Earthquake

Earthquake

Frequency	50+ yrs	10-50 yrs	1-10 yrs	Annually
People	<1,000	1,000-10,000	10,000-50,000	50,000+
Economy	1% GDP	1-2% GDP	2-3% GDP	3%+ GDP
Environment	<10%	10-15%	15%-20%	20%+
Property	<$100M	$100M-$500M	$500M-$1B	$1B+
Hazard scale	< Low to High >			

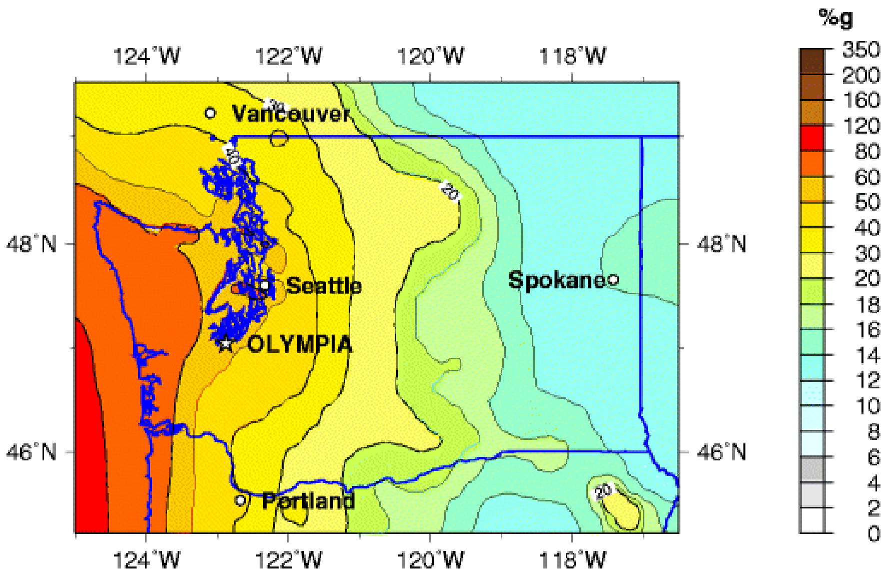
Risk Level

- Frequency – According to Washington State Department of Natural Resources, over 1,000 earthquakes occur annually in the state. This is an average of approximately 3 per day though most go unfelt and do not cause damage.[1] Larger magnitude earthquakes, which result in damage, occur less frequently in the state.
- People – The population affected in an earthquake depends on many variables like the magnitude of the earthquake, the population present in the areas of strongest shaking, the time of day, the age of buildings affected, soil at the location, and many other factors. It is plausible that an earthquake in the state could injure or kill anywhere between 0 and 10,000 or more people.
- Economy – The economy affected by an earthquake depends on variables similar to above and if there is a large magnitude earthquake near the major Puget Sound ports in Olympia, Seattle, Tacoma, and Everett could cause significant damage to the state's economy.
- Environment – The type of environmental impact or damage that occurs in the event of an earthquake does not meet the minimum threshold of ten percent or more loss of a single species or habitat.
- Property – Statewide annualized loss estimates from Hazus-MH 2.1 indicate total losses over $300,000 million. Property damage could be in excess of $20 billion dollars in the event of a catastrophic earthquake.

Hazard Area Map

Figure 5.4-1 Peak Acceleration (gravity % (g)) with 2% Probability of Exceedance in 50 Years.

The USGS map shows how the State's Peak Ground Acceleration (PGA) is much higher in the heavily populated and highly urbanized Puget Sound region than in other parts of the state.



Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
site: NEHRP B-C boundary
National Seismic Hazard Mapping Project (2008)

Summary

The hazard – An earthquake is the sudden release of stored energy that produces a rapid displacement on a fault and radiates seismic waves. Although over a thousand earthquakes are recorded in Washington each year, only a few have shaking strong enough to be felt by people. Infrequent large earthquakes such as the 2001 Nisqually event produce very strong ground shaking. This strong shaking causes damage directly to structures and a variety of secondary effects such as ground failure, landslides, and liquefaction. Earthquakes also have a high potential for causalities given their sudden onset.

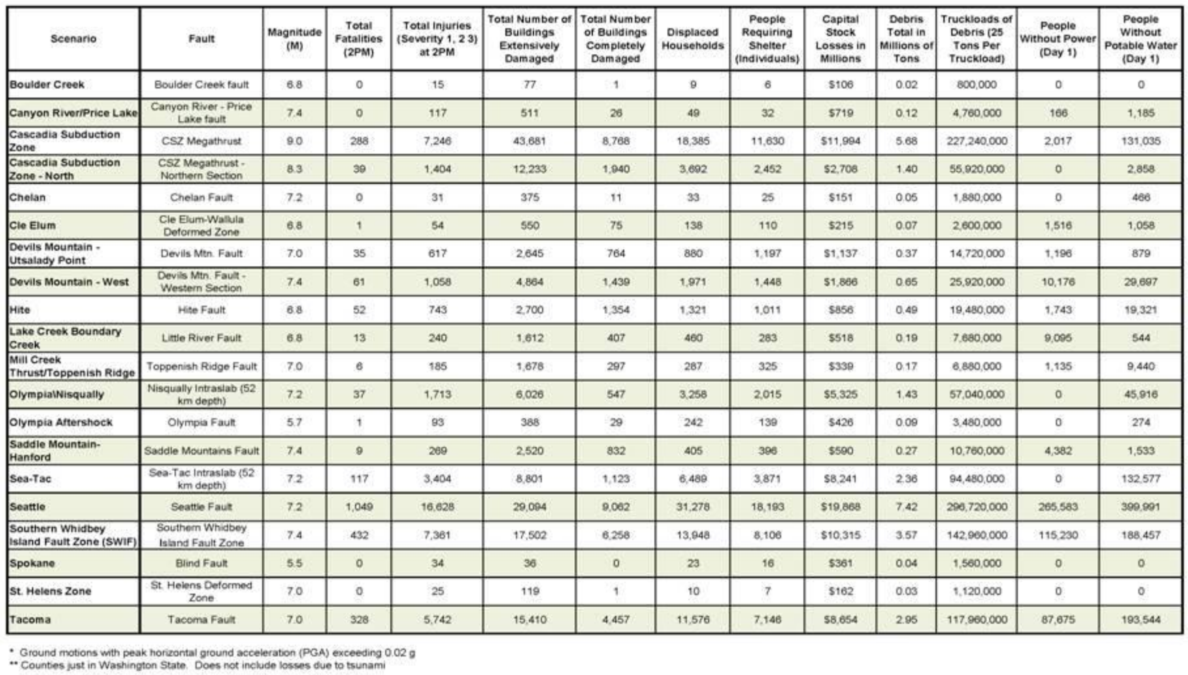
Previous occurrences – The Washington coast and the greater Puget Sound Basin are most at risk although damaging temblors have occurred east of the Cascades. The Puget Sound basin had damaging earthquakes in 1909, 1939, 1946, 1949, 1965, and 2001. Eastern Washington had a large earthquake in 1872 near Lake Chelan and in 1936 near Walla Walla.

Probability of future events - Because of its location near the collision boundary of two major tectonic plates, Washington State is particularly vulnerable to a variety of earthquakes. FEMA has determined that Washington State ranks second (behind only California) among states most susceptible to damaging earthquakes in terms of economic loss. FEMA notes that a majority of the state is at risk to strong shaking (on a scale of minimal to strong) with shaking magnitude generally decreasing from west to east.

Jurisdictions at greatest risk – Communities in western Washington, particularly those in the Puget Sound Basin and along the Pacific coast, are most at risk from earthquakes. Some counties in eastern Washington (Chelan, Douglas, Grant, Kittitas, Yakima, Benton, Franklin, Walla Walla, and Spokane) are also vulnerable.

Table 5.4-1 below uses United States Geological Service data and Hazus-MH to model several scenarios completed throughout the state.

Table 5.4-1. The Washington State Earthquake Hazards Scenario Catalog.



Scenario	Fault	Magnitude (M)	Total Fatalities (2PM)	Total Injuries (Severity 1, 2 3) at 2PM	Total Number of Buildings Extensively Damaged	Total Number of Buildings Completely Damaged	Displaced Households	People Requiring Shelter (Individuals)	Capital Stock Losses in Millions	Debris Total in Millions of Tons	Truckloads of Debris (25 Tons Per Truckload)	People Without Power (Day 1)	People Without Potable Water (Day 1)
Boulder Creek	Boulder Creek fault	6.8	0	15	77	1	9	6	$106	0.02	800,000	0	0
Canyon River/Price Lake	Canyon River - Price Lake fault	7.4	0	117	511	26	49	32	$719	0.12	4,760,000	166	1,185
Cascadia Subduction Zone	CSZ Megathrust	9.0	288	7,246	43,681	8,768	18,385	11,630	$11,994	5.68	227,240,000	2,017	131,035
Cascadia Subduction Zone - North	CSZ Megathrust - Northern Section	8.3	39	1,404	12,233	1,940	3,692	2,452	$2,708	1.40	55,920,000	0	2,858
Chelan	Chelan Fault	7.2	0	31	375	11	33	25	$151	0.05	1,880,000	0	466
Cle Elum	Cle Elum-Wallula Deformed Zone	6.8	1	54	550	75	138	110	$215	0.07	2,600,000	1,516	1,058
Devils Mountain - Utsalady Point	Devils Mtn. Fault	7.0	35	617	2,645	764	880	1,197	$1,137	0.37	14,720,000	1,196	879
Devils Mountain - West	Devils Mtn. Fault - Western Section	7.4	61	1,058	4,864	1,439	1,971	1,448	$1,866	0.65	25,920,000	10,176	29,697
Hite	Hite Fault	6.8	52	743	2,700	1,354	1,321	1,011	$856	0.49	19,480,000	1,743	19,321
Lake Creek Boundary Creek	Little River Fault	6.8	13	240	1,612	407	460	283	$518	0.19	7,680,000	9,095	544
Mill Creek Thrust/Toppenish Ridge	Toppenish Ridge Fault	7.0	6	185	1,678	297	287	325	$339	0.17	6,880,000	1,135	9,440
Olympia\Nisqually	Nisqually Intraslab (52 km depth)	7.2	37	1,713	6,026	547	3,258	2,015	$5,325	1.43	57,040,000	0	45,916
Olympia Aftershock	Olympia Fault	5.7	1	93	388	29	242	139	$426	0.09	3,480,000	0	274
Saddle Mountain-Hanford	Saddle Mountains Fault	7.4	9	269	2,520	832	405	396	$590	0.27	10,760,000	4,382	1,533
Sea-Tac	Sea-Tac Intraslab (52 km depth)	7.2	117	3,404	8,801	1,123	6,489	3,871	$8,241	2.36	94,480,000	0	132,577
Seattle	Seattle Fault	7.2	1,049	16,628	29,094	9,062	31,278	18,193	$19,868	7.42	296,720,000	265,583	399,991
Southern Whidbey Island Fault Zone (SWIF)	Southern Whidbey Island Fault Zone	7.4	432	7,361	17,502	6,258	13,948	8,106	$10,315	3.57	142,960,000	115,230	188,457
Spokane	Blind Fault	5.5	0	34	36	0	23	16	$361	0.04	1,560,000	0	0
St. Helens Zone	St. Helens Deformed Zone	7.0	0	25	119	1	10	7	$162	0.03	1,120,000	0	0
Tacoma	Tacoma Fault	7.0	328	5,742	15,410	4,457	11,576	7,146	$8,654	2.95	117,960,000	87,675	193,544

* Ground motions with peak horizontal ground acceleration (PGA) exceeding 0.02 g
** Counties just in Washington State. Does not include losses due to tsunami

Source: https://fortress.wa.gov/dnr/seismicscenarios/

The Hazard[2,3,4]

An earthquake is the sudden release of stored energy that produces a rapid displacement on a fault and radiates seismic waves. Earthquakes in Washington, and throughout the world, occur predominantly because of plate tectonics - the relative movement of plates of oceanic and continental rocks that make up the rocky surface of the earth. Earthquakes can also occur because of volcanic activity and other geological processes. With plate tectonics, accumulated stress is released as a result of the rupture of rocks along opposing fault planes in the Earth's outer crust. These fault planes are typically found along borders of the Earth's 10 tectonic plates (including the Juan De Fuca Plate impacting the Northwestern United States. Faults are arbitrary mapped and can be viewed in Figure 5.4-2 and Figure 5.4-3. The areas of greatest tectonic instability occur at the perimeters of the slowly moving plates, as these locations are subjected to the greatest strains from plates traveling in opposite directions and at different speeds. Deformation along plate boundaries causes strain in the rock and the consequent buildup of stored energy. When the built-up stress exceeds the rocks' strength, a rupture occurs. The rock on both sides of the fracture is snapped, releasing the stored energy and producing seismic waves, generating an earthquake.

