The Relationship of Seismic Hazard and Building Codes in Supercities

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Abstract

The intersection between the scientific fields of seismology and seismic hazard analysis with the engineering field of building construction is seen in the development and modification of regional building codes for earthquake hazard mitigation. As science continues to evolve, these building codes, which regulate the methodology and standards used during construction, are also evolving, but often at a much different pace. In this essay, I evaluate the overlap and transfer of information between these two fields in three specific example supercities which have experienced a varying level of seismic activity. After analyzing these cities, I reach the conclusion that increased enforcement through inspection of existing building codes would be the best way to minimize damage, economic loss, and loss of life following major seismic events.

1. Introduction

In today's world of increasingly high seismic hazard and dramatically growing populations which are primarily centered in major urban areas, there are many considerations to be made when it comes to protecting these areas from future seismic risk. While seismology and Earth science data are always changing, there are limited changes to building codes or engineering standards. For example, the New York City building codes of 2014 still reference the 1968 Building Code for their seismic loads section (1601.2.3), and even this old, outdated science sees relatively limited adoption in the engineering and construction world (FEMA, Building Codes). These limitations are felt even more strongly in developing nations where governmental control and regulation cannot keep up with the rapidly expanding population. In an effort to better understand how new information is translated from the Earth scientists to the laws that govern construction of buildings in these supercities, the following analysis of seismic hazard maps and exiting building codes was completed while taking into account cultural and economical variation.

The current methodology of understanding the seismic hazard of a particular location is a seismic hazard map. These maps are compiled based on previously collected seismic data for the given region, which is then plotted onto a map to showcase the location and intensity of estimated future seismic hazard. According to the USGS, the compilers of these maps, hazard maps are “aimed at improving earthquake-resilient construction” (USGS, What is Seismic Hazard). Construction of different types of buildings requires paying attention to different data subsets; small residential structures are more subjected to high frequency ground motion whereas taller buildings and long bridges are more subjected to long wavelength ground shaking. While these maps do help engineerings and scientists understand where they might be able to expect to see future ground motion, they are in large part a representation of the previous ground shaking events and therefore may not actually be the best tools for predicting the future. This point was made by Roger Bilham when he described how a seismic hazard map is not actually a representation of probability of future shaking, nor is the most recent seismic hazard map necessarily the most reliable (Bilham, 2009). This is due to the fact that when a rare earthquake occurs, the seismic hazard maps get a “bullseye” of sorts in that area, which might make people think that is an area of high seismic risk. However, in reality, the seismic energy in that area is most likely spent, meaning that there may not be any real likelihood of another large event in the near future. This is still a debated topic in seismology, but the potential risks of relying only on seismic hazard maps are still worth noting at the very least.

Once scientists have compiled a seismic hazard map, the baton is passed to the engineers who will take the data from the hazard map and determine building codes to regulate construction in the area based on the anticipated seismic hazard and many other factors. An issue with this process, as outlined by FEMA, is that "Adoption of the model codes is uneven across and within states, even in areas with high levels of seismic hazard. Some states and local jurisdictions have adopted the codes but have made amendments or exclusions relating to the seismic provisions" (FEMA, Building Codes). Something that needs to be better understood is where those shortcomings in adoption lie and how they could be corrected to ensure the safest possible structures in rapidly growing supercities around the world.

In this study, I will be analyzing three cities with varied levels of seismic activity and varied levels of structural preparedness to attempt to understand areas of strength and weakness in the connection between seismology and civil engineering. The three cities chosen are all classified as "supercities" and rank among the largest built-up urban areas in the world (Deomgraphia). The first city that was selected is Los Angeles, California, USA. This city was selected due to high population - ranking number 18 on the list of largest built-up urban areas in the world with a county-wide population of 15,620,000 and an average population density of over 6,000 per square mile. The Los Angeles area is a known source of seismic hazard due to its location on a prominent strike-slip fault, the San Andreas Fault, and the building codes in the area have been adapted to control for that known risk. The second city that was selected in New York City, New York, USA. This city ranks number eight on the list of largest built-up urban areas in the world, with a population of 21,575,000 and a population density of 4,500 per square mile. In New York, unlike Los Angeles, there is a lower but poorly known seismic hazard due to its location in the middle of a plate. The final city is Lima, Peru which ranks number thirty on the list of largest built-up urban areas with a population of 11,355,000 and a population density of 32,900 per square mile. Lima sits on an active subduction zone where it is expected that there will be large earthquakes, but due to the incredibly high population density and lack of enforceable regulation, building codes have not been maintained and updated the way they have in cities like Los Angeles. While these three cities are in very different plate tectonic settings, they are similar in their classification as supercities as well as in their role as major metropolises of their respective countries, and they highlight different areas of weakness in the collaboration between seismology and civil engineering.

2. Background: Seismic hazard maps and building vodes

As background information for the following case studies, it is important to understand how and why seismic hazard maps and building codes are formed as well as how they influence each other. These two tools will be fundamental in the analysis of these different seismic areas.

2.1 Construction of seismic hazard maps

A seismic hazard is defined by the USGS as “the hazard associated with potential earthquakes in a particular area, and a seismic hazard map shows relative hazards in different areas” (USGS, What is Seismic Hazard). The factors that are used to determine these hazard maps include mapped faults and past earthquakes, seismic attenuation and the charactaristics of how waves propogate through the earth in speicific areas, and near-surface site conditions, which can amplify ground motion. This ground motion is determined by the selection of appropriate ground motion prediction equations (GMPEs) which is an in depth process that can lead to significant variation in outcomes of seismic hazard maps (Boomer, 2010). Once this data is compiled, scientists predict the relative seismic hazard in the areas in question, which is called probabilistic ground motion, and generate the seismic hazard map. Probabilistic ground motion is the measure of how likely it is that the ground motion will be exceeded for an individual earthquake. These calculations were first done by Carl Allen Cornell and Luis Esteva in 1968 (Boomer, 2010). Large probabilities indicate a high level of possibly damaging ground shaking, as seen in the western US, whereas small probabilities show that ground shaking is much less likely to cause damage in areas like the eastern US. An example seismic hazard map of the United States is shown below. The areas of high likelihood for ground shaking based on previous events, wave behavior, and site conditions are shown in red, and the areas of lower risk of ground shaking are shown in blue or white.

