5.1 Earthquakes

- Earthquakes are the most serious hazard facing Seattle. Unlike other potentially catastrophic hazards, Seattle has had and will experience powerful earthquakes.
- The Seattle area experiences three earthquake types with varying consequences:
    - **Crustal or Shallow Quakes** occur in the North American plate at 0-30 km near the crust's surface along faults. Intense shaking occurs near the epicenter but usually diminishes quickly with distance relative to the other earthquake types. Crustal earthquakes are expected on the Seattle Fault Zone, which is the primary but not only source for this type of quake in Seattle. An example of a crustal earthquake is the magnitude (M)6.2 Christchurch, New Zealand earthquake that occurred in 2011.
    - **Intraplate or Deep Quakes** occur at depths of 30-70 km in oceanic crust as it dives under lighter continental crust. Because of the depth, even buildings located right above them are far enough away that seismic waves are attenuated. An example of a deep earthquake is the M6.8 Nisqually Earthquake that occurred in the Pacific Northwest in 2001.
    - **Subduction Zone or Megathrust Quakes** occur on the interface between the North American plate and the Juan de Fuca plate, a small plate extending from northern California to British Columbia. An example of a megathrust earthquake is the M9.0 Tōhoku Earthquake that occurred off the coast of Japan in 2011.
- The amount of shaking at a location depends on an earthquake's magnitude, the distance between the location and the earthquakes 's source, and local geology. Other factors like the frequency of seismic waves also affect how structures shake in earthquakes.
- Earthquake frequency intervals are estimates, not predictions. The estimated occurrence rate of a M6.0 or larger deep earthquake is about every 30-50 years. The estimated occurrence rate of a megathrust earthquake is every 200 to 1,100 years, or on *average,* every 500 years. The estimated frequency of a Seattle Fault earthquake is difficult to determine due to lack of data. Estimated recurrence intervals range from every 200-15,000 years.
- An earthquake on the Seattle Fault poses the greatest risk to Seattle because:
    - The Seattle Fault Zone extends east-west through the middle of the city.
    - A Seattle Fault quake could be as large as M7.5,[160] but less than M7.0 is more probable.
    - The most recent Seattle Fault earthquake was about 1,100 years ago;
    - The Seattle Fault has been active about three or four times in the past 3,000 years.
- Deep quakes are the most common large earthquakes that occur in the Puget Sound region. Quakes larger than M6.0 occurred in 1909, 1939, 1946, 1949, 1965 and 2001.
- Megathrust earthquakes are the greatest risk to the broader west coast region. A megathrust earthquake could reach M9.0+ and affect an area from Canada to northern California. A Cascadia megathrust earthquake could rank as one of the largest earthquakes ever recorded, but because Seattle is several hundred miles from the source seismic waves would weaken slightly before they reach Seattle. Shaking would be violent and prolonged, but not as intense as in a Seattle Fault quake.

- About 15% of Seattle's total area is soil that is prone to ground failure in earthquakes. The Duwamish Valley, Interbay, and Rainier Valley are vulnerable to ground failure and shaking because of the liquefiable soils in these areas.
- Seattle has over 1100 unreinforced masonry buildings (URMs) that are prone to collapse in earthquakes. These older brick buildings tend to be concentrated in areas expected to experience the strongest ground motion during earthquakes.
- Seattle has many bridges that, despite seismic retrofits, may not be useable after a strong earthquake. Damage to them would impair emergency services and the economy.
- An earthquake will produce costly damage. Combined property damage for quakes in 1949 and 1965 in the region amounted to roughly $400 million (2010 dollars). The 2001 Nisqually Earthquake resulted in damage to City of Seattle buildings, infrastructure, and response costs that exceeded $20 million. Adding in the costs of repairing arterial road structures, the figure topped $36 million.
- Secondary impacts such as landslides, tsunami, fires, infrastructure failures, and hazardous materials releases could become disasters themselves. In past earthquakes, more people have died from fire than building collapse.
    - 2013 research finds that Seattle could experience *thousands* of landslides following a strong (M7.0) Seattle Fault earthquake. Estimates range from 5,000 in dry conditions to 30,000 in the wettest conditions.
    - A large Seattle Fault earthquake could trigger a tsunami up to 16 ft high that would strike the Seattle shoreline within seconds of the earthquake and flood it within 5 minutes. A megathrust earthquake will not cause a tsunami with inundation for Seattle but is expected to cause strong currents in Seattle's waters that may be dangerous for vessels. A deep earthquake could cause landslides that trigger a tsunami.
    - A M7.0 Seattle Fault earthquake could cause dozens of fires. Suppressing the fires may be more difficult due to severed transportation routes and possible damage to the water system, which could reduce water pressure in many parts of the city.
    - Structural failure and fires would probably cause multiple hazardous materials releases. They could range from minor spills to major incidents with public health and environmental ramifications.

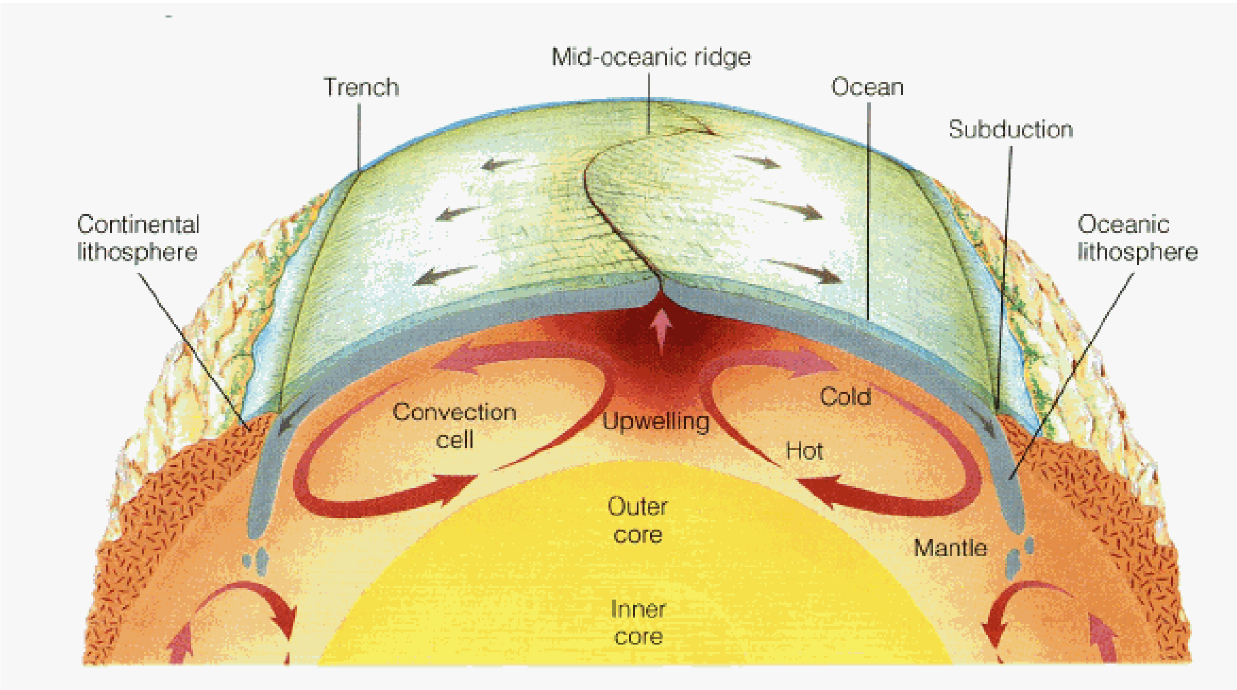
5 1.1 Context

Plate Tectonics

Earthquakes happen when the strain accumulating in rock becomes greater than the strength of the rock or the pressure keeping it from slipping. Plate movement is primarily driven by very slow convection currents in a hot, dense, plastic rock layer of the Earth called the mantle (see Figure [Convection in the Earth's Crust]). Just as hot air rises and cool air sinks, hot mantle material rises, cooling as it nears the surface. The cooler material then begins to slowly sink down, which creates a convection cell. Hot rising rock pushes plates across the surface of the earth. When plates collide, the thinner, denser ocean plate is usually forced under the thicker, lighter rock of the continent.

In the Pacific Northwest, the Pacific Plate is moving northwest and is pushing the smaller Juan de Fuca plate clockwise under the North American Plate. This process is known as subduction. The motion of the plates is not smooth. Friction and pressure along the interface of the plates prevents the ocean plate from moving under the continent, locking them together for decades or centuries. Strain builds up until the fault breaks and a few meters of the Juan de Fuca plate slips under the North America Plate, causing a megathrust earthquake.

