Risk Analysis and Assessment of Non-Ductile Concrete Buildings in Los Angeles County Using HAZUS-MH

by

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To my Mom and Rudy

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List of Abbreviations

AEBM	Advanced Engineering Building Model
APN	Assessor's Parcel Number
CDMS	Comprehensive Data Management System
CEM	Comprehensive emergency management
CSV	Comma-separated values
FEMA	Federal Emergency Management Agency
GIS	Geographic information system
HAZUS-MH	Hazards United States – Multi Hazard
LA	Los Angeles City
LAC	Los Angeles County
M	Magnitude
MAUP	Modifiable Areal Unit Problem
NIF	Newport-Inglewood Fault
PESH	Potential Earth Science Hazard
SCEC	Southern California Earthquake Center
USGS	United States Geological Survey

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Abstract

Los Angeles County (LAC) is the most populous county in the United States and is simultaneously vulnerable to numerous natural disasters, particularly earthquakes. LAC is situated on ~68 active seismic zones and studies suggest that LAC is expected to experience a 7.8 magnitude earthquake on the southern section of the San Andreas Fault sometime in the next 30 years. Consequently, it is critical to understand the extent of damage LAC could face from a large earthquake. This study analyzed potential damage to non-ductile concrete buildings in LA City Districts 1, 9, 10, 13, and 14 should a repeat 1933 Long Beach earthquake occur on the Newport-Inglewood fault. The Hazards United States Multi-Hazard (HAZUS-MH) program was used to analyze the impact of a M_w 6.4 earthquake, assess the amount of damage, identify areas of vulnerability, and examine economic impacts of a repeat event. The M_w 6.4 event was run three times to show how HAZUS-MH results improve when the model includes updated datasets. The first analysis used built-in HAZUS-MH data, the second incorporated independent datasets, and the third deployed the Advanced Engineering Building Model (AEBM). Pre-1976 non-ductile concrete building data was added to the AEBM to evaluate the damage to individual structures. This study furthered the work done by Comerio and Anagnos (2012) by utilizing the AEBM to evaluate which of the concrete buildings are the most vulnerable.

Chapter 1 Introduction

Earthquakes are unpredictable naturally occurring disasters that take place all around the world. Southern California alone could experience 2,000 to 10,000 earthquakes per year (Institute for Crustal Studies 2014). Past events have shown that not only is the occurrence of earthquakes unpredictable, but that not all fault line locations are known making it difficult to be aware of all potential seismic threats (Britannica Academic 2015). There are several active faults in the Southern California area, many of which could be the source of large damaging earthquakes. One fault of concern in Southern California is the southernmost section of the San Andreas Fault (SAF); research has shown that the next rupture could be large and cause a great deal of damage (Jones and Benthien 2011). The United States Geological Survey (USGS) has developed an open-file report that examines all the known faults in California and the potential for any of these faults to be the source of magnitude 6.5, 7, or 8 earthquakes. This report is used as a forecast to better understand and prepare for potentially damaging earthquakes (Field et al. 2013).

Motivation

The Los Angeles area is susceptible to large earthquake events, causing concern for when a large earthquake will occur, and is the main reason for establishing mitigation protocol in the event that the earthquake takes place. According to the United States Census Bureau (U.S. Department of Commerce 2015), Los Angeles County (LAC), California has been the most populous county in the United States since 2010. LAC is home to nearly 10.1 million people but is also the location of major ports and businesses. The safety of LAC citizens is of great concern, but it is also important to understand potential nationwide or worldwide effects should business, airports, or shipping ports be damaged. The Los Angeles Tourism & Convention Board (2015) calculated a total of 44.2 million tourist visits for LAC in 2014.

The most recent event to cause significant destruction to Los Angeles County is the 6.7 magnitude 1994 Northridge earthquake. Southern California experiences seismic events regularly. However, these events are usually small and not very destructive. The 1994 Northridge earthquake occurred on a fault that was unknown prior to the event and was the most destructive earthquake in California since the 1906 San Francisco earthquake (Britannica Academic 2015). This event showed how important earthquake research is because even though scientists are aware of many faults that pose a threat to the state of California, there are also many unknowns. The Southern California Earthquake Center (SCEC) is a research collaborative dedicated to earthquake research to better understand how large of a threat potential seismic events are to urban areas and their population. SCEC is one of five organizations that helped produce the publication, *Putting Down Roots in Earthquake County* (Jones and Benthien 2011). The *Putting Down Roots* handbook shows a 99.7% chance that California will experience a magnitude 6.7 (M_w 6.7) earthquake and a 37% chance that a M_w 7.5 or greater earthquake will occur within the next 30 years.

Knowing that a large event is highly probable for LAC, it is important to understand the potential impacts, especially since an event of this size in Southern California has yet to be monitored by a strong motion instrument (Olsen et al. 2006). The USGS National Strong Motion Project has been recording ground motion during major earthquakes in highly dense urban areas to develop building standards so structures will be less prone to earthquake damage (Earthquake Hazards Program 2014).

Study Area

Studies have been completed in the past on the potential threat of earthquakes in Southern California, which consists of several counties. This study examined LAC, specifically Los Angeles City Council Districts 1, 9, 10, 13, and 14 (Figure 1), to assess seismic hazards at a smaller scale. These specific city districts were chosen because they surround Los Angeles City (LA), the most populous of the 88 cities in LAC. As of 2015, Los Angeles is home to 3.8 million people, which is 39% of the total LAC population (U.S. Department of Commerce 2015). Long Beach, the next most populous city in LAC, makes up only 5% of the total LAC population. The City of Los Angeles is approximately 50,000 meters from the epicenter of the earthquake. There are 284 non-ductile concrete buildings from the dataset of 1454 that fall within this study area. The non-ductile structures in this particular study are the focus of this research because non-ductile concrete buildings are made of materials that do not have plastic deformation properties (Seymour et al. 2009). Non-ductile concrete structures do not absorb energy from external forces properly and are at a high risk of failure without warning.

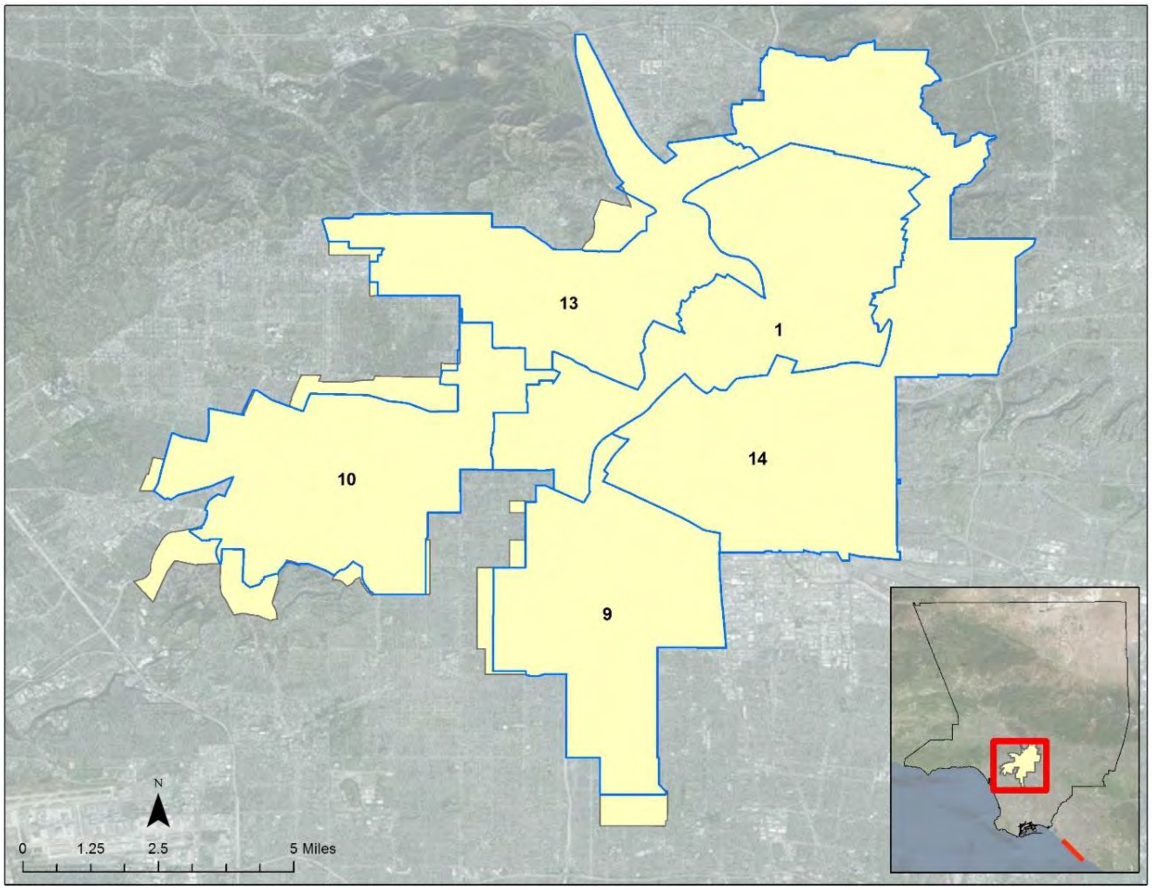

Figure 1: The proposed study area, Los Angeles City districts 1, 9, 10, 13, and 14.

Research Questions

The goal of this thesis is to estimate the potential destruction which may impact the documented non-ductile concrete structures in Los Angeles County, and identify which of those with a high potential for collapse with current building conditions in the event of a Mw 6.4 earthquake on the Newport-Inglewood Fault.

HAZUS-MH was used to investigate the dangers that the downtown Los Angeles area is susceptible to, and which areas show higher loss probabilities. Structures that were built prior to stricter building code requirements or those that have not been retrofitted were expected to experience the most damage and pose the most threat for building failure. Areas that were developed on softer soils may also experience more damage as they are more susceptible to shaking during a seismic event (Figure 2). The modeling technique used considers the underlying geology of the study area, PESH (ground motion), and inventory (infrastructure and demographics) to best assess general building stock damage, casualties, and damage to schools.

Damage State		Description
	**Slight**	Small plaster cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneers. Small cracks are assumed to be visible with a maximum width of less than 1/8 inch (cracks wider than 1/8 inch are referred to as "large" cracks).
	**Moderate**	Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.
	**Extensive**	Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations.
	**Complete**	Structure may have large permanent lateral displacement or be in imminent danger of collapse due to cripple wall failure or failure of the lateral load resisting system; some structures may slip and fall off the foundation; large foundation cracks. Three percent of the total area of buildings with Complete damage is expected to be collapsed, on average.

Figure 2: HAZUS-MH Damage Classifications (Federal Emergency Management Agency 2015a)

The second objective is to see how HAZUS-MH results improved with each analysis. Performing multiple, different analyses allowed a thorough comparison of HAZUS-MH results between the default datasets and updated datasets, and how helpful the AEBM can be for assessing specific buildings.

The main questions that this thesis aims to answer are:

1. Which areas of Los Angeles City Districts 1, 9, 10, 13, and 14 show vulnerability?
2. Which (if any) of the non-ductile pre-1976 concrete buildings show potential for high levels of damage or collapse?
3. Does HAZUS-MH show more accurate results when independent data sources are added to the program?

More accurate results are expected from the analyses that include independent datasets because they allow for HAZUS-MH to use data specific to the study region, rather than having HAZUS-MH produce results only based on the generalized datasets that come installed with the program. There are approximately 200 data layers within HAZUS-MH when the program is installed. These layers along with intricate HAZUS-MH models allow for HAZUS-MH to evaluate a study region based on the specified hazard without the addition of additional sources (Buriks 2004). The HAZUS-MH data includes inventory on population, buildings, facilities, as well as social and economic details from national databases such as the U.S. Census Bureau (Buriks 2004). The data within HAZUS-MH can be improved with local datasets giving more accurate hazard model results.

The data that comes installed with HAZUS-MH was used for analysis 1. Local soils data was added to analysis 2 and 3, the user-defined facilities was updated with the 248 non-ductile concrete buildings for analysis 2, and the AEBM was updated with the 248 non-ductile concrete buildings for analysis 3. The user-defined facilities inventory uses data for specific structures to produce more accurate damage results. These data include the building design properties, location, year built, replacement cost, soil type, water depth, and liquefaction and landslide susceptibility. The AEBM incorporates the same data categories as the user-defined facilities, but also includes more detailed financial data, building occupants during the day and night, spectral displacement, spectral acceleration, and duration of the event (Federal Emergency Management Agency 2015a).

HAZUS-MH

Organizations such as the United States Geological Survey (USGS) and the Southern California Earthquake Center (SCEC) have completed research studies to better understand the potential threat of faults in California. Version 3 of the Uniform California Earthquake Rupture Forecast (UCERF3) gives magnitude estimates for 5270 fault segments throughout California. UCERF3 shows that the offshore segment of the Newport-Inglewood Fault (NIF) could be responsible for a 6.7 magnitude (M) or greater (Field et al. 2013).

Using the Hazards United States Multi-Hazard (HAZUS-MH) program, this study evaluated the potential damage to Los Angeles City Districts 1,9, 10, 13, and 14 (Figure 1) in the event a repeat Mw 6.4 earthquake occur on the NIF. Damage is defined as the number of buildings that are partially or completely destroyed by the earthquake. HAZUS-MH is a free ArcGIS extension developed by the Federal Emergency Management Agency (FEMA) with the main purpose of hazard mitigation of earthquakes, floods, and hurricanes in the United States. Using the 200 data layers within HAZUS-MH, a potential earth science hazard (PESH) can be identified, modeled, and results can be evaluated. Loss estimation can be completed using the results to aid in mitigation efforts for risk reduction and risk insurance (Buriks et al. 2004).

HAZUS-MH was used to analyze the spatial distribution of buildings throughout LA by building material using the building schemes data found within HAZUS-MH (Appendix F 2013). Updated building datasets were used to generate results that better reflect the current building materials. HAZUS-MH simulated an earthquake using the parameters for the 1933 Long Beach earthquake to assess potential damage to the downtown Los Angeles area in the event of a Mw 6.4 earthquake on the NIF. Using the results from the rendered earthquake model, maps and tables were generated to evaluate damage estimates from the scenario defined in HAZUS-MH. The Mw 6.4 earthquake was run using HAZUS-MH three times; each analysis is an improvement over the prior analysis to show how HAZUS-MH can become more accurate with the proper data. The first analysis utilized the layers that come installed with HAZUS-MH, the second updated the User-defined Facilities inventory with 284 non-ductile concrete buildings, and third used the Advanced Engineering Building Model (AEBM) to better asses the 284 non-ductile concrete buildings built prior to 1976 building codes.

Thesis Organization

This thesis is presented in five Chapters, each of which describes a specific stage of the thesis process. Chapter 2 discusses the literature that shaped this research project, studies that have also used HAZUS-MH, and studies on the 1933 Long Beach Earthquake. Chapter 3 presents the various datasets that are used to complete this study. Chapter 3 discusses where these datasets were acquired, how they were utilized, any post-processing that was completed and concludes with an in-depth outline of the methods used. Chapter 4 presents all the results and findings of the study, and Chapter 5 is a discussion of the results followed by limitations of the study and future considerations.

Chapter 2 Background

Chapter 2 discusses past research studies that used geographic information systems (GIS) to evaluate seismic hazards. Chapter 2 reviews how GIS has been applied in emergency management, has helped in mitigation planning, and discusses how HAZUS-MH has been applied to earthquake studies and potential concrete dangers in LAC.

GIS in emergency management

Geographic information systems is becoming a more reliable and important tool in regards to comprehensive emergency management (CEM). Cova (1999) describes CEM as four phases for addressing emergency management: 1) mitigation, 2) preparedness, 3) response, and 4) recovery. Through analyzing earth hazards and addressing CEM, we can assess the amount of property damage that may ensue as well as the effects on the community. Figure 3 shows the flow of CEM as discussed by Cova (1999) adapted from Godschalk (1991).

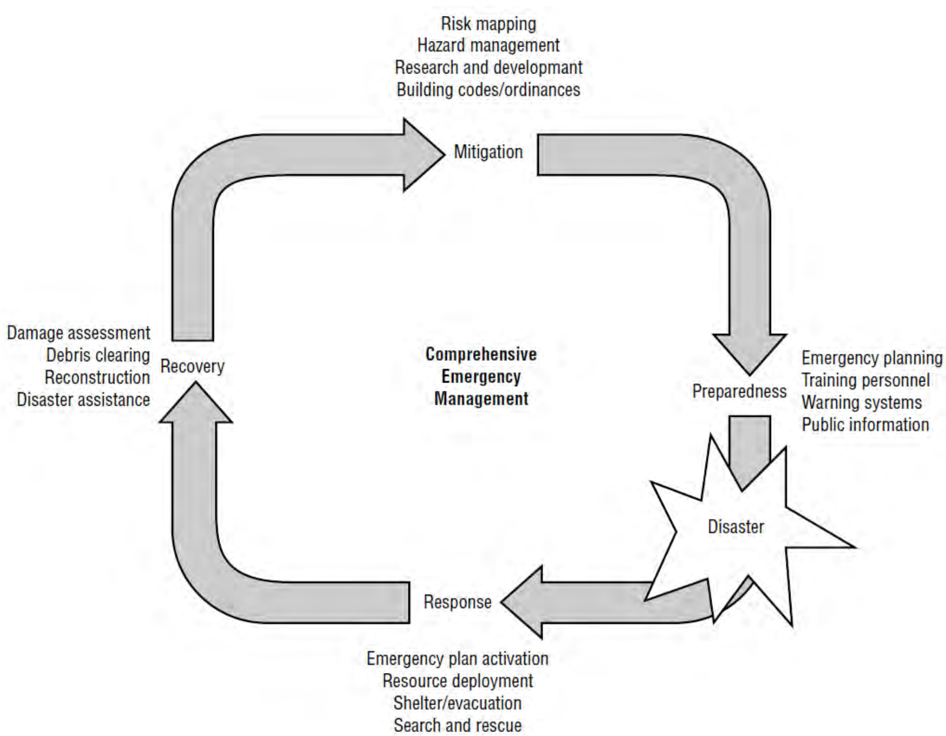

Figure 3: Work flow of comprehensive emergency management as presented by Cova (1999)

Godschalk (1991) describes CEM by first defining hazard, risk, and vulnerability in the context of CEM. A hazard is defined as a threat to civilians, buildings, or the environment, the risk is defined as the probability of a hazard occurring, and vulnerability is defined as the amount of potential injury and damage due to the hazard being analyzed. The resulting formula for risk being determined by hazard and vulnerability combined (Cova 1999) is the following:

$$Risk = elements\ of\ risk * (hazard * vulnerability)$$

Defining risk in this way was important because the three elements that determine risk can also be spatial layers that can be evaluated using spatial modelling techniques (Cova 1999). The incorporation of spatial modelling gave emphasis to the role of GIS in CEM. CEM is beneficial because of the detailed planning and management that comes from risk evaluations. GIS has made it possible for researchers to locate hazard-prone areas and assess the amount of potential damage to civilians, property, and the environment (Johnson 2000). Through combining natural, technological, and vulnerability hazard layers, a GIS can be used to model and map risk (Cova 1999, Johnson 2000).

HAZUS-MH for emergency management

Before 1989, there were no formal regulations to determine loss estimation methodology (Kircher et al. 2006). FEMA produced a report in 1989 that defined a set of guidelines for loss estimation research. HAZUS-MH was developed by FEMA with the main purpose of being used for hazard mitigation of earthquakes, floods, and hurricanes in the United States. Utilizing the 200 data layers within HAZUS-MH, a potential earth science hazard (PESH) can be identified, and loss estimation can be completed to aid in mitigation efforts that allow for risk reduction and risk insurance (Buriks et al. 2004). The development of HAZUS-MH provided a tool for standardized loss estimation experiments, allowing for comparison of assessments of various studies. To better understand the HAZUS-MH model, three journal articles were reviewed. These papers addressed loss estimation of building due to historical data and a specified seismic event (Kircher et al. 2006), loss estimation of a specified scenario to analyze the impacts of an event occurring during business hours (Ploeger et al. 2010), and loss estimation based on monetary building damages based on building type (Neighbors et al. 2013).

Kircher et al. (2006) explain how to interpret the results produced by HAZUS and the inputs and parameters used for modeling with HAZUS in great detail (Figure 4). Six inputs and components were used for creating the earthquake scenario, and although they are independent components, they influence each other. Using historical data from the 1994 Northridge earthquake, an assessment was completed for each building type. Scales were created to define building damage from slight to complete for a M_w 7.2 event along the Sierra Madre fault. This study was able to derive damage and loss estimates for the number of building affected as well as the monetary loss that results from property damage. Most importantly, this study showed how HAZUS could be used to facilitate rapid post-event evaluation to aid in earthquake response and recovery efforts.

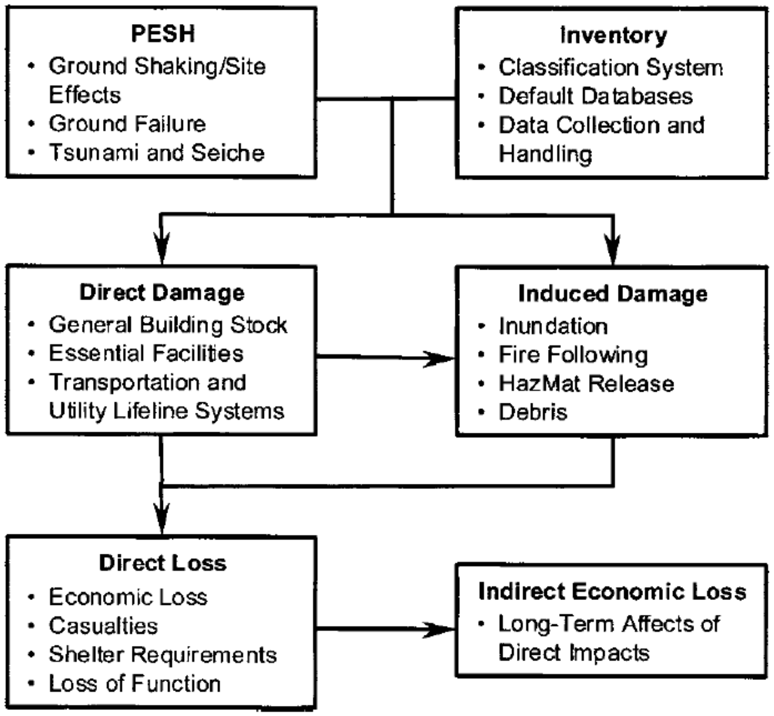

Figure 4: Flow chart image of how the multiple components of the HAZUS-MH model influence each other (Kircher et al. 2006)

Ploeger et al. (2010) builds upon the HAZUS analysis by including loss estimates based on the event occurring at a certain time of day and includes demographics for casualty assessment. There were five steps developed for this methodology:

1. Evaluating the seismic hazard
2. Collecting relevant data
3. Compile and prepare data
4. Analyze calculated loss for scenario(s)
5. Interpret results to incorporate disaster response plans and mitigation

Their study identified vulnerable regions in Ottawa, Canada based on building loss, debris, and social loss using ground motion, soil conditions, building inventory, and demographics as inputs. Maps were developed to show what areas are most susceptible to building and social loss. This discussion identified the importance of these results based on their usefulness in mitigation and hazard planning, especially during a time-of-day when a majority of individuals are away from their homes.

Neighbors et al. (2013) assessed the building damage monetarily based on building type. Seven different historical event datasets were used to achieve a variety of results that helped in assessing the accuracy of HAZUS estimates. The result of this study emphasized the importance of verifying source parameters rather than accepting all default values. This study was critical in showing how the high peak ground acceleration and economic building damage is probably a result of inaccurate default source parameters.