Figure 5.4-2: Tectonic Plates of the World[5]

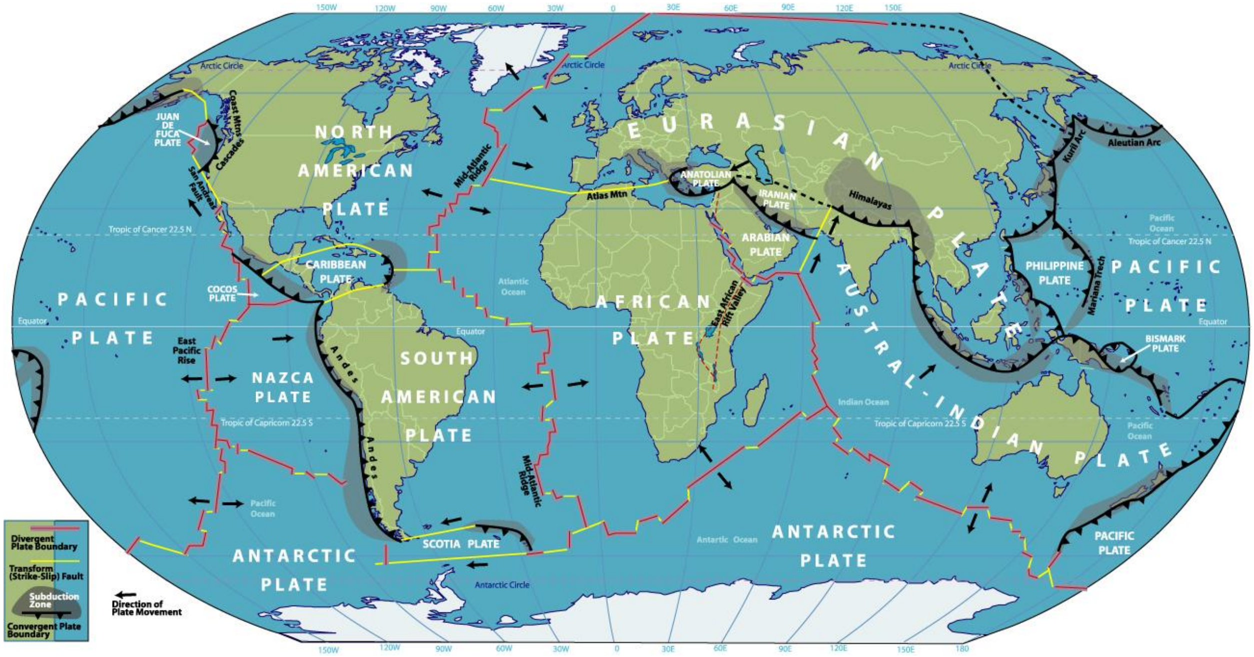
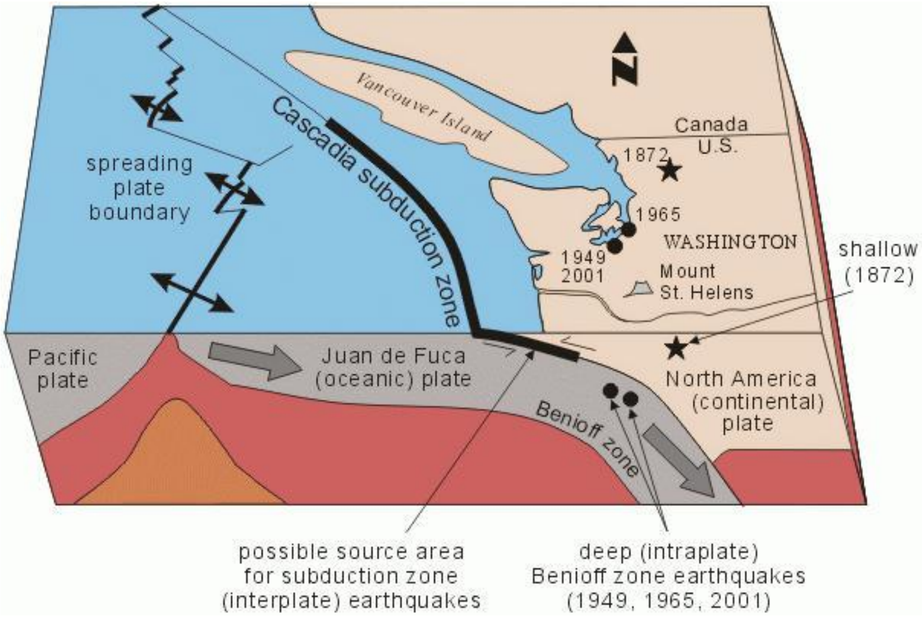


Figure 5.4-3: Cascadia Subduction Zone[6]



Earthquakes are measured in terms of their magnitude and intensity. Magnitude (M) is a measure of the total energy released by an earthquake, and intensity refers to the shaking an earthquake produces. The most common magnitude measure used is the "moment magnitude" which is calculated by seismologists from the amount of slip (movement) on the fault causing the earthquake and the area of the fault surface that ruptures during the earthquake. Moment magnitudes are similar to the Richter magnitude, which was used for many decades but has now been replaced by the moment magnitude. Beginning in 2002, the USGS began using Moment Magnitude as the preferred measure of magnitude for all USGS earthquakes greater than magnitude 3.5. This was primarily due to the fact the Richter scale has an upper bound, so large earthquakes were difficult to measure.

The magnitudes for the largest earthquakes recorded worldwide and in Washington are shown in Table 5.4-2 below.

Table 5.4-2 Largest Recorded Earthquakes in the World and Washington[7, 8]

Worldwide	Magnitude	Washington	Magnitude
1960 Chile	9.5	1872 Chelan	6.8[a]
1964 Prince William Sound, Alaska	9.2	1949 Olympia	6.8
2004 Sumatra, Indonesia	9.1	2001 Nisqually	6.8
2011 Japan	9.0	1965 Tacoma	6.7
1952 Kamchatka, Russia	9.0	1939 Bremerton	6.2
2010 Chile	8.8	1936 Walla Walla	6.1
1906 Ecuador	8.8	1909 Friday Harbor	6.0

[a] Estimated magnitude.

In evaluating earthquakes, it is important to recognize that the earthquake moment magnitude scale is not linear, but rather logarithmic. Each one step increase in magnitude, for example from M7 to M8, corresponds to an increase of about a factor of 30 in the amount of energy released by the earthquake, because of the mathematics of the magnitude scale.

Thus, a M7 earthquake releases about 30 times more energy than a M6, while a M8 releases about 30 times more energy than a M7 and so on. Thus, a great M9 earthquake releases nearly 1,000 times more energy than a large earthquake of M7 and nearly 30,000 times more energy than a M6 earthquake.

The public often assumes that the larger the magnitude of an earthquake, the “worse” it is. That is, the “big one” is the M9 earthquake and smaller earthquakes such as M6 or M7 are not the “big one”. However, this is true only in very general terms. Higher magnitude earthquakes do affect larger geographic areas, with much more widespread damage than smaller magnitude earthquakes. However, for a given site, the magnitude of an earthquake is <u>not</u> a good measure of the severity of the earthquake at that site. Instead, severity can be measured by ground shaking, or the intensity of the earthquake.

For any earthquake, the intensity of ground shaking at a given site depends on four main factors:
- Earthquake magnitude,
- Earthquake epicenter, which is the location on the earth’s surface directly above the point of origin of an earthquake,
- Earthquake depth, and
- Soil or rock conditions at the site, which may amplify or deamplify earthquake ground motions

An earthquake will generally produce the strongest ground motions near the epicenter (the point on the ground above where the earthquake initiated) with the intensity of ground motions diminishing with increasing distance from the epicenter. The intensity of ground shaking at a given location depends on the four factors listed above. Thus, for any given earthquake there will be contours of varying intensity of ground shaking vs. distance from the epicenter. The intensity will generally decrease with distance from the epicenter, and often in an irregular pattern, not simply in concentric circles. This irregularity is caused by soil conditions, the complexity of earthquake fault rupture patterns, and possible directionality in the dispersion of earthquake energy.

The amount of earthquake damage and the size of the geographic area affected generally increase with earthquake magnitude:
- Earthquakes below about M5 are not likely to cause significant damage, even locally very near the epicenter.
- Earthquakes between about M5 and M6 are likely to cause moderate damage near the epicenter.
- Earthquakes of about M6.5 or greater (e.g., the 2001 Nisqually earthquake in Washington) can cause major damage, with damage usually concentrated fairly near the epicenter.
- Larger earthquakes of M7+ cause damage over increasingly wider geographic areas with the potential for very high levels of damage near the epicenter.
- Great earthquakes with M8+ can cause major damage over wide geographic areas.
- A mega-quake M9 earthquake on the Cascadia Subduction Zone could affect the entire Pacific Northwest from British Columbia, through Washington and Oregon, and as far south as Northern California, with the highest levels of damage nearest the coast.

There are many measures of the severity or intensity of earthquake ground motions. The Modified Mercalli Intensity scale (MMI) was widely used beginning in the early 1900s. MMI is a descriptive, qualitative scale that relates severity of ground motions to the types of damage experienced. MMIs range from I to XII. More accurate, quantitative measures of the intensity of ground shaking have largely replaced the MMI and these are used in this mitigation plan.

Modern intensity scales use terms that can be physically measured with seismometers, such as the acceleration, velocity, or displacement (movement) of the ground. The intensity of earthquake ground motions may also be measured in spectral terms, as a function of the frequency of earthquake waves propagating through the earth. In the same sense that sound waves contain a mix of low-, moderate- and high-frequency sound waves, earthquake waves contain ground motions of various frequencies. The behavior of buildings and other structures depends substantially on the vibration frequencies of the building or structure vs. the spectral (frequency) content of earthquake waves. Earthquake ground motions also include both horizontal and vertical components.

A common physical measure of the intensity of earthquake ground shaking, and the one used in this mitigation plan, is Peak Ground Acceleration (PGA). PGA is a measure of the intensity of shaking, relative to the acceleration of gravity (g). For example, an acceleration of 1.0 g PGA is an extremely strong ground motion, which does occur near the epicenter of large earthquakes. With a vertical acceleration of 1.0 g, objects are thrown into the air. With a horizontal acceleration of 1.0 g, objects accelerate sideways at the same rate as if they had been dropped from the ceiling. 10% g PGA means that the ground acceleration is 10% that of gravity, and so on.

Damage levels experienced in an earthquake vary with the intensity of ground shaking and with the seismic capacity of structures. The following generalized observations provide qualitative statements about the likely extent of damages for earthquakes with various levels of ground shaking (PGA) at a given site:

- Ground motions of only 1% g or 2% g are widely felt by people; hanging plants and lamps swing strongly, but damage levels, if any, are usually very low.
- Ground motions below about 10% g usually cause only slight damage.
- Ground motions between about 10% g and 30% g may cause minor to moderate damage in well-designed buildings, with higher levels of damage in more vulnerable buildings. At this level of ground shaking, some poorly built buildings may be subject to collapse.
- Ground motions above about 30% g may cause significant damage in well-designed buildings and very high levels of damage (including collapse) in poorly designed buildings.
- Ground motions above about 50% g may cause significant damage in most buildings, even those designed to resist seismic forces.

The maps on the following pages show contours of Peak Ground Acceleration (PGA) with 10% and 2% chances of occurring over the next 50 years. Because the earthquake sources are not uniform, the earthquake threat in Washington is also not uniform. These maps are created with data from the United States Geological Survey (USGS) to produce uniform probabilistic seismic hazard maps for the United States. The ground shaking values on the maps are expressed as a percentage of g, the acceleration of gravity. For example, the 10% in 50 year PGA value means that over the next 50 years there is a 10% probability of this level of ground shaking or higher.

In very qualitative terms, the 10% in 50 year ground motion represents a likely earthquake while the 2% in 50 year ground motion represents a level of ground shaking close to but not the absolute worst case scenario.

A very important caveat for interpreting these maps is that the 2008 USGS seismic hazard maps show the level of ground motions for rock sites. Ground motions on soil sites, especially soft soil sites will be significantly higher than for rock sites. Thus, for earthquake hazard analysis at a given site it is essential to include consideration of the site's soil conditions.

Figure 5.4-4 on the following page, the statewide 2% in 50 year ground motion map, is the best statewide representation of the variation in the level of seismic hazard in Washington with location:

- The dark red, pink and orange areas have the highest levels of seismic hazard.
- The tan, yellow and blue areas have intermediate levels of seismic hazard.
- The bright green and pale green areas have the lowest levels of seismic hazard.

The highest hazard is along the Washington coast—these areas are immediately above the Cascadia subduction zone (Figure 5.4-3). Moving inland, the contours bend inland around the greater Puget Sound area from about the Columbia River; this bending is largely due to the hazard from deep earthquakes like the 2001 Nisqually earthquake. Generally, the effect of crustal faults is muted because they are poorly defined; however, these earthquakes are the most damaging due to their proximity to the earth's surface. Two notable exceptions are the bubble of higher hazard (red color) over the Seattle fault and the southern Whidbey Island fault in Puget Sound. While most earthquakes occur in Western Washington, earthquake hazards are significant east of the Cascades to about the Columbia River. The green area to the west of the Columbia shows acceleration values comparable to those seen over portions of western Washington in the Nisqually earthquake.

The detailed geographical patterns in the maps reflect the varying contributions to seismic hazard from earthquakes on the Cascadia Subduction Zone and crustal earthquakes within the North American Plate. For example, the bands of dark red (high hazard) in the Puget Sound area shown in Figures 5.4-4 and 5.4-5 reflect areas with a moderately high earthquake hazard from Cascadia Subduction Zone earthquakes combined with a high hazard from the most active crustal faults in the Puget Sound Area – the Seattle Fault System and the Southern Whidbey Island Fault.

The differences in geographic pattern between the 2% in 50 year maps and the 10% in 50 year maps reflect different contributions from Cascadia Subduction Zone earthquakes and crustal earthquakes.

These maps are generated by including earthquakes from all known faults, taking into account the expected magnitudes and frequencies of earthquakes for each fault. The maps also include contributions from unknown faults, which are statistically possible anywhere in Washington. The contributions from unknown faults are included via "area" seismicity which is distributed throughout the state.

The current scientific understanding of earthquakes is incapable of predicting exactly where and when the next earthquake will occur. However, the long term probability of earthquakes is well enough understood to make useful estimates of the probability of various levels of earthquake ground motions at a given location.

The current consensus estimates for earthquake hazards in the United States are incorporated into the 2008 USGS National Seismic Hazard Maps. These maps are the basis of building code design requirements for new construction, per the International Building Code adopted in Washington. The earthquake ground motions used for building design are set at 2/3rds of the 2% in 50 years level of ground motion.