Figure 5-1. Convection in the Earth's Crust

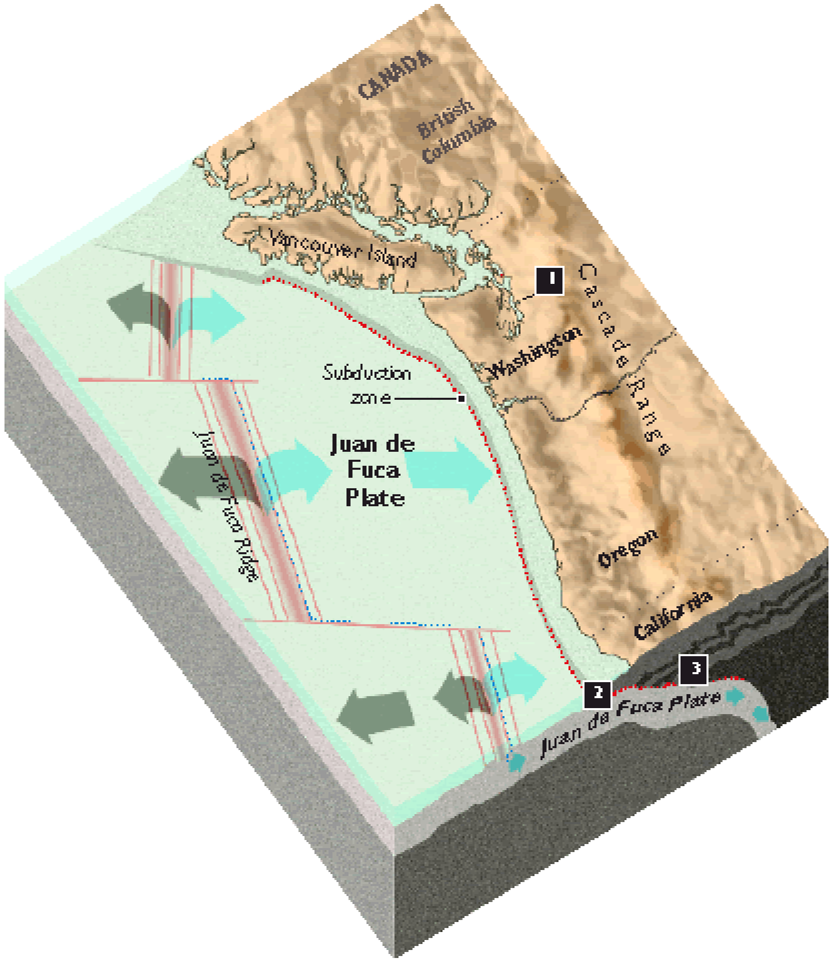


Source: http://clarkscience8.weebly.com/forces-inside-earth.html.

Types of Earthquakes

The Puget Sound region experiences three types of earthquakes:

1. **Crustal earthquakes** (also called "shallow") occur in the North American Plate as it adjusts to the build-up of strain along the interface of the North American and Juan de Fuca Plates. Depths vary from 0 to 30km (about 21 miles). They are usually felt intensely near their epicenter, but their effects diminish relatively quickly with distance. There is an active shallow fault system running through the middle of Seattle, called the Seattle Fault Zone.
2. **Megathrust earthquakes** (also called "subduction") happen when pressure at the interface between the Juan de Fuca plate and North American plate unlocks along a sloped plane from where the plates meet off the Washington coast. This fault is over 1,000 km (620 miles) long. Megathrust earthquakes are the largest type of quake, with magnitudes from M8.0 to over M9.0. They have occurred at about 500-year intervals, on average, ranging along the Pacific Coast.[161]
3. **Intraplate earthquakes** (also called "deep") occur at depths between 35 and 70km (about 21 - 43 miles). Since they are farther from the surface, they are not felt as intensely, but are experienced over a wider area than crustal quakes. They are the most common type of large earthquake in our region. Western Washington has experienced three since 1949.



Source: http://www.burkemuseum.org/static/earthquakes/bigone/threekinds.html. Accessed: 3/5/2019

Measures

Moment Magnitude

Moment magnitude measured the amount of energy released by an earthquake. It has three components: the size of the area that has slipped, the amount of slippage, and the viscosity of the material. Low viscosity is like fingers scraping a stick of butter; high viscosity is like fingers scraping a blackboard. Earthquakes of magnitude M5 are considered “moderate;” above M8, they are considered “great.”

Moment magnitude is a different measure from the Richter scale, which was designed in 1935 for small to medium earthquakes in California, within 600 km of the recording seismograph. Because of these shortcomings, Moment magnitude is the most common scale used by the United States Geological Survey (USGS).

Modified Mercalli Intensity (MMI) Scale

The Modified Mercalli Intensity (MMI) Scale is a subjective measurement of earthquake effects and damage (see Table 5-1). The MMI scale uses twelve steps to describe how the earthquake felt to people and its damage to structures. Maps drawn from reports of what people felt are useful in determining areas of damage concentration. Because effects differ in and across areas, an earthquake can have multiple intensities.

Table 5-1. Modified Mercalli Intensity (MMI) Scale

I. Instrumental	Not felt by many people unless in favorable conditions.
II. Feeble	Felt only by a few people at best, especially on the upper floors of buildings. Delicately suspended objects may swing.
III. Slight	Felt quite noticeably by people indoors, especially on the upper floors of buildings. Many do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.
IV. Moderate	Felt indoors by many people, outdoors by few people during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rock noticeably. Dishes and windows rattle alarmingly.
V. Rather Strong	Felt outside by most, may not be felt by some outside in non-favorable conditions. Dishes and windows may break and large bells will ring. Vibrations like large train passing close to house.
VI. Strong	Felt by all; many frightened and run outdoors, walk unsteadily. Windows, dishes, glassware broken; books fall off shelves; some heavy furniture moved or overturned; a few instances of fallen plaster. Damage slight.
VII. Very Strong	Difficult to stand; furniture broken; damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by people driving motor cars.
VIII. Destructive	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture moved.
IX. Ruinous	General panic; damage considerable in specially designed structures, well designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X. Disastrous	Some well built wooden structures destroyed; most masonry and frame structures destroyed with foundation. Rails bent.
XI. Very Disastrous	Few, if any masonry structures remain standing. Bridges destroyed. Rails bent greatly.
XII. Catastrophic	Total damage - Almost everything is destroyed. Lines of sight and level distorted. Objects thrown into the air. The ground moves in waves or ripples. Large amounts of rock may move position.

Acceleration

Acceleration is the rate of change of velocity in a unit of time. During an earthquake, ground shaking experiences acceleration. Peak ground acceleration is the largest increase in velocity experienced by particles on the ground. Spectral acceleration is what is experienced by a building, modeled after the velocity of the ground shaking. In other words, it is what the building would experience at its base during an earthquake. All structures have a "natural period," or, the rate at which they move back and forth from horizontal force.[162] For example, 10-20 story buildings typically have a natural period of 1 to 2 seconds. The natural period of the ground is between 0.4 and 2 seconds. In an earthquake, if the natural period of the ground movement is close to the natural period of the structure movement, the additional small pushes from the ground can increase acceleration by up to 5 to 6 times. This phenomenon is known as resonance.

Typically, the higher the acceleration, the more stress on a building. Peak ground acceleration can be a good measure for smaller buildings (below 7 stories), while spectral acceleration can be a good measure for larger buildings when also taking building design into account. Seismic acceleration is divided into horizontal (east-west and north-south) and vertical components. The distinction can be critical as some structures are designed to withstand motion in some directions better than others. Acceleration varies with distance from the epicenter and local conditions, like soil type.

In 2007, the USGS developed a series of maps that estimated the maximum acceleration Seattle neighborhoods would face in the next 50 years. They are explained below.

Sometimes duration is also used as a measure because the longer shaking occurs, the greater the likelihood of damage, especially in soft soils. Duration is most concerning in a megathrust earthquake, where shaking can last several minutes.

Geology

The upper level of soil greatly modifies seismic waves that travel through it. The amplification and directionality of seismic waves depends on soil type, soil stiffness, soil thickness and soil geometry (see Figure 5-2).[163] Soft soils, especially those that overlay hard rock, amplify seismic waves. The amplification causes more vulnerable soil farther from the epicenter to shake more intensely than less vulnerable soils closer to the epicenter. Notice how in Figure 5-2, the Duwamish Valley area experiences more intense shaking than the surrounding hills even though they are the same distance from the epicenter. This is because the Duwamish Valley sits on artificial fill that is more susceptible to ground shaking.

Local geology contributes to secondary incidents such as liquefaction and landslides. Liquefaction is a special type of ground settlement that occurs in water-saturated sands, silts, and gravels. In an earthquake, loose soils compact, displacing and pressurizing the water. The “solid ground” then liquefies. Whole buildings have overturned when the underlying soils lose enough tensile strength to support the structure. More commonly, only part of a building sinks, causing uneven settling. If liquefaction occurs on a slope, even if it is gentle, the muddy soil can flow laterally and cause severe structural damage. Earthquakes can trigger landslides by shaking unstable or steep slopes. Wet conditions can exacerbate landslide potential because waterlogged soils are less able to resist shear stress in slopes. More information about landslides can be found in the chapter on them below.