1933 Mw 6.4 Long Beach Earthquake

The 1933 Long Beach Earthquake is thought of as one of the most destructive earthquakes to occur in California in terms of damage and lives lost (Swift et al. 2012). The 1933 earthquake occurred on an offshore segment of the Newport-Inglewood fault zone and was felt strongly in the city of Long Beach as well as Los Angeles. Although research has shown that the Newport-Inglewood fault zone has a large recurrence interval, the fault is still considered a threat due to the magnitude of a potential future rupture (Swift et al. 2012). The Mw 6.4 earthquake was felt in 10 of the southernmost counties of California but caused the most damage to Long Beach and Los Angeles counties (U.S. Department of the Interior 2016). Most of the casualties from the 1933 Long Beach Earthquake were caused from building debris. The Field Act was established after the event because of the amount of destruction caused to school buildings. Although schools were not in session at the time of the earthquake, more than 230 school buildings were highly if not completely damaged (Alquist 2007). This event gave great importance to the level of building code and the type of building materials used.

Non-ductile Concrete Buildings

Non-ductile concrete buildings are considered a great threat during seismic events because of their high potential for building damage and collapse. There are about 40,000 non-ductile concrete buildings throughout California, and approximately 1600 of them are within LAC. To better understand the threat these buildings pose the National Science Foundation developed a project called the “Grand Challenge” (Anagnos et al. 2008). The purpose of the “Grand Challenge is to document and collect data on all the non-ductile concrete buildings within LAC and use this data to update risk assessment tools to obtain better damage estimates and improve mitigation planning. Data was collected on the 1600 concrete buildings through several different public sources such as the LAC assessor’s office and the Los Angeles Department of City Planning, and then verified their findings using web applications such as Google Maps, Streetview, and ZIMAS (Anagnos et al. 2008).

A preliminary HAZUS-MH study by Comerio and Anagnos (2012) using a dataset of 1500 concrete buildings shows that the structures of greater concern are high-rise, buildings that are 4 or more stories tall. Comerio and Anagnos (2012) note that more trials need to be completed to recommend better which buildings should be retrofitted. Based on the preliminary study, 50% of the buildings are considered high-rise, but further research would show if all high-rise buildings are considered high risk, or if buildings that are 8+ stories high should be the main focus of a retrofit project.

Modifiable Areal Unit Problem

O’Sullivan and Unwin (2010) explain spatial autocorrelation as spatial data that violates assumptions of statistical analysis because they are not random. Spatial autocorrelation is a term used to describe how locational data is more likely to be similar when in close proximity rather than far way. The modifiable areal unit problem (MAUP) is important to understand because it has an effect on data aggregation and scale (University of Southampton 2016). MAUP is a term used to describe how statistics are skewed due to specific data points being generalized and arbitrarily applied. Generalizing the data may cause different spatial patterns to appear. MAUP has both scalar and aggregation effects on the results of this study. Results for analysis 1 and two are evaluated at the census tract level and building level. MAUP is also a reason for spatial data violating statistical analysis (University of Southampton 2016). The scale is effected based on the size of the areal units, and aggregation effects occur based on how the data is assembled (Figure 5).

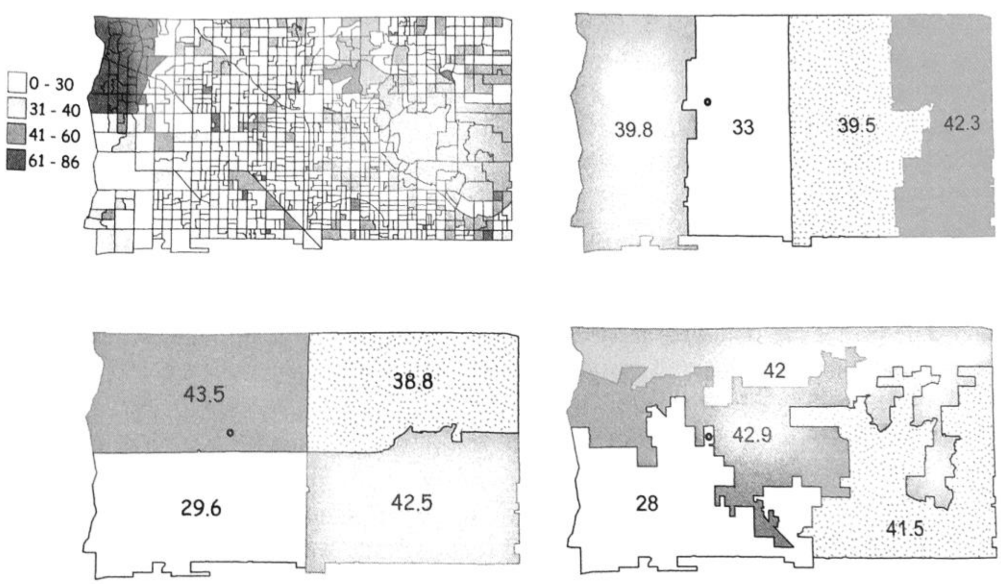

Figure 5: MAUP aggregation effect examples as presented by Bolstad (2012), showing how the population mean age differs based on how census blocks are arranged and evaluated.

This study aims to build upon the work completed by Comerio and Anagnos (2012) by further analyzing potential damage estimates to the non-ductile concrete buildings dataset through using the user-defined facilities and AEBM inventories to obtain more accurate damage results. This process is detailed in Chapter 3. The effect of the MAUP is discussed in Chapter 4.

Chapter 3 Data Sources and Methodology

Chapter three discusses the various data sources used to complete the thesis project, any processing that was necessary for each dataset, and the methodology followed to achieve results. The methodology section discusses how each of the three HAZUS-MH analyses differs and what was added to the model as an improvement. Each data source listed in this Chapter is described in detail to give an understanding of its importance and application to the project.

Objectives

The amount of non-ductile concrete buildings throughout California is a growing concern for organizations dedicated to hazard planning and mitigation. This study examined the potential damages to non-ductile concrete structures in the downtown area of Los Angeles, California in the event of a Mw 6.4 earthquake on the NIF, as estimated using HAZUS-MH. The specific objectives this analysis include the following:

1. Use HAZUS-MH to evaluate building damage percentages in the event of a repeat 1933 Long Beach Earthquake.
2. Use HAZUS-MH to compare damage results between three analyses.
3. Identify any areas or buildings that show a high risk of failure (50% or higher damage estimate).

Datasets

Five datasets were used in the analyses completed in this study. An overview of these sources and their resolutions is provided in Table 1.

Table 1: Overview of datasets used in this study.

Dataset	Format	Temporal Resolution	Spatial Resolution	Source
Los Angeles County Soils	Shapefile	2007	Soil Map Unit	Lam et al. (2007)
USGS Fault Lines	Shapefile	2006	County	United States Geological Survey (2015)
2010 Census Tracts	Shapefile	2010	Tract	U.S. Department of Commerce (2010)
LA City Districts	Shapefile	2012	Parcel	Los Angeles City Bureau of Engineering (2013)
Non-ductile Concrete Buildings	CSV Spreadsheet	2014	Parcel	Anagnos et al. 2008

Los Angeles County Soils

A current soil map of LAC was used to update HAZUS-MH data (Lam et al. 2007, Figure 6). Data that comes with the HAZUS-MH program are generalizations of the underlying geology and it is recommended that soil data is entered to achieve more accurate results (Lam et al. 2007). Using *A Digital Soil map for the Green Visions Plan for 21st Century Southern California Study Area* (Lam et al. 2007), soil colors are displayed based on the soil type. The soils dataset described is also provided in shapefile format by the Spatial Sciences Institute at USC at a parcel level accuracy. The spatial resolution is at a soil map unit level, where a soil map unit can range between "a few acres to thousands of acres" and is "between one and three major soil series" (Lam et al. 2007). To utilize the soils dataset, the values were reclassified to coordinate with the soil categories accepted by HAZUS-MH. HAZUS-MH soil values are listed in HAZUS-MH

Appendix B (Federal Emergency Management Agency 2015c). Soil types were be reclassified into the soil types listed in Appendix B based on the average shear-wave velocity of each soil type as defined by the National Earthquake Hazards Reduction Program. Current soil maps in HAZUS-MH are generalized estimates based on local geology, required to be able to estimate earthquake losses. The HAZUS-MH user manual states that in order to account for local soil types, local data needs to be added.

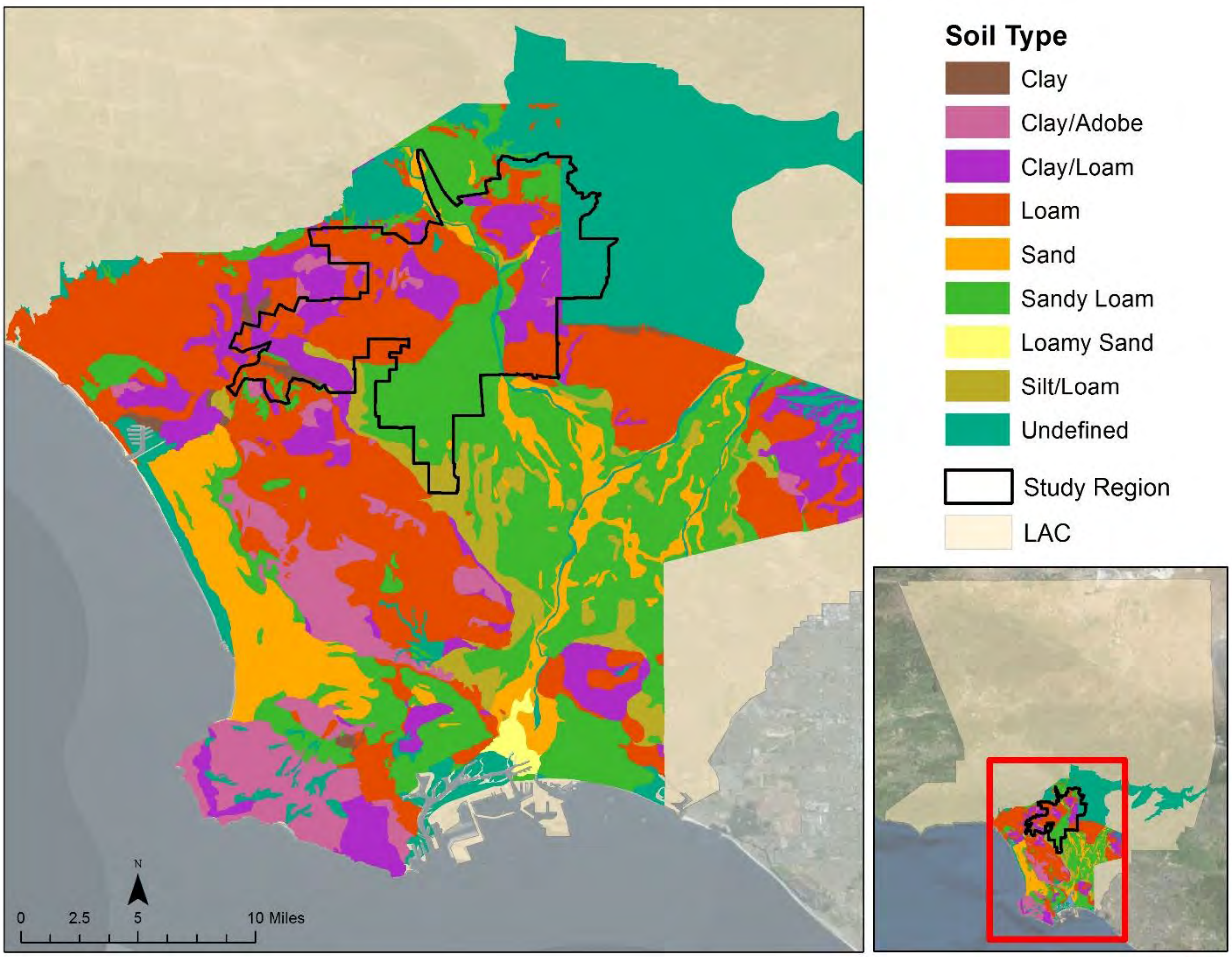

Figure 6: Los Angeles County Soil Types provided by Lam et al. (2007).

USGS Fault Lines

Fault line data for the Newport-Inglewood fault was used to validate the length and direction of the fault created in HAZUS-MH. The United States Geological Survey (USGS) fault line data was obtained from the Quaternary Fault and Fold Database (U.S. Geological Survey and California Geological Survey) provided by the USGS Earthquake Hazards Program (Figure 7). The GIS shapefile is of Quaternary faults in the United States that have been identified as a potential source of a magnitude 6 or higher earthquake.

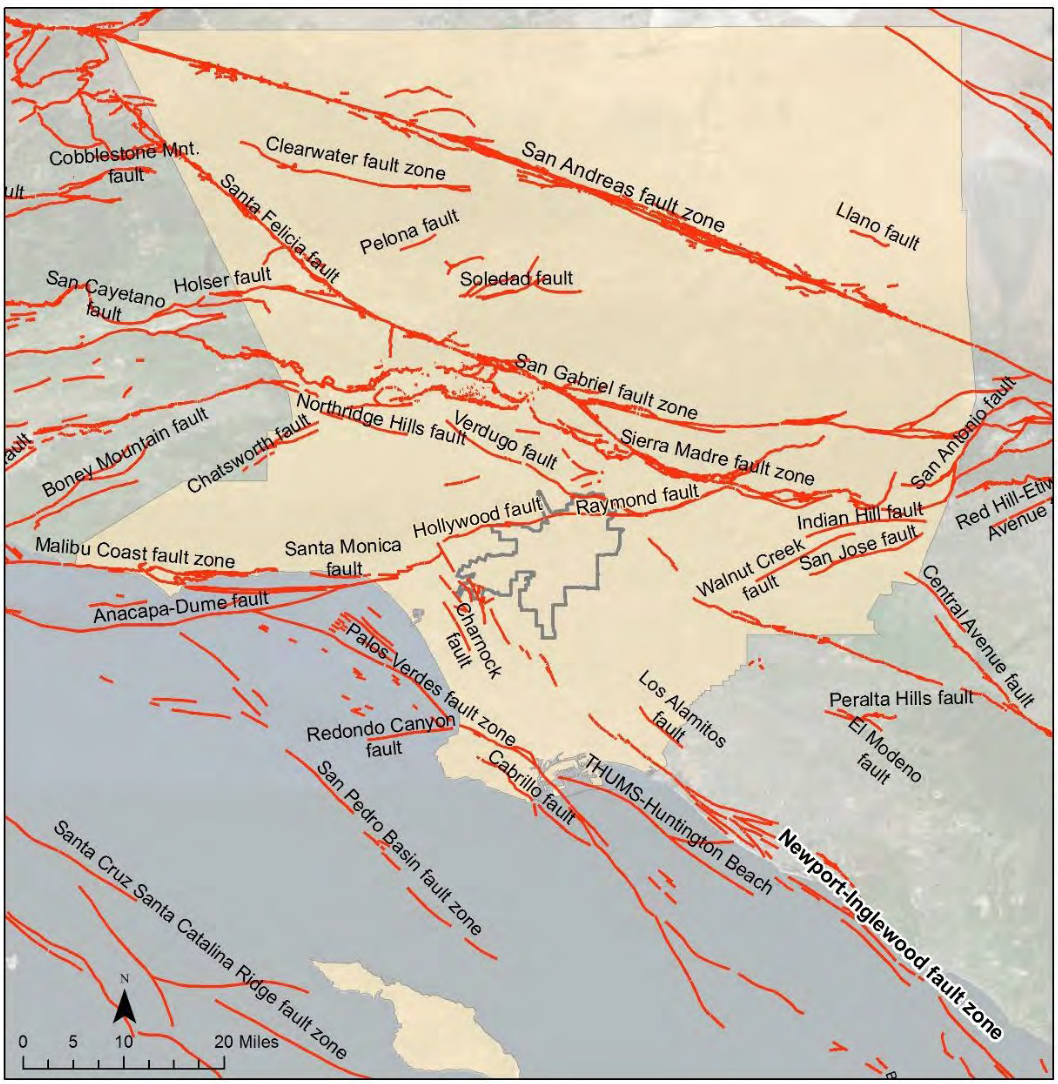

Figure 7: USGS faults identified as potential sources of a M_w 6 or higher earthquake within Los Angeles County shown in red. Study area displayed in gray.

2010 Census Tracts

Census tract data was obtained from the LA County geoportal via the United States Census Bureau (U.S. Department of Commerce 2010). The tiger shapefile was projected in NAD 1983 State Plane California V FIPS 0405 Feet and has census tract parcel level accuracy (Figure 8). Census tract data was used to define the study region within HAZUS-MH and for population analyses.

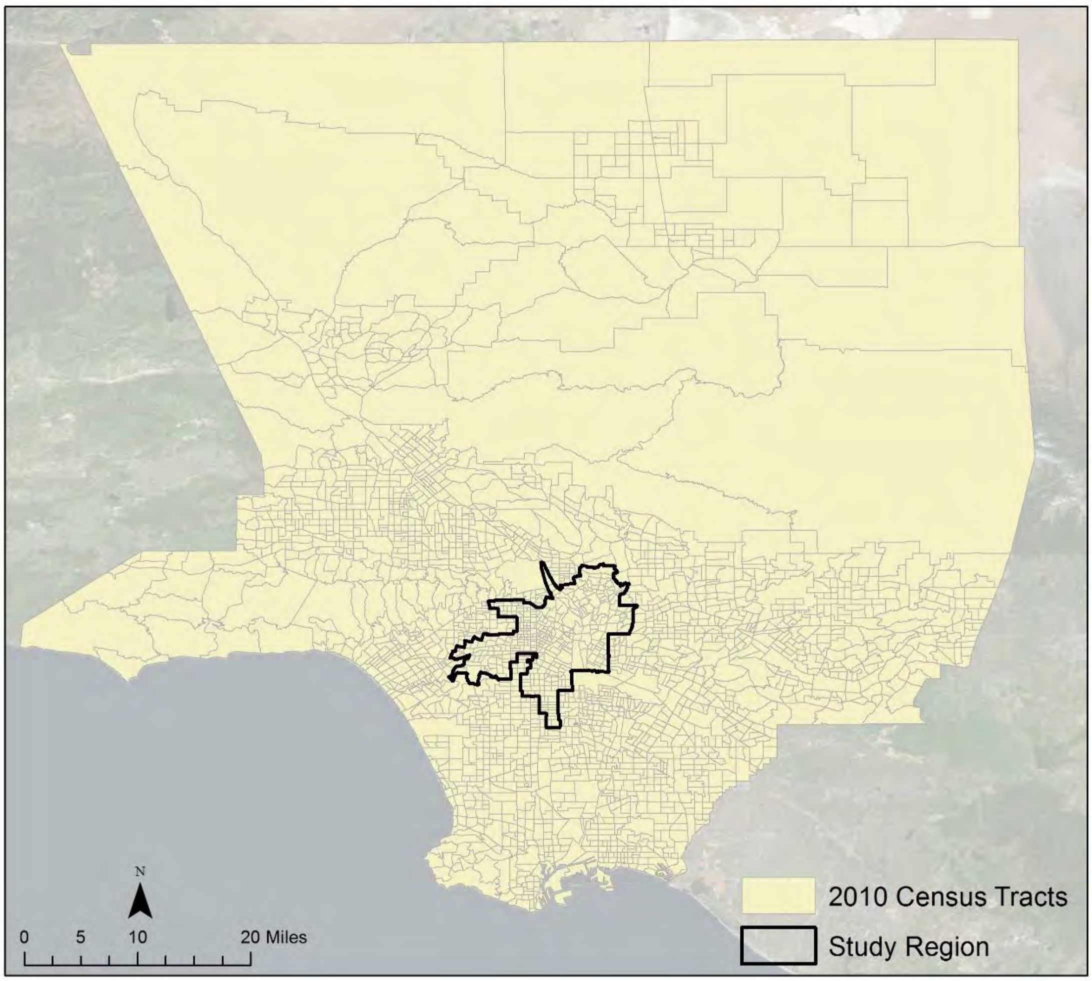

Figure 8: Los Angeles County 2010 census tract data.

Los Angeles City Districts

Los Angeles City Council districts layer was downloaded from the Los Angeles County GIS Data Portal (Los Angeles City Bureau of Engineering 2013, Figure 9). The city districts layer was overlaid on the Los Angeles County census tracts layer and the tract number for the census tracts that fell within city districts 1, 9, 10, 13, and 14 were extracted. The tract numbers were then used to create the HAZUS-MH study area via the HAZUS-MH Start-up Wizard.

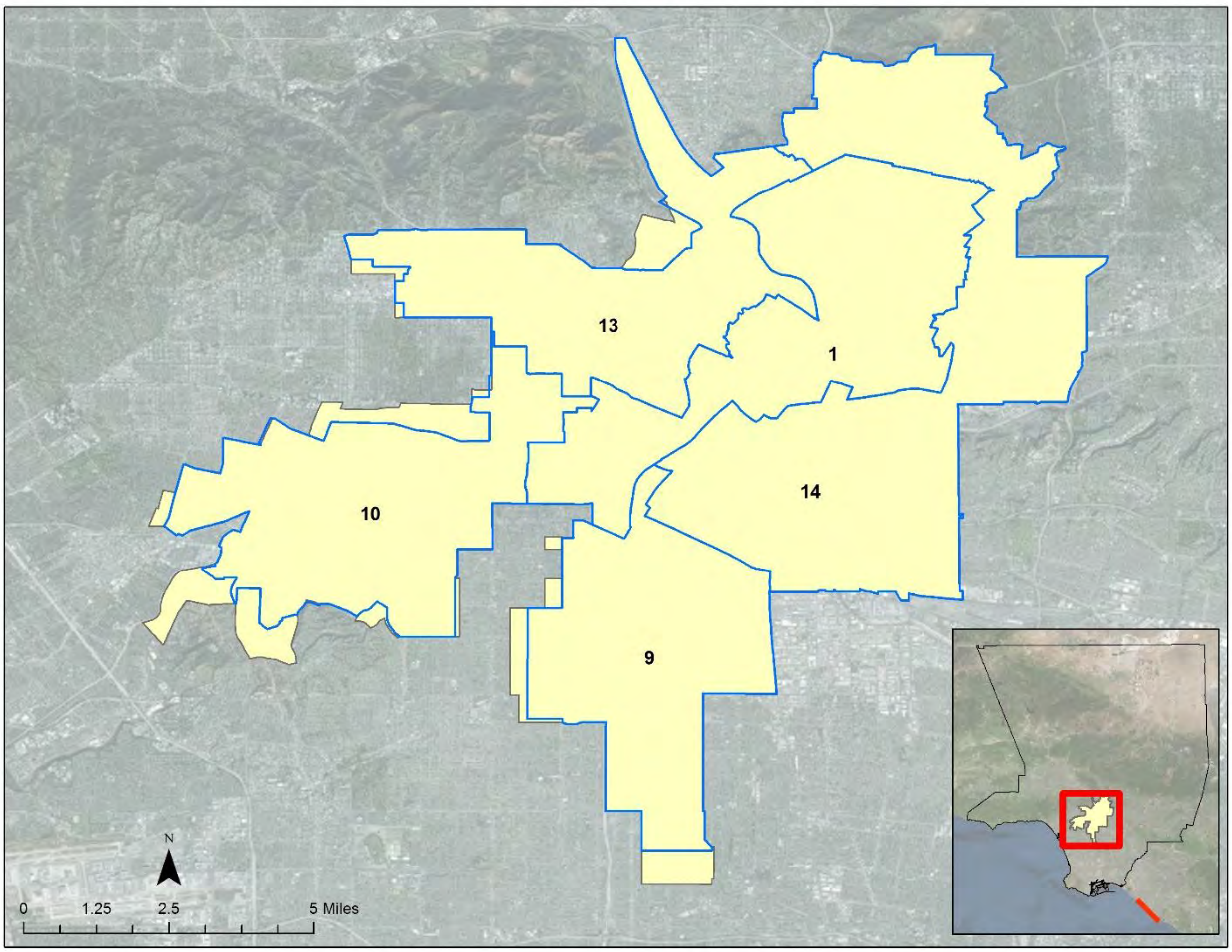

Figure 9: Los Angeles City Council Districts 1, 9, 10, 13, and 14 overlaid on 2010 Census Tracts

Pre-1976 Concrete Buildings

There are approximately 1600 non-ductile concrete buildings throughout LAC, and it is not certain which pose the most danger in a large seismic event. The University of California, Berkeley created a dataset of older concrete buildings within Los Angeles County that have been labeled as pre-1976 building code non-ductile concrete buildings (Anagnos et al. 2008). The CSV file dataset contains 1454 building locations, and each entry has the latitude, longitude, address, occupancy type, occupancy type code, the number of stories, year built, square feet, HAZUS-MH building construction code, building value, adjusted value, contents value, and day and night time occupants for the structure. This data was incorporated into the study using the HAZUS-MH AEBM to evaluate the potential damage for each individual concrete structure (Anagnos et al. 2008). There are 284 buildings from this list that fell within the study area of this thesis work and thus were analyzed in this study. To better show results for specific building types, buildings with similar functionalities have been group together by code (Figure 10). Building descriptions are found in Table 2 below. These building categories are used to better describe results from analysis 3. Figure 11 shows the locations of the 284 non-ductile concrete buildings within the study area and within the five city council districts. Figure 12 gives an overview of the age of the buildings within the dataset, and Figure 13 show the amount of buildings for each specific building code.