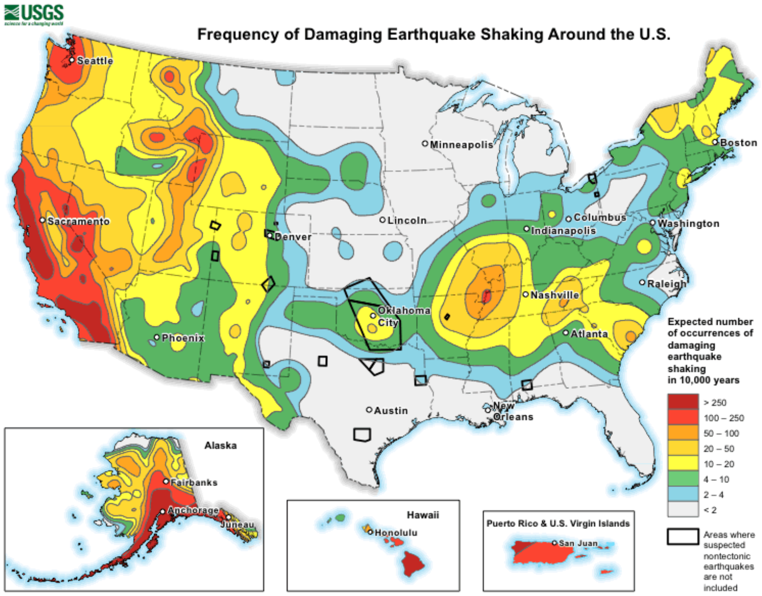


Figure I: An example seismic hazard map of the United States. The red areas of the map show higher seismic hazard associated with the west coast of the country, which has active plate boundaries, and the blues and greens show the lower seismic hazard associated with the mid-plate regions of the middle and east coast of the country. (USGS)

2.2 Uses and limitations of seismic hazard maps

Seismic hazard maps can be used by the general population as well as those working in more technical fields such as construction. In construction, seismic hazard maps can be used to influence building codes and recommendations so as to be as concious of the potential risk as possible. The general population is able to use seismic hazard maps to provide information about an area of potential interest for living or working. Based on the probability of high ground shaking shown in these maps, people might be able to choose to live in an area where damaging ground shaking is less likely, but still possible, than in other areas.

While the seismic hazard maps are great for showing levels of earthquake *hazard*, they do not show levels of earthquake *risk* despite being commonly perceived to do so by the general public. It is important to remember that seismic risk is the level of seismic hazard predicted for a given area multiplied by the vulnerability that a particular structure has to that hazard (Wang, 2009). A seismic hazard map shows data from previous earthquakes, not necessarily predictions of upcoming seismic events and these maps should not be used to do that. The map allows people to compare areas of historically higher or lower shaking, but they do not show individual earthquake risk or predict the location of the next earthquake. This “flaw” has been highlighted by many scientists, including Roger Bilham, who point out that people should not necessarily be making living or building decisions based solely on where earthquakes have occurred in the past (Bilham, 2009).

2.3 Building codes: creation and seismic hazard considerations

Building codes have long existed in order to create some level of uniformity in construction standards, in fact, the earliest building codes can be found in the Code of Hammurabi from 1772 B.C. or even in the Bible (Hammurabi). In the modern era, building codes became more common following major disasters in large urban areas such as the Great Fire of London in 1666 which led to the creation of the Rebuilding of London Act drawn up by Sir Matthew Hale in the same year. This early building code regulated how the city would be rebuilt, included stipulations requiring housing to have fire resistance capacities, and authorised the city to reopen and widen roads (Charles II, 1666). The declared purpose of building codes is to "provide minimum standards for safety, health, and general welfare including structural integrity, mechanical integrity, means of egress, fire prevention and control, and energy conservation."

Particularly focused on seismic hazard codes, restrictions such as ductility of materials, construction methodology and tools, and other factors are controlled in order to reduce the damage to structures during an earthquake. These are typically established and refined following major seismic events which serve to highlight flaws or oversights in the previous regulations. However, it can take years for these codes to be proposed and approved by the local or national government, and even longer for changes to start effectively taking place and being enforced. In order to guarantee effective and correct building codes, there are many steps in a typical development process. These steps may vary from location to location, but are good examples of what the process of making chances to existing building codes might look like. Firstly, agreement is needed from all parties - government, citizens, building industry representatives - and each of their interests must be balanced and considered. Then, the proposed revision or addition is carefully vetted by all groups through one or more of several possible processes such as ANSI, the American National Standards Institute, Consensus, a process by which codes and other standards are approved for public use (ANSI). The entire process, because of its complex, multi-step, and inter-departmental nature, can commonly take between three and five years (WBDG).

Throughout time, strong enforcement of local building codes have significantly reduced the damages seen following large seismic events. For example, in 2012 when a magnitude 7.4 earthquake hit Mexico, they had recently corrected their building codes and saw significantly less damage to buildings than in previous earthquakes of similar magnitude (King, 2012). As reported by the Insurance Institute for Business and Home Security, the 2012 earthquake saw 60 homes destroyed and 800 homes damaged whereas a magnitude 8 earthquake in 1985 saw thousands of homes damaged, 400 homes destroyed, and 10,000 people killed. This dramatic difference can be credited to the dramatic changes made to the Mexico building codes following the disaster in 1985. This success story is a clear indication that strong, well-enforced building codes can be instrumental in preventing both loss of life and serious economic impacts following major seismic events and that building codes in other parts of the world need to be modified and enforced to similar standards (King, 2012).