5 1.2 History

The Puget Sound region is been the most seismically active area in Washington.[164] Nineteen earthquakes that were large enough to be felt by humans (approximately greater than M3.0) have occurred in western Washington since 1880 (see Figure [Major earthquakes since 1880 in Washington State]). Twelve of these ten were centered in the Puget Sound region.

Around 900. M7.5 Seattle Fault earthquake. It caused massive landslides and a tsunami. Whole hillsides slid into Lake Washington and Puget Sound. A tsunami estimated to be 16ft flooded much of the low-lying area around the mouth of the Duwamish River. It is estimated that the Seattle Fault has been active 3 – 4 times in the last 3,000 years. Glaciers covering the Puget Sound region probably destroyed any evidence for earthquakes over 15,000 years old.[165]

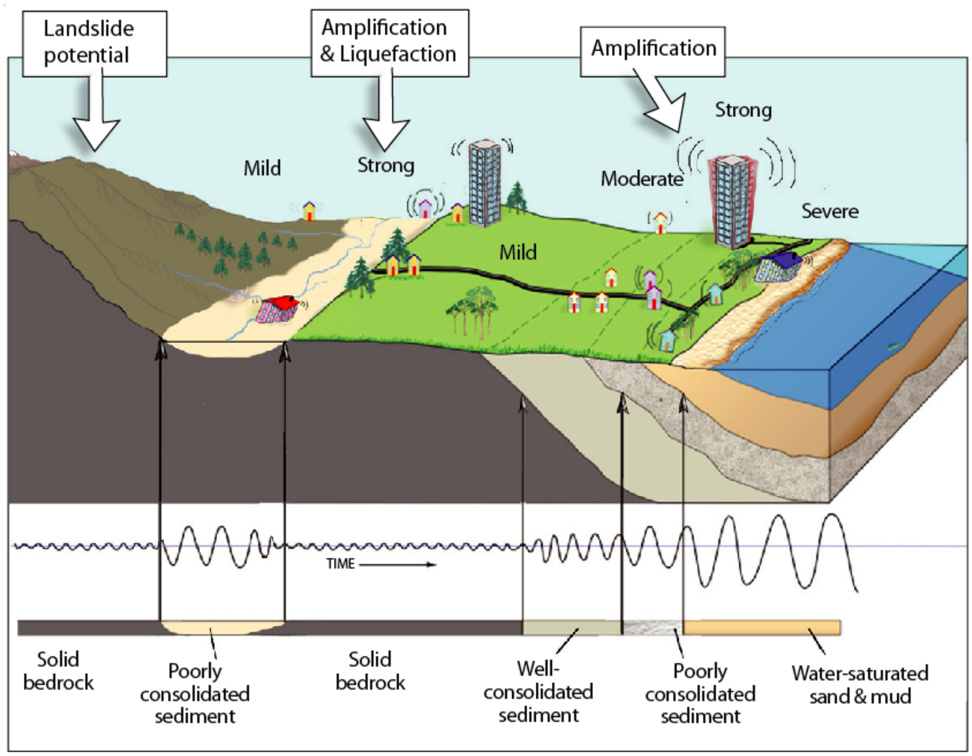
Jan. 1700. M9.0 megathrust earthquake along the Pacific Northwest Coast. Coastal areas dropped 1.5 meters as the Cascadia Subduction Zone ruptured along its 1000 km length. It generated a tsunami that struck Japan.

Dec. 1872. M6.8 shallow earthquake shook the North Cascades. It triggered a huge landslide that temporarily blocked the Columbia River.

Jan. 1909. M6.0 deep earthquake centered in the San Juan Islands.

Nov. 1939. M5.75 deep earthquake centered near Olympia. Chimney and building façade damage near the epicenter. No damage reported in Seattle.

Figure 5-2. Soil Amplification, Liquefaction, and Landslide Hazards from Earthquake Ground Shaking



Apr. 1945. M5.5 (no data on depth) earthquake centered under North Bend. Chimney and building façade damage near the epicenter. Boy hit by falling brick in Cle Elum. No damage reported in Seattle.

Feb. 1946. M6.3 deep earthquake centered under mid-Puget Sound. Damage in Seattle mainly limited to the Duwamish Valley and structures built on pilings.

Apr. 1949. M6.8 deep earthquake centered near Olympia. The earthquake had a peak acceleration of .3g and produced type VIII MMI damage at its highest intensity. Eight people were killed, mostly from falling brick and the region suffered $314 million in damages (2010 dollars). In Seattle, the earthquake's effects were felt mainly in the northern section of West Seattle and at the mouth of the Duwamish River.

Apr. 1965. M6.5 deep earthquake with the epicenter closer to the city than the 1949 quake. The earthquake's acceleration was lower, .2g. While it did cause type VIII MMI damage, most of its effects were limited to type VII MMI. As in 1949, many ground failures occurred in the Alki and Harbor Island areas, but they were not as concentrated as in the 1949 quake. Six people were killed, mostly by falling debris. Damage was $104 million (2010 dollars). Based on these records, one report estimates that M6.5 events have a repeat rate of 35 years and M7.0 events have a repeat rate of 110 years.[166]

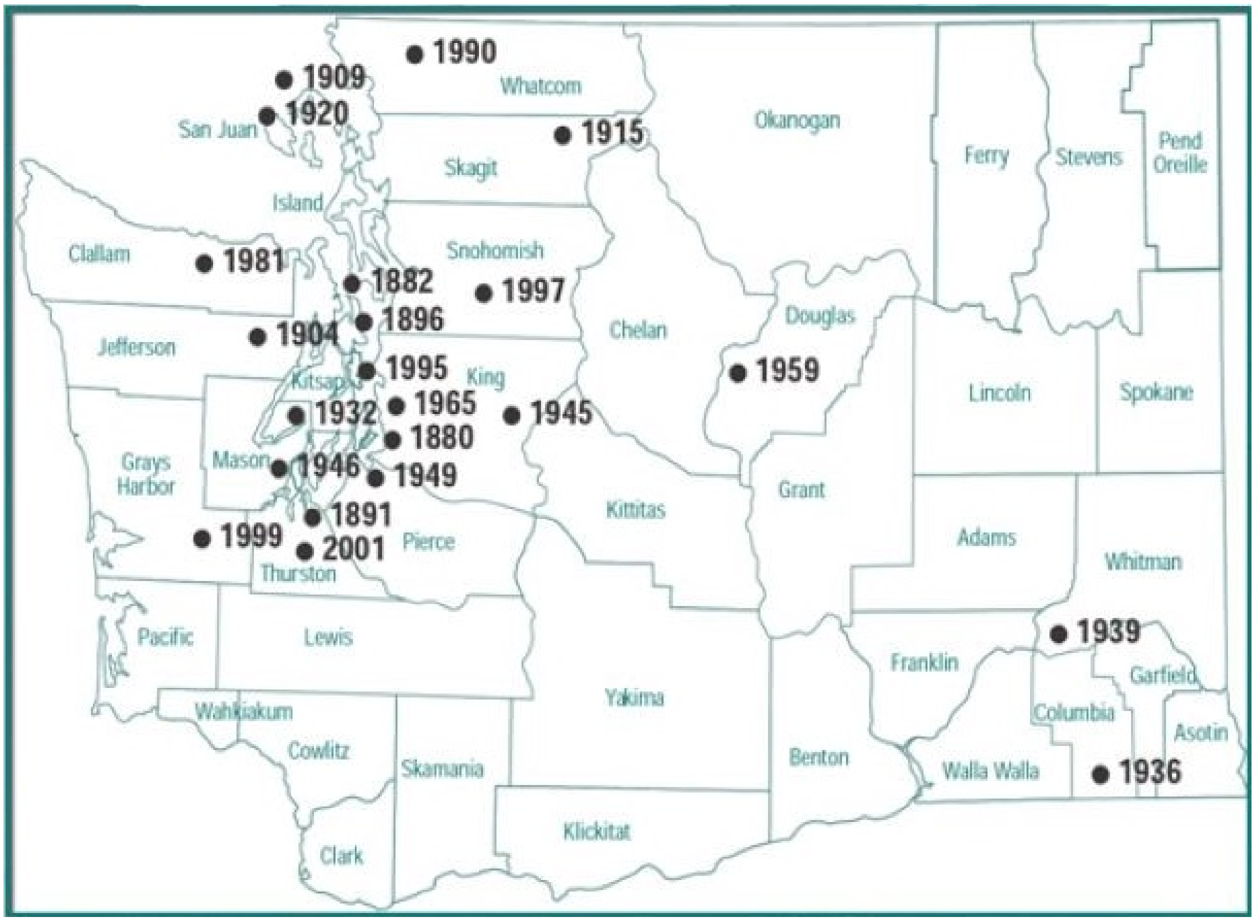
Jan. 1995. M5.0 shallow quake, with a depth of 11 miles. Centered under Robinson Point on Bainbridge Island. No damage reported.