Table 2: Building category descriptions that are used to better describe results in Chapter 4

Category	Description	Code	Amount	Percentage of Dataset
Commercial	Retail trade, Wholesale trade, Service station, Office, Bank, Restaurant, Theater	COM1, COM2, COM3, COM4, COM5, COM8, COM9	101	36%
Medical	Hospitals, Medical office, Nursing home	COM6, COM7, RES6	44	15%
Education	Grade school & Universities	EDU1, EDU2	66	23%
Government	Offices	GOV1	8	3%
Industrial	Factories (light), Food/drugs/chemical factories	IND2, IND3	10	4%
Residential	Multiple family dwelling (20-49 & 50+), Hotel/motel, Church	RES3E, RES3F, RES4, REL1	55	19%

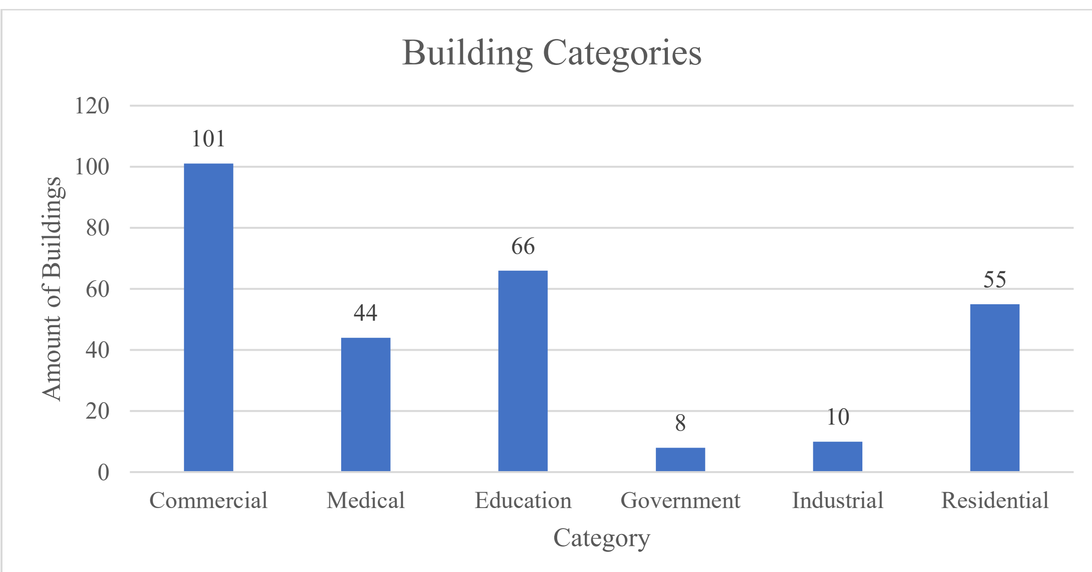

Figure 10: Graph of the range of building amounts for each building category.

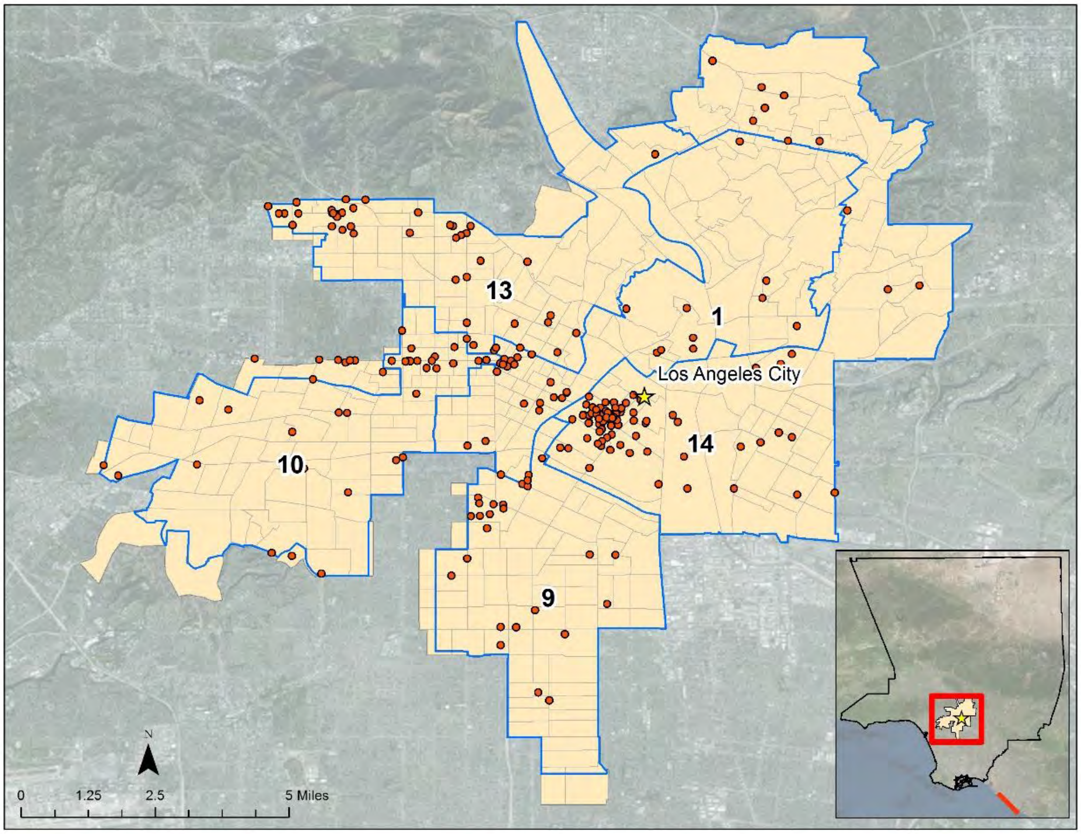

Figure 11: Locations of the 284 building used in the AEBM analysis. Inset map shows location of the buildings within Los Angeles County and in relation the Newport-Inglewood Fault (shown in red). Yellow star denotes Los Angeles City.

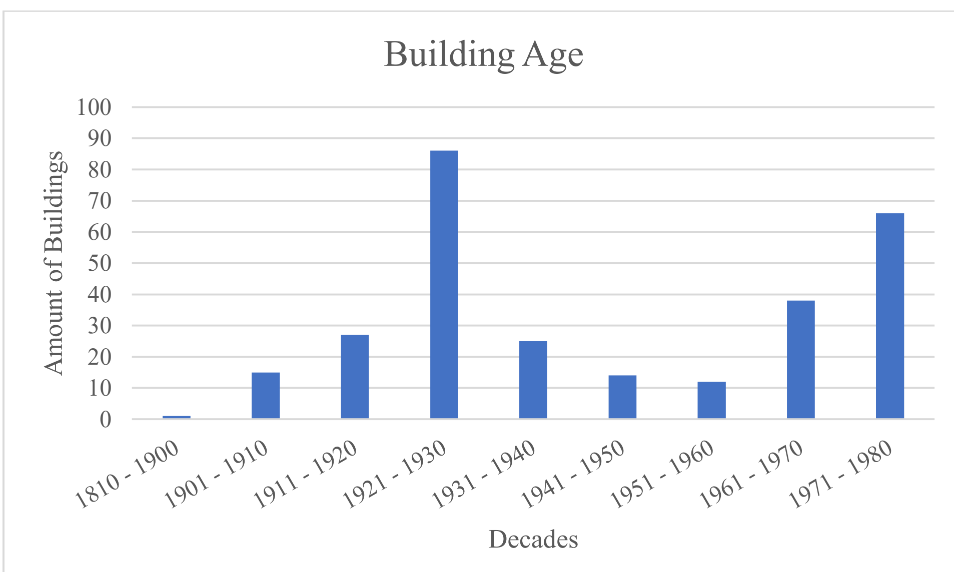

Figure 12: Amount of buildings per decade for the 284 buildings analyzed. All structures were built before 1976.

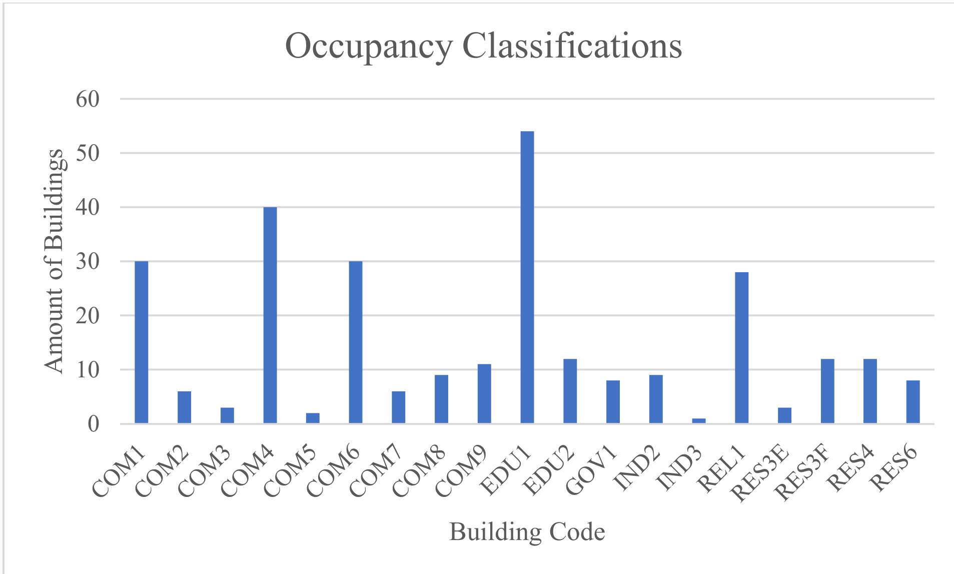

Figure 13: Amount of buildings for each occupancy class for the 284 buildings analyzed

Post-Processing

Each dataset must be in ArcGIS format and projected in the correct coordinate system to be used in HAZUS-MH. Data must be in latitude/longitude; the World Geodetic Survey 1984 coordinate system must be in decimal degrees (Buriks 2004). After data has been properly formatted, it was added to a geodatabase or the data was added to the CDMS to update HAZUS-MH defaults.

The concrete building dataset was converted to shapefile format for display purposes, but more importantly, it was converted to a Microsoft Access Database (.mdb) file to be imported into the AEBM Profile and Inventory list. Information required for the AEBM to be used are: profile name, address, city, state, zip code, building area (sq. ft.), building value, content value, business inventory, business income, wages, relocation disruption cost, rental cost, latitude, longitude, occupancy (Table 3), building type (Table 4), and design level (Table 5).

Table 3: HAZUS-MH Occupancy Classifications (Federal Emergency Management Agency 2015b).

Label	Occupancy Class	Example Descriptions
	Residential	
RES1	Single Family Dwelling	House
RES2	Mobile Home	Mobile Home
RES3	Multi Family Dwelling RES3A Duplex RES3B 3-4 Units RES3C 5-9 Units RES3D 10-19 Units RES3E 20-49 Units RES3F 50+ Units	Apartment/Condominium
RES4	Temporary Lodging	Hotel/Motel
RES5	Institutional Dormitory	Group Housing (military, college), Jails
RES6	Nursing Home	
	Commercial	
COM1	Retail Trade	Store
COM2	Wholesale Trade	Warehouse
COM3	Personal and Repair Services	Service Station/Shop
COM4	Professional/Technical Services	Offices
COM5	Banks	
COM6	Hospital	
COM7	Medical Office/Clinic	
COM8	Entertainment & Recreation	Restaurants/Bars
COM9	Theaters	Theaters
COM10	Parking	Garages
	Industrial	
IND1	Heavy	Factory
IND2	Light	Factory
IND3	Food/Drugs/Chemicals	Factory
IND4	Metals/Minerals Processing	Factory
IND5	High Technology	Factory
IND6	Construction	Office
	Agriculture	
AGR1	Agriculture	
	Religion/Non/Profit	
REL1	Church/Non-Profit	
	Government	
GOV1	General Services	Office
GOV2	Emergency Response	Police/Fire Station/EOC
	Education	
EDU1	Grade	Schools
EDU2	Colleges/Universities	Does not include group housing

Table 4: HAZUS-MH Building Types. HAZUS-MH has 36 building types, but only those used in the study have been listed (Federal Emergency Management Agency 2015a).

No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
16	C1L	Concrete Moment Frame	Low-Rise	1 - 3	2	20
17	C1M		Mid-Rise	4 - 7	5	50
18	C1H		High-Rise	8+	12	120
19	C2L	Concrete Shear Walls	Low-Rise	1 - 3	2	20
20	C2M		Mid-Rise	4 - 7	5	50
21	C2H		High-Rise	8+	12	120
22	C3L	Concrete Frame with Unreinforced Masonry Infill Walls	Low-Rise	1 - 3	2	20
23	C3M		Mid-Rise	4 - 7	5	50
24	C3H		High-Rise	8+	12	120
25	PC1	Precast Concrete Tilt-Up Walls		All	1	15
26	PC2L	Precast Concrete Frames with Concrete Shear Walls	Low-Rise	1 - 3	2	20
27	PC2M		Mid-Rise	4 - 7	5	50
28	PC2H		High-Rise	8+	12	120

Table 5: HAZUS-MH Seismic Design Level Classifications (Federal Emergency Management Agency 2015b).

UBC Seismic Zone (NEHRP Map Area)	Design Vintage		
	Post-1975	1941 - 1975	Pre-1941
Zone 4 (MA 7)	High-Code	Moderate-Code	Pre-Code
Zone 3 (MA 6)	Moderate-Code	Moderate-Code	Pre-Code
Zone 2B (MA5)	Moderate-Code	Low-Code	Pre-Code
Zone 2A (MA 4)	Low-Code	Low-Code	Pre-Code
Zone 1 (MA 2/3)	Low-Code	Pre-Code	Pre-Code
Zone 0 (MA 1)	Pre-Code	Pre-Code	Pre-Code

Methodology

The hazard identified for this study is the M_w 6.4 Long Beach earthquake that occurred on March 11, 1933. To begin the HAZUS-MH study, a study region was created using the Create New Region Wizard. The region was duplicated twice, and different data sources were added to the three different HAZUS-MH documents based on which of the three analyses the document housed. Once the documents were set up, a basemap was created, and the other data layers were added.

Data sources were added to the HAZUS-MH map document via direct add, the Comprehensive Data Management System, and SQL Server Management Studio. After all data layers had been loaded into HAZUS-MH, the earthquake scenario parameters were set using the Scenario Wizard (Figure 14). This study examined only one scenario, but the three analyses differed based on the data layers in the map document.

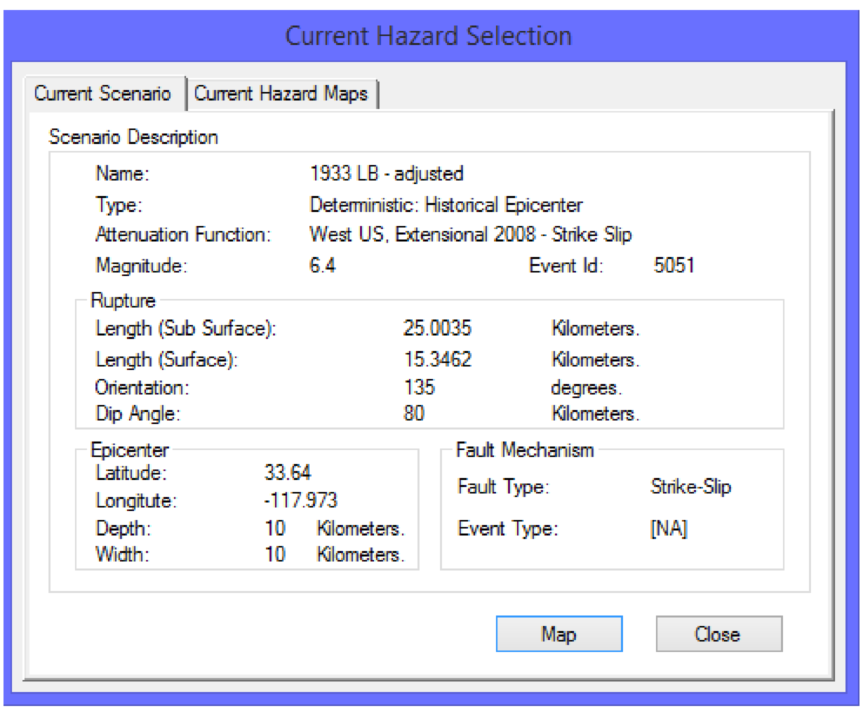

Figure 14: Parameters used to define the 1933 Long Beach Earthquake scenario.

Analysis 1

The first analysis only utilized data layers built into HAZUS-MH upon program installation. The scenario was run using the Analysis Toolbar. The analysis options selected in the inventory wizard were general building stock, essential facilities, indirect economic impact, and contour maps. After the analysis was completed, map and report outputs were generated for the results of the scenario.

Analysis 2

The second HAZUS-MH analysis utilized the previously processed data layers and the user-defined facilities option. The soils data layer was used to update HAZUS-MH program via the CDMS to achieve more accurate results than analysis 1. Although HAZUS-MH comes with data layers built into the program, they are generalizations and have inaccuracies (Federal Emergency Management Agency 2015c). Details for the 284 buildings were entered into the User-Defined Facilities Inventory Using the independent data layers; the Mw 6.4 earthquake scenario was run again using the same analysis options (general building stock, essential facilities, indirect economic impact, and contour maps) plus the user-defined facilities option. Maps and reports of the results were generated when the analysis was complete.

Analysis 3

The third HAZUS-MH analysis utilized the AEBM to give even more specific results for each building entered in the AEBM Inventory. The 284 buildings that fell within the study area were added to the AEBM Inventory and Profile list using SQL Server Management Studio 2014. The AEBM, general building stock, essential facilities, indirect economic impact, and contour maps were then be selected in the analysis options to run the model. Individual building reports were created in order to review damage results for each building entered into the AEBM inventory based on the building occupancy class, building type, and design level. A portfolio building report was generated to show the average damage and losses for all buildings in the AEBM inventory (Federal Emergency Management Agency 2015b).

Chapter 4 Results

The results of the three HAZUS-MH analyses in the event of a repeat M_w 6.4 1933 Long Beach earthquake are presented herein according to individual analyses, and the outputs of the different analyses are compared. Results presented show how each set of results differs, with the intention of illustrating whether using more precise or detailed input data gives more meaningful results. For example, the AEBM results provide information to find out if any of the buildings analyzed pose a high risk of failure. In the context of this analysis, high risk is defined as buildings with 50% or higher damage estimate.

The six different building types (Table 6) listed in the non-ductile concrete buildings were used in the anaylses and results comparison between analysis 1 and 2. Building types shown in Table 5 are found within the non-ductile concrete building dataset, but not all building code types had HAZUS-MH generated results for analysis 1. It is assumed that this is because data that comes installed with the HAZUS-MH program are generalizations and are not accurate enough to determine the full range of building types for each census tract.

Table 6: Building types that were used to analyze damage in all analyses.

<table>
<tr><th>Type</th><th>Description</th><th colspan="2">Code</th></tr>
<tr><td>C2L</td><td rowspan="3">Concrete Shear Walls</td><td>Pre-Code</td><td>Low Code</td></tr>
<tr><td>C2M</td><td>Pre-Code</td><td>Low Code</td></tr>
<tr><td>C2H</td><td>Pre-Code</td><td>Low Code</td></tr>
<tr><td>C3L</td><td rowspan="3">Concrete Frame with Unreinforced Masonry Infill Walls</td><td>Pre-Code</td><td>Low Code</td></tr>
<tr><td>C3M</td><td>Pre-Code</td><td>Low Code</td></tr>
<tr><td>C3H</td><td>Pre-Code</td><td>Low Code</td></tr>
</table>

Analysis 1 – General Analysis

Structural damage was analyzed for the M_w 6.4 1933 Long Beach earthquake event by using the General Building Stock and the Damage by Building Type outputs for the building types and codes listed in Table 6. Although these building types were found in the non-ductile concrete building dataset, a majority did not have result outputs for the general analysis. This is because HAZUS-MH data are generalizations and are not accurate enough to determine the full range of building types for each census tract.   No results were available for C2M, C2H, C3L, C3M, and C3H. C2L results are found in Figures 15 - 20. Figures 15 – 17 show damage results for C2L building types that are pre-code and Figures 18 – 20 show damage results for C2L buildings that are low code. Figure 15 provides moderate damage estimates, which is equivalent to cracks in walls. The two census tracts at the bottom of the study area and closest to the rupture show a 5%-6% chance of moderate damage. Many of the center census tracts show 3%-4% moderate damage. Extensive and complete damage to this building type is estimated to be ≤ 1% (Figures 16 & 17).