2.4 Uses and limitations of building codes

Building codes are used commonly by contractors and construction companies around the world, but there are a multitude of codes, sections, sub-sections, and revisions to these codes. If these are kept well organized, and enforced thoroughly, then the construction groups will be able to maintain compliance to the codes and therefore keep up with the best safety standards available from the most updated science. The problem comes when governments are not able to enforce the most up-to-date codes or make the changes identified following a disaster quickly enough to be effective. This is significantly more common in developing nations where there is rapid population expansion and not enough government oversight. In many cases, there are homes being constructed by hand from any available materials at an uncontrollable pace. Additional problems may come in if governments – either local or national – are not able to keep up with the scientific developments or if the building codes are not able to get specific enough to control for local variations. Even when the codes are made highly specific, that creates an even greater number of codes in play that have to be enforced and that contractors have to keep up with as they go through the fast-paced building process.

3. Case study #1: Los Angeles, CA, USA

3.1 Background

When considering areas of high seismic hazard in the continental United States, very few areas come to mind as quickly and prominently as does the western coast. In particular, cities like Seattle, San Francisco, and Los Angeles are well known for the well-understood risk of impending earthquakes and the many preventative measures that have been taken over the years to ensure that those impending earthquakes will cause as little loss of life and economical damage as possible. For this comparison, the city of Los Angeles will be used as an example of a city in a developed nation with a high level of potential seismic hazard. Los Angeles was selected because of its high population (roughly four million people live within the city limits) its high population density (up to 50,000 people per square mile in the most populated areas) and for its proximity to a major fault zone, the San Andreas fault. This fault is located as close as 33 miles away from the downtown Los Angeles area and currently poses a major threat of rupture, as discussed below. However, in addition to this particular fault, Los Angeles is also surrounded by many other faults which have also generated recent seismic activity; these faults are sometimes completely undiscovered until they generate a significant seismic event.

3.2 Seismic hazard analysis

Below, in Figures II and III, are seismic hazard maps for the California and Southern California areas. As is clear through these maps as well as the seismic hazard map of all of the continental united states, this is an area of significantly high seismic risk. Figure II shows that the Los Angeles area can expect to see earthquakes that exceed 20% the force of gravity and cause significant damage at least once per century, if not up to five times per century. Although these two maps demonstrate the same thing, a very high level of seismic risk in the Los Angeles area, they appear different as different groups utalize different considerations or ground motion prediction equations to construct their maps. This demonstrates another point of difficulty in using these seismic hazard maps, they don't always perfectly agree on the level of hazard at a given location and can therefore make it challenging to design the "correct" buildling codes.

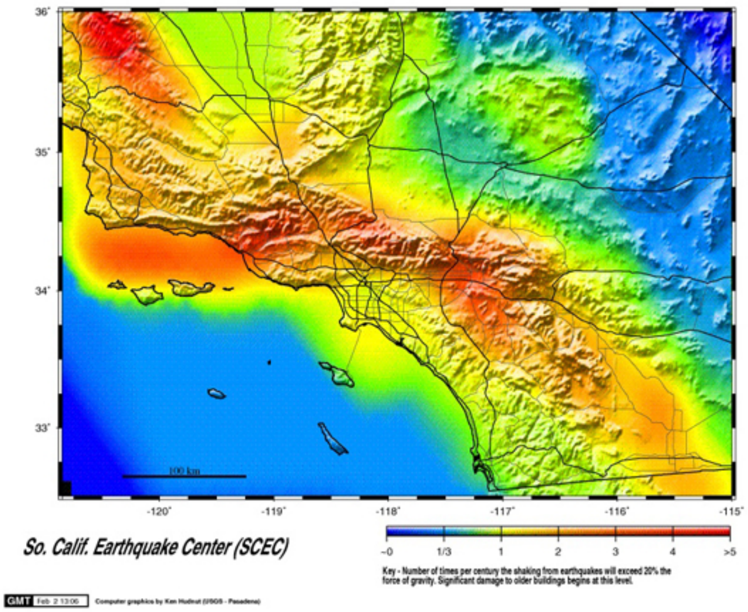


Figure II: Seismic hazard map of Southern California showing the areas of high seismic hazard around the San Andreas fault system which passes near Los Angeles. The red indicates a high number of times per century that ground shaking will exceed 20% the force of gravity. (Southern California Earthquake Data Center at Caltech)

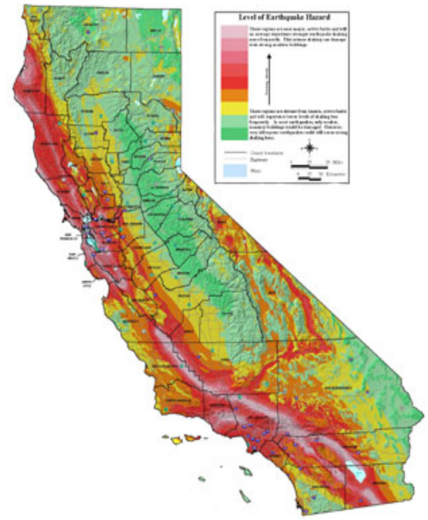


Figure III: Seismic hazard map of all of California with the red areas as relatively high seismic hazard and the green areas as relatively low seismic hazard. (California Department of Conservation)

3.3 Historical earthquakes and building code changes

Southern California and the Los Angeles area have been home to many major historical earthquakes which have been pivotal in building the current understanding of seismic hazard, ground motion, and civil engineering in seismically active locations. While the San Andreas fault is relatively well known, new faults in the area are also commonly discovered following the occurrence of a major earthquake either on the fault or near enough to the fault to cause small earthquakes or aftershocks. The Northridge earthquake is an example of a prominent Los Angeles area earthquake, on Martin Luther King Jr. Day in January of 1994, a magnitude 6.7 earthquake occurred on what is now known as the the Northridge blind thrust fault, its epicenter located only about 20 miles outside of downtown Los Angeles (history). Only 57 fatalities were caused by this event, either directly or indirectly, and this relatively small number was likely due in large part to the fact that in the early morning on a national holiday many people were still at home. There were many structural failures, from highways to parking garages to an apartment complex, that occurred and would have led to significantly higher fatalities had more people been out and about at this time. These damages cost an estimated $20 billion or more, and this became the most costly earthquake in United States history (history).