May 1996. M5.3. A shallow quake centered under Duvall. Some light damage reported, mainly objects falling from shelves. No damage reported in Seattle.

Jun. 1997. M4.9. Another shallow quake centered under Bremerton. No damage reported in Seattle.

Feb. 2001. M6.8. Large deep quake under South Puget Sound, the "Nisqually Earthquake." One death was attributed to a stress-related heart attack during the earthquake. 400 people were injured, but only 4 were serious injuries.[167]

Figure 5-3. Major earthquakes in Washington since 1880

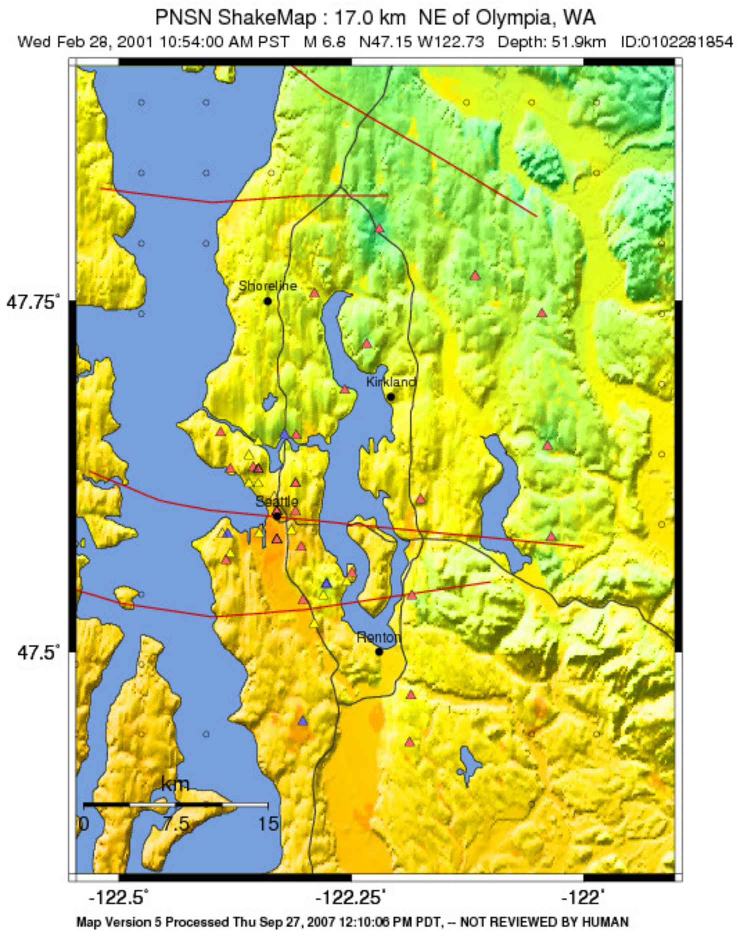


Significant public and private damage occurred as a result of this deep quake. Four residential homes were destroyed, 46 suffered major damage and 120 had minor damage.[168] 217,000 people lost power but only for a few hours. The City of Seattle incurred over $36 million in response costs and repairs to city-owned facilities and systems, and costs from damage to arterial roads and bridges. Eighteen bridges were damaged in the city.[169] Total damages in Seattle were estimated to be over $200 million.[170]

The quake's damage to structures serving vulnerable populations raised concerns. Seattle's Office of Housing (OH) did an unofficial survey of 45 non-profit assisted housing properties serving low-income residents post-Nisqually.[171] Most faced minor structural or plaster damage. One men's homeless shelter, the Compass Center, was red tagged and its 75 male residents were forced to vacate. The building was repaired and seismically upgraded in 2005. The Seattle Housing Authority (SHA) also faced damage to its buildings, which house low-income and elderly people. The two buildings that suffered the most damage were older brick structures that were sold after being repaired. In total, the earthquake cost SHA over $200,000, mostly to repair elevators (most of this cost was reimbursed by the U.S. Department of Housing and Urban Development and FEMA).[172]

The earthquake had direct and indirect impacts on many businesses. The northern end of the Boeing Field runway was closed for two weeks after the earthquake. Results from a survey of 832 small businesses (less than 500 employees) in the Puget Sound area revealed that 20% incurred direct physical losses from the earthquake. Of these, 6.5% suffered losses over $1,000 and 2% suffered losses over $10,000. Overall, average losses amounted to 1.3% of annual revenue. The three areas with the most

Figure 5-4. Nisqually Intensity Measured By Modified Mercalli Intensity Scale



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

identifiable, concentrated small business damage were Downtown Olympia, Seattle's Pioneer Square, and Seattle's Harbor Island.

The largely industrial Harbor Island experienced the highest level of shaking in Seattle, similar to that experienced in heavily damaged areas in the 1994 Northridge, California earthquake. Nearly 40% of Harbor Island firms had direct losses exceeding $20,000. They also suffered high rates of indirect losses from disruption of operations.[173]

5 1.3 Likelihood of Future Occurrences

The USGS estimates that intraplate earthquakes of M6.0 or greater (like the Nisqually quake) occur *about* every 30 to 50 years. Crustal earthquakes with a magnitude of 5.5 to 6.5 occur about every 100 years. Megathrust earthquakes occur every 200 to 1,100 years, or on *roughly* every 500 years.

The last megathrust earthquake occurred in 1700 AD. The last Seattle Fault earthquake was around 900 AD, 1,100 years ago. The USGS sees evidence that the Seattle Fault has been active 3 to 4 times in the past 3,000 years, with an earthquake about M6.5 or greater occurring roughly every 1000 years. Due to