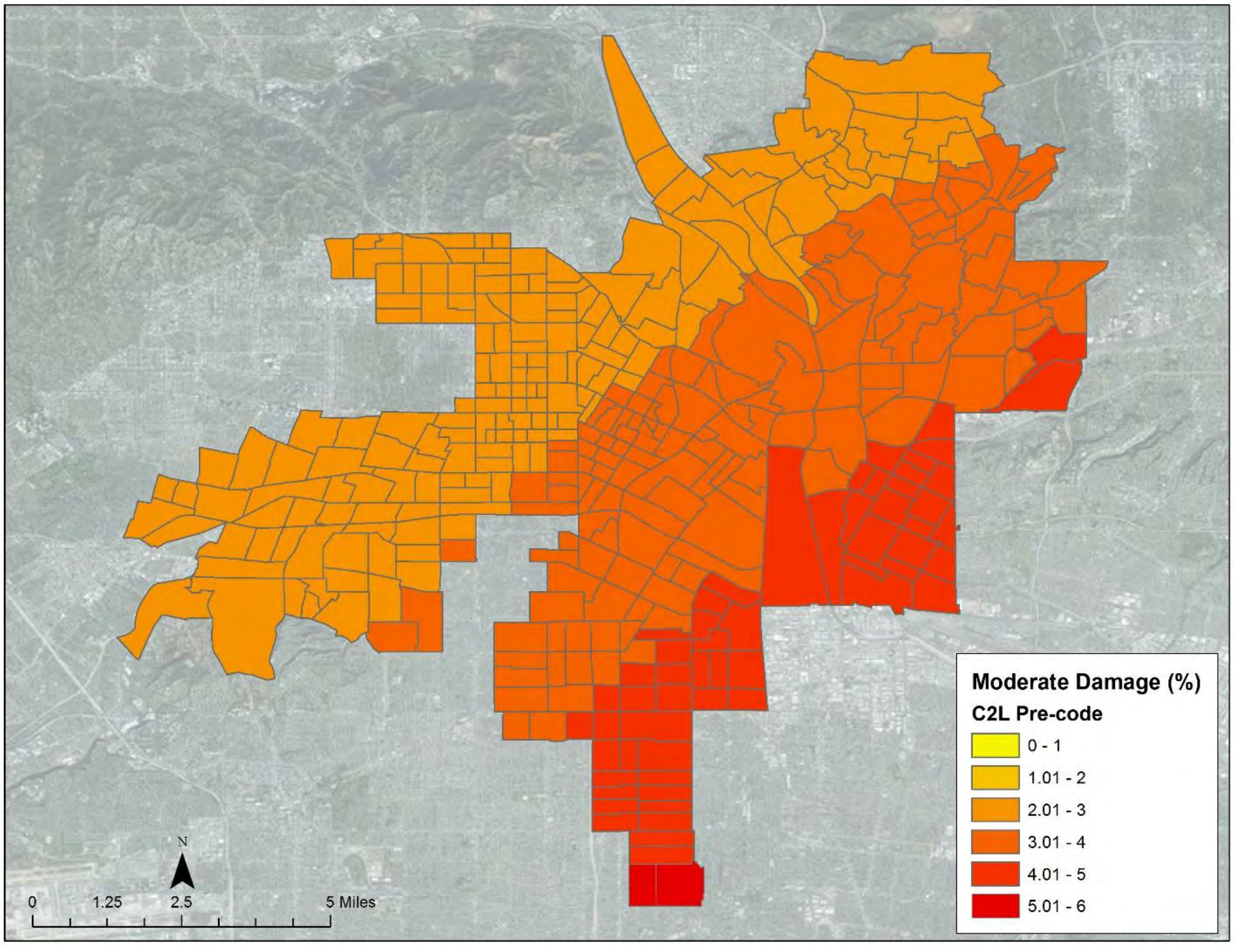

Figure 15: Moderate damage estimates for pre-code C2L buildings (shear wall concrete buildings not designed to any seismic standard).

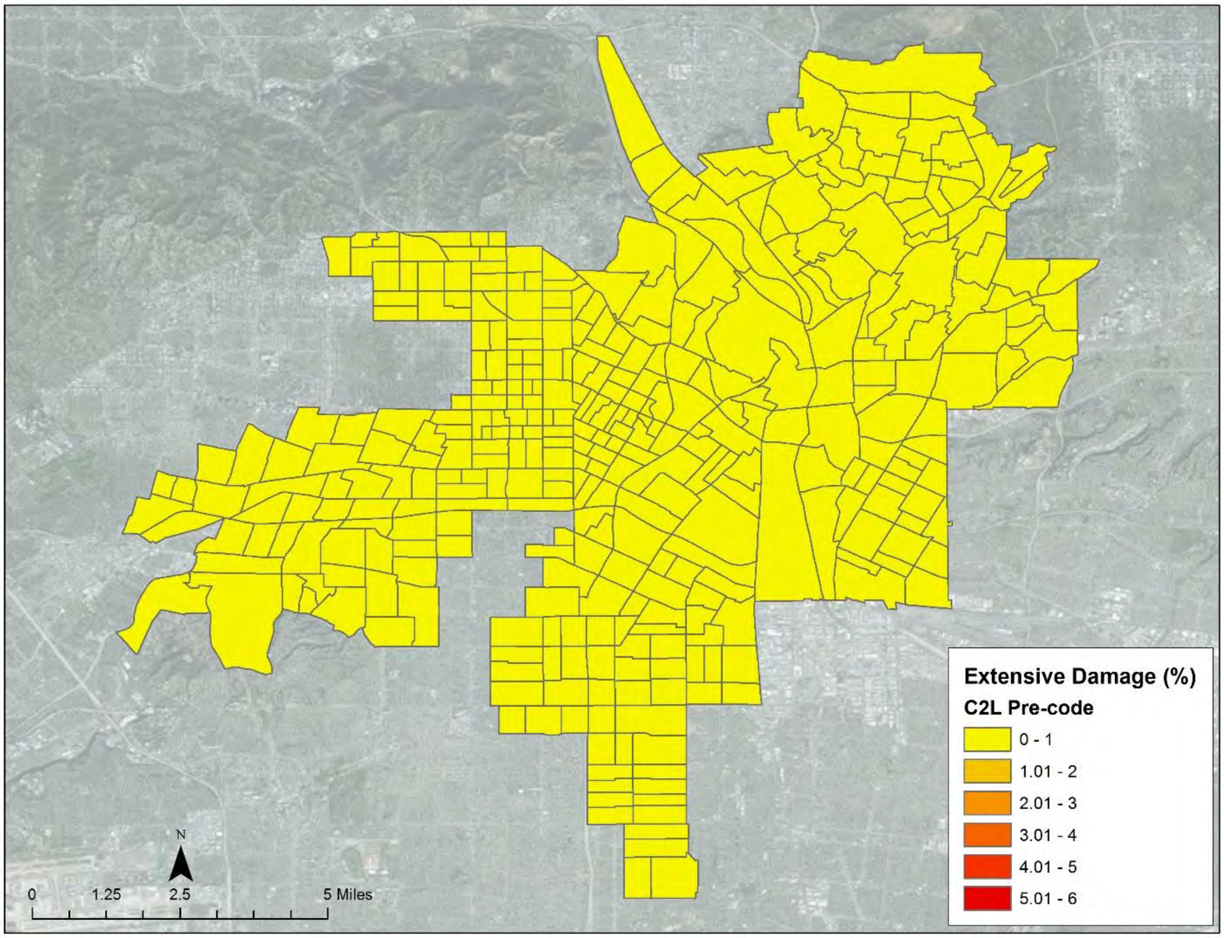

Figure 16: Extensive damage estimates for pre-code C2L buildings (shear wall concrete buildings not designed to any seismic standard).

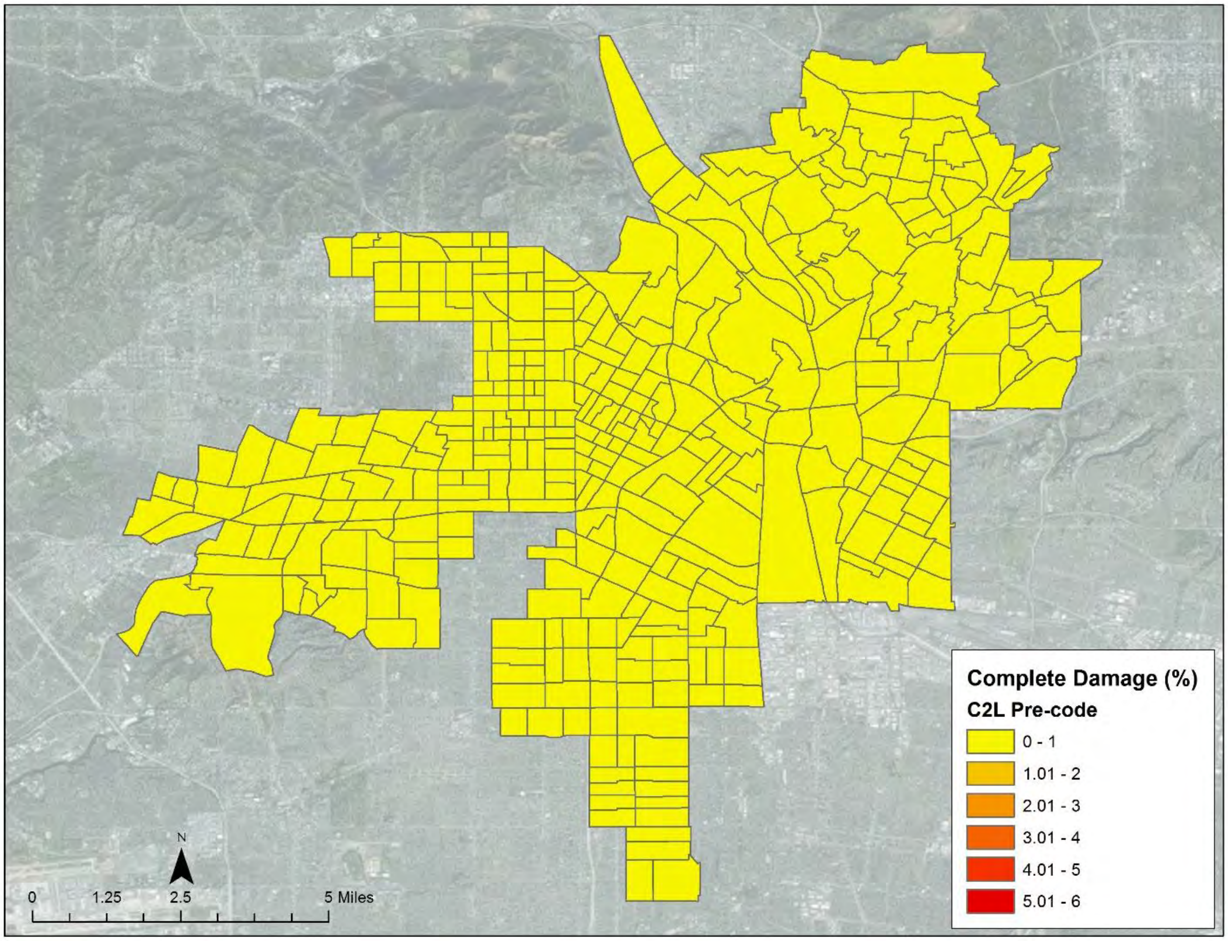

Figure 17: Complete damage estimates for pre-code C2L buildings (shear wall concrete buildings not designed to any seismic standard).

Moderate damage has a lower range for low code C2L buildings (Figure 18). The most moderate damage shown for low code C2L buildings is 2%-3%. Extensive building damage estimates are ≤ 1% for low code C2L buildings (Figure 19). No complete damage was detected in the general analysis HAZUS-MH for C2L low code buildings (Figure 20).

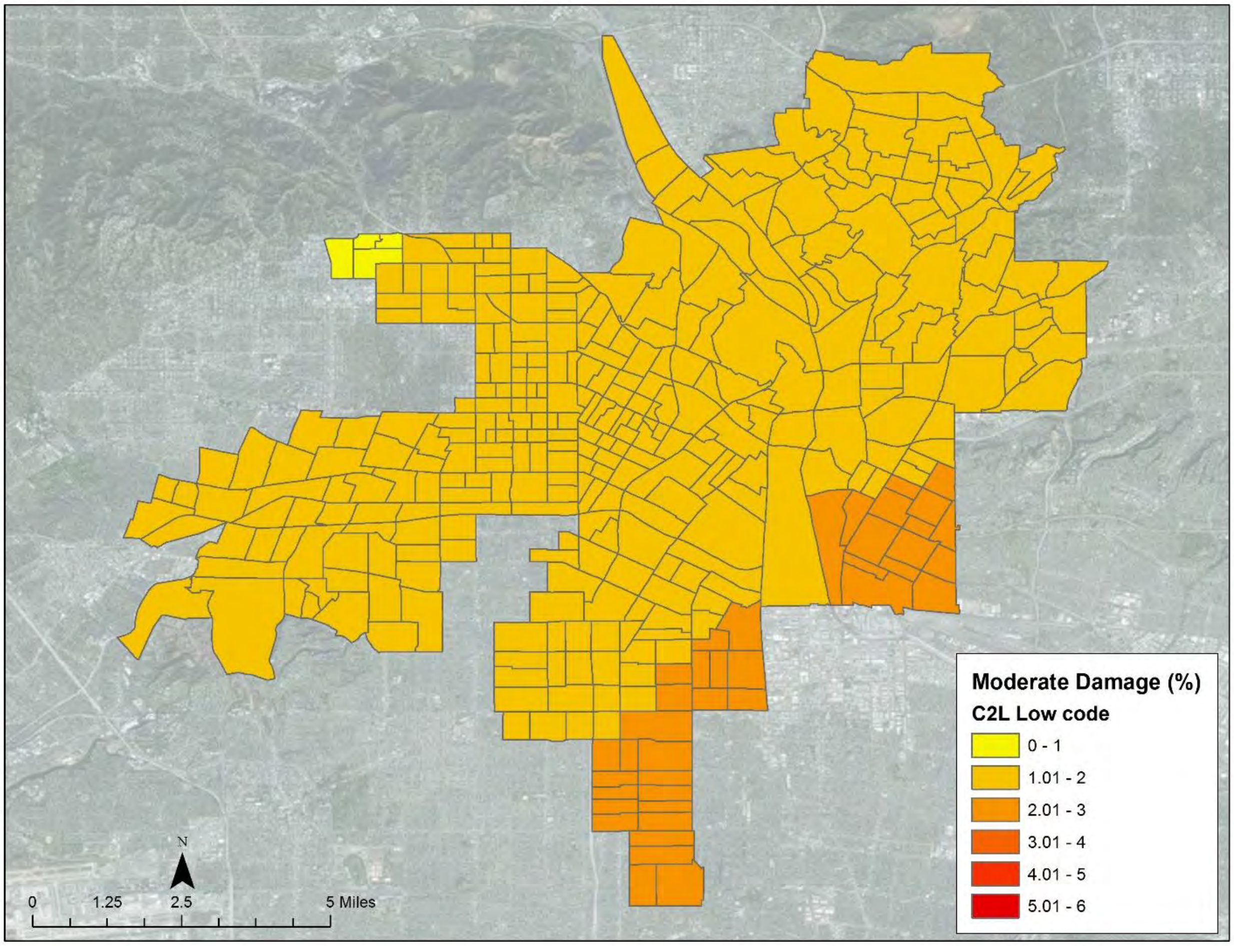

Figure 18: Moderate damage estimates for low code C2L buildings (shear wall concrete buildings with low seismic standards).

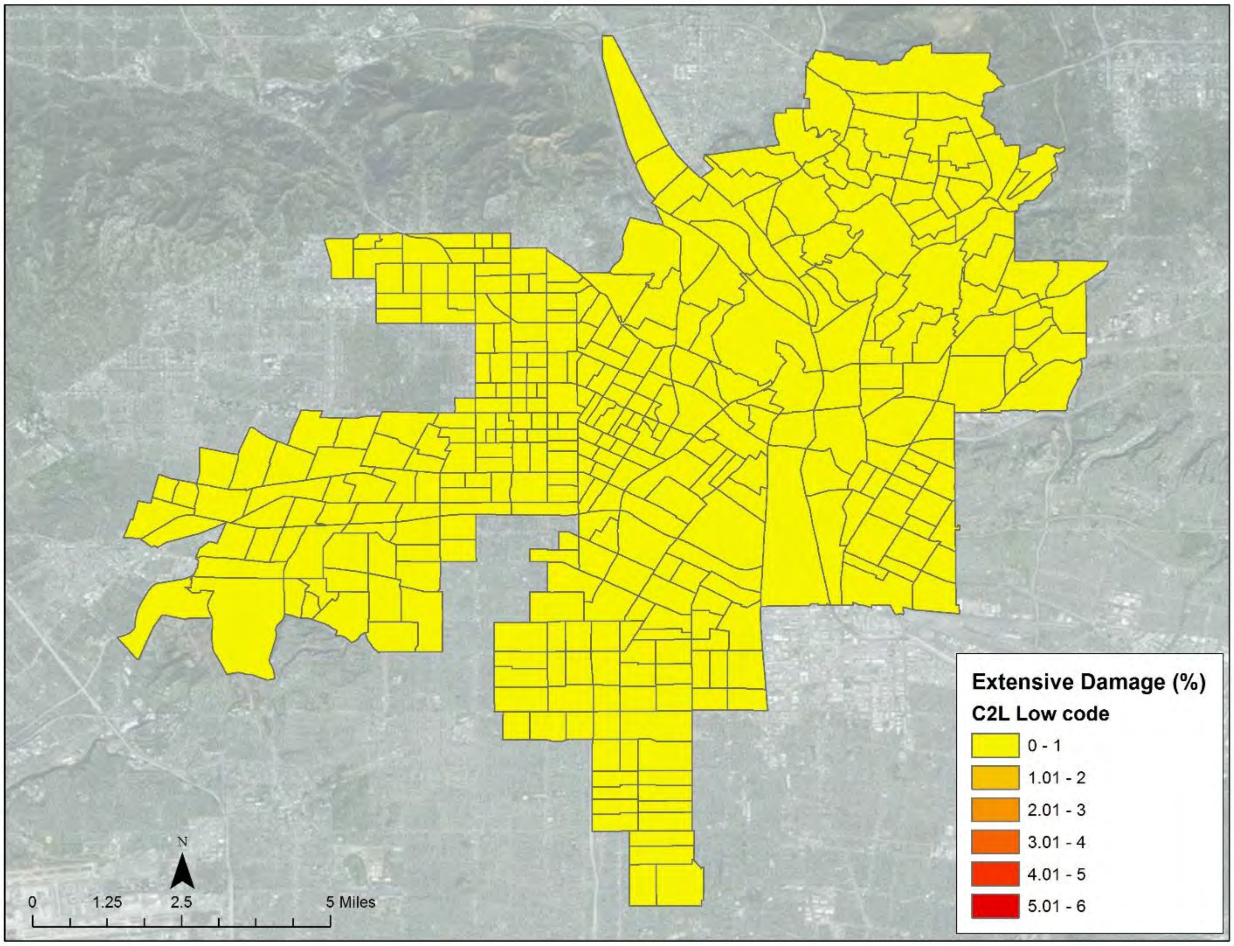

Figure 19: Extensive damage estimates for low code C2L buildings (shear wall concrete buildings with low seismic standards).

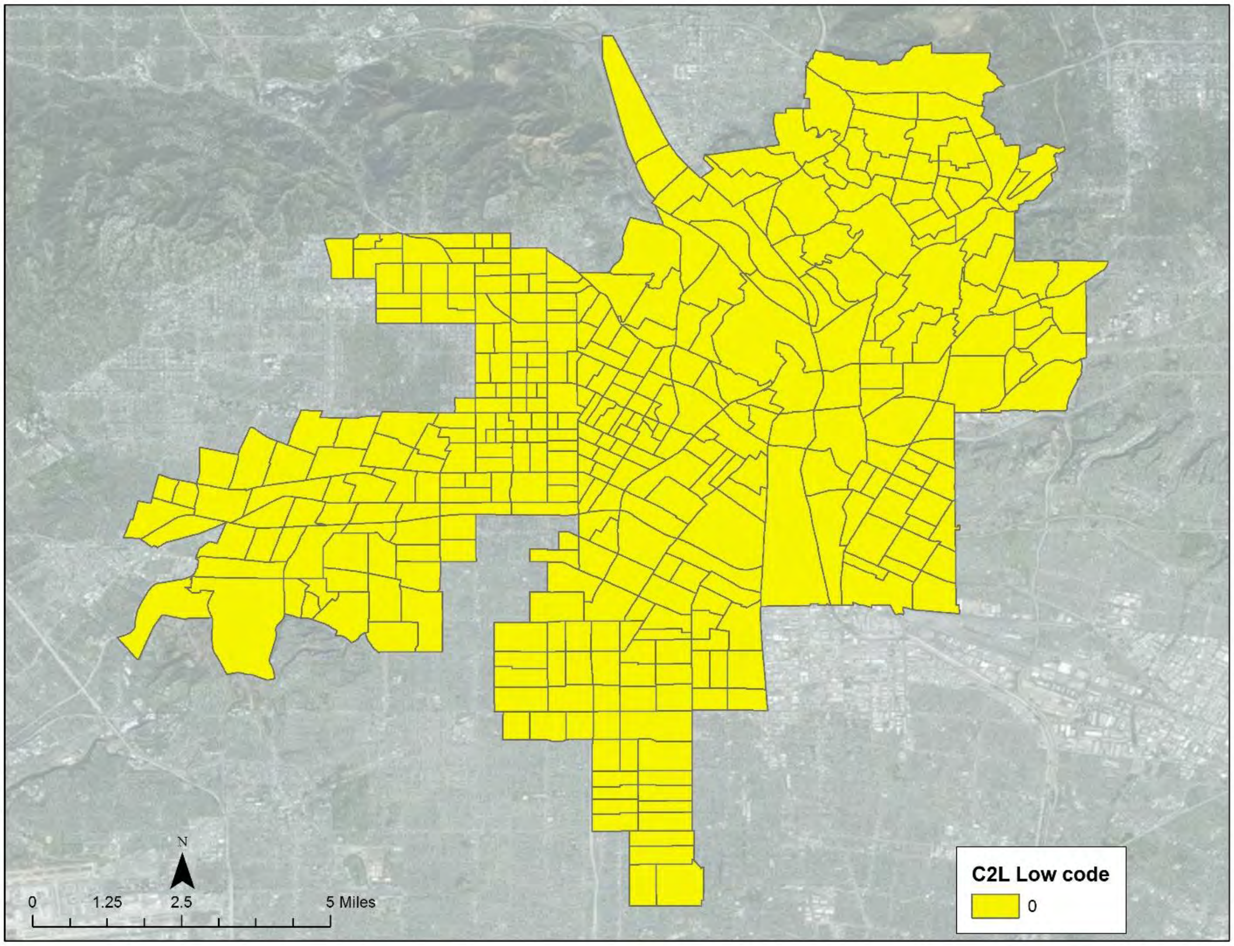

Figure 20: Complete damage estimates for low code C2L buildings (shear wall concrete buildings with low seismic standards).

Analysis 2 – User-defined Facilities and Updates

User-defined facilities and damage by building type are considered in order to analyze if there is a recognizable relationship between the two and to determine if there is a difference between damage outputs between analysis 1 and analysis 2. Functionality was also analyzed to see if there were any user-defined facilities that would have a 50% chance of not being fully functional at day one. Analysis 2 analyzed user-defined facilities damages against C2L pre-code and low code structure damage results. C2L pre-code structure exhibiting moderate, extensive, and complete damages are shown in Figures 21-23. C2L low code structure damages for moderate, extensive, and complete are shown in Figures 24-26. Figure 27 shows which of the user-defined facilities have a 50% possibility of being fully functional the first day after the earthquake. The structures are displayed as points overlain on a choropleth map of distance (km) from the defined scenario earthquake (Figures 21-27).