The Northridge earthquake occurred less than two decades after another major earthquake in the area, the Sylmar earthquake of 1971, and therefore benefitted from some minor structural code changes, but the collapses of buildings and highways indicated that there was still significant work to be done in shoring up this area against future seismic events. The structures which collapsed entirely were made of concrete, so their collapse was to be expected. However, there was also significant damage to non-collapsed steel buildings that was found over the course of the following years (Miller, 1998). This was caused by failures found in the welding of these structures due to both poor workmanship and extreme ground shaking. The Northridge earthquake was unique in that the majority of the ground motion occurred in a very brief, six second, period as opposed to a gradual building of shaking. This caused extremely high accelerations of up to 1.8g in the horizontal and 1.2g in the vertical which were occurring in phase with each other (Miller, 1998). This in phase motion can be thought of as combining the effects of the large vertical and large horizontal forces, which the buildings were not prepared for. In addition to these extreme ground shaking circumstances, there were workmanship and inspection errors found with these failed welds. It was discovered that many of the welds were actually in violation of the D1.1 code (Miller, 1998), and that the current inspection methods did not require a thorough visual inspection, which would have revealed these flaws. The style of weld that was used actually prevented the steel-framed buildings, which should have been among the safest structures from properly absorbing the energy from the earthquake, and were instead cracking under the pressure.

After the Northridge earthquake, building codes were changed again, requiring owners of these steel-framed buildings within a specified earthquake zone to inspect the welding and repair any cracks that they were able to find. Of the 243 buildings required, over 60% of them found cracked weldings (LA Times), but it is unclear as to if they were all repaired, or even if all the buildings actually completed the mandatory inspection. This serve to highlight the troubles with retroactive building codes - sometimes it is difficult to see the future pay-off that is coming from the sunk cost of making and enforcing these changes. These retrofits, like many others, were incredibly expensive, costing landlords up to $5,000 per joint for weld inspection and up to $10,000 per joint for repair (LA Times). Previous retrofitting mandates had occurred in Los Angeles, particularly the retrofitting of unreinforced masonry buildings required in 1981, with much obvious success, but many retrofitting orders have not yet seen obvious payoffs so there is always a significant amount of pushback when it comes to the costly process of completing these retrofits. As said in the LA Times, “seismic codes in general are a problematic mismatch between economic necessity and the murky world of earthquake science.”

3.4 Major areas of concern today

In developed nations and areas with relatively well-known probabilistic seismic hazard such as Los Angeles, the major area of concern is typically the economic cost of repairing the infrastructure damaged as opposed to the potential loss of life. This is because the building codes are maintained to a high enough standard that loss of life is significantly less common than it would be in a less developed nation. Since it is fairly common for problems in current building codes to be exposed through a future earthquake, there is a lot of potential concern over what flaws in the codes could be found with the next major earthquake, especially if it ends up being “the big one” that is overdue to occur in this area. Even in a developed nation where building codes are far more easily enforced, there has been difficulty in ensuring the enforcement of these codes from both a workmanship and an inspection point of view, so if Los Angeles is to survive the impending big one as successfully as possible, those codes will need to be enforced to an even higher degree and more retrofitting may need to be funded.

4. Case study #2: New York, NY, USA

4.1 Background

New York City, New York is another major metropolitan area in a highly developed country. However, unlike Los Angeles, this city is not one that is popularly associated with significant seismic hazard because of the city’s location within a plate interior. Despite there not being much seismicity associated with the east coast of the United States, there has been some significant activity such as detailed in Wolin et al.’s paper on the Mineral, VA earthquake (Wolin, 2012). In this comparison, New York City will be used as an example of a highly populated city in a developed nation with an unknown or unpredictable level of seismic hazard. New York City was selected because of its very high population (roughly 8.6 million in the five boroughs) its relatively high population density (27,500 people per square mile), and for its location in a part of the United States with potentially active faults that are less well studied than in plate boundary regions.

4.2 Seismic hazard analysis

As previously mentioned, there are very few well-studied faults predicted to be active in the near future around the New York City area. Therefore, it makes sense that the seismic hazard map, seen below in Figure IV, of the surrounding area is drastically different in appearance from that of the Los Angeles area. In the New York City area, there is only a 2% chance in 50 years of a seismic event with peak accelerations of 14-20% of gravity. Earthquake rates in the northeastern United States are 50 to 200 times lower than in California (NYCS). Scientists say that New York is overdue for a magnitude 5 earthquake; a magnitude 5 has a recurrence interval of 100 years, a magnitude 6 has a recurrence interval of 670 years, and a magnitude 7 has a recurrence interval of 3,400 years and it has been 134 years since New York had a magnitude 5 earthquake (Fitzgerald 2008). There is only one major fault system in the New York area, the Ramapo Fault System, shown below in Figure V, but even this system is not incredibly well understood. This is a fault system made up of many small, inactive faults, which increases the difficulty of studying them, but also could increase their ability to cause damage if they were to all become active together or through a chain reaction. At their nearest, this fault system is only about 25 miles from New York City and only about two miles away from the Indian Point nuclear power plant (Columbia).