Figure 5.4-4 2008 USGS Seismic Hazard Map: Washington State PGA value (%g) with a 2% Chance of Exceedance in 50 years (source: http://earthquake.usgs.gov/earthquakes/states/washington/hazards.php)

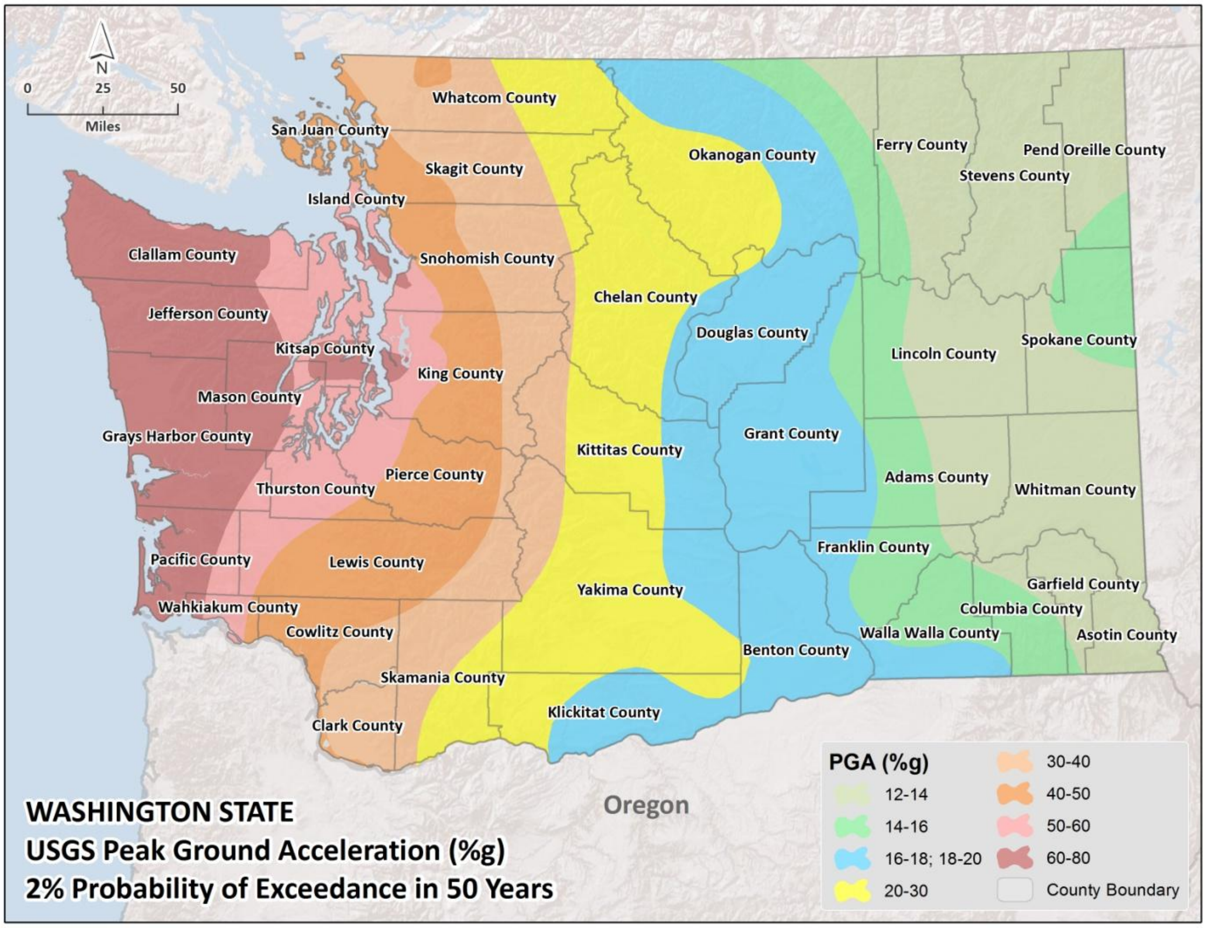
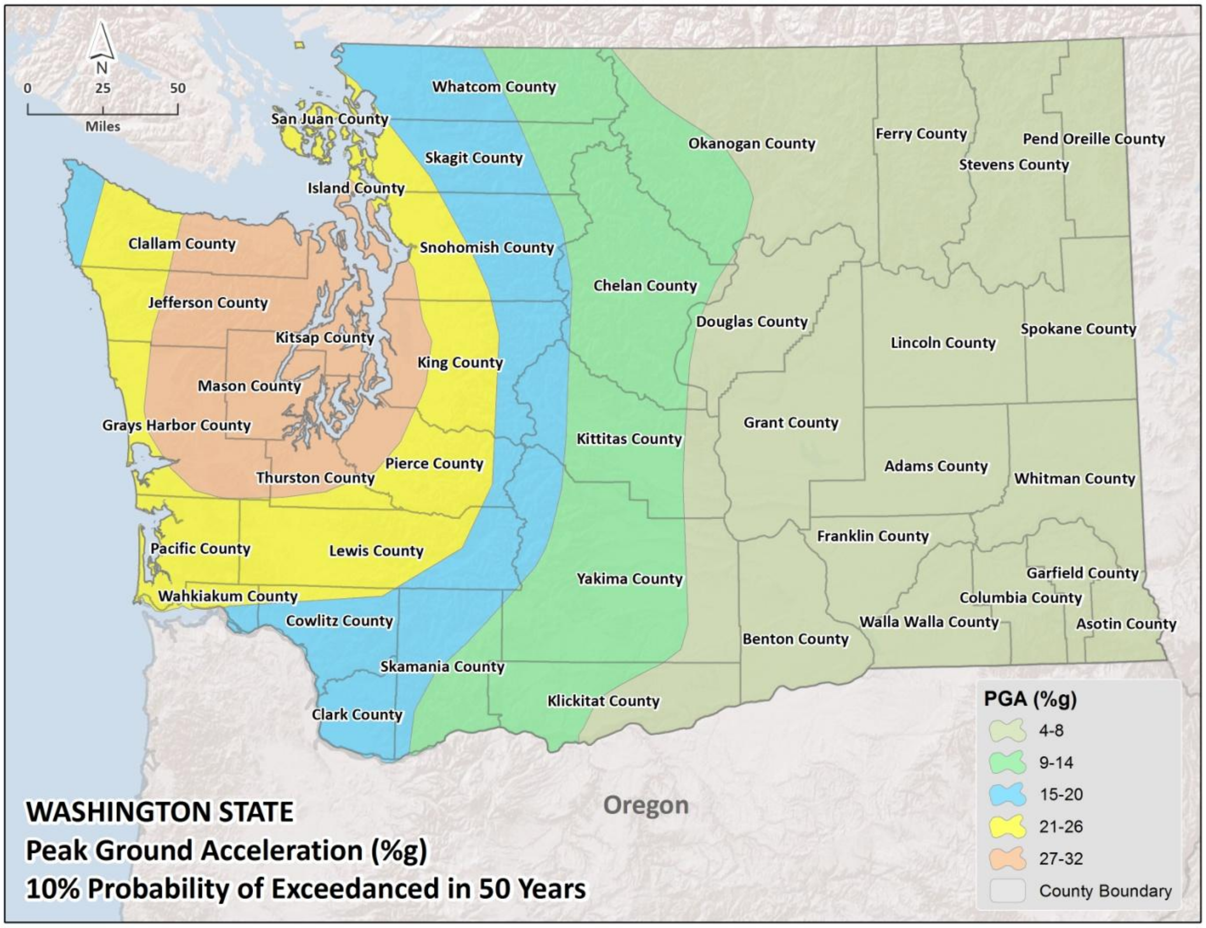


Figure 5.4-5 2008 USGS Seismic Hazard Map: Washington State PGA value (%g) with a 10% Chance of Exceedance in 50 years

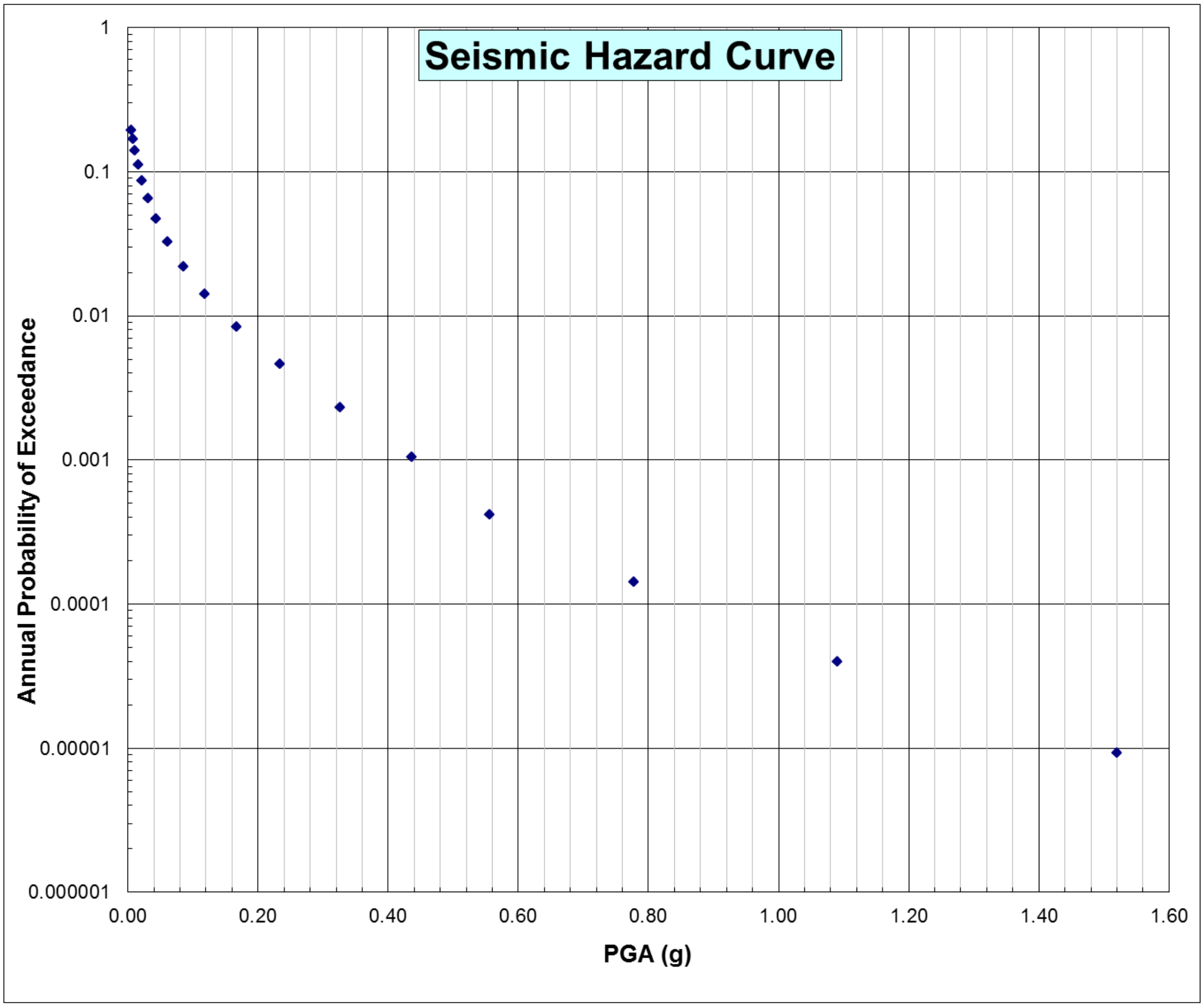


The ground motions shown in the previous figures represent ground motions with the specified probabilities of occurrence. At any given site, earthquakes may be experienced with ground motions over the entire range of levels of ground shaking from just detectible with sensitive seismometers to higher than the 2% in 50 year ground motion.

The complete probabilistic picture of earthquake ground motions at a given site is shown in a seismic hazard curve, which shows the annual probability of ground motions covering the full range of ground motions (Figure 5.4-6). For any site, the annual probability always decreases with increasing level of ground shaking (PGA).

However, as illustrated in the preceding figures, the levels of ground shaking vary markedly with location in Washington.

Figure 5.4-6 Seismic Hazard Curve Example



Although over one thousand earthquakes occur in Washington each year, most produce ground shaking that is too small to be felt. Occasionally large earthquakes produce very strong ground shaking. It is this strong shaking and its consequences – ground failure, landslides, liquefaction – that damages buildings and structures and upsets the regional economy.

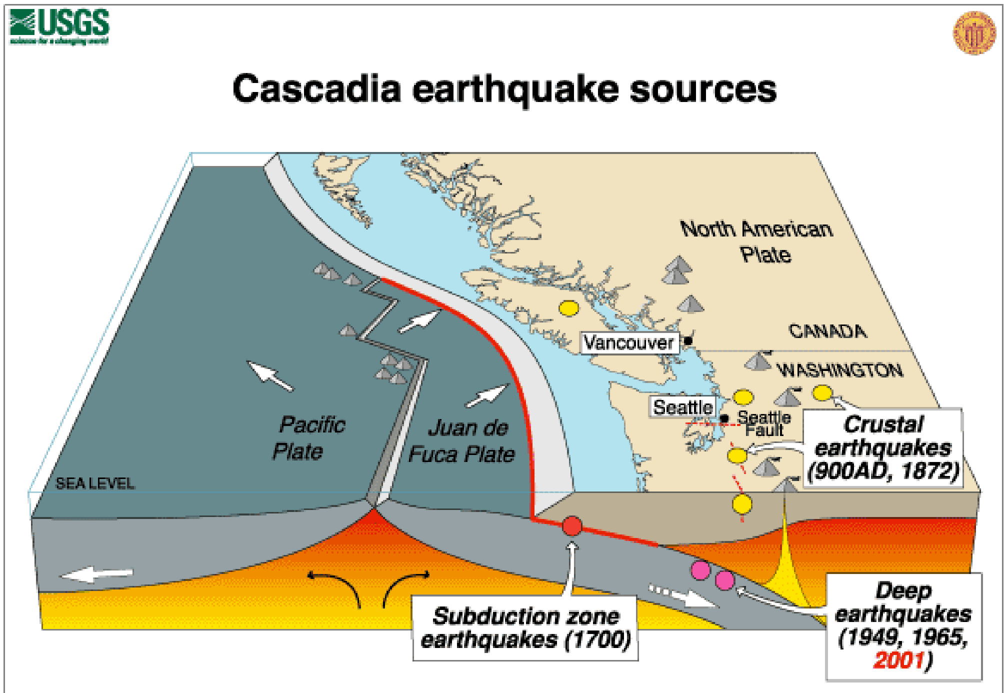
Washington's earthquake hazards reflect its tectonic setting. The Pacific Northwest is at a convergent margin between two tectonic plates of the Earth's crust. The Cascadia Subduction Zone (CSZ) is the long fault boundary between the continental North America plate and the oceanic Juan de Fuca plate that lies offshore from northern California to southern British Columbia. The two plates are converging at a rate of about 2 inches per year. The interaction between these two plates creates a complicated system of three distinct earthquake source zones. The earthquakes produced by each source zone are responsible for the earthquake hazards across Washington.