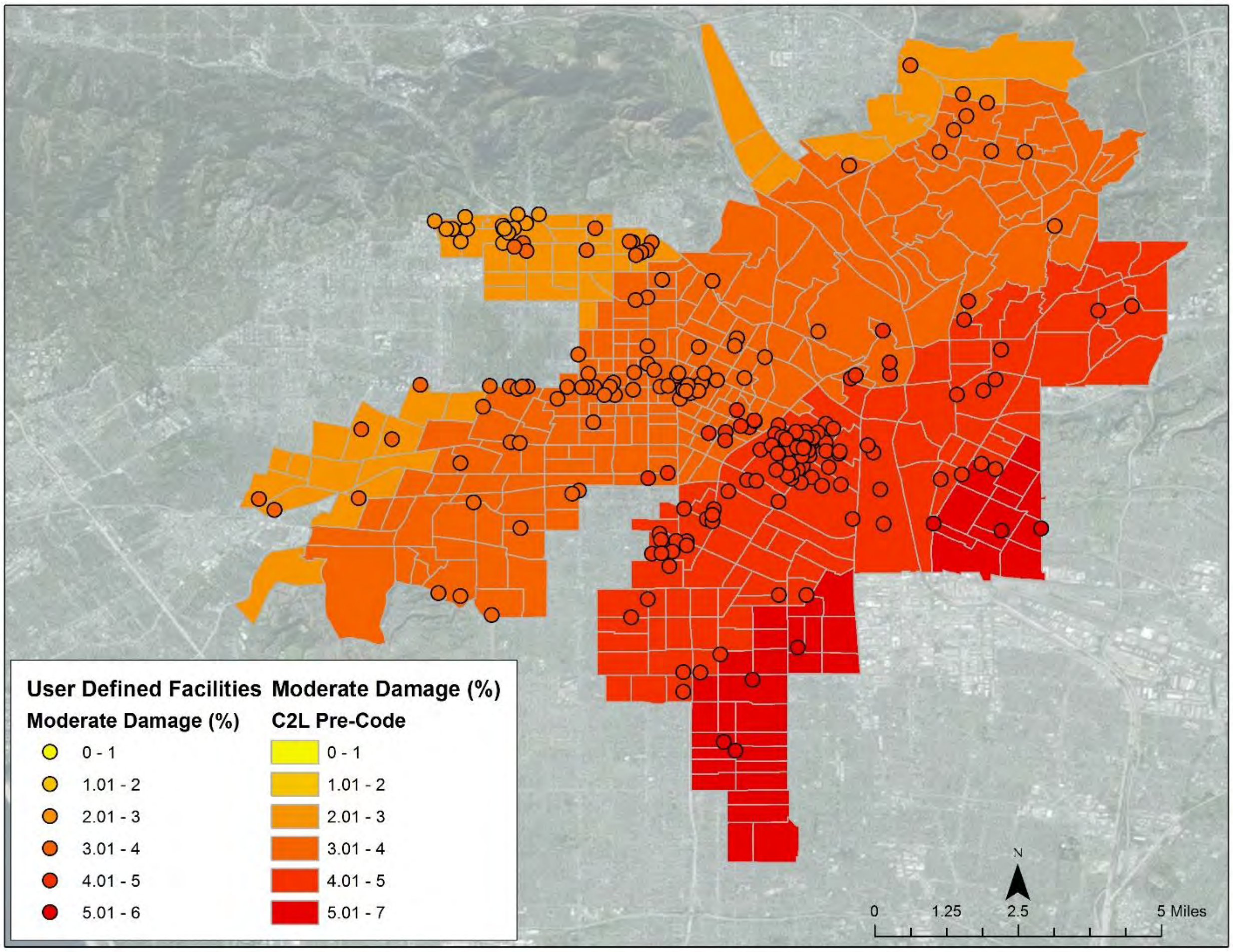

Figure 21: Estimated moderate damage to user-defined facilities overlaid on the percent of moderate damage to pre-code C2L structures (shear wall concrete buildings not designed to any seismic standard).

Figure 21 shows that the user-defined facilities results almost match the census tract result classifications. The cluster of buildings in the center of the study area exhibit 4%-5% of moderate damage, and the associated census tracts also exhibit 4%-5% range of moderate damage. Similarly, the more severe results have comparable classification ranges. MAUP is found in areas where census tract damage is between 2%-3% and 3%-4%. Select user-defined facilities showing 4%-5% moderate damage fall within census tracts that show 3%-4% moderate damage. Also, select user-defined facilities showing 3%-4% moderate damage fall within census tracts that show 2%-3% moderate damage. It was important to recognize how the data viewed at two different scales had an effect on the results because one objective of this thesis was to look at how results became more accurate. The most moderate damage exhibited was 5.5% to the southernmost building in Figure 21 and falls within census tracts that exhibit 6% moderate damage. The bottom right census tract exhibited the most moderate damage (6.5%).

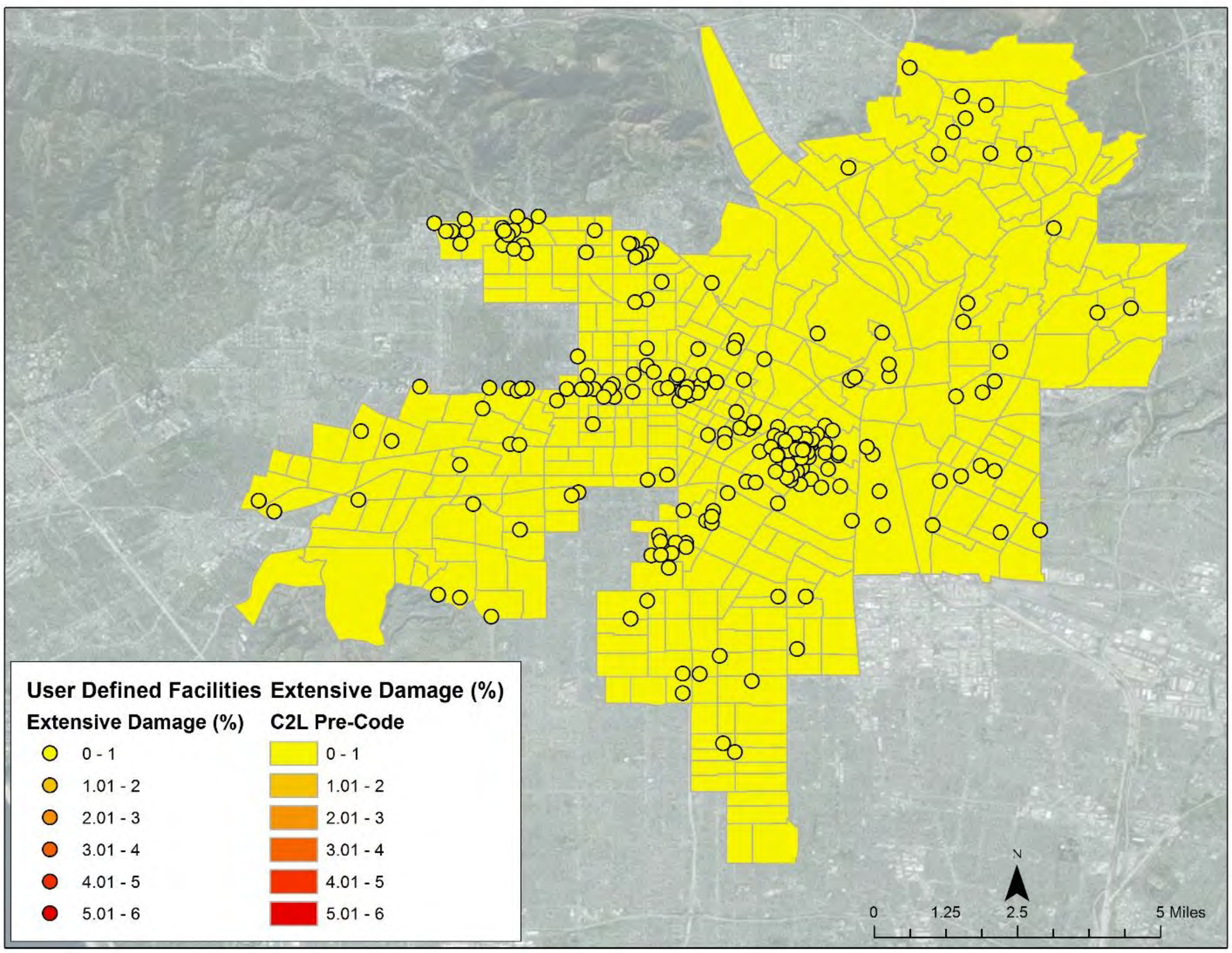

Figure 22: Extensive damage to user-defined facilities overlaid on the percent of extensive damage to pre-code C2L (shear wall concrete buildings not designed to any seismic standard).

Extensive damage fell far less than moderate damage, but the buildings still fall within census tracts that show similar damage percentages. All buildings and census tracts showed ≤ 1% of extensive damage (Figure 22).

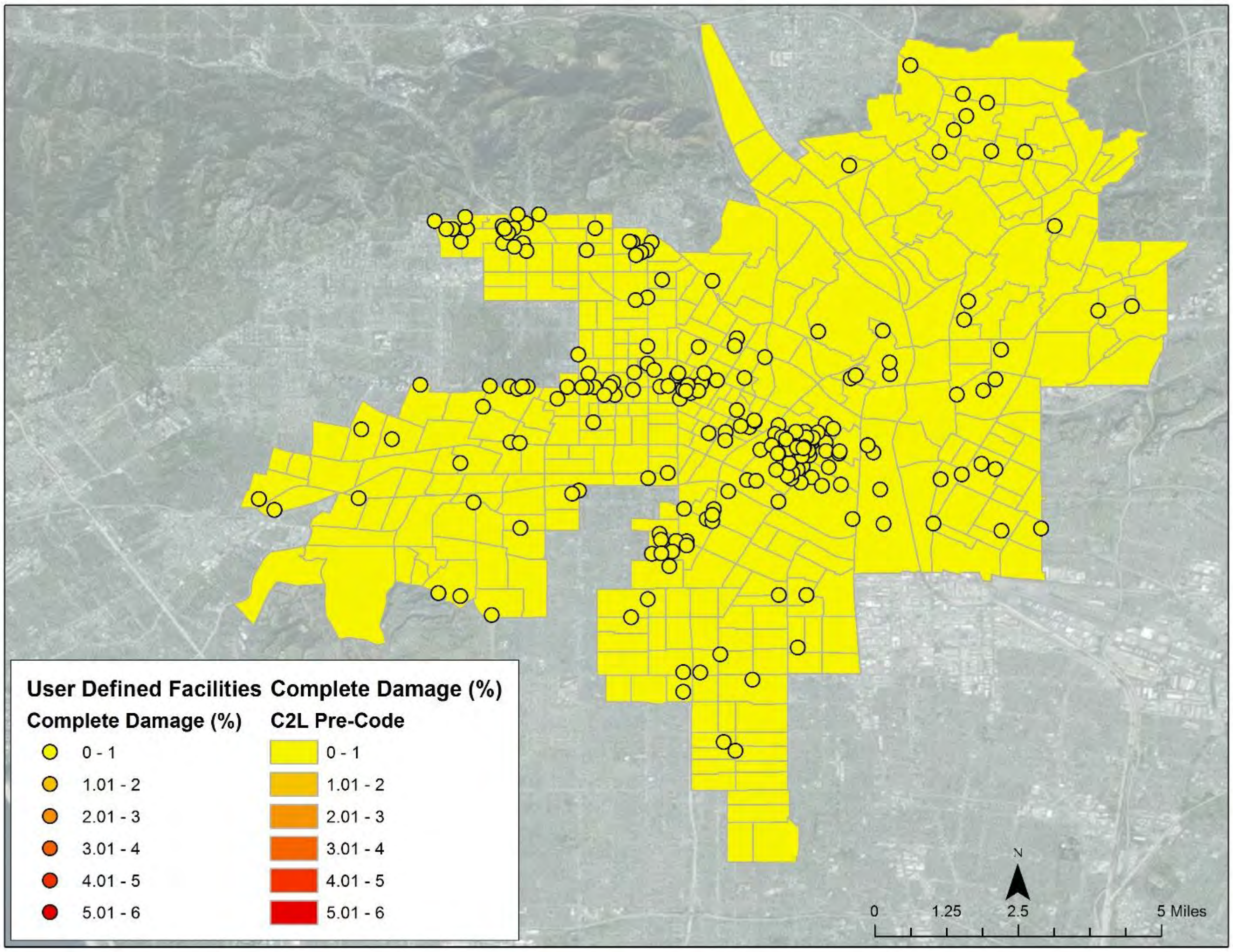

Figure 23: Complete damage to user-defined facilities overlaid on the percent of complete damage to pre-code C2L (shear wall concrete buildings not designed to any seismic standard).

Complete damage estimates for user-defined facilities overlaid on census tracts from C2L pre-code structures are found in Figure 23. Again, damage estimates for both the user-defined facilities and the census tracts are ≤ 1% for complete damage.

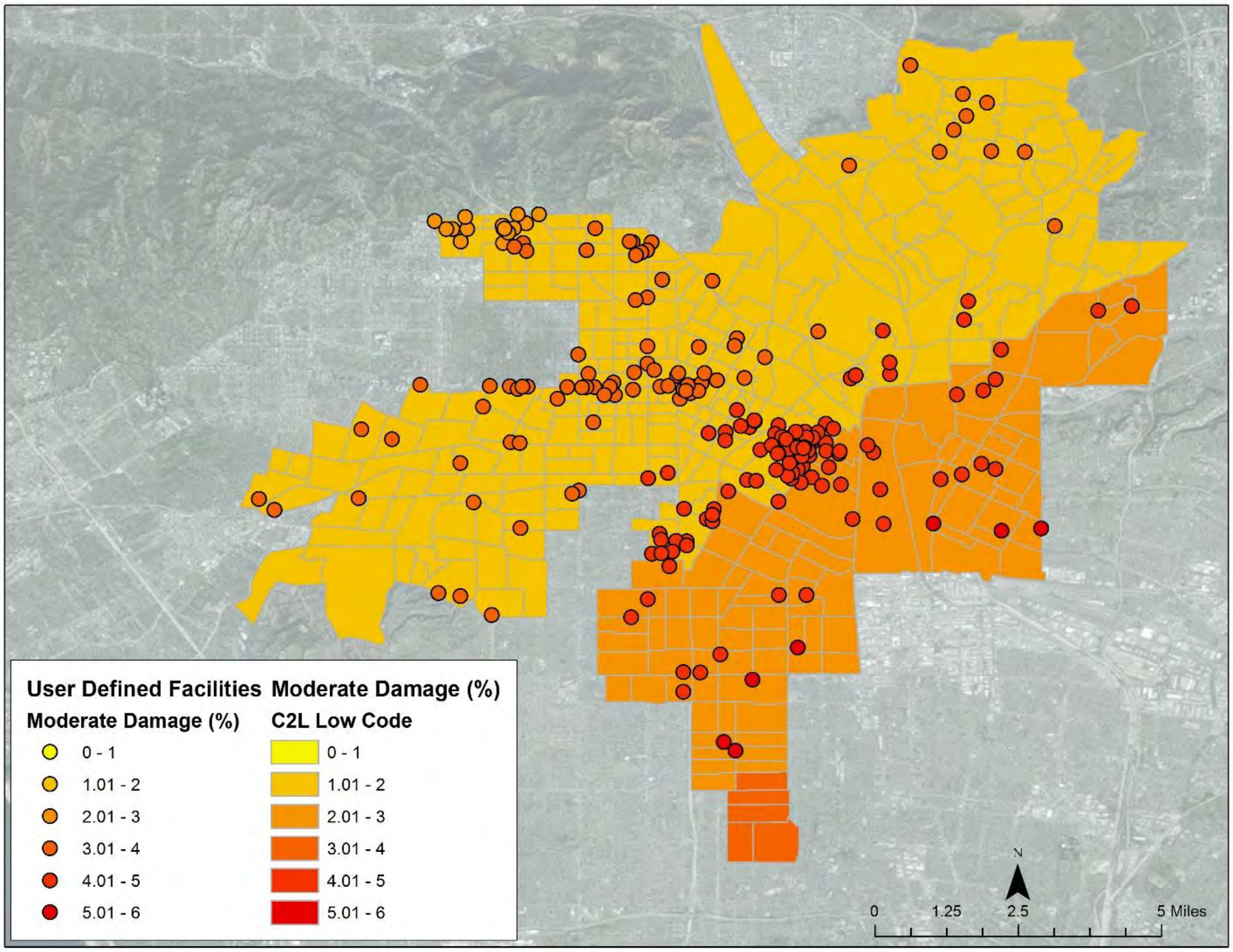

Figure 24: Moderate damage to user-defined facilities overlaid on the percent of moderate damage to low code C2L (shear wall concrete buildings with low seismic standards).

Figure 24 shows that the user-defined facilities estimates are higher than the underlying census tracts. This shows how the most accurate data within the user-defined facilities inventory allows for more accurate building damage results. The user-defined facilities for low code C2L moderate damage also demonstrate aggregation effects. The center cluster of facilities shows 4%-5% moderate damage. However the underlying census tracts show 2%-4% moderate damage.

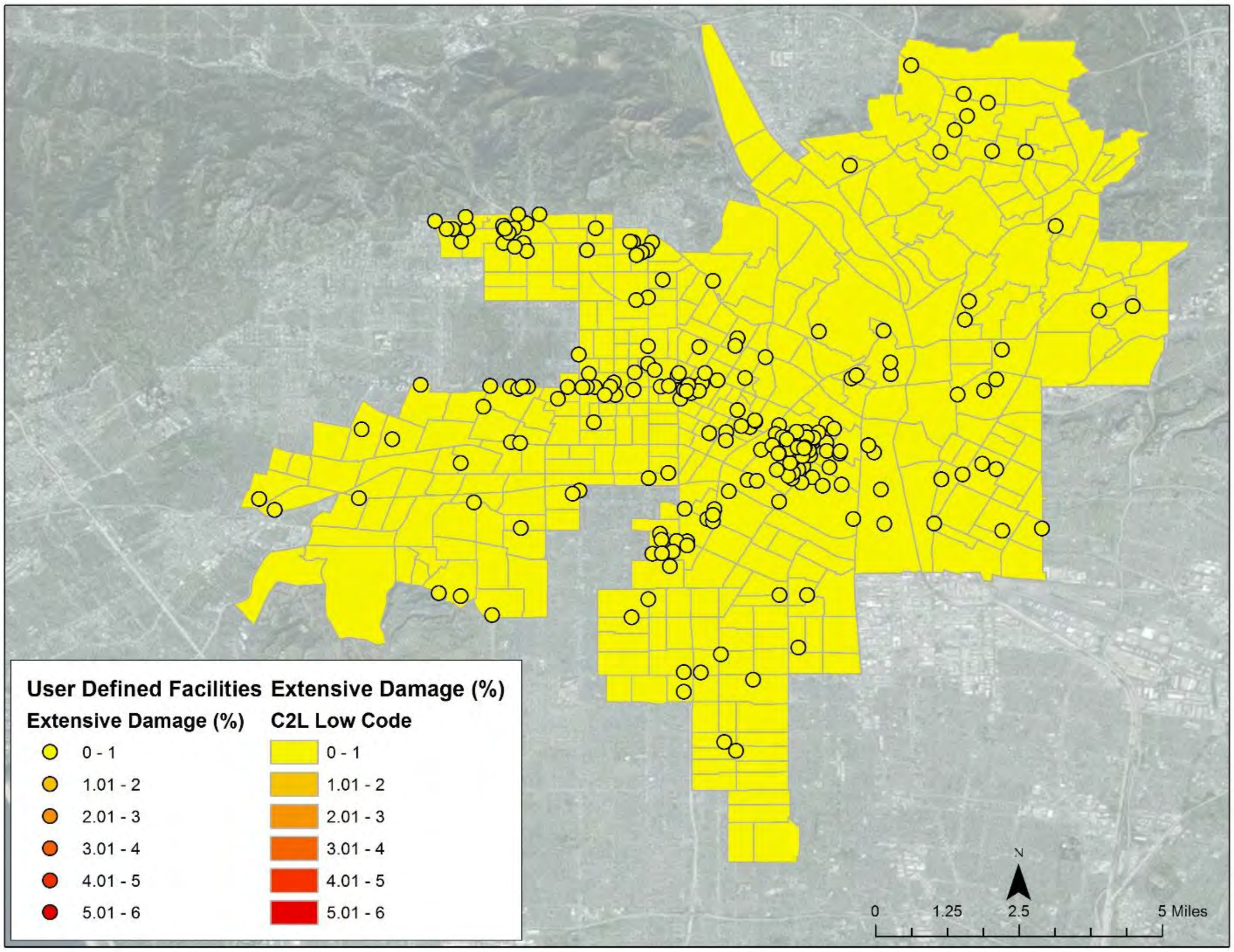

Figure 25: Extensive damage to user-defined facilities overlaid on the percent of extensive damage to low code C2L (shear wall concrete buildings with low seismic standards).

Figure 25 shows extensive damage percentages to user-defined facilities and C2L low code census tracts. These damages are all ≤ 1%.

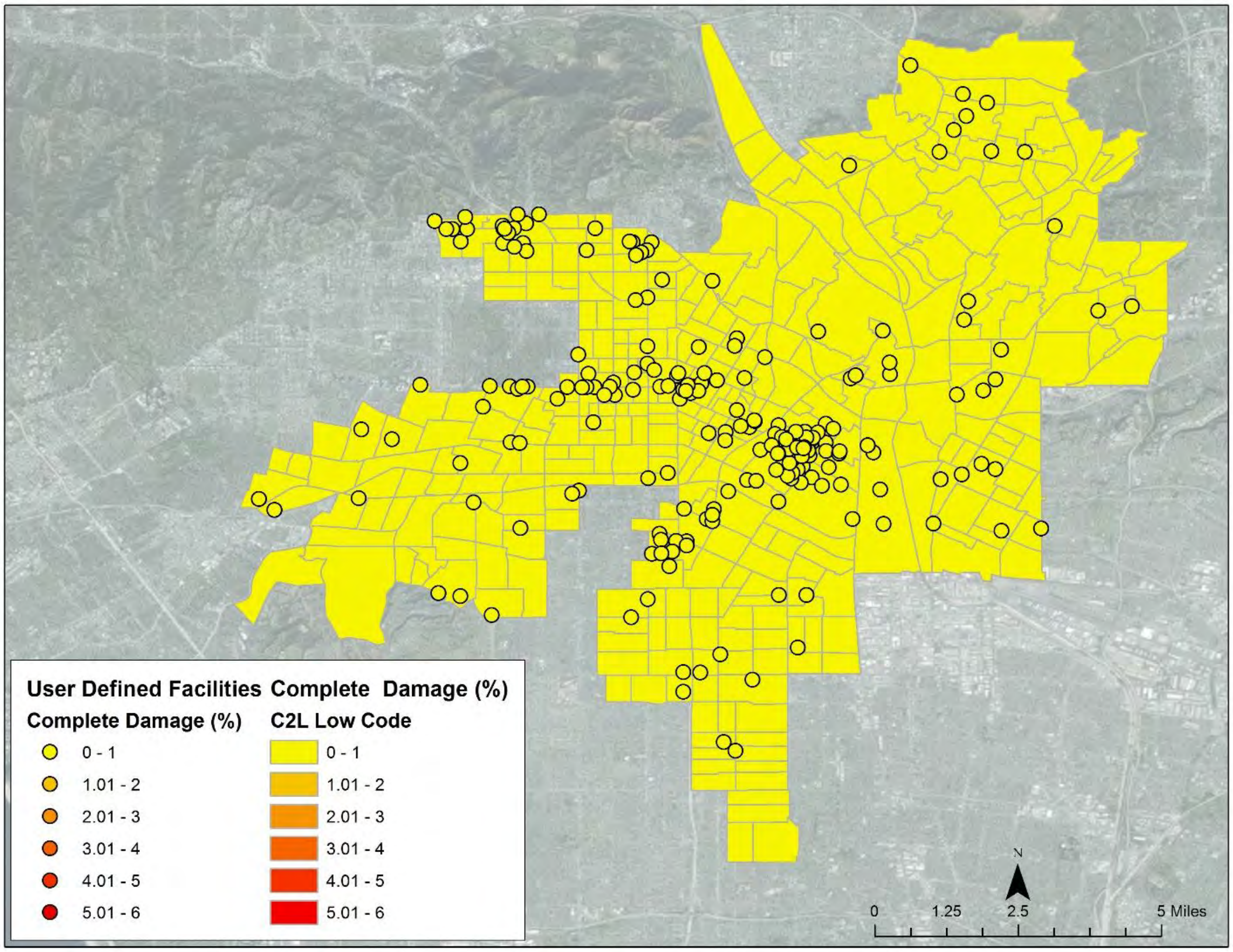

Figure 26: Complete damage to user-defined facilities overlaid on the percent of complete damage to low code C2L (shear wall concrete buildings with low seismic standards).