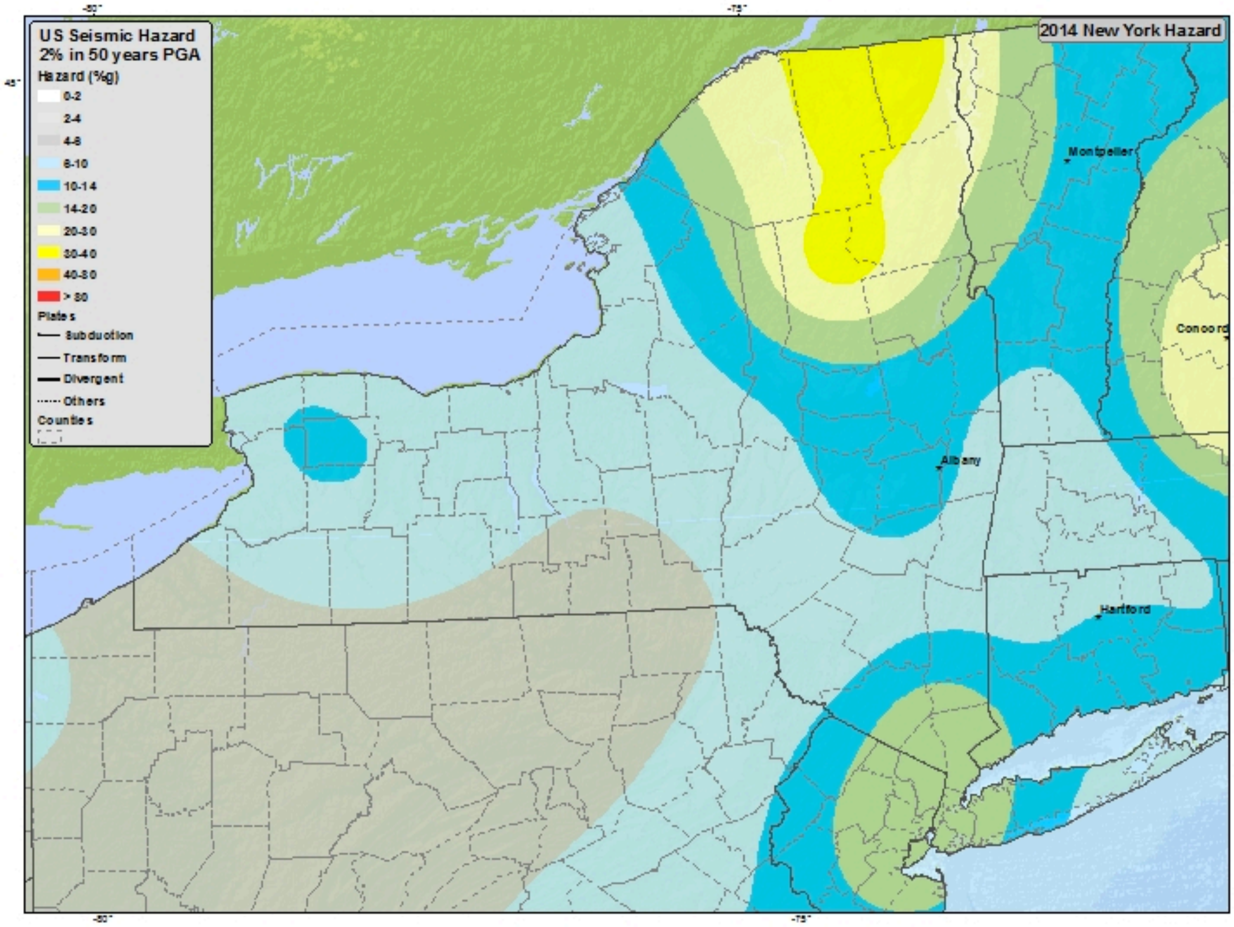


Figure IV: Seismic hazard map of New York, USA showing that there is a 2% chance of 14-20% of gravity ground shaking in the New York City area in the next 50 years.

(USGS)

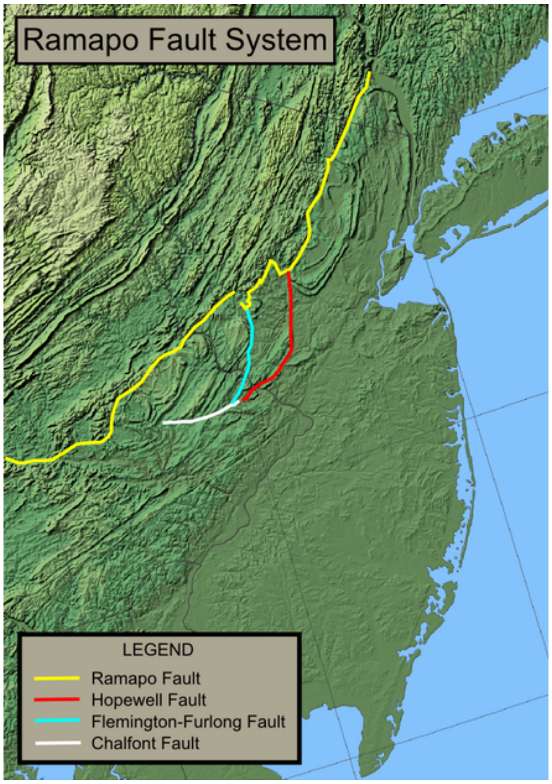


Figure V: Depiction of Ramapo Fault system in the Northest U.S.

(Atlas of New Jersey)

Although the likelihood of these medium to large earthquakes is significantly less than the likelihood of equal magnitude or even larger earthquakes on the west coast of the United States, I note that a few important factors could make these east coast earthquakes potentially more dangerous than those in the LA area. Firstly, there is significantly less scientific research going into when or where these seismic events might be coming in the New York City area, so it is much more difficult to be adequately prepared. Secondly, the attenuation rate of the east coast is significantly lower than that of the west coast. Seismic attenuation "describes the energy loss experienced by seismic waves as they propagate" (Dalton). This means that an earthquake of equal magnitude will be felt at much greater distances from the epicenter if it occurs on the east coast than if it occurs on the west coast, where energy loss is higher. This is due to the higher quality factor found on the east coast, meaning that there are less faults or other “impurities” to break up or cause decay of the seismic waves, allowing them to propagate for significantly greater distances (Dalton) Attenuation is calculated as $\frac{1}{Q}$ so a higher quality factor means a lower attenuation or energy loss.