The first source zone is the Cascadia Subduction Zone; the long fault boundary between the North American and Juan de Fuca plate (see Figure 5.4-3 and Figure 5.4-7). This source zone produces great earthquakes, similar to the 2004 Indonesian earthquake, about every 500 years. Most of the fault area is offshore, so most of the ground shaking effects is expected in western Washington.

As the Juan de Fuca plate subducts (slides) beneath North America, the plate begins to bend more steeply into the earth. The area near this bend is the second source zone, usually called the deep (Benioff) zone. This is the most frequent source of damaging earthquakes for Puget Sound and the source of the 2001 Nisqually earthquake (This fault can be seen in see Figure 5.4-3).

The third zone is the earth's shallow crust and is the most poorly understood of the three source zones. Since 2000, geologists have discovered over 12 active crustal faults in Puget Sound, but new geologic assessments east of the Cascade Range indicate that the earthquake hazard in central and northeast Washington maybe greater than previously thought. This is a topic of active research within the scientific community. (Crustal faults can be seen in Figure 5.4-7.)

Figure 5.4-7. Earthquake source zones for Washington with maximum earthquake magnitude and estimated recurrence time.



	Source	Affected area	Max. Size	Recurrence
🔴	Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
🟣	Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
🟡	Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?

Understanding local earthquake hazards requires understanding of how each of the three source zones will affect individual localities. West of the Cascade Mountains, all three source zones combine to determine local hazards. East of the Cascade Mountains will usually not be affected by ground shaking from deep earthquakes due to the manner in which seismic waves travel greater distances, and, therefore, most structures will likely show minimal effects from Cascadia ground shaking. However, certain large structures in eastern Washington, such as dams and bridges, may be vulnerable to very long period shaking expected from a Cascadia earthquake. Crustal (shallow) faults, which are closer to the surface, are located throughout the entire state, and can produce intense, localized ground shaking.

Although the probabilistic maps in Figure 5.4-4 and Figure 5.4-5 are the primary input to the International Building Code and the code governing highway construction, it is sometimes useful to consider the effects from an individual fault. This requires calculating "deterministic" ground motion models. For a deterministic model, seismologists calculate the expected ground shaking but do not consider how often the earthquake may occur. They pick reasonable faulting parameters and generally use a known fault. The USGS, Washington Department of Natural Resources, and Washington Emergency Management Division produced a series of 15 deterministic ground motion models (Table 5.4-3) for selected shallow faults, deep earthquakes, and the Cascadia subduction zone. Again, these deterministic models ignore the likelihood of an earthquake occurring, but focus on the shaking expected should such an event occur. While many of these scenario models are centered on known faults, some events have been developed for research purposes. Some of these ground motion models, called ShakeMaps, are available at http://earthquake.usgs.gov/eqcenter/shakemap/list.php?s=1&y=2009.[1]

Table 5.4-3: Deterministic Ground Motion Models (USGS ShakeMaps) for Selected Sources

Scenario	Magnitude	Basis	Source zone
Boulder Creek	6.8	Trenching	**Crustal**
Canyon River-Price Lake	7.4	Trenching	**Crustal**
Chelan	7.1	Scenario: Not on a known fault	**Crustal**
Cle Elum	6.8	Scenario: Not on a known fault	**Crustal**
Lake Creek fault	6.8	Trenching	**Crustal**
Mill Creek (Toppenish Ridge)	7.1	Scenario weakly based on trenching, known fault	**Crustal**
Saddle Mountains (eastern WA)	7.35	Trenching	**Crustal**
St. Helens Seismic zone	7.0	Seismicity	**Crustal**
Seattle fault	6.7	Trenching, uplift	**Crustal**
Southern Whidbey Island fault	7.4	Trenching, uplift	**Crustal**
Spokane	5.5	Seismicity, not on a known fault	**Crustal**
Tacoma	7.1	Trenching, uplift	**Crustal**
Cascadia	9.0	Paleoseismology	**Subduction**
Nisqually	7.2	Historical seismicity	**Deep**
Seattle-Tacoma	7.2	Historical seismicity	**Deep**

Generally, most of these ground motion models are considered well determined. Faults with estimates based on trenching (and in some cases uplift of coastal features) have at least some known history of movement. Likewise, the models for the two deep events are very well constrained, in part because of their familiar occurrence in Puget Sound. The parameters used to model Cascadia are well constrained,

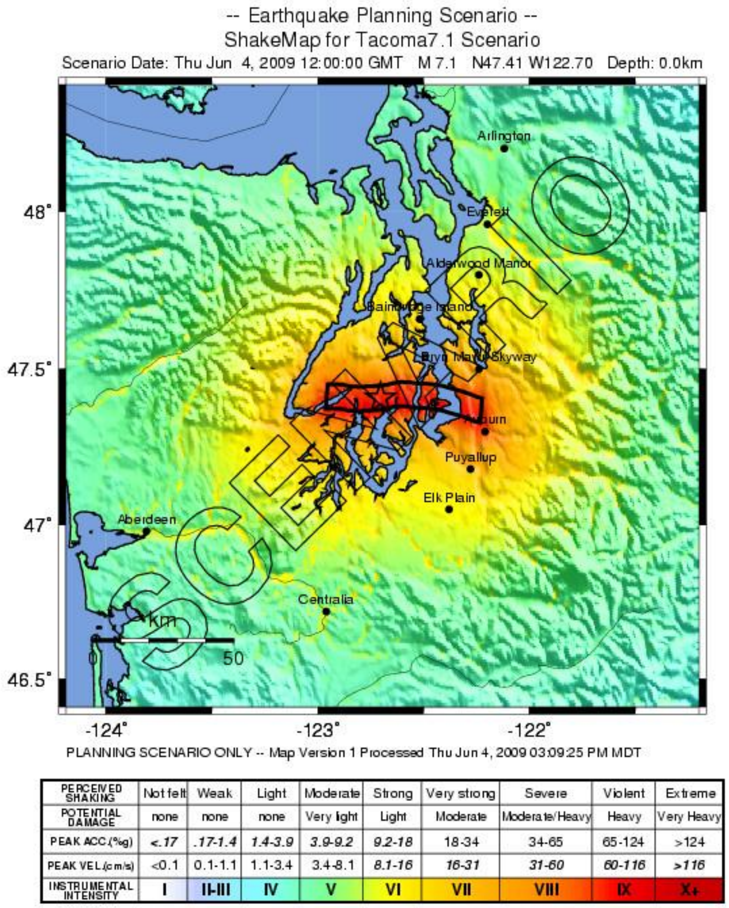
---

[1] Additional information on ShakeMaps and their usability can be found in the Earthquake Loss Avoidance Study (2013).

but certain characteristics of the ground motion (such as duration of strong shaking and the effect on long or tall structures) are not modeled. In some cases, such as Chelan, the historical record documents a strong earthquake, but the actual fault and fault parameters are still not known. The same is true for the Spokane models. Finally, the Mill Creek and Saddle Mountain scenarios are based on limited trenching but the fault traces themselves are known.

The Tacoma fault scenario (Figure 5.4-8) is an example of these new deterministic maps. For this map, seismologists picked specific traces of the mapped fault to break during an earthquake. With the fault trace and the magnitude of 7.1, seismologists then estimated the length of the fault, the depth of the fault, its orientation in the earth, how much the fault moves to calculate the ground motions. The ground motions attenuate as they move away from the source and then are usually amplified by local geologic site conditions as the seismic waves reach the earth's surface.

Figure 5.4-8: Tacoma fault scenario. This is a deterministic model, as opposed to the probabilistic PGA seismic hazard maps in Figure 5.4-4 and 5.5-5. This map is for a single fault and does not represent the entire earthquake hazard in nearby communities.



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+

Deep or Benioff Zone Earthquakes[9]

These earthquakes occur within the subducting Juan de Fuca plate at depths of 15 to 60 miles, although the largest events typically occur at depths of about 25 to 40 miles. They may produce events with magnitudes exceeding 9.0. Until recently the Olympia quake in 1949 was thought to be the largest of these deep earthquakes. The USGS recalculated this event, changing the magnitude from the original 7.1 to 6.8, the same size as the 2001 Nisqually event. Other significant Benioff zone events include the magnitude 6.5 Seattle-Tacoma quake in 1965, the magnitude 5.8 Satsop quake in 1999, and the magnitude 6.8 Nisqually quake of 2001. Strong shaking during the 1949 Olympia earthquake lasted about 20 seconds; during the 2001 Nisqually earthquake, strong shaking lasted about 15 to 20 seconds.

The probability of future occurrence for earthquakes similar to the 1965 magnitude 6.5 Seattle-Tacoma event and the 2001 magnitude 6.8 Nisqually event is about once every 35 years. The USGS has estimated that there is an 84% chance of a magnitude 6.5 or greater deep earthquake over the next 50 years.

Subduction Zone (Interplate) Earthquakes[10],[11]

These earthquakes occur along the interface between tectonic plates. Scientists have found evidence of great-magnitude earthquakes along the Cascadia Subduction Zone. These earthquakes are very powerful, with a magnitude of 8 to 9 or greater; they have occurred at intervals ranging from as few as about 100 years to as long as 1,100 years. The last of these great earthquakes struck Washington in 1700. Scientists currently estimate that a magnitude 9 earthquake in the Cascadia Subduction Zone occurs about once every 500 years.

Subduction zone earthquakes are particularly dangerous in that they produce strong ground motions and in nearly all cases, damaging tsunamis. Along the Washington coast, the red colors in Figure 5.4-4 indicate that very strong shaking is anticipated there. A seismic wave loses energy as it propagates through the earth (attenuation). Along the Puget Sound Basin, the ground shaking will be attenuated by the greater distance from the source zone, but significant damage will result. Tall buildings and long bridges may be especially susceptible to long-period ground shaking produced on the subduction zone. Finally, the long-period motions of the seismic wave may affect the large dam structures in eastern Washington and can generate standing waves or seiches in susceptible water bodies like reservoirs.

Shallow or crustal Earthquakes[12]

These earthquakes occur in the earth's crust within the upper part of the North American plate (Figure 5.4-7). Crustal earthquakes are shallow earthquakes, typically within the upper 5 or 10 miles of the earth's surface and some ruptures may reach the surface. Although there are numerous examples of moderate magnitude shallow earthquakes occurring in Washington, most of these events cannot be directly related to an individual fault. Recent examples in western Washington are earthquakes near Bremerton in 1997, Duvall in 1996, off Maury Island in 1995, near Deming in 1990, near North Bend in 1945, just north of Portland in 1962, and at Elk Lake on the St. Helens seismic zone (a fault zone running north-northwest through Mount St. Helens) in 1981. These earthquakes had a magnitude of 5 to 5.5.

The 1872 earthquake near Lake Chelan was the state's most widely felt shallow earthquake. The magnitude for this event has been estimated at 7.4. The 1936 magnitude 6.1 earthquake near Walla Walla was also a shallow event. Because of their remote locations damage was light from these two quakes.

Of the three earthquake sources, the shallow zone is the least understood. Until 2000, geologists had not located a fault trace, where deformation breaks to the surface, anywhere in the Puget lowlands. Without knowing the location of fault traces, geologists were unable to determine how often faults moved and how large their movements were. Therefore, they were unable to determine how often these events occurred. This has changed dramatically with the development of Light Detection and Ranging (LiDAR), a technique that can generally penetrate forest canopy and vegetation to image the actual ground surface with an unprecedented accuracy of approximately one foot (30 cm). Since 2000, geologists have documented at least 12 major faults with recent motion in the Puget Sound region. A systematic assessment of earthquake hazards in eastern Washington started in 2008.

The findings of ongoing research on surface faults (see below) may lead to an assessment of greater earthquake risk in parts of Washington.

Puget Lowland[13,14, 15, 16, 17]

Recent geologic studies have greatly enhanced scientists' ability to locate and study active faults, particularly in the Puget Sound basin. Using a combination of aeromagnetic surveys, high-resolution light detecting and ranging data (LiDAR), and geological field investigation, studies have documented about a dozen active faults or fault zones in the greater Puget Sound basin (Figure 5.4-9). Field evidence shows magnitude 7 or greater earthquakes occurred on at least eight of these faults. These faults include: the Seattle fault, Tacoma fault, Darrington-Devils Mountain fault, Utsalady Point fault, Southern Whidbey Island fault, Frigid Creek fault, Canyon River fault and the Lake Creek fault.

While investigation continues on Puget Lowland faults in an effort to better define the recurrence and magnitude, scientists already have learned much about them. For example, evidence points to a magnitude 7 or greater earthquake on the Seattle fault about 900 A.D. Such evidence includes a tsunami deposit in Puget Sound, landslides in Lake Washington, rockslides on nearby mountains, and a seven-meter uplift of a marine terrace.