Complete damage results for user-defined facilities and C2L low code census tracts all exhibit ≤1% of damage (Figure 26).

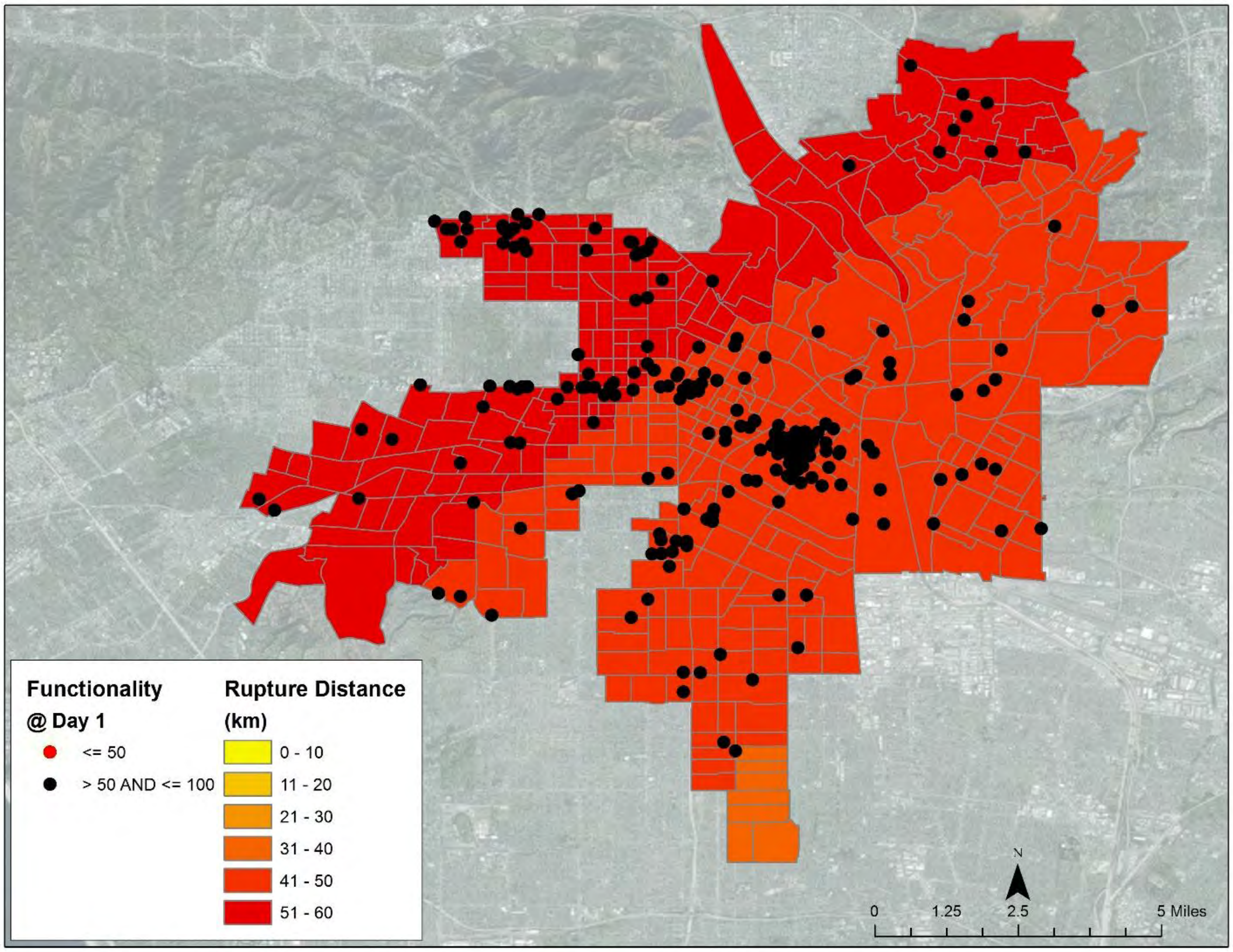

Figure 27: Functionality likelihood of user-defined facilities on day one overlaid on distance from rupture.

Analysis 3 – AEBM Analysis Utilizing Input Data Updates

The results of the AEBM analysis performed using manually prepared input data are displayed using map outputs and graphs. Economic loss is also analyzed through graph and map outputs for analysis 3. The AEBM portfolio building report for the 284 buildings analyzed shows moderate structural damage is predicted at 3.9%, extensive damage 0.61%, and complete damage would be 0.06%. Although these are still low probabilities of damage, they are much higher percentages in comparison to the results of analysis 1 and 2. Total building-structural damage is approximately $1.9 billion, and contents damage is $1.8 billion.

Table 7 shows the number of buildings that experienced specified levels of loss. Loss estimates are shown as classifications ranging from 1 to 6, where one is least severe, and six is most severe. A majority of structural loss, 93%, exhibit the least amount of loss. Most content loss falls under class 1 (65%) and class 2 (21%).

Table 7: Loss classifications for structural, content, and total losses.

	Loss Classifications											
	Least Severe		--								Most Severe	
	1		2		3		4		5		6	
	$0 - $20,000		$20,001 - $40,000		$40,001 - $60,000		$60,001 - $80,000		$80,001 - $100,000		≥ $100,001	
Structural Loss	231	93.1%	32	12.9%	12	4.8%	4	1.6%	3	1.2%	2	0.8%
Contents Loss	163	65.7%	33	13.3%	20	8.1%	7	2.8%	8	3.2%	53	21.4%
Total Loss	90	36.3%	64	25.8%	26	10.5%	14	5.6%	14	5.6%	76	30.6%

AEBM damages are shown against C2L pre-code and low code buildings in the following Figures. Moderate, extensive, and complete damage results for C2L pre-code structures with corresponding moderate, extensive, and complete AEBM damage results are shown in Figures 28-30. Similarly, damage results for C2L low code structures are shown in Figures 31-33.

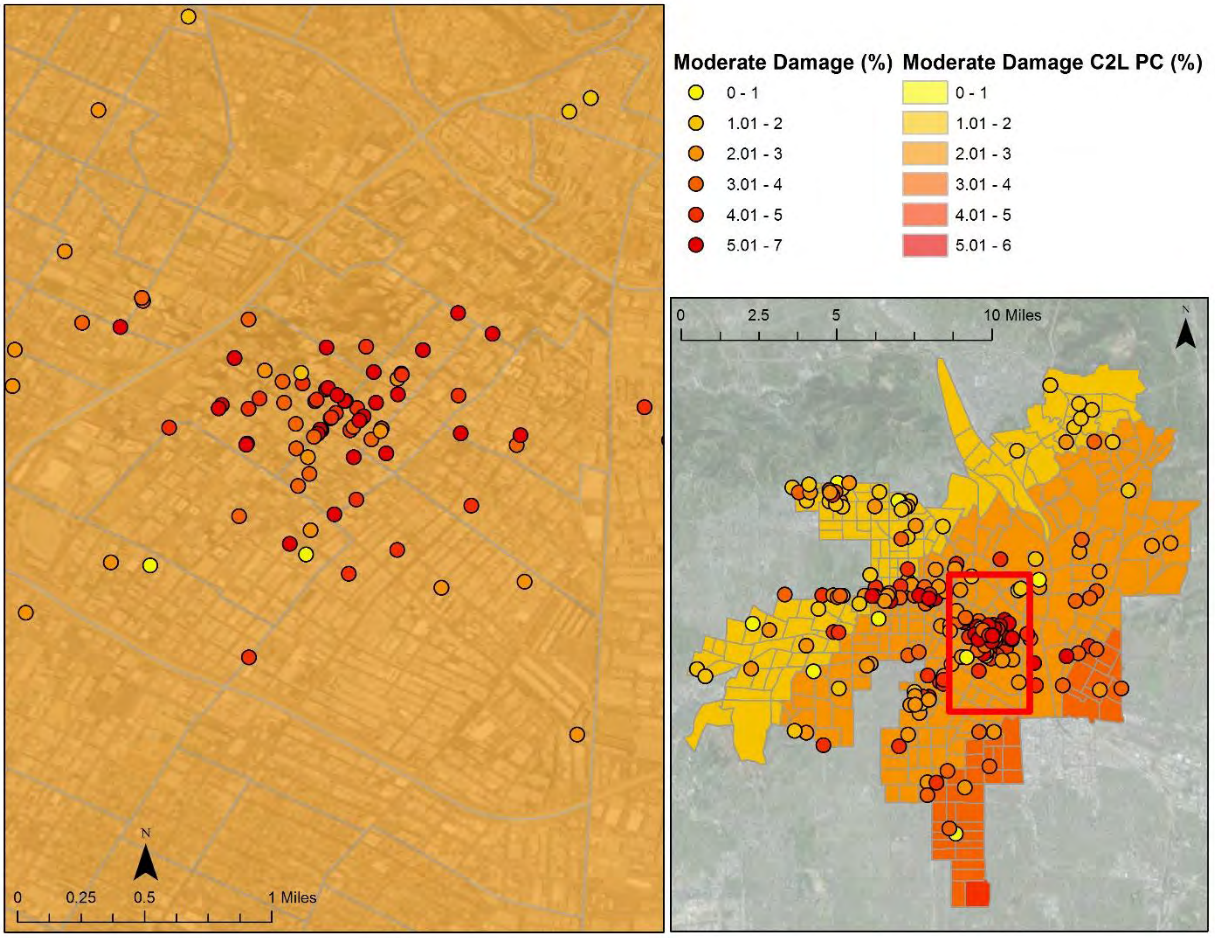

Figure 28: AEBM moderate damage shown as dots overlaid on the moderate damage of C2L pre-code structures (shear wall concrete buildings not designed to any seismic standard) by census tract.

Figure 28 shows that a majority of the buildings with higher damage fall within the center of the study area where census tract data damages range from 2%-3 % moderate damage. It is assumed that this is simply because there are a greater number of non-ductile buildings in the area, to begin with.

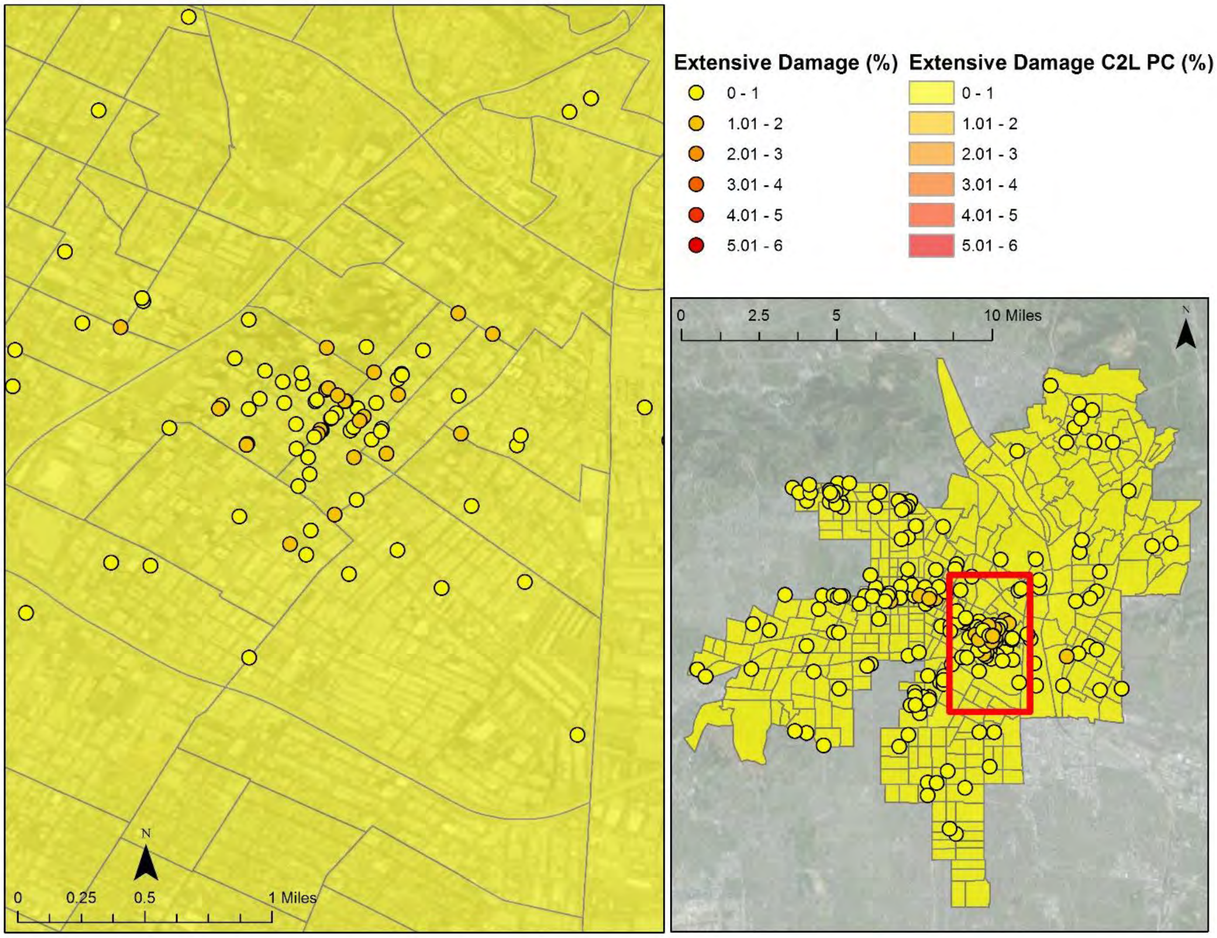

Figure 29: AEBM extensive damage shown as dots overlaid on extensive damage of C2L pre-code structures (shear wall concrete buildings not designed to any seismic standard) by census tract.

In the AEBM results, the estimates of extensive damage to structures appear to be less in terms of the number of building affected, compared to those which may experience moderate or low damage. The results indicate that the group of buildings in the center of the study area experience the most amount of damage (between 0%-2% extensive damage), and now the census tracts they spatially overlay show damage percentages between 0% - 1% (Figure 29).

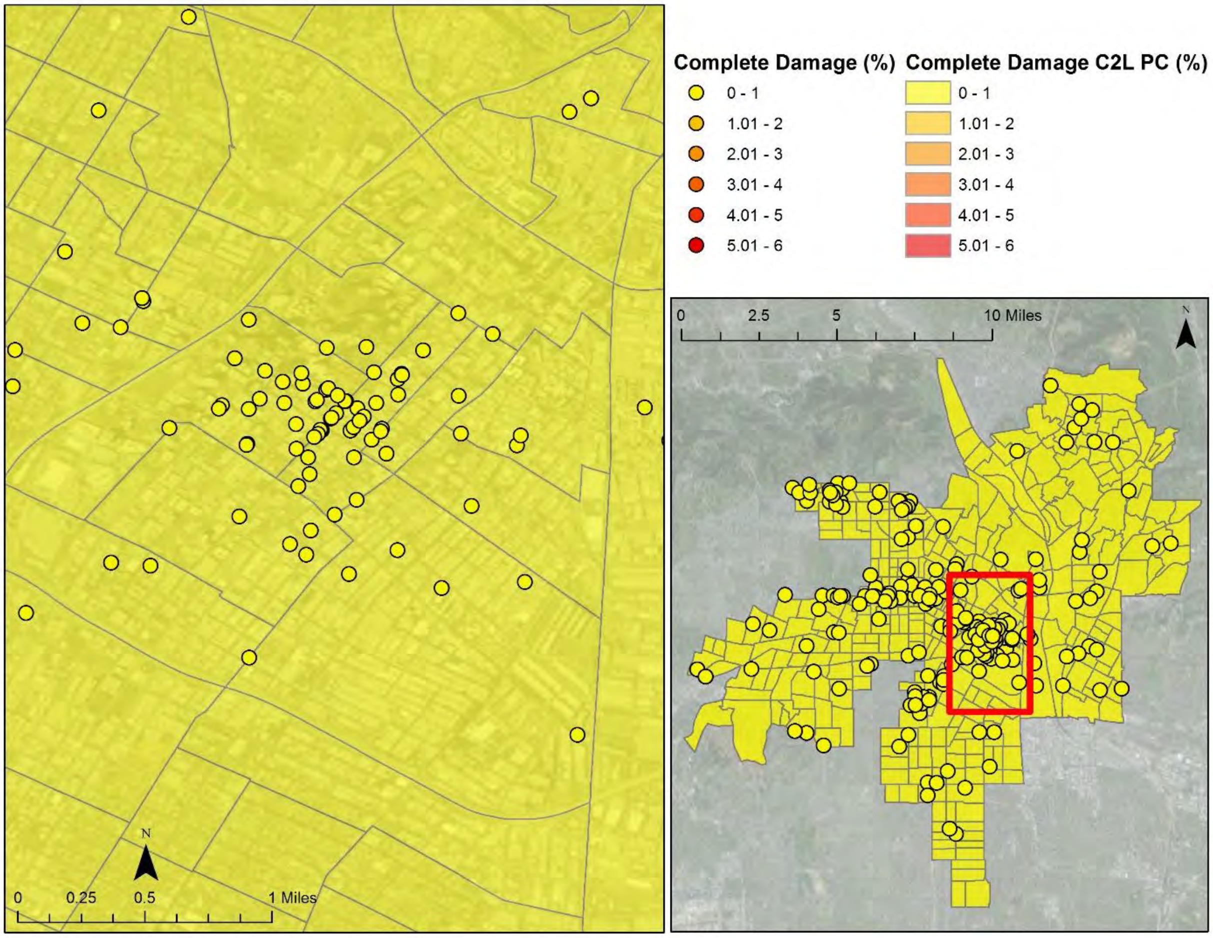

Figure 30: AEBM complete damage shown as dots overlaid on the complete damage of C2L pre-code structures (shear wall concrete buildings not designed to any seismic standard) by census tract.

Census tract damage estimates are also very low for complete damages. Most of the census tracts in the study area show 0%-1% of damage. The AEBM structures show the same damage estimates (0%-1%) as the census tracts (Figure 30).

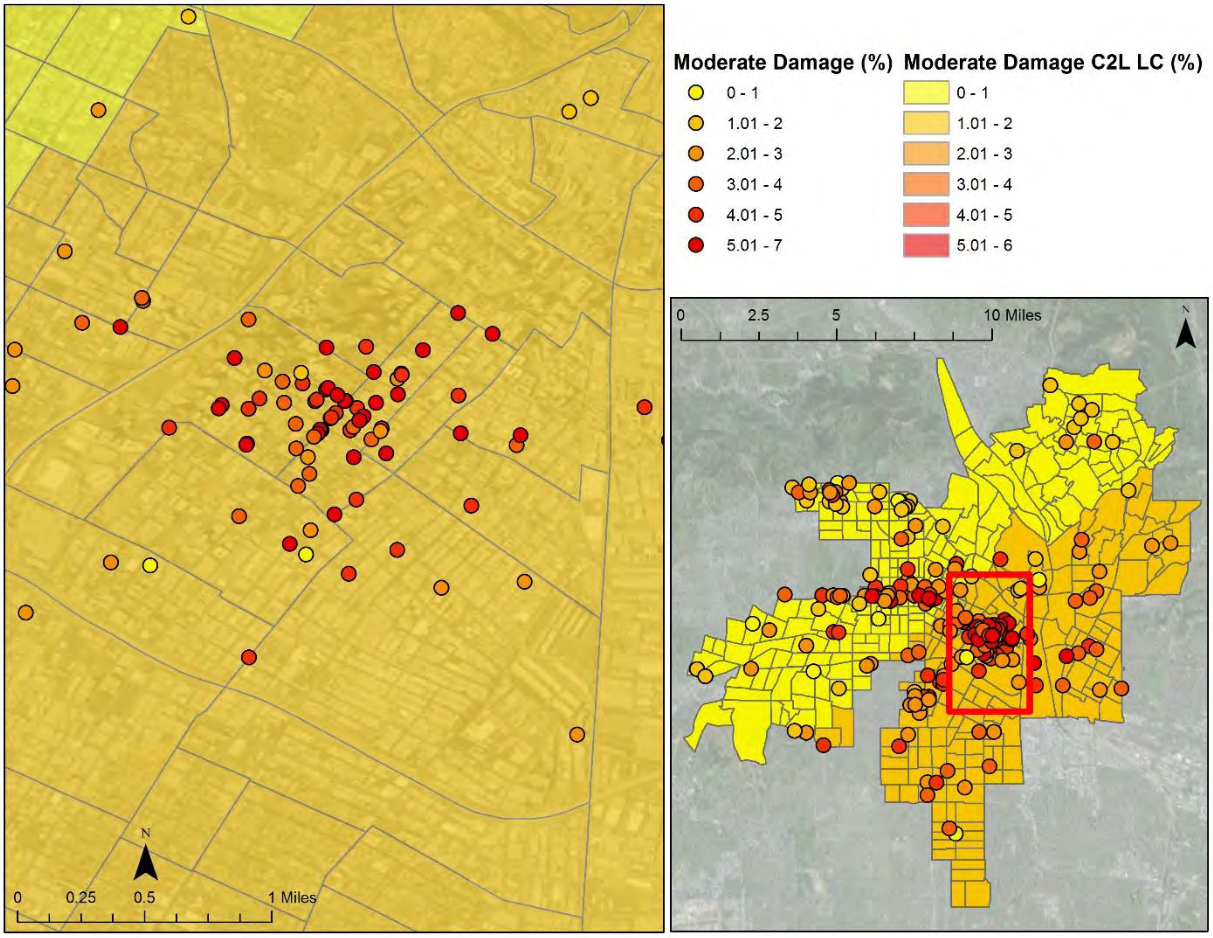

Figure 31: AEBM moderate damage shown as dots overlaid on moderate damage of C2L low-code structures (shear wall concrete buildings with low seismic standards) by census tract.

Similar to the C2L pre-code moderate damage results, the buildings that show higher predicted amounts of damage are in the center of the study area and are within census tracts that show a 1%-2% damage estimate. Figure 31 shows a strong difference in census tract results compared to AEBM results. A majority of AEBM results fall within the higher three classes (3%-4%, 4%-5%, and 5%-7% moderate damage), yet the underlying census tracts only show 0%-2% moderate damage.