4.3 Historical earthquakes and building code changes

There have been two very large earthquakes throughout history in the New York City area. The first was a magnitude 5.2 in 1737 and the second was also a magnitude 5.2 in August of 1884. The 1884 earthquake was felt over a very large area, due to the low attenuation rate of the east coast of the United States, some reports of shaking as far away as Maine, Ohio, Maryland, and other surrounding states. The shaking caused plaster and chimney cracking, window breaking, and objects being thrown from shelves (NESEC).

While it has been a long time since this area experienced a high magnitude earthquake, scientists believe that one could be coming in the near future. In a 2008 report, scientists from Columbia University indicated that a magnitude 6 or 7 event, although uncommon, could originate from the Ramapo fault system (Fitzgerald, 2008). An event of this magnitude would likely lead to many fatalities and billions of dollars in damage, especially considering the lack of preparedness of major cities located near the fault system such as New York City.

New York City first adopted seismic provisions into its building codes in 1995 (NYCS), which means that a vast majority of the incredibly densely packed buildings in city and surrounding areas were built prior to these code updates and therefore were not built with seismic considerations in mind. The adaptations to the building code from 1995 focused mostly on the preservation of human life in the case of a seismic event. The codes were updated again in

2008 and focused on making buildings stronger and also more flexible so as to better absorb the energy produced in the case of a seismic event (NYCS). These changes were crucial to protecting the buildings that would be constructed after these codes came into effect, but they also still allowed for the construction of unreinforced masonry buildings in some cases, which are known to be high risk in the case of an earthquake. In 2014, the building codes were updated again, this time choosing to use a risk-based approach which means that "instead of designing against an earthquake happening, we are designing against the probability of a new structure collapsing or sustaining significant damage during an earthquake" (NYCS). This update also placed a focus on site-specific conditions and unique soil features of New York, which had previously been mostly ignored.

Today, it is much more common to see earthquake preparedness education taking place in cities like New York, which are not typically thought of as being high seismic risk. Groups like NYC Emergency Management have online planning tools for people to access and begin the process of thinking about the actions to be taken in the event of a large earthquake (NYCEM). The combination of this increased education, the updated building codes, and better inspection and enforcement could prove to be crucial in preventing irreparable damage, physically or financially, to a city like New York.

4.4 Major areas of concern today

The major area of concern in a city like New York is the financial impact that a large seismic event could have. According to a 2008 analysis done by FEMA, New York City and the surrounding metropolitan areas rank as the twenty-first most-at-risk metro region from seismic hazard in the United States (NYCS). This is due to the density of very high-value buildings which could, in the case of an earthquake, collapse and create “millions of of tons of debris and billions of dollars of damage” (NYCS). According to this report, the city has over 100,000 unreinforced masonry buildings which serve as multi-family homes and are sometimes up to seven stories tall. These buildings, mostly build prior to the 1930s, are at incredibly high risk, and even more so if they are not built attached to another building for additional support.

In addition to the concerns over the structural integrity of civilian housing, many emergency response services are still housed in unreinforced masonry buildings and may not yet have been retrofitted. This lack of retrofitting to meet the current code not only puts the occupants of those buildings in danger, but also amplifies the potential damage that could be caused to the rest of the city, if emergency responders are unable to perform their vital services. There are also concerns that, in the case of an earthquake, fundamental utilities of the city could be damaged and lead to secondary impacts such as fires, water contamination, power outages, and more. These impacts could increase the economic loss and potentially the loss of life due to a seismic event.

There have been several studies completed on the seismic hazard of various bridges in and around the city, as those would serve as a major evacuation route in the case of emergency and must therefore be able to withstand a higher level of ground shaking than other structures around them. For example, the 1998 study by Weidlinger Associates looked at inspection and rehabilitation done to the Queensboro Bridge in 1994, the Bronx Whitestone Bridge in 1995, and JFK Airport in 1996 by outside consultant companies. This study outlined a plan for retrofitting these “critical bridges” as well as some changes to be made to “essential and other” bridges in order to ensure that the critical bridges remain functional in the case of a major seismic event and that the essential and other bridges are either damaged minimally or experience controlled collapse that will not result in loss of life. However, it is difficult to tell if these changes and retrofitting suggestions were actually taken into account, so it is possible that these heavily trafficked areas are still susceptible to high levels of damage from an earthquake.

In order to accurately address these, and other, areas of concern in the city, there needs to firstly be a thorough investigation and data collection done to understand the exact composition of the types of buildings in the city. Information needed includes building age, type, quality, height, square footage, and seismic design level. Once this information is collected, better steps could be taken to ensure that older buildings are correctly retrofitted and reinforced. The newer buildings should be constructed to the most updated code, but a strict level of enforcement and inspection needs to be maintained so that the cost of extensive retrofitting or repair on these buildings could be avoided in the future.

5. Case study #3: Lima, Peru

5.1 Background

Lima is the capital and largest city of Peru, located in the central coastal part of the country. The population of Lima is 8.5 million people with a population density of approximately 9,000 residents per square mile in the city as compared to the 62 residents per square mile on average throughout the country. Lima is estimated to generate 70% of the entire country of Peru's economic output (Degg, 2005). Lima's seismic risk landscape is quite similar to that of Los Angeles, in that there is a known high seismic risk and people in and around the area expect large earthquakes to happen on a relatively frequent basis. However, there is a key difference between Lima and either Los Angeles or New York City in that Lima is located in a developing nation whereas the other two cities are located in a highly developed nation.

5.2 Seismic hazard analysis

Lima is located closer to a major subduction zone than any other city of comparable size in the Americas (Degg, 2005). This subduction zone is caused by the collision of the Nazca oceanic plate and the South American continental plate, where the Nazca plate thrusts beneath the South American. The friction caused by this subduction, at a particularly minimal angle, causes significant earthquake activity as well as volcanic activity throughout the western coast of Peru. Subduction zones generate the largest earthquakes of all fault types due to the friction building during the subduction process and the posibility for deeper earthquakes and the plate decends towards the mantle. Therefore, Lima, located on a subduction zone, likely has a worst case scenario even worse than that of Los Angles, which is located on a strike-slip fault. The South American subduction zone has hosted magnitude 9 earthquakes in the past and will certainly do so again in the future.