Figure 5-5. Seattle Fault Zone, Liquefaction Areas and Ground Failures

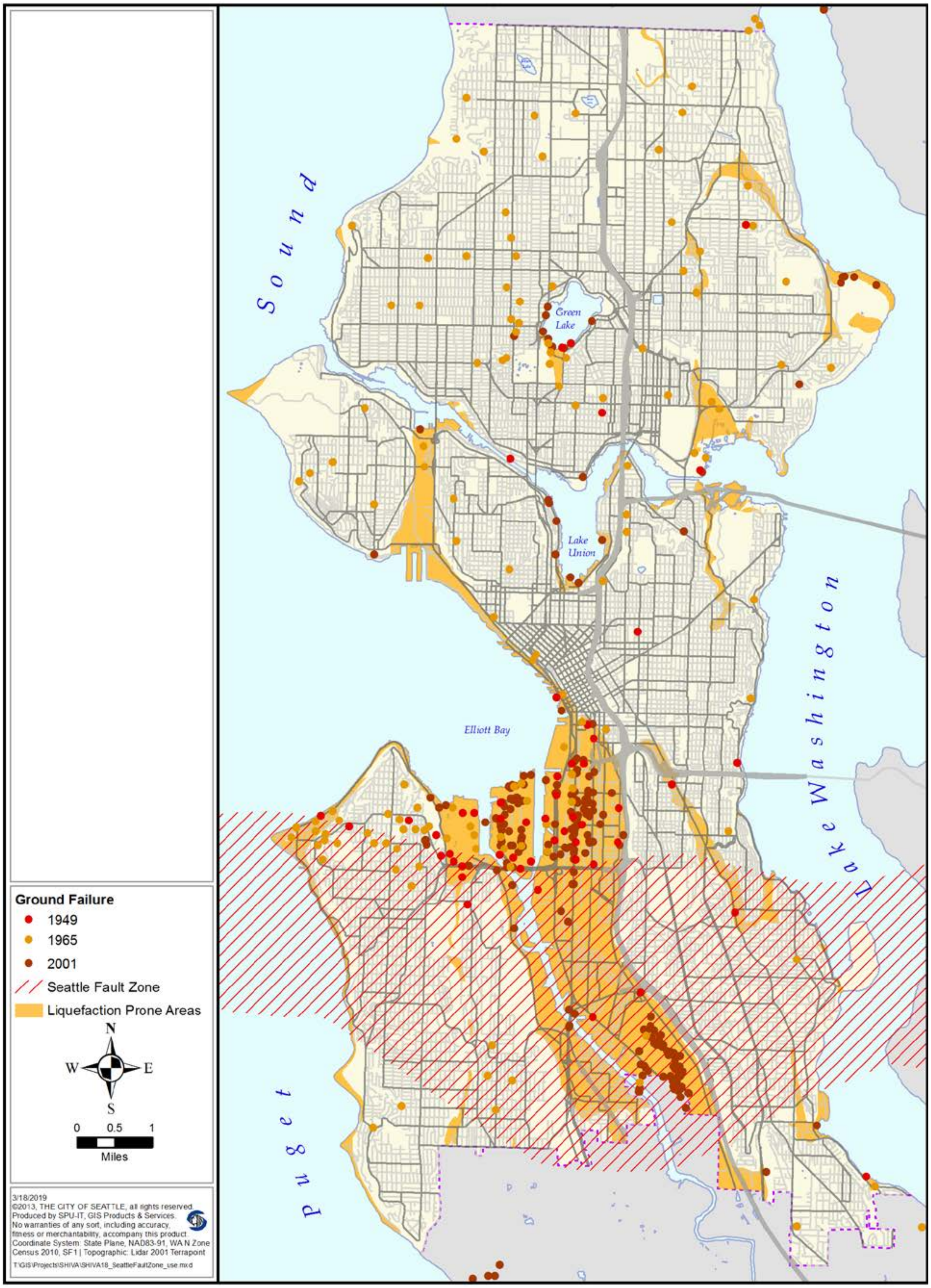


Table 5-2. Earthquake Type and Estimated Frequency

Type	Size	Estimated Frequency
Deep Earthquakes like Nisqually	Over 6.0	Every 30 to 50 years
Megathrust Earthquakes	8.0 to 9.0+	Every 500 years on average
Seattle Fault	Over 5.5	Every 200 – 12,000 years
Seattle Fault	Over 7.2	Every 5000 – 15,000 years

the lack of data for Seattle Fault events, the estimated recurrence intervals have wide ranges. Taking into account estimates from local earthquake scientists and the USGS, the recurrence interval for smaller Seattle Fault earthquakes is every 200 to 12,000 years, and larger events every 5,000 to 15,000 years.[174]

In 2007, the USGS produced a series of probabilistic earthquake hazard maps for Seattle (**Error! Reference source not found.** [Probabilistic Ground Motions]). These maps illustrate the chance that different areas will exceed a certain level of shaking over a 50-year period. The maps were primarily developed to understand the effects of shaking on tall buildings (over 10 stories) and URMs. However, they display the underlying geology, such as areas with artificial fill and soft soils, which are expected to amplify ground shaking for many building types. Ground shaking is measured as a percentage of the force of gravity. It requires more than 100% of the force of gravity to throw objects up in the air. For comparison, reports of "dishes, windows, and doors disturbed" corresponds to about 1.4% to 4% of gravity. Reports of "some chimneys broken" correspond to a range of 18% to 34% of gravity.[175] Areas in dark red have the potential for the highest level of ground shaking, while areas in green are expected to experience less shaking due to the underlying geology.

5 1.4 Vulnerability

Seattle's most vulnerable parts are where fragile populations, soft soils, and weak buildings come to together in areas that could be easily isolated due to breaks in the transportation network. These locations produce vulnerabilities for the whole city because of their social, political, or economic importance.

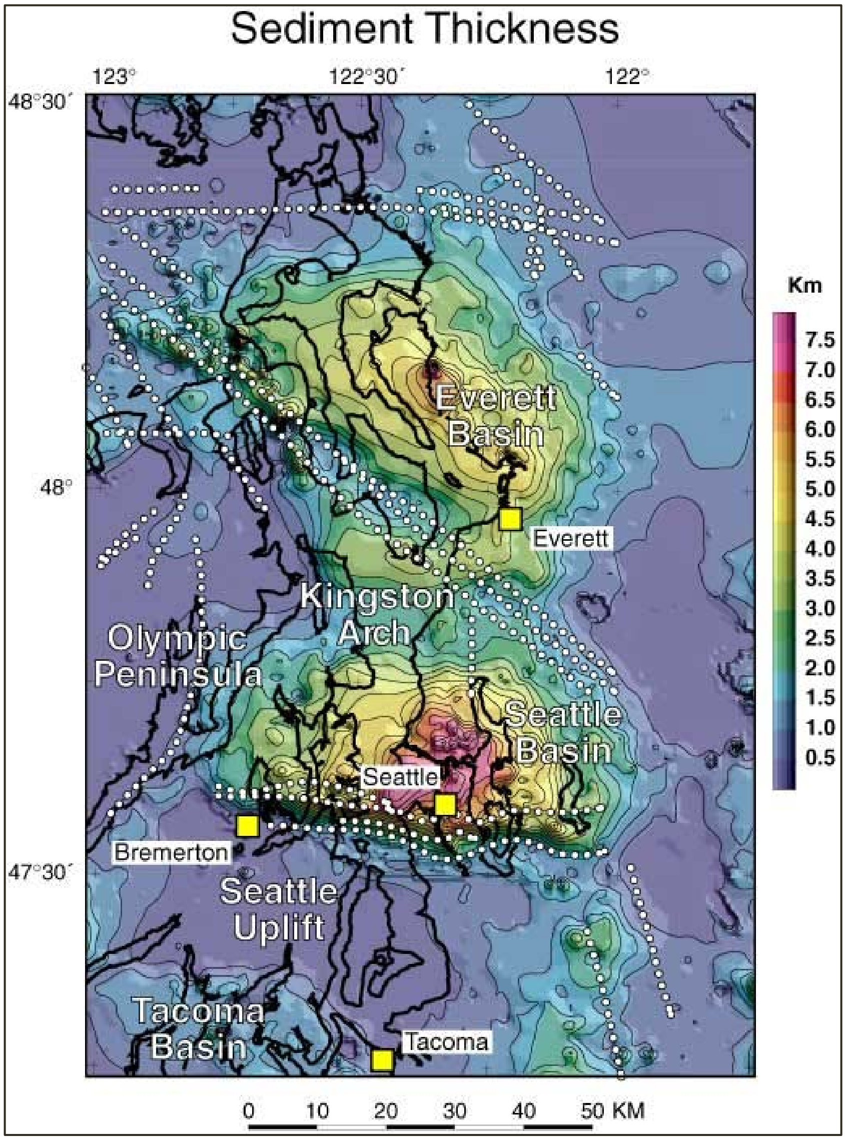
Seattle has a heightened vulnerability to earthquakes because the middle of the city sits on top of the "Seattle Basin," a deep geologic basin filled with glacial deposits, sediments, and sedimentary rock, roughly 7 km deep (see Figure [Sediment thickness in the Seattle Basin]). This looser ground material within the basin amplifies ground shaking in an earthquake and prolongs its duration. The USGS modeled basin effects for a M6.5 Seattle Fault earthquake and estimated that ground motions would last about 25 seconds.[176] Additional modeling is being done by the University of Washington's M9 group, to understand the effects of the Seattle Basin on ground motion in a megathrust earthquake.

While the Seattle Basin will influence ground motions for all of Seattle, surface geology creates variability in shaking for different parts of the city. The 2007 USGS seismic hazard maps (see Figure 5-9 Probabilistic Ground Motions) reveal that Seattle's neighborhoods experience dramatically different levels of shaking. Seattle's liquefaction and landslide-prone areas appear to experience more severe ground motion than other areas and southeast Seattle is likely to experience serious but comparatively less shaking than the rest of the city.

Liquefaction

Looser, fill soils that are prone to liquefaction are present in Seattle's Duwamish area, including Harbor Island, the east side of West Seattle, the Interbay area, University Village area and along the Puget

Figure 5-6. Sediment Thickness in the Seattle Basin



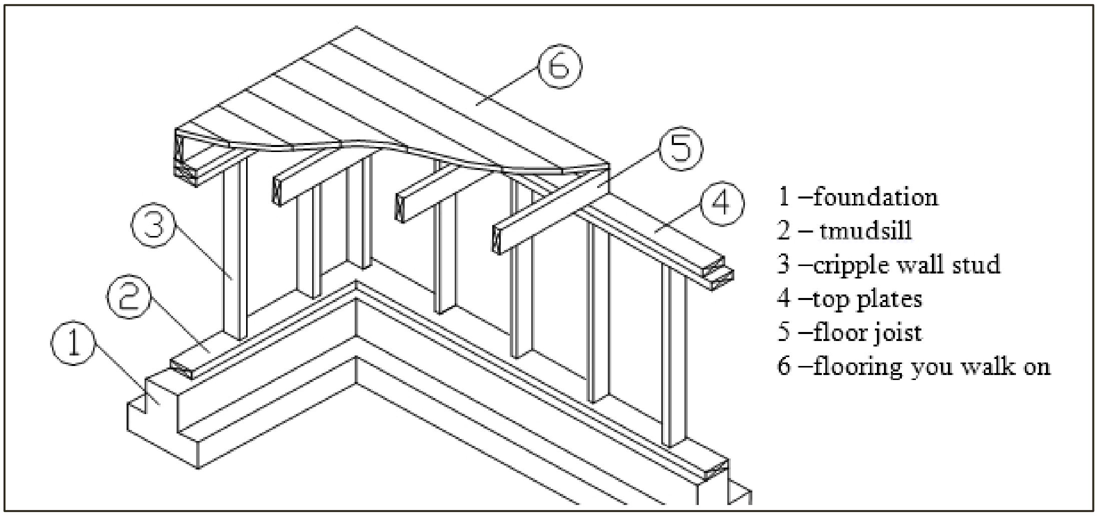
Sound. Ground failures caused by previous earthquakes in Seattle have primarily been located in these areas of artificial fill (see **Error! Reference source not found.** [Seattle Fault Zone, Liquefaction Areas and Ground Failures]). The tables below summarize land use in liquefaction prone areas.

