should have emergency response plan in place in case of earthquake event. To facilitate this, the damage to the area should be estimated prior to an earthquake. The transportation lifeline should have planned detours. Finally, critical facilities such as hospitals and schools in Alameda, San Mateo, and San Francisco counties should be considered in all mitigation strategies.

Disclaimer of Uncertainties

The risk assessment, the loss estimates, and exposure assessments rely on the best available data and methodologies. Uncertainties are inherent in any loss estimation methodology and arise in part from incomplete scientific knowledge. Potential exposure and loss estimates are approximate. These results do not predict precise results and should be used to understand relative risk. The estimates are not a determination of total risk and not all aspects of earthquake characteristics were addressed herein.

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