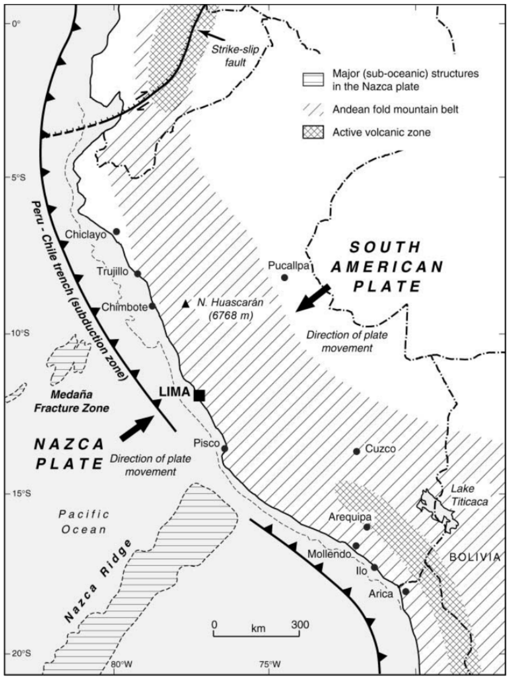


Figure VI: plate motion occurring off the coast of Lima, Peru showing the subduction zone along the South American coast

(Degg, 2005)

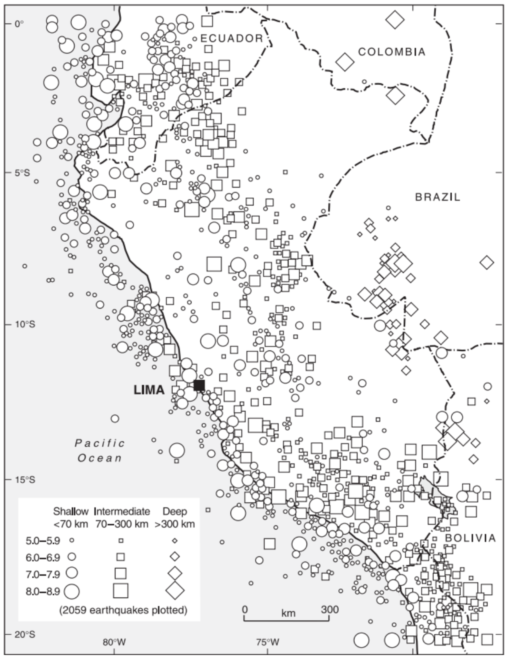


Figure VII: Historical earthquakes in and around Peru.

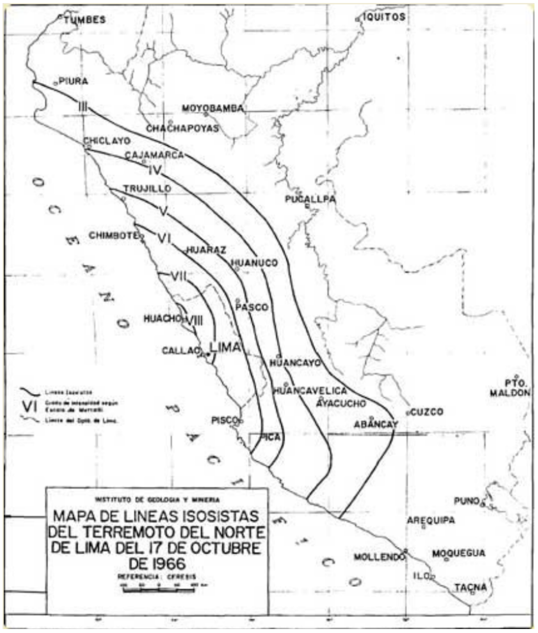
(Degg, 2005)

As shown above in Figure VII, it is clear that the subduction zone causes a significant number of shallow and intermediate type earthquakes of varying, but often large, magnitudes in and around the Lima area and many of these events trigger damaging tsunamis.

Something unique about Lima, and other major cities in South America, is that there has been an extensive population growth in the last half century, averaging 3.9% growth yearly brought about mostly through rural to urban migration (Degg). As thousands more people move into the city, Lima is quickly running out of places to affordably house all of them. In many cases, low income urban dwellers are forced to build their own homes out of whatever materials may be available, and these homes, unsurprisingly, are not in compliance with the national or local building codes.

5.3 Historical earthquakes and building code changes

There have been many major earthquakes in and around the Lima area throughout history, but two in particular which had significant impacts on the building code in the city were the 1974 and 1966 earthquakes. These influenced a set of changes that would be seen in a 1977 building code update than has been hugely successful for public buildings and spaces. The 1966 earthquake was a magnitude 8.1 just off the coast of Callao, coastal town very near Lima.



VIII: Map of Peru, showing location of Callao and the affected region of Peru and their respective Mercalli intensities

(LimaEasy)

This earthquake left over 200,000 people homeless, 3,000 people injured, and 125 people dead. Many churches collapsed, which was a significant problem because at the time there was a religious festival being held in the area so many people were injured or killed in those public spaces. In Lima itself, more than 2,000 homes suffered severe structural damage (LimaEasy). The 1974 earthquake was also a magnitude 8.1 and struck only about 80 kilometers from Lima. This earthquake caused extensive damage to churches, historical monuments, public buildings, and residences - particularly of the older adobe style of construction. However, even modern reinforced buildings were severely damaged or collapsed, which shed light on the need to modify the existing building codes to account for an unexpected higher horizontal ground shaking that had been observed (LimaEasy).