An earthquake with such a magnitude today would cause tremendous damage and economic disruption throughout the central Puget Sound region. Using estimates of damage and loss developed in the scenario for a magnitude 6.7 event on the Seattle fault showed such a quake would result in extensive or complete damage to more than 58,000 buildings with a loss of $36 billion, more than 55,000 displaced households, and up to 2,400 deaths and 800 injuries requiring hospitalization. Although losses would likely be less from similar earthquakes on other Puget Sound faults away from the core of the Seattle urban area, all of the newly defined active faults represent the possibility of very high damage, loss of life, and major economic impact.

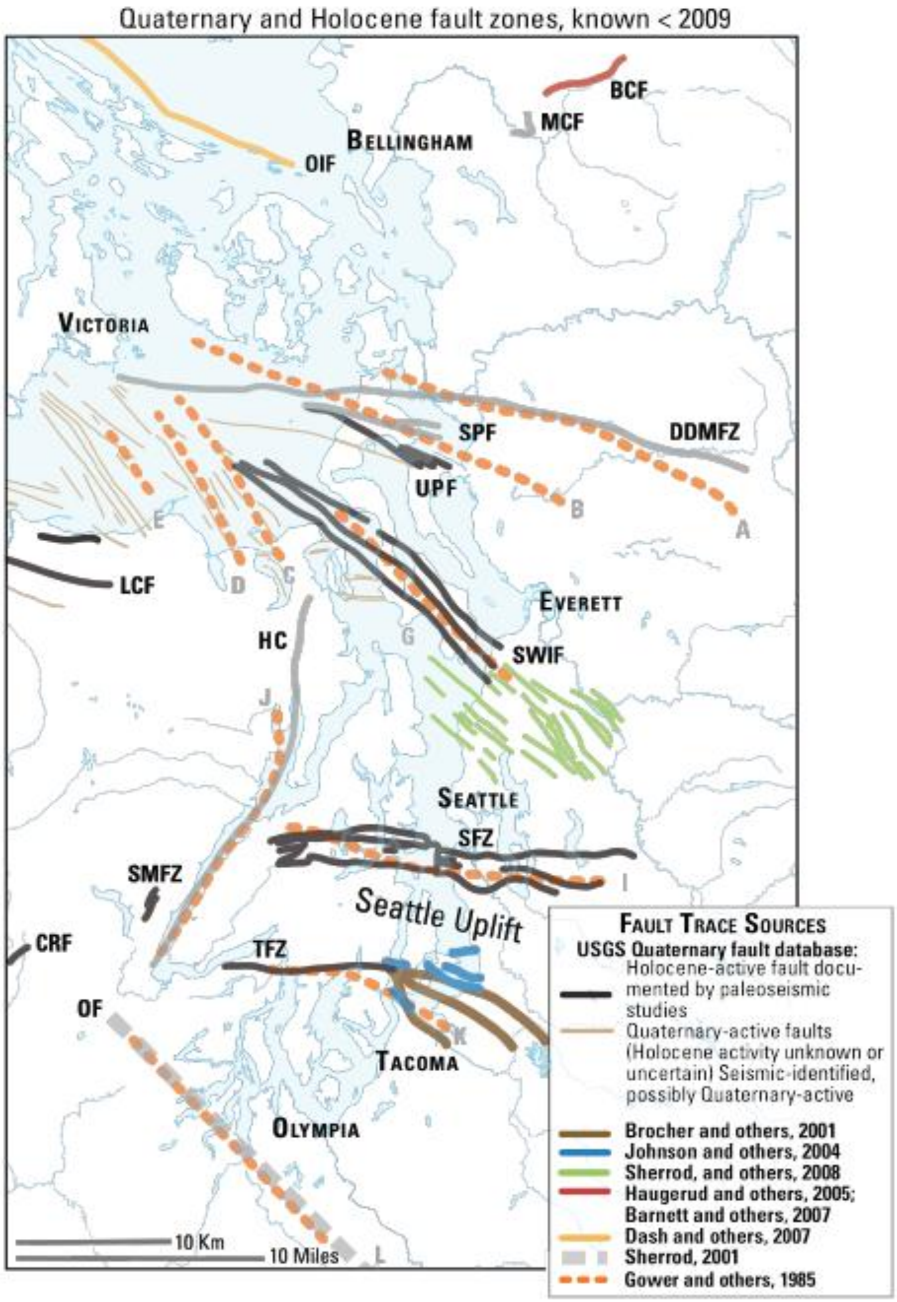
Scientists currently estimate the approximate recurrence rate of a magnitude 6.5 or greater earthquake on the Seattle Fault at about once every 1,000 years and for an earthquake of this magnitude anywhere on a fault in the Puget Sound basin to be once in about 350 years. Several known earthquake faults in the Pugent Sound areas area shown below in Figure 5.4-9

Figure 5.4-9. Known earthquake crustal faults in the greater Puget Sound area.

The map shows the location of faults under study by earth scientists. Active faults as determined by documented evidence of Holocene surface deformation or surface rupture are abbreviated as:

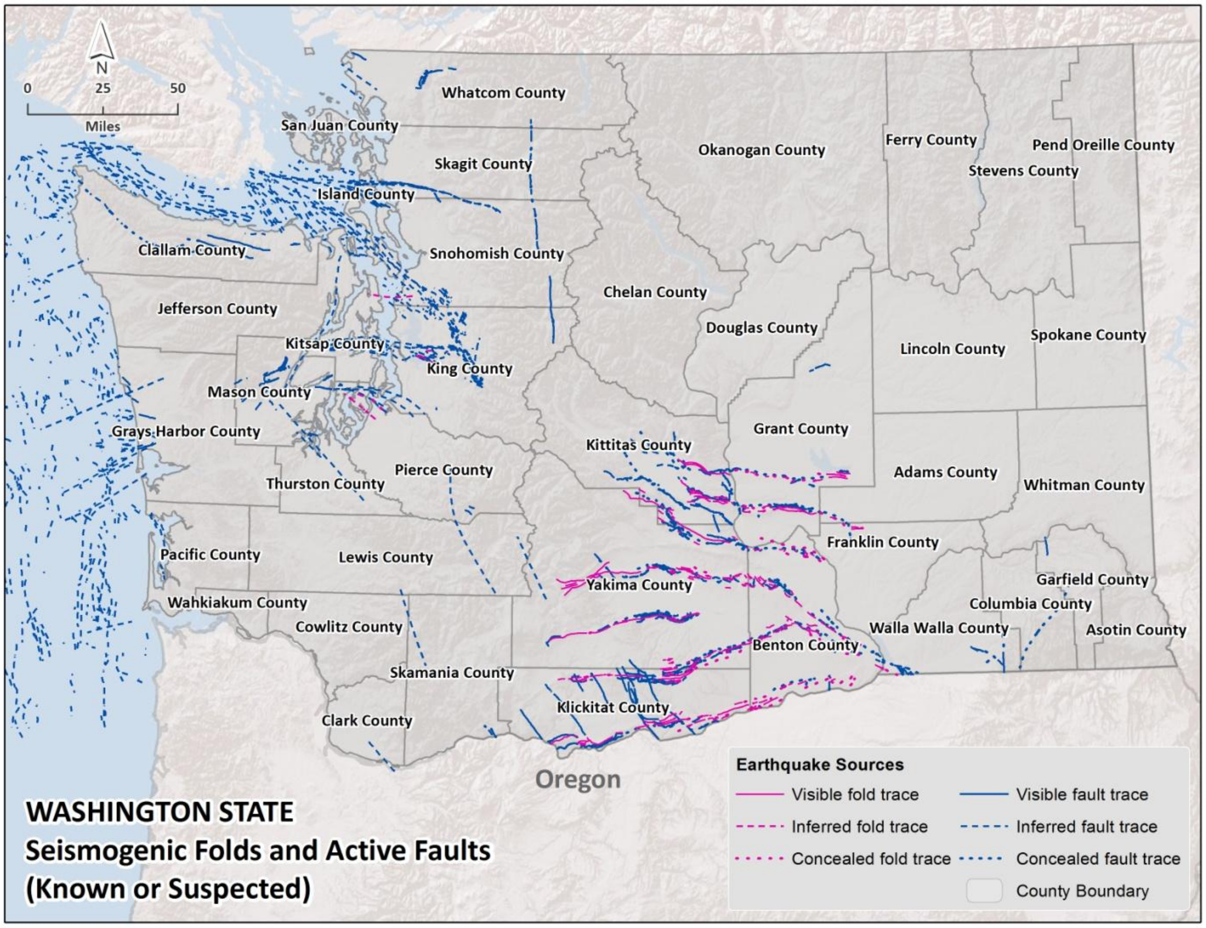
- BCF, Boulder Creek fault;
- OIF, Outer Island fault,
- DDMFX, Devils Mountain-Darrington fault zone,
- UPF, Utsalady Point fault;
- LCF, Lake Creek fault,
- SWIF, Southern Whidbey Island fault;
- SFZ, Seattle fault zone;
- TFZ, Tacoma fault zone;
- SMFZ, Saddle Mountain fault zone;
- CRF, Canyon River fault zone.

Source: USGS and Washington DNR.



Fault zones and seismogenic fold zones in Washington which are known to be active of suspected of being active by the Washington State Department of Natural Resources are shown in Figure 4.5-10.

Figure 5.4-10 Faults and Seismogenic Folds in Washington Known or Suspected to be Active[18]



Eastern Washington[19, 20, 21]

The state's two largest crustal earthquakes felt by European settlers occurred in Eastern Washington – the 1872 quake near Lake Chelan and the 1936 earthquake near Walla Walla. More recently, residents of Spokane strongly felt a swarm of earthquakes in 2001; the largest earthquake in the swarm had a magnitude of 4.0.

The recent Spokane earthquakes were very shallow, with most events located within a few miles of the surface. The events occurred near a suspected fault informally called the Latah Fault; however, the relation between the fault and the swarm is uncertain. Geologists have mapped the Spokane area, but none confirmed the presence of major faults that might be capable of producing earthquakes. State geologists continue to investigate the local geology and earthquake risk in Spokane.

Elsewhere in Eastern Washington, geologists have uncovered evidence of a number of surface faults; however, they have not yet determined how active the faults are, nor determined the extent of the risk they pose to the public. One fault, Toppenish Ridge, appears to have been the source of two earthquakes with magnitudes of 6.5 to 7.3 in the past 10,000 years.

Forecasting Future Earthquakes[22]

The size of a fault segment, the stiffness of rocks, and the amount of accumulated strain energy combine to control the magnitude and timing of earthquakes. Fault segments most likely to break can be identified where faults and plate motions are well known. If a fault segment is known to have broken in a past large earthquake, recurrence time and probable magnitude can be estimated based on fault segment size, rupture history, and accumulation of strain. Such a forecast, however, can be used only for well-understood faults, such as the San Andreas fault in California. No such forecasts can be made for poorly understood faults. Faults in the Pacific Northwest are complex, and research on them is continuing. It is not yet possible to forecast when any particular fault in Washington State will break.

Earthquake Effects

Earthquakes cause damage by strong ground shaking and by the secondary effects of ground failures, tsunamis, and seiches. The strength of ground shaking generally decreases with distance from the earthquake source. Shaking can be much higher when soft soils amplify earthquake waves. West Seattle and downtown Olympia are examples where amplification repeatedly has occurred and ground shaking was much stronger than in other nearby areas.

Ground failures caused by earthquakes include fault rupture, ground cracking, lateral spreading, slumps, landslides, rock falls, liquefaction, localized uplift and subsidence. Faults often do not rupture through to the surface. Unstable or unconsolidated soil is most at risk. Any of these failures will affect structures above or below them.

Large and disastrous landslides can often result from an earthquake. Soil liquefaction describes a phenomenon whereby a saturated soil substantially loses strength and stiffness in response to an applied stress like an earthquake's ground shaking, causing it to behave like a liquid. Liquefaction can cause building foundations to fail and low-density structures such as underground fuel tanks and pilings to float. Liquefactions examples can be seen in Figures 5.4-11 and Figure 5.4-12 below.

Figure 5.4-11. Japan's Niigata Earthquake, 1964. Source: Wikipedia.

Figure 5.4-12. New Zealand's Christchurch Earthquake, 2011. Source: Wikipedia.

Tsunamis are waves that result from the displacement of the water column by changes in the sea floor, by landslides or submarine slides, or by volcanic explosions in the water. Tsunamis can also be created by crustal earthquakes, such as the Seattle Fault System and the Tacoma Fault System which cross parts of Puget Sound because these earthquakes are likely to include vertical movements of the floor of the sound which will generate tsunamis. In fact, the Seattle Fault and Cascadia Subduction Zone earthquakes, however, have caused tsunamis. The warning times for such tsunamis would be only a few minutes. Washington is also at risk from tsunamis from distant earthquakes (see the Tsunamis Hazard Profile, Tab 5.1.7 for more information on their impacts).

A similar earthquake phenomenom is "seiches" which are standing waves in an enclosed or partially enclosed body of water similar to sloshing waves in a bathtub. Historically, Washington has had minor damage from seiches. Seiches may result in damages to docks and other shoreline or near-shore structures. Seiches within water tanks may also results in roof damage or, in extreme case, rupture of the entire tank with resulting flooding.

As noted above , in terms of economic impact, Washington ranks second in the nation after California among states susceptible to economic loss caused by earthquake, according to a Federal Emergency Management Agency (FEMA) study. The study predicts that the state faces a probable annualized economic loss of $366 million due to earthquake; average annualized loss is an equivalent measure of future losses averaged on an annual basis. The Seattle-Tacoma-Bellevue area is fifth and Tacoma is 22nd on a list of metropolitan areas with more than $10 million in annualized earthquake losses.

Earthquake Monitoring Entities in Washington State

The USGS Earthquake Hazards Program is part of the National Earthquake Hazards Reduction Program (NEHRP), established by Congress in 1977. They monitor and report earthquakes, assess earthquake impacts and hazards, and research the causes and effects of earthquake.

The Cascade Volcano Observatory monitors the Washington State volcanoes for unrest and eruptive behavior and provides an early warning system.