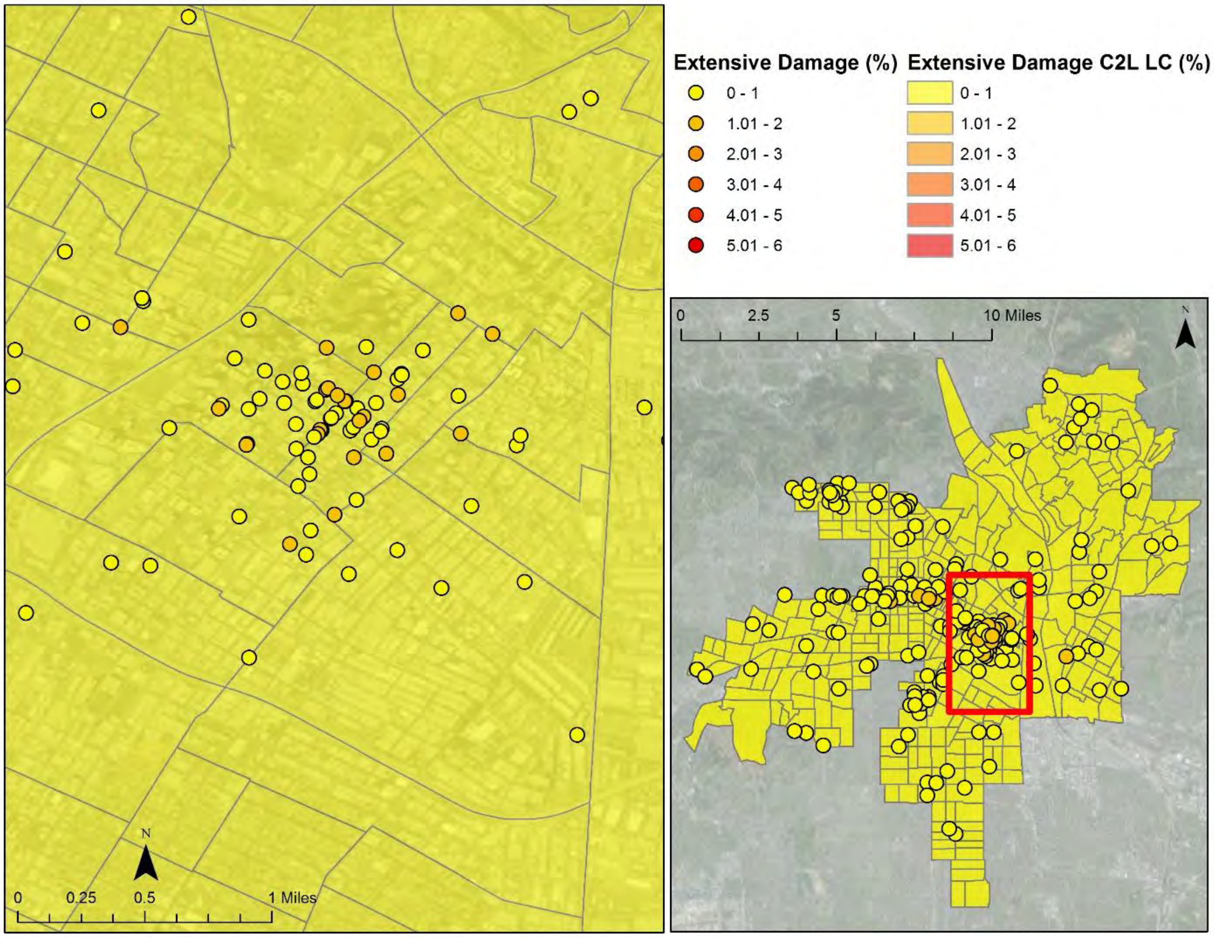

Figure 32: AEBM extensive damage shown as dots overlaid on the extensive damage to C2L low-code structures (shear wall concrete buildings with low seismic standards) by census tract.

Extensive AEBM damage estimates are significantly less in comparison to moderate AEBM damages. Many more buildings classify as having 0%-2% chance experiencing extensive amounts of damage. Damage classifications for census tracts also decrease. The buildings that within the 0%-1% moderate damage range are located within the dense cluster of buildings in the center of the study area (Figure 32).

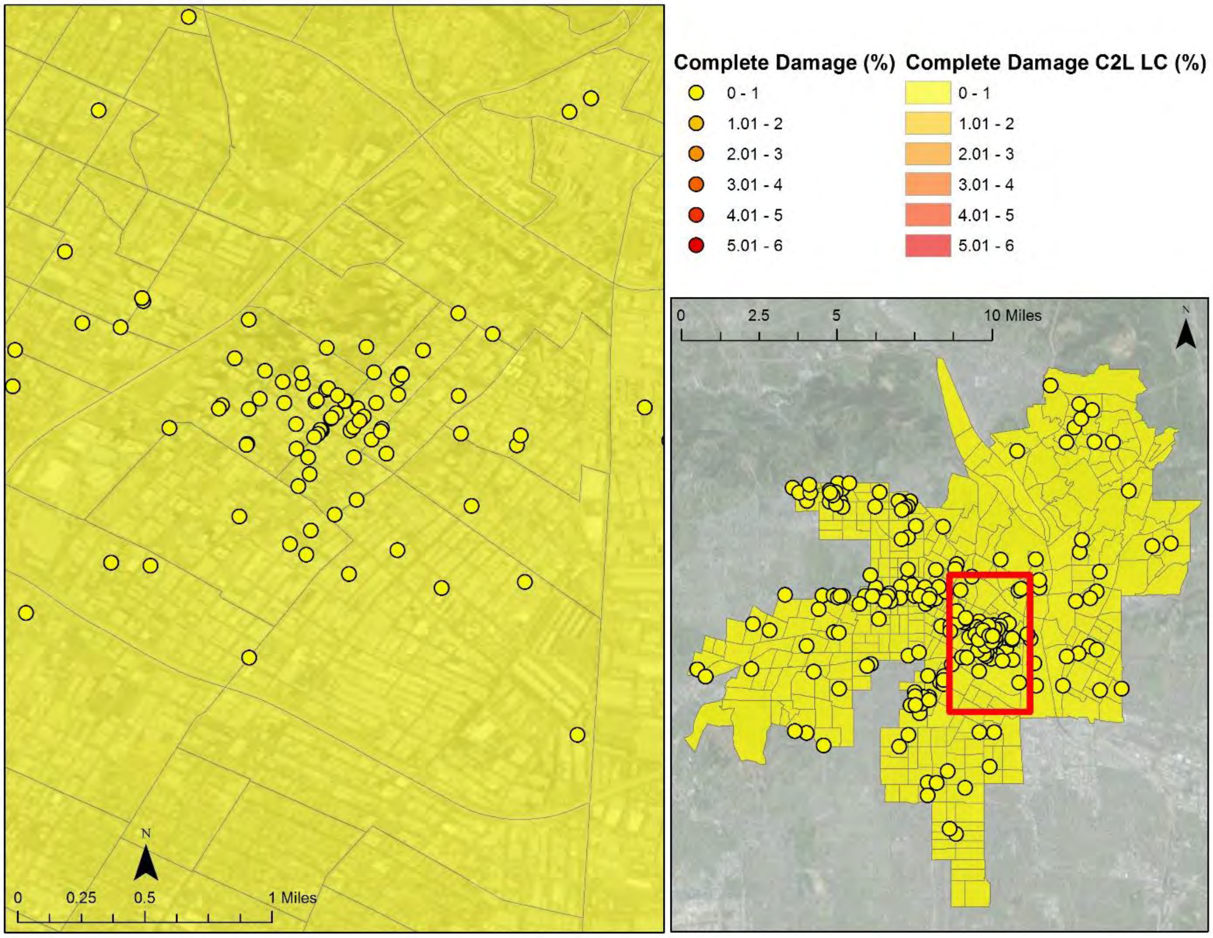

Figure 33: AEBM complete damage shown as dots overlaid on complete damage of C2L low-code structures (shear wall concrete buildings with low seismic standards) by census tract.

Census tract damage estimates are between 0%-1% for complete damages. The AEBM structures also show 0%-1% complete damage (Figure 33).

Figures 34, 35, and 36 show the number of buildings that experienced moderate, extensive, and complete damage. Damage probabilities comprise the x-axis and the number of buildings that experienced a certain amount of damage comprise the y-axis.

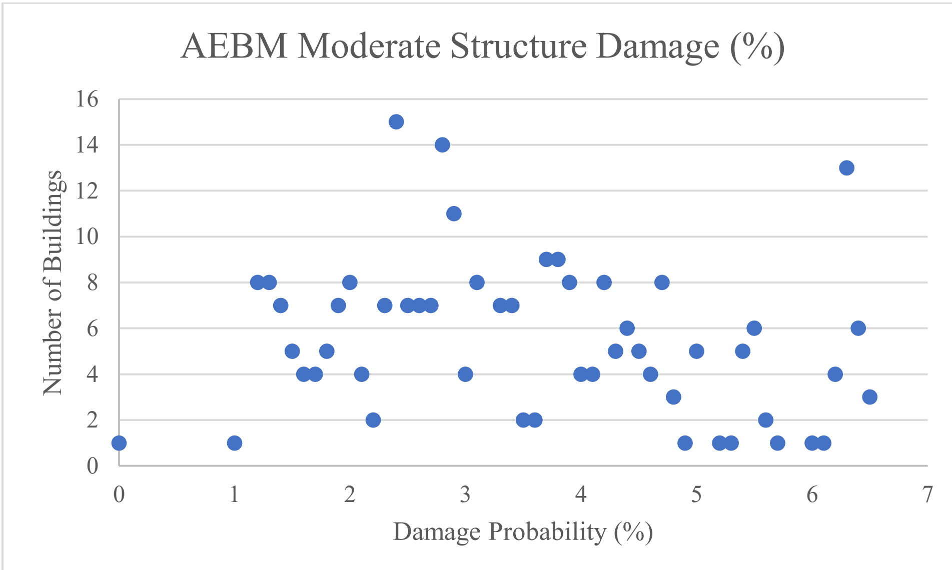

Figure 34: Number of buildings that experienced moderate structural damage.

Of the 284 AEBM structures that experienced moderate amounts of damage, 13 are predicted to experience 6.3% moderate damage, 14 showed 2.8% moderate damage, and 15 showed 2.4% moderate damage. More than 65% of the structures experienced less than 4% moderate damage (Figure 34).

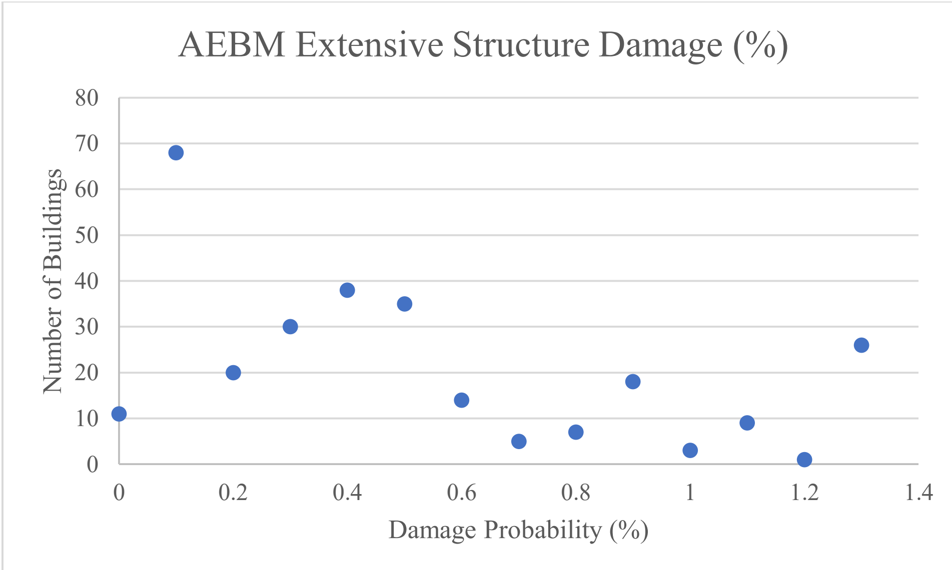

Figure 35: Number of buildings that experienced extensive structural damage.

Of the 284 AEBM structures, 68 (24% of the AEBM dataset) experienced only <1% extensive damage. More than 75% of the AEBM structures experienced less than 0.6% extensive damage (Figure 35).

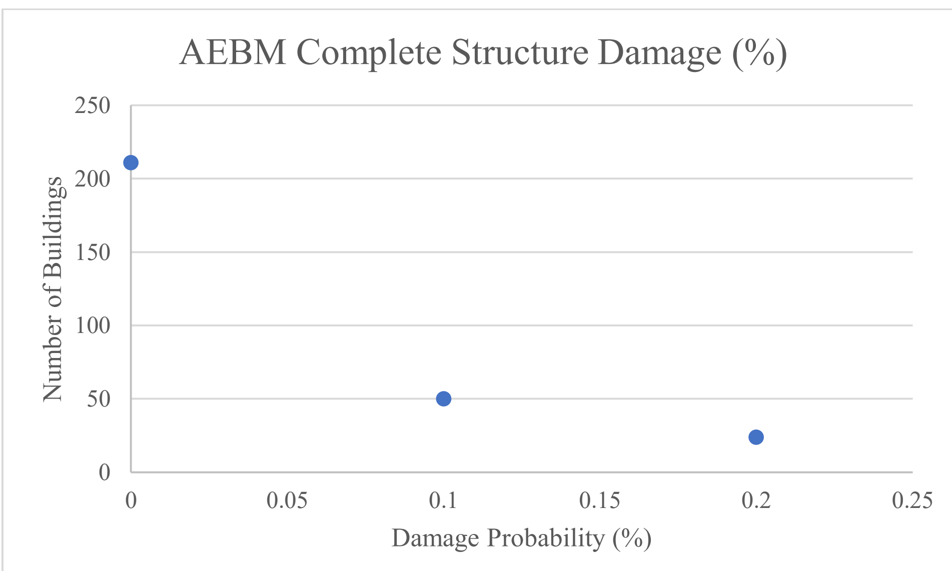

Figure 36: Number of buildings that experienced complete structural damage.

Damage results for complete damage to AEBM structures fell under three probabilities, 0%, 0.1%, and 0.2%. 74% of the structures showed no complete damage (Figure 36).

Table 8: Table showing how many tracts fall within each of the 5 city districts used in the study. Some tracts fall within two districts. This overlap caused the total area percent to be above 100. Because there is tract overlap, these values are approximated.

						Total
District	1	9	10	13	14	5
Number of buildings	50826	63435	70765	53707	78609	317342
Number of Non-ductile Concrete Buildings	40	25	47	61	111	284
Tracts	77	67	81	77	77	356
Population	269558	285205	304153	283510	294453	1436879
Percent of study area	21.63	18.82	22.75	21.63	21.63	106.46

Table 8 shows how many tracts fall within the five districts used in the study and what percent of the entire study area each district is. Some of the census tracts border two of the city districts so there is some overlap found in the total area percentage.

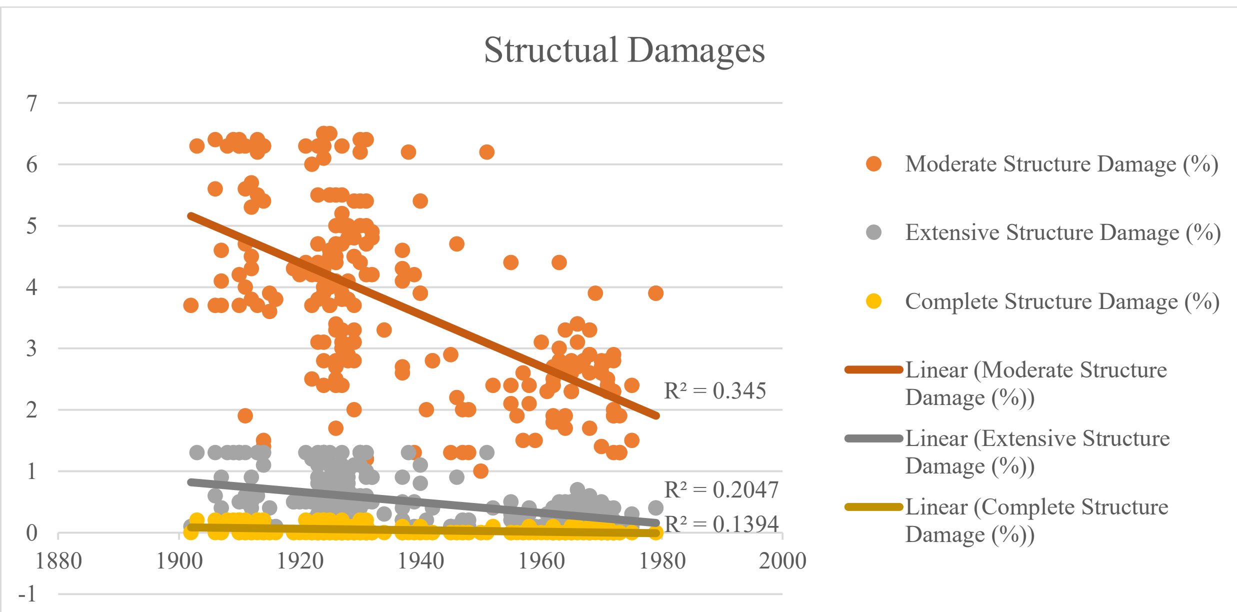

Figure 37: Structural damage percentage comparison by decade.

Figure 37 shows the differences in moderate, extensive, and complete damage percentages. Percentages are shown by year to provide an idea of how the age of the structure plays a role in the damage estimates. Structures built before 1940 show higher damage percentages for moderate and extensive damage results. Moderate and extensive results show a downward trend in damage rates as building age increases. This trend is more prominent in moderate damage results, but still noticeable in complete damage results. Complete damage results are all very low, but the data shows that structures built before 1940 also exhibit a slight increase in damage percentages.

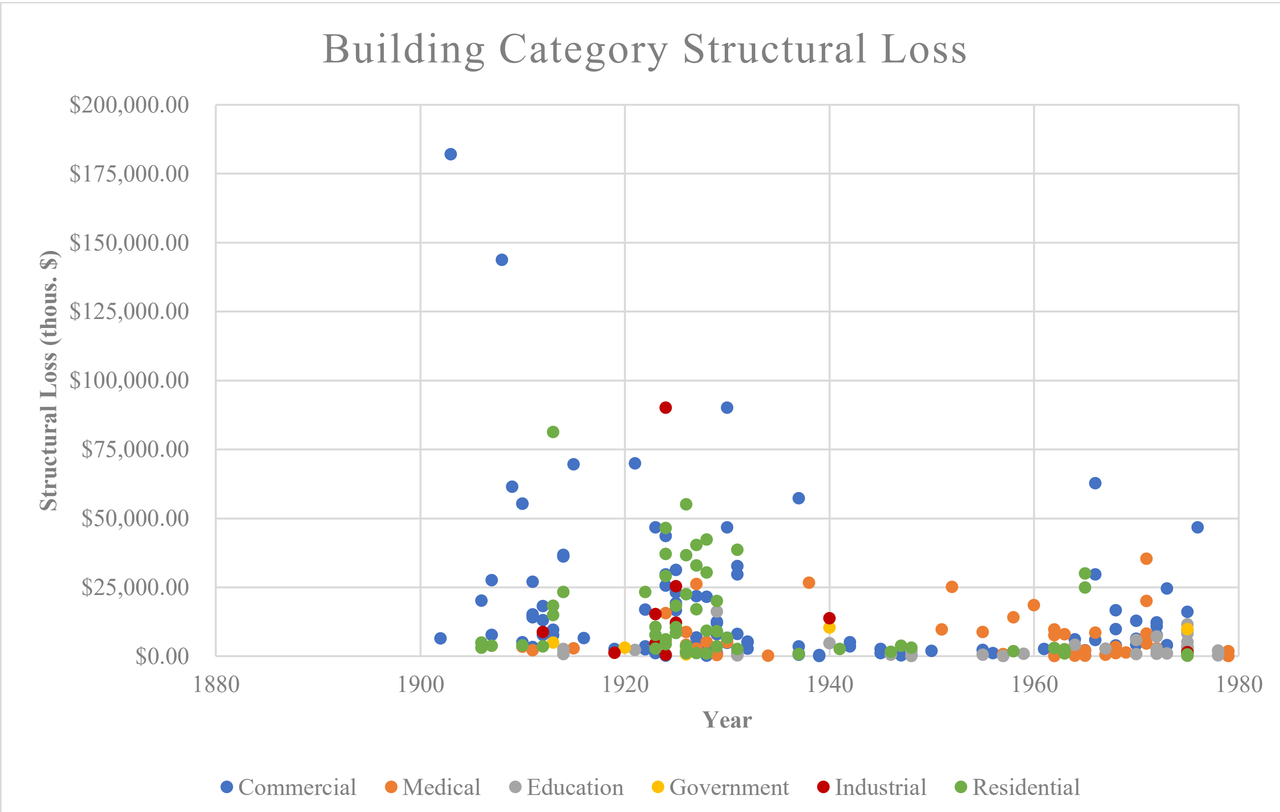

Figure 38: Structural loss in thousands by year for six building categories. Categories are explained in Table 2.

Figure 38 shows the structural loss for the AEMB buildings by year for each of the six building categories described in Table 2. Structures built before 1940 showed higher loss values than those built after 1940. The two structures exhibiting the highest potential for loss are commercial structures built in 1903 and 1908. Many of the structures built between 1920 and 1940 are residential. Educational buildings and medical facilities estimated lesser amounts of structural loss.

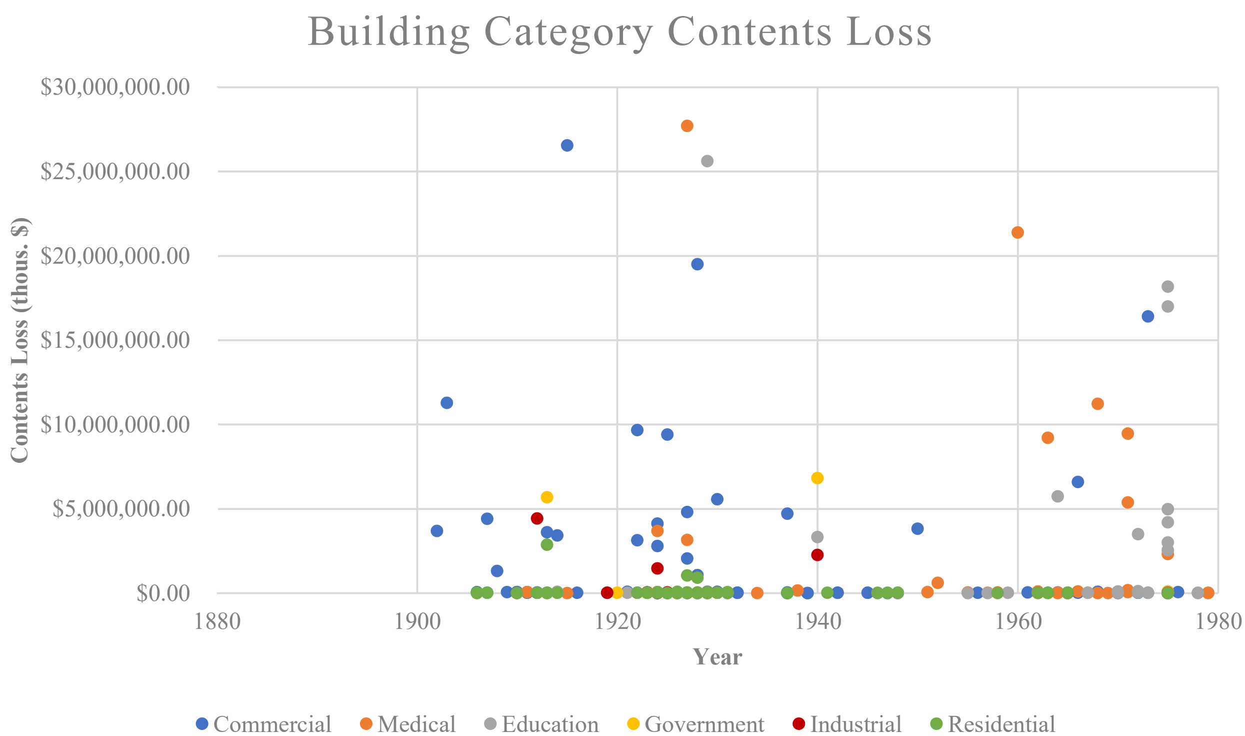

Figure 39: Contents loss in thousands by year for six building categories. Categories are explained in Table 2.