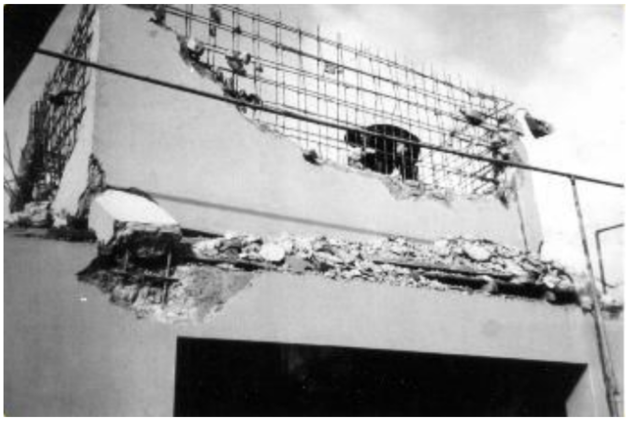


Figure IX: Damage to a more modern building from the 1974 earthquake in Lima, Peru (LimaEasy)

In 1977, the Peruvian government made a few crucial modifications to its building codes for the first time in twenty years. Notably, the lateral displacement requirements were increased three-fold, meaning that buildings were now required to be able to withstand three times the amount of lateral displacement that they had been before. This change was observed to be effective when, following a 2001 magnitude 8.4 earthquake in Arequipa which caused some moderate ground shaking in Lima, the school buildings constructed using this modified code showed no evidence of damage as compared to the school buildings constructed on the previous code, which was on par with international standards, saw widespread short column failures (IITK).

In 2004, the building codes were updated again, but of particular note is the fact that the building type classifications covered in the code does not seem to include average residential homes, meaning that there is little to no formal documentation and control for the construction of the structures where many people spend a majority of their time (IISEE). Lima's government focuses its efforts on creating well-established building codes for their public, state, and emergency facilities, but does not seem to have expanded those regulations to residential areas.

5.4 Major areas of concern today

As discussed previously, a major area of concern for Lima is the unplanned and uncontrolled housing settlements that have been popping up due to the massive migration of people from rural to urban areas. These housing developments are highly vulnerable to seismic hazard, as there is very little to no regulation involved in their creation, but they can be homes for hundreds or thousands of Lima's poorer residents. According to Inside Disaster, "an earthquake-resistant home costs 10-20% more to build than an unsound structure." (Inside Disaster) When these unsound homes are damaged during an earthquake, these is very little financial burden placed on Lima from their repair or reconstruction, but a very significant economic burden due to the loss of life that these poorly constructed homes can cause. Unlike major urban areas in developed nations, Lima - a major urban area in a developing nation - has far greater concerns about human capital loss. As more and more of these unplanned developments spring up every day, Lima needs to be able to do something to regulate their construction. This could be done through providing or subsidizing better building materials, constructing more low-cost housing in these areas, or having inspections of the home-made settlements to ensure that minimum standards are being met. These are obviously all costly options, but the upfront cost of these preventative measures would surely be dwarfed by the cost of reconstruction and loss of life if no action is taken. A potentially less costly option would be to provide more in depth education to the people of Lima about how to construct their homes in a more durable and safe fashion – what materials to use, how to prepare for an earthquake, et cetera. This problem was also pointed out in great detail following the 2010 earthquake in Haiti where over 200,000 people were killed in comparison to a higher magnitude earthquake in Chile the same year with a death toll of merely 700 people. This difference was credited primarily to different construction techniques in these two countries with varied wealths and construction practices. Providing a basic construction education to the citizens of these less wealthy nations could make a big differecne. An example of a simple education tool to increase earthquake preparedness in building construction is the Imagination Station in website and lab space in Toledo where people can go through the excersize of building a more earthquake-proof city. If these opportunities were presented to people in developing nations with high seismic risk, such as Lima, perhaps safer construction practices could be implemented and the death toll could be decreased significantly in future earthquakes (Imagination).

6. Discussion and summary

Through the examination of the three cities, Los Angeles, New York City, and Lima, it has become clear that there are a variety of concerns and factors to consider when attempting to provide the most effective form of earthquake damage and hazard mitigation. From these examples and the additional example of revamping building codes and inspection policies in

Mexico, the suggestion could, and should, be made to dedicate the up-front cost of ensuring that all buildings and building components are properly inspected and meeting the codes that are established in the given regions. While this can be a large cost, the advantage of utilizing this method is that the costs would be spread out over time as the inspections would not be able to be done all at once. Even if the regional code is not perfect, as it has been shown that codes will never be completely perfect and that science will always be evolving as new and different seismic events occur, being up to that code will be the best way to guarantee minimal financial loss or loss of life.

As shown in the Los Angeles example, even when building codes are imperfect and need to be changed following a major seismic event, damage and immediate massive spending could have been avoided if the welds were created to code originally. For a major city in a developed country, such as Los Angeles or New York City, the greatest concern following a major seismic event is the financial impact that it will have on the city to repair all the damage, and maintaining the current building code would hopefully prevent that large financial burden from being imposed all at once in the immediate aftermath.

For a large city in a developing nation, such as Lima, the greatest concern following a major seismic event is the loss of life, especially because the building affected are not particularly high cost. In cases like these, having more strict control over the inspection process and maintaining the codes as they are specified would lead to a significantly less impactful economic loss of human life. Additionally, increased education, such as the Imagination Station site, could be useful so that individuals constructing their own homes out of available materials could have suggestions or direction to do so with increased safety and therefore decreased risk. By applying a bit more force to the upholding of existing codes in all settings and increasing education in developing nations, both economic loss and loss of life can be reduced all while not applying an unreasonable burden on a city in a short period of time. This theory has been demonstrated to be successful in Mexico, as they have implemented much stronger enforcement policies on their building codes and seen significantly decreased losses following major seismic events. If other parts of the world, of both low and high expected seismic risk, were to adopt this practice of highly enforced inspections, the damages related to earthquakes could be significantly reduced over time.

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