The Pacific Northwest Seismic Network (PNSN) monitors ground motions within the region in order to better understand earthquake and volcano hazards and their impacts on the physical, economic, political, and social environment; provides the most accurate information about earthquakes and volcanoes as rapidly as possible to public officials, the public, and for education; and advocates comprehensive and cost-effective measures for reducing the harmful effects of earthquakes and volcanoes.

Previous Occurrences

Washington State, especially the Puget Sound basin, has a history of relatively frequent damaging earthquakes. Large earthquakes in 1946 (magnitude 5.8), 1949 (magnitude 7.1) and 1965 (magnitude 6.5) killed 15 people and caused more than $200 million (1984 dollars) in damage throughout several counties. The state has experienced at least 20 damaging events in the last 125 years. This averages to about one earthquake every 6 years though the interval time in between earthquakes is unpredictable.

The Nisqually earthquake on February 28, 2001 was the most recent damaging earthquake. This was a deep earthquake of magnitude 6.8 earthquake. It was centered about 10 miles northeast of Olympia and at a depth of about 30 miles. One person died of a stress induced heart attack, 407 people were injured of which 4 were considered serious, and estimates place damage at $2 billion. Table 5.4-4 shows selected damaging earthquakes in Washington.

Table 5.4-4. Selected Earthquakes of Washington State, Magnitude 5.0 or Greater*[23]

Date/Time (standard)	Depth	Moment Magnitude	Location
12/14/1872, 9:40 p.m.	0.0 km	6.8 (est.)	1.4 km SE of Chelan
01/11/1909, 3:49 p.m.	31.0 km	6.0	23.8 km NE of Friday Harbor
07/17/1932, 10:01 p.m.	0.0 km	5.7	15.6 km SE of Granite Falls
07/15/1936, 11:07 p.m.	0.0 km	6.1	8.1 km SSE of Walla Walla
11/12/1939, 11:45 p.m.	31.0 km	6.2	18.7 km S of Bremerton
04/29/1945, 12:16 p.m.	0.0 km	5.7	12.5 km SSE of North Bend
02/14/1946, 7:14 p.m.	25.0 km	5.8	28.4 km N of Olympia
04/13/1949, 11:55 a.m.	54.0 km	6.8	12.3 km ENE of Olympia
04/29/1965, 7:28 a.m.	57.0 km	6.7	18.3 km N of Tacoma
05/18/1980, 7:32 a.m.	2.8 km	5.7	1.0 km NNE of Mt St Helens
02/13/1981, 10:09 p.m.	7.3 km	5.5	1.8 km N of Elk Lake
01/28/1995, 7:11 p.m.	15.8 km	5.0	17.5 km NNE of Tacoma
07/02/1996, 8:04 p.m.	4.3 km	5.4	8.5 km ENE of Duvall
07/02/1999, 6:44 p.m.	40.7 km	5.8	8.0 km N of Satsop
02/28/2001, 10:54 a.m.	51.9 km	6.8	17.0 km NE of Olympia
06/10/2001, 5:19 a.m.	40.7 km	5.0	18.3 km N of Satsop

*Note: no earthquakes of magnitude 5.0 or greater have occurred since 2001.

The impacts caused by the earthquakes shaded in the table above are described in narratives below.

Lake Chelan – December 14, 1872[24]

The magnitude 6.8 (est.) earthquake occurred about 9:40 p.m. This earthquake was felt from British Columbia to Oregon and from the Pacific Ocean to Montana. The location for this earthquake was most likely northeast of the town of Chelan. Because there were few man-made structures in the epicenter area near Lake Chelan, most of the information available is about ground effects, including huge landslides, massive fissures in the ground, and a 27-foot high geyser.

Extensive landslides occurred in the slide-prone shorelines of the Columbia River. One massive slide, at Ribbon Cliff between Entiat and Winesap, blocked the Columbia River for several hours. A field reconnaissance to the Ribbon Cliff landslide area in August 1976 showed remnants of a large landslide mass along the west edge of Lake Entiat (Columbia River Reservoir), below Ribbon Cliffs and about 3 kilometers north of Entiat. Although the most spectacular landslides occurred in the Chelan-Wenatchee area, slides occurred throughout the Cascade Mountains.

Most of the ground fissures occurred in the following areas: at the east end of Lake Chelan in the area of the Indian camp; in the Chelan Landing-Chelan Falls area; on a mountain about 12 miles west of the Indian camp area; on the east side of the Columbia River (where three springs formed); and near the top of a ridge on a hogback on the east side of the Columbia River. These fissures formed in several locations. Slope failure, settlements, or slumping in water-saturated soils may have produced the fissures in areas on steep slopes or near bodies of water. Sulfurous water was emitted from the large fissures that formed in the Indian camp area. At Chelan Falls, "a great hole opened in the earth" from which water spouted as much as 27 feet in the air. The geyser activity continued for several days, and, after diminishing, left permanent springs.

Reports of structural damage are limited because of the epicenter's remote location. Heavy damage occurred to a log building near the mouth of the Wenatchee River. Ground shaking threw people to the floor, wave ripples were observed in the ground, and loud detonations heard. About two miles above the Ribbon Cliff slide area, the logs on another cabin caved in.

Damaging ground shaking extended to the west throughout the Puget Sound basin and to the southeast beyond the Hanford Site. Individuals in Idaho, Montana, Oregon, and Canada felt the earthquake. Aftershocks occurred in the area for two years.

State-Line Earthquake – July 15, 1936[25,26, 27]

The earthquake, magnitude 6.1, occurred at 11:05 a.m. The epicenter was about 5 miles south-southeast of Walla Walla. It was widely felt through Oregon, Washington and northern Idaho, with the greatest shaking occurring in Northeast Oregon. Property damage was estimated at $100,000 (in 1936 dollars) in this sparsely populated area.

The earthquake moved small objects, rattled windows, and cracked plaster in the communities of Colfax, Hooper, Page, Pomeroy, Prescott, Touchet, Wallula, and Wheeler. However, most of the impact and damage was in the Walla Walla area. The earthquake alarmed residents of Walla Walla, many of whom fled their homes for the street. People reported hearing moderately loud rumbling immediately before the first shock. Standing pictures shook down, some movable objects changed positions, and doors partially opened. The earthquake was more noticeable on floors higher than the ground floor. It knocked down a few chimneys and many loose chimney brick; damaged a brick home used by the warden at the State Penitentiary that was condemned and declared unsafe; and damaged the local railroad station. Several homes moved an inch or less on their foundations, Five miles southwest of Walla Walla, the quake restored the flow of a weakened 600-foot deep artesian well to close to original strength; the flow had not diminished after several months. Walla Walla residents reported about 15 - 20 aftershocks.

Olympia Earthquake – April 13, 1949[28, 29]

The earthquake, magnitude 6.8, occurred at 11:55 a.m. The epicenter was about eight miles north-northeast of Olympia, along the southern edge of Puget Sound. Property damage in Olympia, Seattle, and Tacoma was estimated at $25 million (in 1949 dollars); eight people were killed, and many were injured.

School buildings in widely separated towns were seriously damaged. Thirty schools serving 10,000 students were damaged; 10 were condemned and permanently closed. Chimneys on more than 10,000 homes required repair. Water spouted from cracks that formed in the ground at Centralia, Longview, and Seattle. One new spring developed on a farm at Forest. Ground water, released by the shaking, flooded several blocks of Puyuallup. Downed chimneys and walls were reported in towns throughout the area.

In Olympia, damage primarily was confined to the old part of the city and to areas of the port built on artificial fill. Most large buildings were damaged, including eight structures on the Capitol grounds. Many chimneys and two large smokestacks fell. Public utilities sustained serious damage; water and gas mains were broken and electric and telegraph services were interrupted. Breaks in 24 water mains temporarily closed the downtown business district.

In Centralia, the earthquake damaged 40 percent of the homes and businesses; two schools and a church were condemned; and the city's gravity-feed water system badly damaged. In Chehalis, damage occurred to four schools, city hall, the library, and county court house; the library was condemned. Seventy-five percent of the chimneys had to be replaced.

In Seattle, houses on filled ground were demolished, many old brick buildings were damaged, and chimneys toppled. One wooden water tank and the top of a radio tower collapsed. A 60-inch main broke at the city's water reservoir. Power failures occurred when swinging transmission lines touched, causing circuit breakers to trip. The gas distribution system broke at nearly 100 points, primarily due to damage caused by ground failure. Three damaged schools were demolished, and one rebuilt.

In Tacoma, many chimneys of older structures were knocked to the ground and many buildings were damaged. Water mains broke from landslides and settling in the Tideflats. Transformers at the Bonneville Power Administration substation were thrown out of alignment. Near Tacoma, a huge section of a 200-foot cliff toppled into Puget Sound three days after the earthquake that produced a tsunami that swept across Tacoma Narrows and reflected back to Tacoma, flooding a group of houses along the shoreline. South of Tacoma, railroad bridges were thrown out of alignment. A 23-ton cable saddle was thrown from the top of a Tacoma Narrows bridge tower, causing considerable damage.

The earthquake was felt in Idaho, Montana, Oregon, and in British Columbia, Canada. Only one small aftershock occurred during the next six months.

Seattle-Tacoma Earthquake – April 29, 1965[30, 31]

The earthquake, magnitude 6.7, struck the Puget Sound area at 7:28 a.m. The epicenter was about 12 miles north of Tacoma at a depth of about 40 miles. The earthquake caused about $12.5 million (in 1965 dollars) in property damage and killed seven people.

A rather large area of ground shaking in Seattle and its suburbs, including Issaquah, characterized the quake. Pockets of intense ground shaking, seen in damage such as fallen chimneys, were associated with variations in the local geology. In general, damage patterns repeated those observed in the April 1949 earthquake, although that event was more destructive. Buildings damaged in 1949 often sustained additional damage in 1965.

Most damage in Seattle was concentrated in areas of filled ground, including Pioneer Square and the waterfront, both with many older masonry buildings; nearly every waterfront building experienced damage. Eight schools serving 8,800 students were closed temporarily until safety inspections could be completed; two schools were severely damaged. Extensive chimney damage occurred in West Seattle. The low-lying and filled areas along the Duwamish River and its mouth settled, causing severe damage at Harbor Island; slumping occurred along a steep slope near Admiral Way. A brick garage partly collapsed at Issaquah; one school was damaged extensively; and chimneys in the area sustained heavy damage. Many instances of parapet and gable failure occurred. Damage to utilities in the area was not severe as in 1949.

Also damaged were two electric transmission towers in a Bonneville Power Administration substation near Everett; the towers each supported 230,000-volt lines carrying power from Chief Joseph Dam to the substation. Three water mains failed in Seattle, and two of three 48-inch water supply lines broke in Everett.

Buildings with unreinforced brick-bearing walls with sand-lime mortar were damaged most severely. Multistory buildings generally had slight or no damage. However, the Legislative Building once again was damaged and temporarily closed; government activities moved to nearby motels. Performance of wood frame dwellings was excellent, with damage confined mainly to cracks in plaster or to failure of unreinforced brick chimneys near the roofline.

The earthquake was felt in Idaho, Montana, Oregon, and in British Columbia, Canada; little aftershock activity was observed.

Nisqually Earthquake – February 28, 2001[32, 33]

The earthquake, magnitude 6.8, struck the Puget Sound area at 10:54 a.m. The epicenter was below Anderson Island near the Nisqually River delta in Puget Sound about 50 miles south of Seattle and 11 miles northeast of Olympia. Ground shaking lasted about 20 seconds. Two minor aftershocks occurred near the epicenter of the main shock. This event was a slab earthquake; its depth calculated at 32 miles below the earth's surface in the Juan de Fuca plate.

The area of most intense ground shaking occurred along the heavily populated north-south Interstate 5 corridor, not around the epicenter. This was due to the amplification of the earthquake waves on softer river valley sediments. The earthquake was felt over a large area – from Vancouver, British Columbia, to the north; to Portland, Oregon, to the south; and Salt Lake City, Utah, to the southeast.

The six counties most severely damaged by the earthquake – King, Kitsap, Lewis, Mason, Pierce, and Thurston – were declared federal disaster areas one day after the event. Eventually, 24 counties received disaster declarations for Stafford Act assistance under Federal Disaster #1361. Stafford Act disaster assistance provided was $155.9 million. Small Business Administration disaster loans approved - $84.3 million. Federal Highway Administration emergency relief provided to date - $93.8 million.

Various estimates have placed damage to public, business and household property caused by the Nisqually earthquake at from $1 billion to $4 billion. A 2002 study by the University of Washington funded by the National Science Foundation estimated the quake caused $1.5 billion in damages to nearly 300,000 households. A second study, also by the University of Washington and funded by the Economic Development Administration of the U.S. Department of Commerce, estimated that 20 percent of small businesses in the region affected by the quake had a direct physical loss and 60 percent experienced productivity disruptions.

Severe damage occurred in Olympia, at SeaTac Airport, and in south Seattle in the Pioneer Square and Sodo areas. Structures damaged included office buildings, residences, schools, hospitals, airport facilities and churches. Many damaged structures and surrounding areas were closed for various lengths of time following the earthquake.

Structural damage was primarily concentrated in older, unreinforced masonry buildings built before 1950, with some damage reported to wood-frame structures and reinforced concrete structures. In general, new buildings and buildings that had recently been seismically upgraded typically displayed good structural performance, but many still sustained non-structural damage.

In the major urban areas of King, Pierce and Thurston counties, 1,000 buildings were rapidly assessed immediately following the earthquake. Of these, 48 buildings were red-tagged, indicating serious damage, and 234 were yellow-tagged indicating moderate damage.

Damaged significantly were several state government buildings in Olympia, including the Legislative Building (the state's Capitol Building). The dome of the 74-year-old building sustained a deep crack in its limestone exterior and damage to supporting columns. There was non-structural damage which occurred throughout the building. Most other state agency buildings closed for one or more days for inspection and repair.