Structures

Vulnerable structures are not evenly distributed throughout the city. Those constructed with unreinforced masonry (URMs) are the most vulnerable, followed by non-ductile concrete frame structures with masonry infill and tilt-up concrete structures. Seattle has over 1100 identified URMs.[177]

The neighborhoods with the greatest number of URMs include Capitol Hill, Pioneer Square, Duwamish/SODO, Queen Anne, and the University District. The majority of URMs are commercial or office buildings, residential buildings, or public assembly buildings. URM damage in Seattle alone amounted to $8 million in the Nisqually earthquake.[178]

Figure 5-7. Cripple Wall Construction



Source: Homeowner's Guide to Seismic Retrofitting, Bay Area Retrofit. Retrieved July 24, 2018, from https://www.bayarearetrofit.com/seismic-retrofit/

The number of non-ductile concrete frame and tilt-up structures is not known; however, these construction types are fairly common in the Pacific Northwest. Many concrete frame structures built before 1980 do not have enough steel reinforcement to withstand the shaking from a strong crustal or megathrust earthquake.[179] Tilt-up structures, commonly used for warehouses or strip malls, often lack adequate connection between their walls and roof, making the roof prone to collapse in an earthquake. There is a concern for structures built before 1995 that have not been retrofitted. Most of these buildings are commercial and older multi-family dwellings. Additionally, many older buildings have parapets that are easily damaged and often fall into the right of way during earthquakes.

Most of Seattle's single family residential housing stock is wood frame, a construction type that performs better than most others in earthquakes. However, having a wood frame does not guarantee that a home will ride out an earthquake problem free. More than half of Seattle homes were built prior to the introduction of modern seismic codes in 1949. Many have short cripple walls (also called "pony walls") between the foundation and floor joists. They are prone to failure, pitching the building off its foundation and causing major utility damage. These homes can be inexpensively retrofitted to eliminate this danger, typically by bolting the home to its foundation. The City of Seattle has sponsored a program since the mid-1990's to promote these retrofits.

Seattle's multi-family structures are vulnerable, too. Many built in the late 1950s and early 1960s have "soft" stories where pillars hold up parking on the ground floors. The soft stories lack shear strength and are prone to failure. Neighborhoods that have concentrations of older and soft-storied multi-family buildings will suffer disproportional impacts. They include Downtown, Belltown, First Hill, Capitol Hill, Queen Anne, University District, and Ballard. Downtown has the highest concentration of high-rise office and apartment buildings. Even if a multi-story building does not sustain much structural damage, there can be damage to utilities or elevators that could contribute to displacement of workers and residents after an earthquake.[180] After Hurricane Sandy hit New York in 2012, there were 65 residential and office buildings in lower Manhattan alone that suffered long-term utility damage and displaced many residents.[181]

A large-scale study of how Seattle's building stock would fare in an earthquake has not yet been conducted. Research from other earthquake-prone areas can shed light on the vulnerabilities of the

Figure 5-8. Home Damage Due to Inadequate Cripple Walls

Photograph by John K. Nakata. Source: Nakata, J. K., Meyer, C. E., Wilshire, H. G., Tinsley, J. C., Updegrove, W. S., Peterson, D. M., Ellen, S. D., Haugerud, R. A., McLaughlin, R. J., Fisher, G. R., & Diggles, M. F. (1999) The October 17, 1989, Loma Prieta, California, Earthquake – Selected Photographs, U.S. Geological Survey. Retrieved July 24, 2018, from https://pubs.usgs.gov/dds/dds-29/

urban environment to intense ground shaking. After reviewing building damage in the 1989 Loma Prieta and 1994 Northridge earthquakes in California, the USGS found that for every collapsed structure, 13 red-tagged buildings can be expected, and for every red-tagged building, 3.8 yellow-tagged buildings can be expected.[182] For the 2001 Nisqually Earthquake, Seattle had 6 yellow-tagged buildings for every red-tagged building.[183]

The Oregon Department of Geology and Mineral Industries (DOGAMI) conducted a study on earthquake damage to structures in an M9.0 Cascadia scenario for a three-county region in Northwest Oregon, including Portland. While the results cannot be directly related to Seattle's vulnerability, it provides a general idea of the amount of destruction we could possibly expect in an urban area from a megathrust earthquake. For Multnomah County (includes Portland), the researchers estimate that in dry conditions, 3,536 (1%) of buildings would have complete damage and 302 would collapse.[184] In wet conditions, that number jumps to 13,039 (5%) completely damaged and 677 collapsed, due to the increased likelihood of landslides and liquefaction.[185] Wood-frame single-family structures fare best while industrial and commercial buildings fare the worst (it should be noted that Portland has around 50% more URMs than Seattle[186]). Injuries and fatalities were studied at the city level. If an M9.0 megathrust earthquake occurs during the day, they estimate that Portland will experience 10,404 injuries, most of which are minor, and 604 fatalities.[187] The nighttime estimation drops to 2,491 injuries and 119 fatalities considering that most people will be in wood-frame structures.[188]

Portland does not sit on top of a deep geologic basin of glacial deposits like Seattle. The effect of basin amplification on structures has been studied. Marafi and colleagues analyzed data from earthquakes that occurred in deep basins in Japan that have a similar profile to the Seattle Basin. They found that in a megathrust earthquake, the basin effects lower the threshold at which reinforced concrete moment frame structures collapse for 30 different building archetypes.[189] In other words, if two identical buildings faced the same ground shaking scenario from a megathrust earthquake, the one located in the basin would collapse easier than the one outside of the basin. A second study by Marafi examined the sway of buildings in an earthquake from 4 to 40 stories high and found that buildings within the Seattle Basin sway three times more than those outside of it.[190]

Another study used past ground motion data to quantify the effects of megathrust earthquakes on 24 older and modern buildings in Seattle and Portland. They concluded that megathrust earthquakes are more likely to cause building collapse than crustal earthquakes and contribute this consequence to the longer duration shaking that is expected in a megathrust earthquake.[191]

Isolation Vulnerability

Seattle is highly dependent on bridges. The City of Seattle owns 159 bridges. Fifty-one have received seismic retrofits or were built to current seismic standards, and an additional 17 are scheduled to receive retrofits pending approval of a levy.[192] A remaining 91 bridges have not been retrofitted as of 2018. The improvements should save these bridges from catastrophic collapse, but many will not be functional after a strong Seattle Fault or megathrust earthquake.