Figure 39 shows content value losses for the AEBM structures by building category. The three structures with the highest amount of content loss were built in 1915 (commercial), 1927 (medical), and 1929 (education). 17% of structures showed losses higher than $1,000,000. All residential buildings show less than $5,000,000,000. Of the 21 buildings that show more than $5,000,000,000 in contents loss, six are medical facilities.

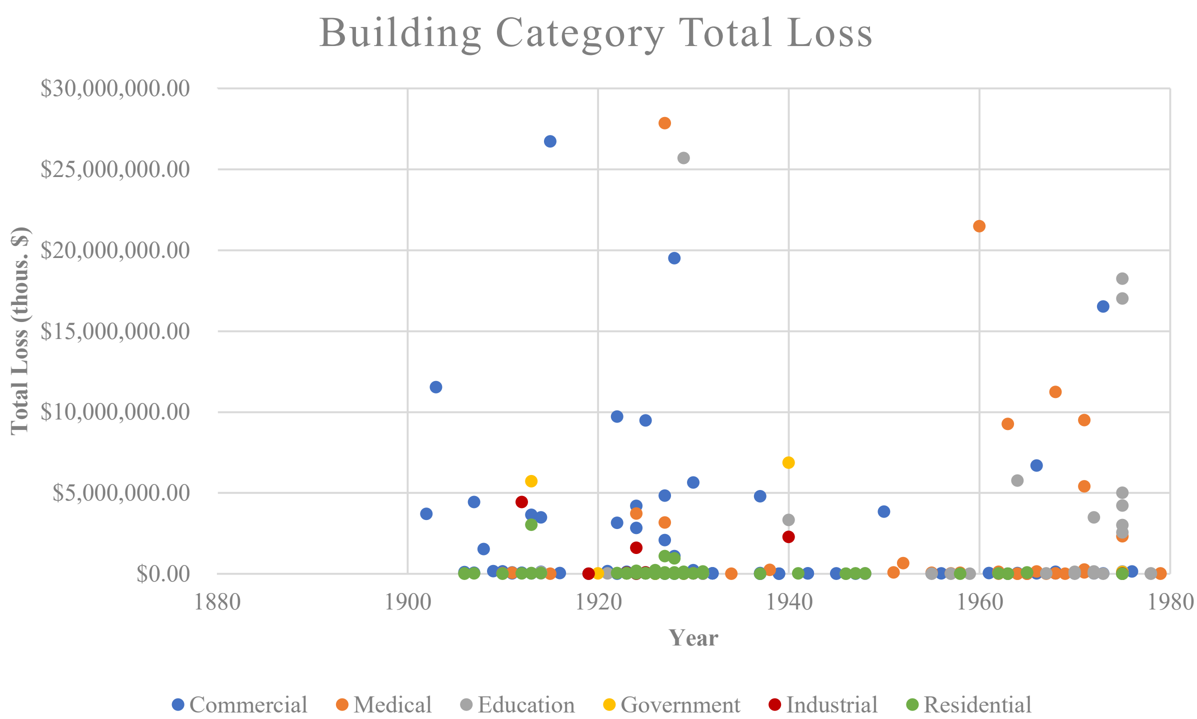

Figure 40: Total economic loss in thousands by year for six building categories. Categories are explained in Table 2.

Figure 40 shows the total economic loss for all AEBM structures by year for six building categories. Again, the three structures with the highest amount of total loss were built in 1915 (commercial), 1927 (medical), and 1929 (education). 17% of structures experienced losses higher than $1,000,000,000.00. The total value of loss for the 17% of structures is approximately $3.6 billion. Just as with the contents loss values estimates, of the 21 buildings that show more than $5,000,000 in contents loss, six are medical facilities.

Table 9: Overview of damages for the six classifications by decade for each level of damage. Bolded values are discussed further on page 61. Table 9 continues on page 60.

		Damage Classifications												
		Least Severe		--								Most Severe		
		1		2		3		4		5		6		Total
Damage	Moderate	0	0.0%	54	19.0%	79	27.8%	55	19.4%	51	18.0%	45	15.8%	284
	Extensive	247	87.0%	37	13.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	284
	Complete	284	100.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	284
Complete Damage by Decade	1810-1900	1	0.4%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	1
	1901-1910	15	5.3%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	15
	1911-1920	27	9.5%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	27
	1921-1930	86	30.3%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	86
	1931-1940	25	8.8%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	25
	1941-1950	14	4.9%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	14
	1951-1960	12	4.2%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	12
	1961-1970	38	13.4%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	38
	1971-1980	66	23.2%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	66
Total		284	100.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	284

		Damage Classifications												
		Least Severe		---								Most Severe		
		1		2		3		4		5		6		Total
Extensive Damage by Decade	1810-1900	0	0.00%	0	0.00%	0	0.00%	1	0.35%	0	0.00%	0	0.00%	1
	1901-1910	4	1.41%	2	0.70%	1	0.35%	1	0.35%	0	0.00%	7	2.46%	15
	1911-1920	8	2.82%	7	2.46%	4	1.41%	1	0.35%	1	0.35%	6	2.11%	27
	1921-1930	16	5.63%	23	8.10%	16	5.63%	12	4.23%	9	3.17%	10	3.52%	86
	1931-1940	9	3.17%	6	2.11%	2	0.70%	5	1.76%	1	0.35%	2	0.70%	25
	1941-1950	11	3.87%	2	0.70%	0	0.00%	1	0.35%	0	0.00%	0	0.00%	14
	1951-1960	7	2.46%	4	1.41%	0	0.00%	0	0.00%	0	0.00%	1	0.35%	12
	1961-1970	15	5.28%	17	5.99%	6	2.11%	0	0.00%	0	0.00%	0	0.00%	38
	1971-1980	40	14.08%	22	7.75%	4	1.41%	0	0.00%	0	0.00%	0	0.00%	66
	Total	110	38.73%	83	29.23%	33	11.62%	21	7.39%	11	3.87%	26	9.15%	284
Moderate Damage by Decade	1810-1900	0	0.00%	0	0.00%	0	0.00%	0	0.00%	1	0.35%	0	0.00%	1
	1901-1910	0	0.00%	0	0.00%	0	0.00%	6	2.11%	1	0.35%	8	2.82%	15
	1911-1920	0	0.00%	4	1.41%	0	0.00%	10	3.52%	5	1.76%	8	2.82%	27
	1921-1930	0	0.00%	3	1.06%	21	7.39%	26	9.15%	22	7.75%	14	4.93%	86
	1931-1940	0	0.00%	6	2.11%	3	1.06%	7	2.46%	7	2.46%	2	0.70%	25
	1941-1950	1	0.35%	9	3.17%	3	1.06%	0	0.00%	1	0.35%	0	0.00%	14
	1951-1960	0	0.00%	5	1.76%	5	1.76%	1	0.35%	0	0.00%	1	0.35%	12
	1961-1970	0	0.00%	7	2.46%	25	8.80%	6	2.11%	0	0.00%	0	0.00%	38
	1971-1980	1	0.35%	27	9.51%	26	9.15%	12	4.23%	0	0.00%	0	0.00%	66
	Total	2	0.70%	61	21.48%	83	29.23%	68	23.94%	37	13.03%	33	11.62%	284

Table 9 outlines the amount of damage within each of the six classifications for moderate, extensive, and complete damage. Bolded values are discussed in this section. For each of the classifications, results show the number of buildings that displayed that particular amount of damage, and what percentage of the total dataset the amount of buildings is. The first three rows show the number of buildings by damage classification (moderate, extensive, and complete). Class 1 damage is the least amount of damage and class 6 is the highest amount of damage. About 27% of moderate damage is considered class 3. 87% of extensive damage classify as class 1 and complete damage results show that 100% fall under class 1. When analyzing the buildings by decade, class 1 was the only damage class for complete damages, with 1921-1930 having the highest damage percentages (30%). The Extensive damage analysis shows that buildings only experienced class 1 or class 2 damage. Two hundred forty-seven buildings, or 87%, of the AEBM buildings showed class 1 extensive damage. Moderate damage results show that roughly 28% of buildings experienced class 3 amounts of damages. Ten percent of structures built between 1921 and 1930 indicate class 5 damage, and 10% of the structures built between 1971 and 1980 might experience class 3 damage.

Chapter 5 Discussion and Conclusions

The ultimate goal of this study was to examine how HAZUS-MH results improved with the addition of independent datasets, and to find if there are any areas of Los Angeles or specific buildings of high concern based on the results. This Chapter summarizes the results presented in Chapter 4 and provides conclusions. Following the conclusions, limitations and future work are discussed.

Discussion

Analysis 1

When evaluating the results of the 1933 Long Beach earthquake scenario, only C2L pre-code and low code buildings results were output by HAZUS. There are six building types found within the AEBM dataset, but internal HAZUS-MH data did not include records for any buildings classified as C2H, C2M, C3H, C3M, or C3L building types. The HAZUS-MH User's Manual does warn that the data within HAZUS-MH is incomplete, and the results of these analyses prove that there is indeed a large gap in the concrete buildings dataset that comes standard in HAZUS-MH. For the first analysis, damage percentage results fall between 3% and 5% for pre-code and 0%-3% for low code structures. Damage percentages are higher in the areas that are closer to the epicenter of the earthquake. As you move further from the epicenter, damage results decrease. Extensive and complete damage results do not exceed 1%; structures built to C2L low code are predicted to have a 0 percent chance of complete damage throughout the study area.

Analysis 2

Damage results for analysis 2 show a similar trend to analysis 1 with damage percentages being higher the closer the area is to the epicenter of the earthquake. The user-defined facilities also share this trend, however it is important to note the difference in scale when examining the results for these two datasets. Although they show to have similar results, the damage percentages for C2L pre-code and low code buildings are at a census tract level causing some aggregation and scale effects. This is most apparent in the moderate damage results. Both datasets are classified using the same number of categories, but results do not completely match up because of the differences in scale.

The damage percentages for the user-defined facilities is smaller in buildings further away from the earthquake epicenter. Moderate damage results for user-defined facilities with pre-code (Figure 21) and low code (Figure 24) buildings show more range in damage percentages for AEBM results and census tract results than extensive (Figure 22 & 25) and complete (Figure 23 & 26) damage results. Moderate user-defined facilities damages were as high as 6%, but no results for extensive or complete damages exceeded 1%. The census tract results for analysis 2 show a slight change in comparison to analysis 1. There are several more census tracts in analysis 2 that show higher probabilities of damage compared to analysis 1. This increase in accuracy supports that adding in local data could allow for more accurate results.

Analysis 3

Since the AEBM incorporates more specific data than the user-defined facilities, the AEBM results show an increase in accuracy among the building point data compared to analysis 2. The buildings in the AEBM do not show the same pattern as the user-defined facilities. Because they can be analyzed individually, there is a mixture of damage results amongst the AEBM structures.

The AEBM results do show that buildings further away from the rupture mostly show very little to no damage, but the trend is not as strong as it was in analysis 2 results. The group of buildings in the downtown area of LA show to have the majority of buildings with a high chance of experiencing damage.

AEBM results for moderate damage to non-ductile concrete buildings and C2L pre-code (Figure 28) and low code (Figure 31) buildings show that the buildings that experienced the most damage are in the center of the study area. There are very few AEBM structures that show 0%-1% moderate damage, but they are not concentrated in any part of the study area. AEBM results of extensive damage to non-ductile concrete buildings and C2L pre-code and low code buildings showed the same group of buildings in the center of the study area experienced the most amounts of damage. Complete damage results for the AEBM and C2L pre-code and low code buildings show very small damage estimates across the whole study area. The surrounding building shows 0%-1% of complete damage experienced. This corresponds to the choropleth map which shows most of the area experiencing 0%-1% complete damage.

Although the damage percentages for analysis 3 are more accurate, none of the probabilities are larger than 50% for moderate, extensive, or complete damage; this study defines buildings with damages ≥50% as high risk. Because of this very small percentage of damage, there are no areas or specific buildings that are considered high risk. While there are no buildings or areas of concern for this study, this does not mean that all the buildings in this analysis are completely safe. A stronger and closer event could cause significate damage to these buildings.

Regardless of the damage percentages, this area still had a significant amount of damage in terms of structural and contents loss. Economic losses were upwards of $100,000,000 for both structural damages and contents value losses.

Limitations

Limitations of this project were with the AEBM, the hazard scenario wizard, and in presenting the results. The AEBM was often temperamental when it came to getting data to upload and save properly in the AEBM Profiles and Inventories. Although the SQL Manager could be used to fix problems, some information would have to be entered several times before it would save properly and display in HAZUS-MH. When setting the parameters for the 1933 Long Beach earthquake, all were true to the original event except for the depth of the hypocenter of the earthquake. The actual depth of the hypocenter is 13km, however, the current version of HAZUS-MH locked the field at 10km so it could not change. The last limitation was with how results are displayed. When displaying AEBM and user-defined facilities results, all buildings entered into these databases were displayed together based on the amount of damage. Results cannot be displayed based on a specific building type or code. This was a slight problem when comparing the AEBM results and user-defined facilities results to the census tract results. The two different outputs could be compared based on the percentage of damage overall, but a precise comparison of the building types could not be evaluated.

Future Work

Moving forward with this study, there are a three topics that should be considered. First, the study area should be increased to be able to include all 1454 non-ductile concrete buildings in the original dataset. This will allow for a better understanding of the total distribution of non-ductile concrete buildings in the entire LAC, and the total damage in dollars LAC might be faced with following a large event. Another topic to be considered is the inclusion of casualties, debris, and fire flow following a similar large event. The non-ductile concrete building dataset did include the number of people within each building during the day and at night, but it was left out of this study in order to focus on building damages. Casualties and injuries are generally unavoidable in a large seismic event, and knowing how many there may be would help in mitigation planning. Lastly, future studies should consider a larger seismic event, or an event likely to occur on an active surface or subsurface fault closer to the downtown area. Analyzing a stronger event would indicate if these buildings might experience a large amount of damage if the same or similar event were to occur closer to the center of the county.

HAZUS Appendix B. Classification Systems

Table B.1 Site Classes
(from the 1997 *NEHRP Provisions*)

Site Class	Site Class Description	Shear Wave Velocity (m/sec)	
		Minimum	Maximum
A	HARD ROCK Eastern United States sites only	1500	
B	ROCK	760	1500
C	VERY DENSE SOIL AND SOFT ROCK Untrained shear strength us > 2000 psf (us > 100 kPa) or N > 50 blows/ft	360	760
D	STIFF SOILS Stiff soil with undrained shear strength 1000 psf < us < 2000 psf (50 kPa < us < 100 kPa) or 15 < N < 50 blows/ft	180	360
E	SOFT SOILS Profile with more than 10 ft (3 m) of soft clay defined as soil with plasticity index PI > 20, moisture content w > 40% and undrained shear strength us < 1000 psf (50 kPa) (N < 15 blows/ft)		180
F	SOILS REQUIRING SITE SPECIFIC EVALUATIONS 1. Soils vulnerable to potential failure or collapse under seismic loading: e.g. liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. 2. Peats and/or highly organic clays (10 ft (3 m) or thicker layer) 3. Very high plasticity clays: (25 ft (8 m) or thicker layer with plasticity index >75) 4. Very thick soft/medium stiff clays: (120 ft (36 m) or thicker layer)		

References

Alquist, Alfred E. 2007. “The field act and public school construction: A 2007 perspective.” *State of California Seismic Safety Commission* (February) 1-16. Accessed April 2, 2016 <http://www.seismic.ca.gov/pub/CSSC_2007-03_Field_Act_Report.pdf>

Anagnos, T., M.C. Comerio, C. Goulet, H. Na, J. Steele, and J.P. Stewart. 2008. “Los Angeles inventory of non-ductile concrete buildings for analysis of seismic collapse risk hazards.” Proceedings of the fourteenth World Conference on Earthquake Engineering, Beijing, China.

Ballmann, Jason. 2015. “SCEC leads great shakout earthquake drills worldwide.” *Southern California Earthquake Center* (August) Accessed September

Bolstad, P. 2012. *GIS Fundamentals: A First Text on Geographic Information Systems,* 4th edition. White Bear Lake, MN, Elder Press

Britannica Academic. 2015. "Northridge earthquake of 1994." *Encyclopaedia Britannica*. Accessed September 15, 2015. <http://academic.eb.com/EBchecked/topic/1138712/Northridge-earthquake-of-1994>.

Buriks, Carla, William Bohn, Milagros Kennett, Lisa Scola, and Bogdan Srdanovic. 2004. “HAZUS-MH Risk Assessment and User Group Series: Using HAZUS-MH for Risk Assessment.” *The Federal Emergency Management Agency* (August) 1-226. Accessed September 10, 2015 <http://www.fema.gov/media-library-data/20130726-1530-20490-5739/fema433.pdf>

Comerio, M.C., T. Anagnos. 2012. “Los Angeles inventory: implications for retrofit policies for non-ductile concrete buildings.” Proceedings of the fifteenth World Conference on Earthquake Engineering, Lisbon, Portugal.

Cova, Thomas J. 1999. "GIS in emergency management." *Geographical Information Systems 2* 845-858.

Earthquake Hazards Program. 2014. “National Strong Motion Project.” United States Geological Survey. Accessed November 2, 2015 <http://earthquake.usgs.gov/monitoring/nsmp/>

Federal Emergency Management Agency (FEMA). 2013. “Appendix F: HAZUS-MH data dictionary.” Federal Emergency Management Agency

Federal Emergency Management Agency (FEMA). 2015a. “Earthquake loss estimation methodology: Hazus-MH 2.1 advanced engineering building module technical and user’s manual.” Mitigation Division (January) 1-121.

Federal Emergency Management Agency (FEMA). 2015b. “Multi-hazard loss estimation methodology: Earthquake model Hazus-MH 2.1 technical manual.” Mitigation Division (January) 1-718.

Federal Emergency Management Agency (FEMA). 2015c. "Multi-hazard loss estimation methodology: Earthquake model Hazus-MH 2.1 user manual." Mitigation Division (January) 1-863.

Field, E.H., G.P. Biasi, P. Bird, T.E. Dawson, K.R. Felzer, D.D. Jackson, K.M. Johnson, T.H. Jordan, C. Madden, A.J. Michael, K.R. Milner, M.T. Page, T. Parsons, P.M. Powers, B.E. Shaw, W.R. Thatcher, R.J. II Weldon , and Y. Zeng. 2013. Uniform California earthquake rupture forecast, version 3 (UCERF3)—The time-independent model: U.S. Geological Survey Open-File Report 2013–1165, 97 p., California Geological Survey Special Report 228, and Southern California Earthquake Center Publication 1792, http://pubs.usgs.gov/of/2013/1165/.

Godschalk, D. R. 1991. "Disaster mitigation and hazard management." *Drabek T E, Hoetmer G J (eds) Emergency management: principles and practice for local government*. Washington DC, International City Management Association: 131–60.

Institute for Crustal Studies. 2014. "Outreach – Frequently Asked Questions." University of California at Santa Barbara. Accessed November 9, 2015 <http://www.crustal.ucsb.edu/outreach/faq.php>

Johnson, Russ. 2000. "GIS technology for disasters and emergency management." *ESRI White Paper* J8474 (May): 1-6.

Jones, Lucile M. and Mark Benthien. 2011. "Putting down roots in earthquake country." *Southern California Earthquake Center* Fall edition: 1-32.

Kircher, Charles A., Rovert V. Whitman, and William T. Holmes. 2006. "HAZUS earthquake loss estimation methods." *Natural Hazards Review* no. 7 (May): 45-59.

Lam, S., J. Swift, and J. P. Wilson. 2007. "A Digital Soil map for the Green Visions Plan for 21st Century Southern California Study Area." Los Angeles, California: University of Southern California GIS Research Laboratory Technical Report No. 5, 58 pages. Los Angeles County Department of Public Works. 2006. "Hydrology Manual." Water Resources Division (January): 1-432.

Los Angeles City Bureau of Engineering. 2013. LA City Council Districts (2012). City of Los Angeles < http://egis3.lacounty.gov/dataportal/2012/08/07/la-city-council-districts-2012/>

Los Angeles Tourism and Convention Board. 2015. "Los Angeles Tourism Statistics 2014." *Los Angeles Tourism and Convention Board* (August). Accessed September 15, 2015 <www.discoverlosangeles.com/tourism/research>

Neighbors, C.J., E.S. Cochran, Y. Caras, and G.R. Noriega. 2013. “Sensitivity analysis of FEMA HAZUS earthquake model: case study from King County, Washington.” *Natural Hazards Review* 14 (May) 134-146.

O’Sullivan, David and David J. Unwin. 2010. Geographic Information Analysis, 2nd Edition. New York: John Wiley & Sons.

Olsen, K.B., S.M. Day, J.B. Minster, Y. Cui, A. Chourasia, M. Faerman, R. Moore, P. Maechling, and T. Jordan. 2006. “Strong shaking in Los Angeles expected from southern San Andreas earthquake.” *Geophysical Research Letters* 33 (April): 1-4. Accessed September 10, 2015, doi: 10.1029/2005GL025472.

Ploeger, S.K., G.M. Atkinson, and C. Samson. 2010. Applying the HAZUS-MH software tool to assess seismic risk in downtown Ottawa, Canada. *Natural Hazards* 53 (May) 1-20.

Porter, Keith, Lucile Jones, Dale Cox, James Goltz, Ken Hudnut, Dennis Mileti, Sue Perry, Daniel Ponti, Michael Reichle, Adam Z. Rose, Charles Scawthorn, Hope A. Seligson, Kimberly I. Shoaf, Jerry Treiman, and Anne Wein. 2011. "The ShakeOut Scenario: A Hypothetical Mw7.8 Earthquake on the Southern San Andreas Fault" *Earthquake Specra* vol. 27, no. 2 (May) 2 239-261. Accessed September 10, 2015 <http://research.create.usc.edu/published_papers/189>

Seymour, Emmett, Marjorie Greene, Thalia Anagnos, & Craig Comartin. 2009. “Inventory of non-ductile concrete buildings in high seismic risk areas of California.” *Pacific Earthquake Engineering Research (PEER)* 1-16.

Swift, Jennifer, John Wilson, and Toan Nguyen Le. 2012. “Estimated temporal variation of losses due to a recurrence of the 1933 Long Beach Earthquake.” *Earthquake Specra* vol. 28, no. 1 (February) 347-365. Accessed March 21, 2016

University of Southampton. 2016. "The Modifiable Areal Unit Problem." National Centre for Research Methods. Accessed May 27, 2016 <http://www.restore.ac.uk/geo-refer/91023cwors00y00000000.php>

U.S. Department of Commerce. 2010. TIGER/Line Shapefile, 2010, Los Angeles County, CA, 2010 Census - Census Tract County-based vector digital data. *United States Census Bureau*, Geography Division <http://www.census.gov/geo/www/tiger>

U.S. Department of Commerce. 2015. “State and Country Quick Facts.” *United States Census Bureau*. Accessed September 15, 2015 <www.census.gov/quickfacts/>

U.S. Department of the Interior. 2016. “Historic earthquake – Long Beach, California.” Accessed March 24, 2016, from U.S. Geological Survey web site: http://earthquake.usgs.gov/earthquakes/states/events/1933_03_11.php.

U.S. Geological Survey. 2006. Quaternary fault and fold database for the United States. Accessed September 15, 2015, from USGS web site: http//earthquakes.usgs.gov/regional/qfaults/.