Lifeline systems generally performed well during the event. Water utilities reported minor structural damages; a number of wells in Eastern Washington reportedly went dry. A gas-line leak caused a fire and explosion when two maintenance workers were resetting an earthquake valve at a correctional facility near Olympia. Seattle City Light reported 17,000 customer power outages, and Puget Sound Energy reported 200,000 customers without power, but power was restored to most customers within a day. The volume of calls placed immediately after the earthquake overloaded landline and wireless communication systems.

Transportation systems also suffered damage. Seattle-Tacoma International Airport closed immediately because its control tower was disabled. A temporary backup control tower allowed reopening of the airport to limited traffic several hours after the quake. King County Airport (Boeing Field) suffered serious cracking and gaps on the runway due to soil liquefaction and lateral spreading. The main runway reopened for business a week later.

While the area's overall road network remained functional, many highways, roads, and bridges were damaged. Several state routes and local roadways closed due to slumping and pavement fractures. The quake badly damaged the Alaskan Way Viaduct (State Route 99), a major arterial in Seattle. Temporary repairs made the structure usable; various proposals to permanently repair or replace it run in the billions of dollars. Two local bridges closed due to significant damage – the Magnolia Bridge in Seattle and the Fourth Avenue Bridge in Olympia.

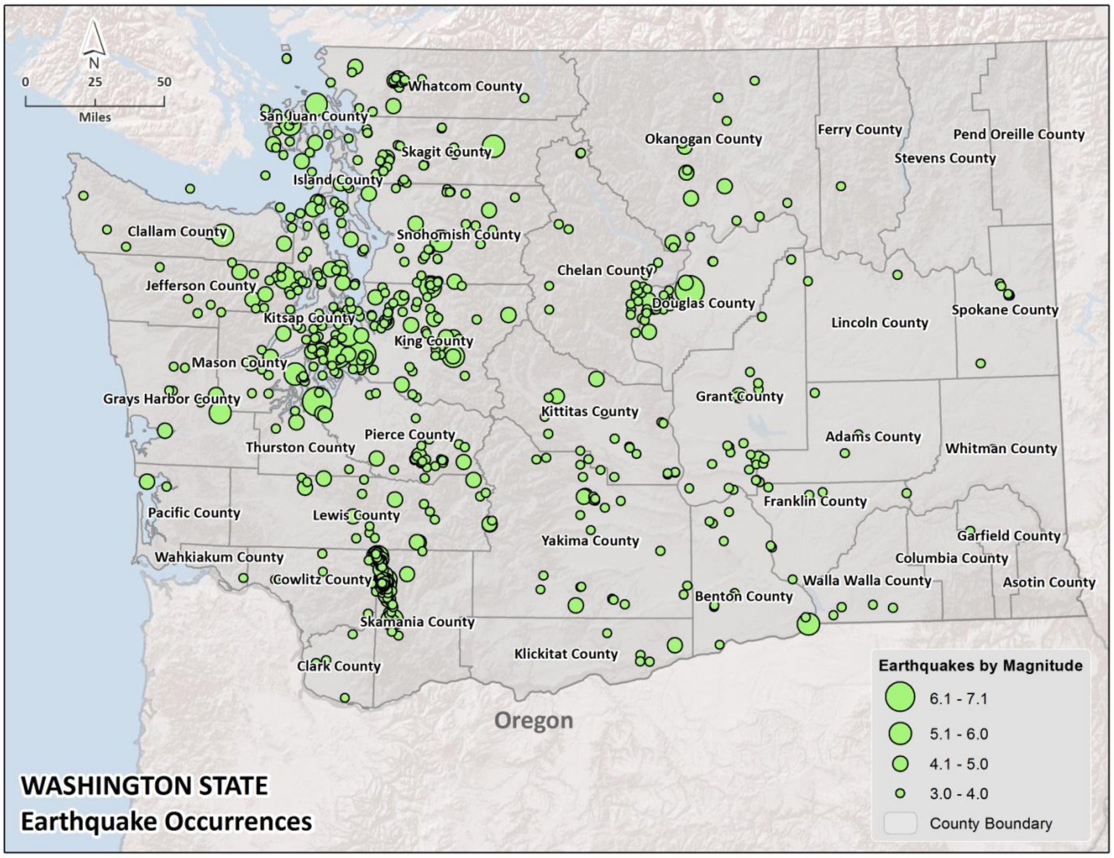
There was minor damage to dock facilities in both Tacoma and Seattle, but not extensive enough to interrupt commercial port services.

The state's dams fared well during the earthquake. Of the 290 dams inspected by state engineers, only five had earthquake-related damage; these dams were susceptible to damage due to their poor construction and weak foundations. Dams controlled or regulated by the Federal Energy Regulatory Commission, the Bureau of Reclamation, or the U.S. Army Corps of Engineers, were not damaged.

Damage to residential structures came in a variety of forms, from severe mudslide destruction of entire homes to breakage of replaceable personal property. A 2002 University of Washington study on residential loss estimated nearly 300,000 residential units – about one of every four Puget Sound households – experienced $1.5 billion in damage. The study indicates that structural damage to roofs, walls and foundations accounted for nearly two-thirds of losses, followed by chimney damage, and damages to nonstructural elements and household contents.[34]

It should also be noted that earthquakes of a lesser magnitude occur frequently in the state. Figure 5.4-13 below shown historic earthquakes in Washington State.

Figure 5.4-13 Historic Earthquake Epicenters with Magnitudes of 3.0 or Greater (1872 -2011)[35]



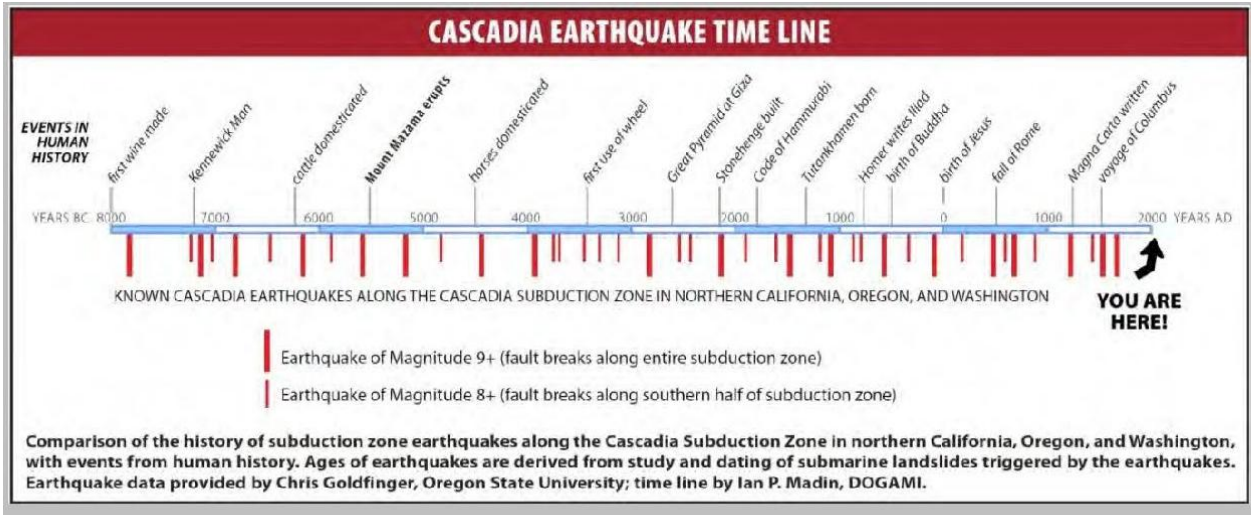
Probability of Future Events

As noted above, it is impossible to forecast earthquakes given our existing technology, but scientists can estimate general probability based on historic occurrences and location among other factors. The size of a fault segment, the stiffness of rocks, and the amount of accumulated strain energy combine to control the magnitude and timing of earthquakes. Fault segments most likely to break can be identified where faults and plate motions are well known. If a fault segment is known to have broken in a past large earthquake, recurrence time and probable magnitude can be estimated based on fault segment size, rupture history, and accumulation of strain.

Scientists currently estimate that a magnitude 9 earthquake in the Cascadia Subduction Zone occurs about once every 500 years. The last one was in 1700. Paleoseismic investigations have identified 41 Cascadia Subduction Zone interface earthquakes over the past 10,000 years, which corresponds to one earthquake about every 250 years. Of these 41 earthquakes, about half are M9.0 or greater earthquakes that represent full rupture of the fault zone from Northern California to British Columbia. The other half of the earthquakes represents M8+ earthquakes that rupture only the southern portion of the subduction zone.

The 300+ years since the last major Cascadia Subduction Zone earthquake is longer than the average of about 250 years for M8 or greater and shorter than some of the intervals between M9.0 earthquakes. The time history of these major earthquakes is shown below in Figure 5.4-14.

Figure 5.4-14. Time History of Cascadia Subduction Zone Interface Earthquakes[36]



Comparison of the history of subduction zone earthquakes along the Cascadia Subduction Zone in northern California, Oregon, and Washington, with events from human history. Ages of earthquakes are derived from study and dating of submarine landslides triggered by the earthquakes. Earthquake data provided by Chris Goldfinger, Oregon State University; time line by Ian P. Madin, DOGAMI.

Scientists currently estimate the probability of future occurrence for deep earthquakes similar to the 1965 magnitude 6.5 Seattle-Tacoma event and the 2001 magnitude 6.8 Nisqually event is about once every 35 years. The USGS has estimated that there is an 84% chance of a magnitude 6.5 or greater deep earthquake over the next 50 years.

Scientists currently estimate the approximate recurrence rate of a magnitude 6.5 or greater earthquake anywhere on a shallow fault in the Puget Sound basin to be once in about 350 years. There have been four earthquakes of less than magnitude 5 in the past twenty years.

Hazus-MH 2.1 Earthquake Methodology and Results

Hazus-MH is a geographic information system (GIS) - based earthquake loss estimation tool developed by the Federal Emergency Management Agency (FEMA) in cooperation with the National Institute of Building Sciences (NIBS). Hazus-MH 2.1 was used to calculate the Average Annualized Loss (AAL) and the Average Annualized Loss Ratios (AALR) for the State of Washington. In order to increase the reliability of the results, enhanced hazard data and inventory was utilized. Two user-supplied data layers for liquefaction and soil class were added to Hazus-MH to more accurately model the effects of the earthquake at each site-specific state facility. These data maps were supplied by the Washington Department of Natural Resources in their June 2010 Ground Response file geodatabase containing GIS data. The two datasets used in this scenario were: liquefaction susceptibility, which contain GIS polygons that provide information regarding the relative liquefaction potential for Washington State; and seismic site class, which contains polygons that provide NEHRP (National Earthquake Hazards Reduction Program) soil data information for Washington State. In addition, enhanced inventory data was provided for five counties courtesy of the Washington Hazus Users Group.[2]

The Average Annualized Loss addresses two key components of seismic risk: the probability of ground motion in terms of physical damage and economic loss. Average Annualized Loss also takes into account the regional variations in seismic risk. Average Annualized Loss annualizes expected losses by averaging losses per return period (100; 250; 500; 750; 1,000; 1,500; 2,000; and 2,500 years), which factors in historic patterns of smaller but more frequent earthquakes with those that are larger in magnitude but are infrequent in nature. This methodology enables the comparison of risk to occur between two geographic areas, such as Skagit County and Asotin County.

The Average Annualized Loss Ratio is the Average Annualized Loss presented as a fraction of the replacement value of the building inventory and is used for comparing the relative risk of a seismic event. Therefore, the annualized loss ratio allows for the relationship between the AAL and the building replacement values to be evaluated. This ratio can be used as a measure of relative risk between regions and within a state, since it is normalized by replacement value, allowing for the direct comparison across metropolitan areas, counties, and even between states.

In addition to the Hazus-MH Average Annualized Loss analysis, inflation was accounted for in order to estimate approximate 2012 value of losses. The Consumer Price Index (CPI) is a common measure of inflation and was used herein. State CPI's are not determined but national and metropolitan-level (with populations over 1.5 million) values are calculated. According to the Washington Office of Financial Management, the Seattle Metropolitan Statistical Area CPI (including Seattle, Tacoma, and Bremerton) is the closest representative to a state CPI. It should also be noted that the CPI at the metropolitan level is subject to measurement errors and can be more volatile given the smaller area. According to the Seattle CPI, the cumulative rate of inflation between 2000 and 2012 was calculated to be 29.9 percent. In other words, $1.00 in 2000 is equivalent to $1.29 in 2012.[37] For comparison purposes, the national rate of inflation during this time was 33.3 percent.

The results of the AAL are shown in Table 5.4-5 and Figure 5.4-15 below.