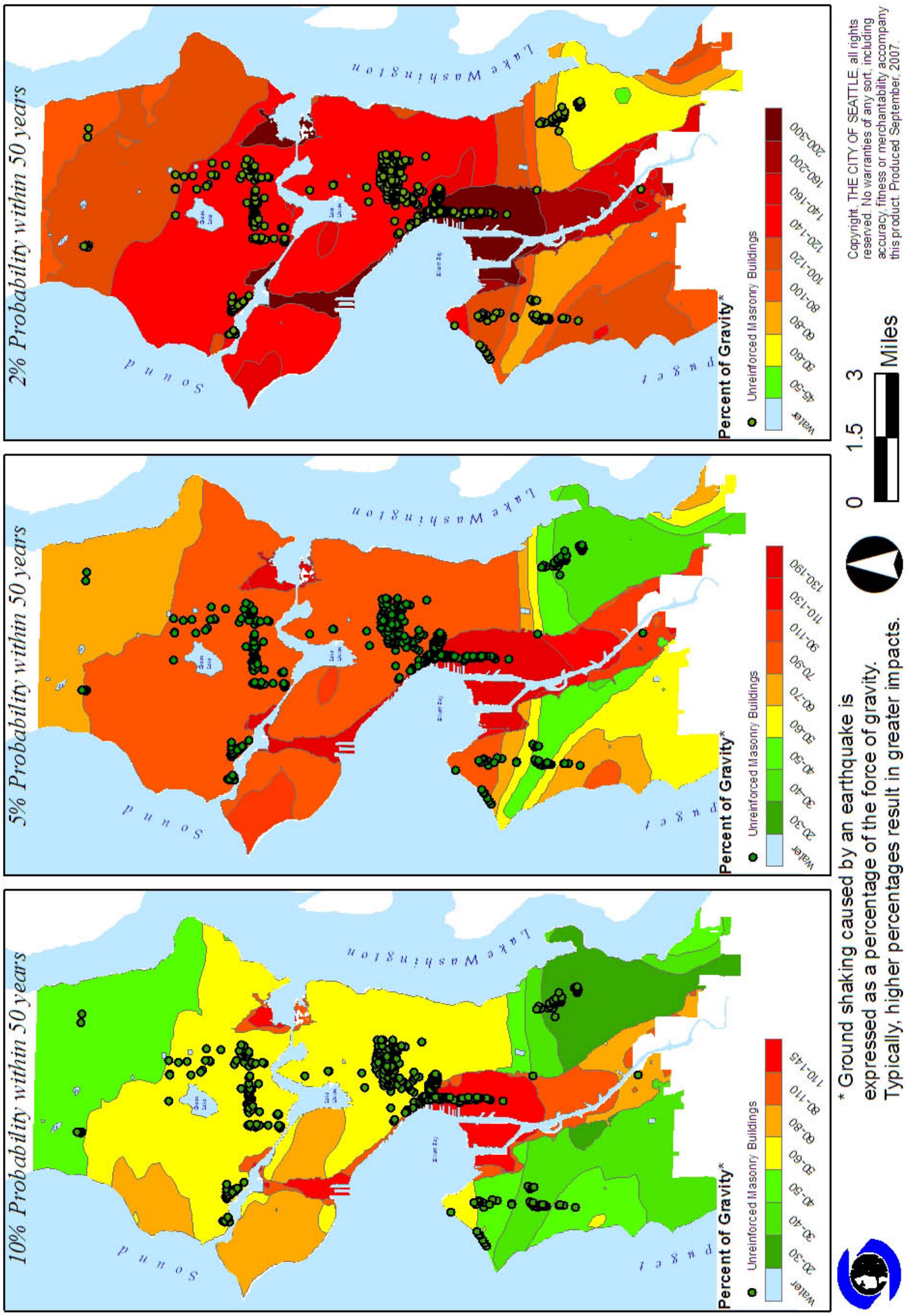
The Loma Prieta, Northridge, and Kobe earthquakes showed that even modern freeways and overpasses can collapse. Large portions of I-5 and I-90 rest on columns and run near slopes prone to failure. The Washington State Department of Transportation (WSDOT) owns the rest of Seattle's bridges including critical ones such as the Aurora Bridge and the I-5 Ship Canal Bridge. Through their own seismic retrofit program, they have completed retrofits for 53 out of 102 state-owned bridges in Seattle as of 2018.[193] The bridge being constructed near the south portal of the new SR 99 tunnel uses both flexible rebar and concrete. Not only should these new materials avoid a collapse, but they should also minimize damage, so the road is still usable after an earthquake.[194] It is the world's first "flexible" bridge.

Breaks in the street and bridge network would impair the delivery of emergency services. The region's largest trauma center and most of the city's medical services are on First Hill or Capitol Hill. These medical centers would be difficult to reach if a major bridge or section of freeway collapsed. Police and fire stations are more decentralized, increasing the likelihood that at least some units could reach an emergency. However, moving police and fire vehicles from a lightly impacted area to a heavily impacted one could be very difficult if bridges fail.

Transportation Vulnerability

Surface, marine, and air elements of Seattle's transportation system are exposed to earthquake hazards. Liquefaction is a common element to this exposure. Most of the Duwamish Valley is a liquefaction zone. Both of Seattle's major north-south corridors, I-5 and SR99/SR509 run through this zone, as well as key bridges and elevated structures, including the Alaskan Way Viaduct, the West Seattle Bridge, the First Avenue South Bridge, and approaches to the end of I-90. The King County International Airport is completely in the liquefaction zone as are most of the city's rail and marine terminals.

Figure 5-9. Probabilistic Ground Motions



Utility Vulnerability

Water systems have suffered significant damage in major earthquakes that have occurred around the world. Damage to treatment facilities, storage (tanks and reservoirs) facilities and pipelines has resulted in significant disruption to water utilities. Power outages and damage to transportation and communications facilities has further complicated water service restoration. In the most catastrophic earthquakes, it has taken over two months to restore water to some customers.

Seattle Public Utilities (SPU) completed a seismic water system evaluation in 1990. Based on this assessment, many SPU water facilities were seismically upgraded or replaced with more seismic-resistant facilities. Examples include the replacement/upgrade of the West Seattle, Myrtle, Beacon and Maple Leaf intown reservoirs, replacement of the Queen Anne Standpipes, building upgrades to the Operations Control Center Warehouse and four pump stations, and upgrades to the Cedar River pipelines where they daylight at Ginger Creek.

A new seismic study was conducted by SPU from 2016 to 2018. Since the original 1990 study was completed, the understanding of the seismicity in western Washington has evolved and building codes have been updated. The determination that large shallow earthquakes are possible in western Washington from such sources as the Seattle Fault Zone has significantly increased the earthquake hazard level that SPU facilities may experience.

The new study estimates that after a M9.0 Cascadia Subduction Zone or M7.0 Seattle Fault earthquake, most or all areas in SPU's direct service area could lose water system pressure within 12-24 hours of the earthquake. The study further estimates that it could take one month to restore customer service to 70% of direct service customers and two or more months before service has been restored to all customers. In smaller, more frequently occurring earthquakes such as the 1949, 1965, and 2001 Puget Sound earthquakes, significantly less damage will occur and little, if any, disruption to the SPU water system is expected.

Efforts in the future to increase seismic resiliency will likely focus on:

- Using isolation and control strategies to mitigate the earthquake effects on the water system
- Improving emergency preparedness and response planning
- Continuing to seismically upgrade existing critical facilities
- Increasing the seismic reliability of the transmission pipeline system that conveys water into Seattle and to SPU's wholesale customers (most of King County)
- Use earthquake-resistant distribution pipe in those areas susceptible to permanent ground displacement

Seattle's power, sewer, and telephone systems have not been recently studied. Their vulnerability can be somewhat deduced from past performance and studies of other earthquakes. A Washington State report mentions that both the 1949 and 1965 quakes interrupted service in water, sewer, gas, and electric systems. The report does not describe any damage to the telephone network. A summary of the infrastructure damages from the 1989 Loma Prieta quake outlines the same problems. It adds that widespread utility outages were common, but most were less than a day long.[195] This performance is quite good, but the epicenters in these quakes were far from the areas studied. Puget Sound Energy has replaced over 8,000 miles of its 12,000-mile network of gas mains with flexible plastic pipe that can withstand earthquakes.[196] During the 2011 Tohoku earthquake in Japan, at least six main submarine fiber optic cables connecting Japan's communication network to other countries were damaged.[197]

The Bonneville Power Administration (BPA), located in Oregon, provides about half of Seattle's power. BPA seismic evaluations have revealed that transmission towers are especially vulnerable to seismicallyinduced ground displacement, landslides, and liquefaction. Other vulnerable equipment includes substations and rigid bus connections. BPA has prioritized anchoring high-voltage transformers to their foundations to ensure that power flow is not compromised in an earthquake. They use base isolation technology for protecting transformers.[198]

Liquefaction may threaten critical utility systems by damaging or isolating infrastructure. SPU's water transmission pipelines cross areas with liquefaction and landslide susceptibility and through the Seattle Fault and South Whidbey Island Fault Zones. The Olympic BP Pipeline and sewer main lines cross the Duwamish liquefaction zone. SCL's South Service Center and two of its substations are in a liquefaction zone, but all sit on pilings. SCL uses an uncommon voltage in their system, so if transformers are destroyed due to liquefaction or other earthquake hazards, they must be rebuilt from scratch. The biggest danger for these facilities is the potential loss of access due to transportation system damage.

Secondary Hazards

Secondary hazards can have more impact than the initial ground shaking. The most significant secondary hazards are fires, hazardous materials releases, tsunamis, and landslides. Each of these hazards is described fully in its own chapter.

Fires

Fires were the most frequent cause of death in the 1995 Kobe earthquake. Additionally, most of the 28,000 buildings destroyed in the 1906 San Francisco earthquake were lost in the conflagration that followed it. Multiple ignitions developing into a conflagration is the most dangerous post-earthquake fire hazard. Khorasani and Garlock (2017) reviewed 20 historic earthquakes of M5.0 or greater, that resulted in multiple fire ignitions. They identified key cause and response factors: wind was a key factor in how much the fire spread; gas pipes, electric wiring, and toppled furniture were the major sources of ignition; and availability of water after an earthquake is a key determinant in the ability to control a conflagration.[199] Scawthorn and colleagues developed an ignition rate based on the MMI scale. For an earthquake with an MMI intensity of VII ("very strong"), one ignition per 18 million square feet of building floor area is expected.[200] In an MMI X ("disastrous") scenario, one ignition per 1.5 million square feet of building floor area is expected.[201] To put these rates in perspective, Amazon, which is believed to occupy about 13.6 million square feet of building space, would experience about 9 ignitions. However, one should note that commercial construction is less vulnerable to fire than wood-frame construction.

Normally, Seattle would call on neighboring city fire departments for help, but in a Seattle Fault earthquake they will probably not be able to provide it. With Seattle's fire-fighting resources spread thin, a conflagration becomes very likely, especially if the water system has been damaged and water pressure drops. There is additional concern for conflagration with the expected increase in development of multi-story wood structures in Seattle (see fires chapter).

Hazardous Materials Incidents

During earthquakes, stored chemical containers can rupture and release their contents. Most of these spills will be small and contained within structures, but they present a serious hazard to people in these buildings. Krausmann and Cruz collected data on 46 chemical facilities in Japan to review damage caused by the 2011 Tohoku earthquake. They found that 28 of these facilities had equipment damages with possible hazardous materials releases.[202] Additionally, building debris often contain toxic substances like asbestos. The Seattle School District implemented a non-structural mitigation program to limit post-earthquake release of hazardous chemicals. A small number of releases could escape into the atmosphere creating a widespread hazard.

Tsunami

Tsunamis in Seattle are not likely, but should they occur they have the potential to be extremely dangerous. New tsunami modeling for a Cascadia Subduction Zone scenario is underway. Preliminary findings show that there would be less inundation in this megathrust earthquake compared to a Seattle Fault earthquake.[203] The most dangerous source of tsunami is the Seattle Fault, which is believed to have produced a 16ft tsunami in the past. Although there is no precise correlation between earthquake size and tsunami size, a rough estimate is that earthquakes usually have a magnitude of 7.0 or greater before they generate a tsunami.[204] In 2001, the National Atmospheric and Oceanic Administration (NOAA) modeled a Seattle Fault-generated tsunami. It is covered in full in the Tsunami chapter. The low-lying areas around the downtown sports stadiums, Harbor Island, and Interbay are the most at risk for inundation in a tsunami. Because a tsunami generated inside Elliott Bay would strike within minutes after the most powerful earthquake Seattle has ever experienced, the only realistic escape option would be into the upper floors of buildings, many of which will be severely damaged. The waterfront is a popular and densely packed area, compounding this exposure.

Landslides

Allstadt and colleagues examined the potential for shallow (less the 2.8 meters deep) landslides following a M7.0 Seattle Fault earthquake. They found that the quake could cause 5,000 landslides in dry conditions and 30,000 in extremely wet conditions. While the study only models a single scenario, and completely wet conditions are unlikely, it is still a sobering look at the potential for landslides following a Seattle Fault earthquake. The study did not model deep seated landslides, which can cause whole hillsides to fail. Landslide prone areas are spread throughout the city along hillsides. These areas are mostly zoned as open space or residential. North Seattle has less landslide-prone areas than the central and southern areas. The major northern landslide area is Golden Gardens in Ballard. In the middle of the city, Magnolia, Queen Anne, Madrona, West Seattle, and the northern end of Beacon Hill are all potential landslide areas.

5 1.5 Consequences

Earthquakes cause widespread physical damage across the whole city through intense ground shaking, with higher damage rates in areas that were once valley bottoms or estuaries. The physical damage can cause high casualties, transportation blockages, utility outages, hazardous materials releases, and fires. If the earthquake is powerful enough it can trigger landslides, tsunamis, and seiches.

When estimating annualized earthquake losses in 2017, FEMA ranked Washington second to California.[205] Among metropolitan areas, FEMA ranked Seattle fifth, behind four metropolitan areas in California: Los Angeles, San Francisco, Riverside, and San Jose.[206]

A megathrust earthquake would cause several times more damage than the 2001 Nisqually Earthquake. Damage locally would be just a small fraction of that extending up and down the whole Pacific Northwest coast. A strong Seattle Fault earthquake would be a catastrophe for Seattle, but outside response and recovery resources would be easier to obtain because the damage would be more localized than in a megathrust earthquake.

In 2005, Earthquake Engineering Research Institute (EERI) worked with the region’s scientific and engineering community to model impacts of a 6.7 magnitude Seattle Fault earthquake. The EERI scenario predicts ground rupture of approximately 6 vertical feet from Harbor Island to Issaquah. Ground motions would be two to five times that of the Nisqually Earthquake. This type of rupture on the Seattle Fault zone would severely disrupt north-south lifeline systems, including utilities and transportation routes.[207] Estimates are 1,600 fatalities regionally. Despite the enormity of the 2005 scenario, the Seattle Fault is capable of causing earthquakes up to magnitude 7.3, but earthquakes of that size are probably much rarer. Modern building code in Seattle requires that structures can withstand the types of ground motions that a 6.7 Seattle Fault earthquake would produce.

Effective earthquake response begins with a working transportation system, yet it would be severely impacted by either a megathrust or Seattle Fault earthquake. Due to its dependence on bridges, Seattle could face major difficulties responding if key structures go out of service. It would be difficult to move emergency personnel and resources to where they are needed or to get the injured to hospitals.

If the region experiences a larger shallow/crustal or megathrust quake, most utility services would be severely impacted in large parts of the city. If trunk lines break or critical substations and transformers are broken, outages would occur over a wide area. If many lines are damaged, outages would persist for a longer time. Another deep quake would probably cause only minor interruptions, but these impacts could be severe if the epicenter were closer to Seattle than the Nisqually Earthquake.

Fire suppression is critical after earthquakes. It is highly probable that Seattle's water distribution system would be damaged in a shallow/crustal or megathrust quake, limiting the ability to fight post-earthquake fires. This danger has been mitigated by plans to reroute water, the ability to draw water from open water sources such as reservoirs, lakes, and the Sound, and the use of flexible overland piping.

The economic impacts of a large earthquake would be enormous. In 2005, EERI estimated that losses for an M6.7 Seattle Fault earthquake would amount to $33 billion (almost $43 billion in 2018 dollars). It's likely that number would be much higher now, considering Seattle's population has grown by about 27% since 2005. A successful recovery would depend on local, regional, and national political and economic conditions. Additionally, in a megathrust earthquake, where consequences will be felt across the whole region, Seattle will have to rely mainly on itself, with reduced outside assistance. Locally, the city would have to be able to work well as a community to develop a set of shared goals. Recovery can be delayed for years if a community cannot achieve consensus about how it should rebuild post-disaster. A recovery would also depend heavily on favorable economic conditions. Overall community and economic health status trending at the time of a disaster can impact recovery.

Seattle's URMs are likely to suffer heavy structural damage or collapse in a large earthquake. About half of the city's URMs are commercial, industrial, or office buildings, while the other half are residential, public assembly, government, and mixed-use spaces, and schools. The consequences of these facilities collapsing could include major economic losses to businesses, and potential injury or death to their inhabitants.

The larger Seattle business community will face challenges if the transportation and telecommunications networks are disrupted. If these systems remain inoperable for a long period of time, Seattle enterprise could face a permanent loss of business, as Kobe did following the 1995 earthquake.

The 2005 Seattle Fault earthquake scenario estimated that 46,000 households would be temporarily displaced. About half will need short term shelter (less than 2 weeks) but the rest will need housing for a few months. 15% or 6,900 of these would be displaced for over six months. Some of these households would find shelter with family, others would find rentals, but the government would have to assist with locating shelter for a large percentage of these households.

Earthquakes are natural events, but they can cause severe environmental damage. The last Seattle Fault earthquake triggered numerous landslides that sent whole hillsides into Lake Washington and Puget Sound. The trees that grew on these hillsides slid into Lake Washington and became navigational hazards for boats. Earthquakes are also expected to trigger hazardous materials releases when structures that house them are damaged or contaminated sediment in the Duwamish Waterway Superfund site is re-suspended.

One factor that could mitigate the loss of life from an earthquake is the development of the Earthquake Early Warning (EEW) system. Strong ground shaking comes after the first wave of energy that radiates from an earthquake's epicenter. An EEW system detects this first wave of energy and instantly sends out a warning that strong shaking is to be expected in a matter of seconds to tens of seconds, depending on the location of the earthquake. These few seconds of warning time could allow people to shelter in a safe place, could warn drivers or train conductors to stop, or could allow workers to isolate or shut down industrial systems. Pilot testing for EEW in Washington, called "ShakeAlert," is underway, with limited public notification set to begin in 2018.[208]

5 1.6 Conclusions

Earthquakes are both high probability and high impact events in Western Washington, making them the most likely source of the most damaging disaster Seattle will face. A large earthquake could cause hundreds of deaths and lasting damage to the city's economic base. Secondary impacts could include hazardous materials spills, infrastructure failure, landslides, conflagrations, seiches, or even a tsunami. Each of these would cause additional damage and potential casualties. Response to and recovery from a large earthquake would be the largest challenge this community has confronted.