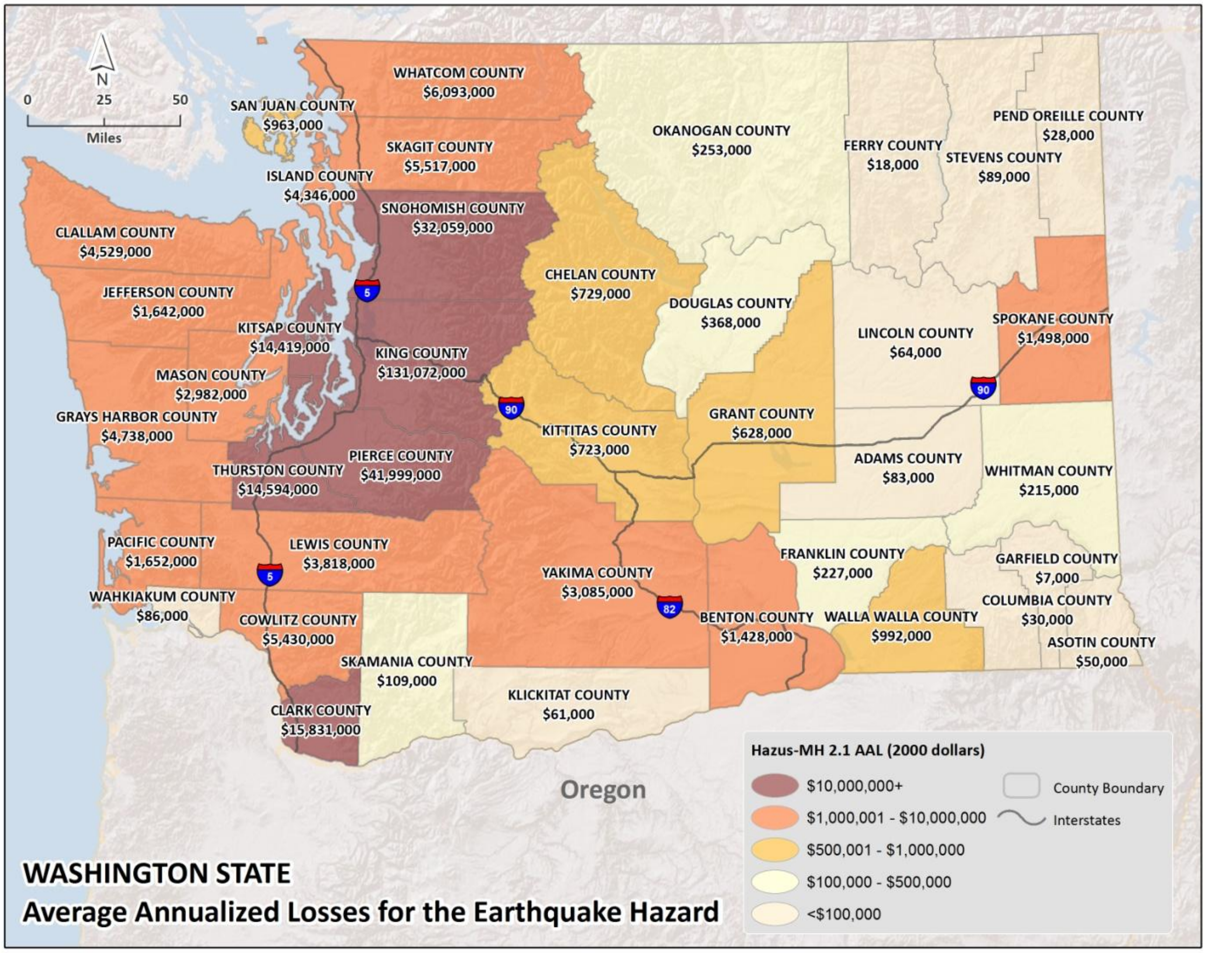
---

[2] Additional information on the data updates can be found in Appendix A.

Table 5.4-5. **Earthquake Average Annualized Loss Estimates from Hazus-MH 2.1**

County	Loss Ratio	Total Average Annualized Losses	Inflated to 2012 dollars
Adams County	0.01	$83,000	$107,070
Asotin County	0	$50,000	$64,500
Benton County	0.01	$1,428,000	$1,842,120
Chelan County	0.01	$729,000	$940,410
Clallam County	0.06	$4,529,000	$5,842,410
Clark County	0.04	$15,831,000	$20,421,990
Columbia County	0.01	$30,000	$38,700
Cowlitz County	0.05	$5,430,000	$7,004,700
Douglas County	0.01	$368,000	$474,720
Ferry County	0	$18,000	$23,220
Franklin County	0	$227,000	$292,830
Garfield County	0	$7,000	$9,030
Grant County	0.01	$628,000	$810,120
Grays Harbor County	0.06	$4,738,000	$6,112,020
Island County	0.05	$4,346,000	$5,606,340
Jefferson County	0.04	$1,642,000	$2,118,180
King County	0.05	$131,072,000	$169,082,880
Kitsap County	0.05	$14,419,000	$18,600,510
Kittitas County	0.02	$723,000	$932,670
Klickitat County	0	$61,000	$78,690
Lewis County	0.05	$3,818,000	$4,925,220
Lincoln County	0	$64,000	$82,560
Mason County	0.05	$2,982,000	$3,846,780
Okanogan County	0.01	$253,000	$326,370
Pacific County	0.05	$1,652,000	$2,131,080
Pend Oreille County	0	$28,000	$36,120
Pierce County	0.05	$41,999,000	$54,178,710
San Juan County	0.03	$963,000	$1,242,270
Skagit County	0.04	$5,517,000	$7,116,930
Skamania County	0.01	$109,000	$140,610
Snohomish County	0.04	$32,059,000	$41,356,110
Spokane County	0	$1,498,000	$1,932,420
Stevens County	0	$89,000	$114,810
Thurston County	0.06	$14,594,000	$18,826,260
Wahkiakum County	0.02	$86,000	$110,940
Walla Walla County	0.02	$992,000	$1,279,680
Whatcom County	0.03	$6,093,000	$7,859,970
Whitman County	0	$215,000	$277,350
Yakima County	0.01	$3,085,000	$3,979,650
Washington State	**0.02**	**$302,456,000**	**$390,166,951**

Figure 5.4-15. Average Annualized Losses from Hazus-MH 2.1



Casualties and injuries are also estimated in Hazus. Estimates are reported at three different times throughout the day including 2:00 AM (people are asleep in houses), 2:00 PM (people are working), and 5:00 PM (people are commuting from work). Injuries range from minor to requiring hospitalization. As would be expected, residential casualties are highest during the 2:00 AM estimate. The following table shows the annualized injury and fatalities based on these assumptions.

Table 5.4-6: Hazus Estimated Injuries and Fatalities

	2:00 AM		2:00 PM		5:00 PM	
Building Type	**Injuries**	**Deaths**	**Injuries**	**Deaths**	**Injuries**	**Deaths**
Commercial	1	0	106	7	77	5
Commuting	0	0	0	0	0	0
Educational	0	0	21	1	3	0
Hotels	1	0	0	0	0	0
Industrial	2	0	14	1	9	1
Other-Residential	42	1	9	0	16	1
Single Family	32	0	6	0	13	0
Total	**78**	**1**	**156**	**8**	**118**	**7**

Jurisdictions Most Threatened and Vulnerable to Earthquake Hazards

The primary factors used to determine the 26 counties that are most vulnerable to future earthquakes were the Annualized Earthquake Loss, as calculated by Hazus-MH 2.1 and the Annualized Earthquake Loss Ratio, as calculated by Hazus-MH 2.1. Counties considered most at risk are those with an Annualized Earthquake Loss of at least $1 million or with an Annualized Earthquake Loss Ratio equal or greater than the state's ratio of 0.02. Twenty-three counties meet one of these two criteria.

Additionally, Douglas and Franklin, which have greater seismic risk than most counties in Eastern Washington but do not have building stock to meet the above criteria, have been added to the list of jurisdictions most vulnerable at the advice of state and federal geologists and seismologists with expertise in earthquakes in Washington. This brings the total counties considered most vulnerable to earthquakes to twenty-five.

Other factors included the size of potentially vulnerable populations like people who do not speak English as their primary language, individuals with disabilities, senior citizens, people living in poverty, and children in school (kindergarten through 12th grade) plus the age of the housing stock built before 1960, when building codes were first enacted in Washington State.

Average Annualized Earthquake Loss and Annualized Earthquake Loss Ratio[38, 39]

A complete description of the Hazus-MH 2.1 Average Annualized Loss methodology can be found in the previous subsection ("Hazus-MH 2.1 Earthquake Methodology and Results"). As noted above, Average Annualized Loss factors in historic patterns of smaller but more frequent earthquakes with those that are larger in magnitude but are infrequent in nature. This methodology enables the comparison of risk to occur between different geographic areas and inputs.

The Average Annualized Loss Ratio is the Average Annualized Loss presented as a fraction of the replacement value of the building inventory and is used for comparing the relative risk of a seismic event. Therefore, the annualized loss ratio allows for the relationship between the AAL and the building replacement values to be evaluated. This ratio can be used as a measure of relative risk between regions and within a state, since it is normalized by replacement value, allowing for the direct comparison across metropolitan areas, counties, and even between states.

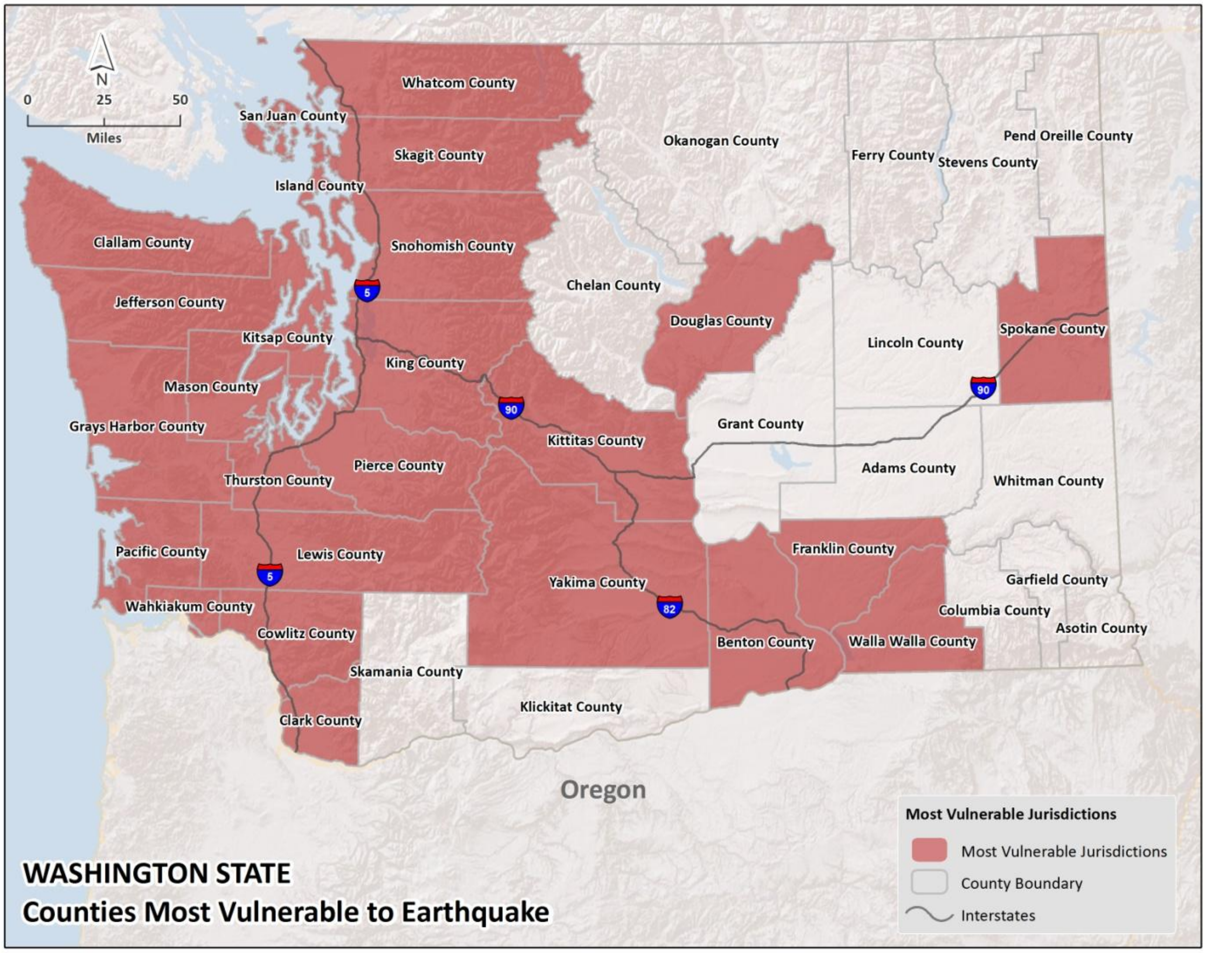
The Average Annualized Loss and Ratios calculated using Hazus-MH for each county in Washington State are not to be seen as determinations of total risk since not all aspects of earthquake are addressed. The value presented in Table 5.4-7 only represent the direct economic loss to buildings, and do not factor in such things as damage to lifelines and critical facilities and the indirect economic losses that can be sustained by communities and as a result of a seismic event. The Hazus-MH estimates annualized loss and annualized loss ratios were calculated using default inventory data for each county. As noted above, counties considered most at risk are those with an Annualized Earthquake Loss of at least $1 million or with an Annualized Earthquake Loss Ratio equal or greater than the state's ratio of 0.02. Twenty-five counties meet one of these two criteria.

Table 5.4-7. Average Annualized Loss Estimates from Hazus-MH 2.1

County	Loss Ratio	Total Average Annualized Losses
Clallam	0.06	$4,529,000
Grays Harbor	0.06	$4,738,000
Thurston	0.06	$14,594,000
Cowlitz	0.05	$5,430,000
Island	0.05	$4,346,000
King	0.05	$131,072,000
Kitsap	0.05	$14,419,000
Lewis	0.05	$3,818,000
Mason	0.05	$2,982,000
Pacific	0.05	$1,652,000
Pierce	0.05	$41,999,000
Clark	0.04	$15,831,000
Jefferson	0.04	$1,642,000
Skagit	0.04	$5,517,000
Snohomish	0.04	$32,059,000
San Juan	0.03	$963,000
Whatcom	0.03	$6,093,000
Kittitas	0.02	$723,000
Wahkiakum	0.02	$86,000
Walla Walla	0.02	$992,000
Adams	0.01	$83,000
Benton	0.01	$1,428,000
Chelan	0.01	$729,000
Columbia	0.01	$30,000
Douglas	0.01	$368,000
Grant	0.01	$628,000
Okanogan	0.01	$253,000
Skamania	0.01	$109,000
Yakima	0.01	$3,085,000
Asotin	0	$50,000
Ferry	0	$18,000
Franklin	0	$227,000
Garfield	0	$7,000
Klickitat	0	$61,000
Lincoln	0	$64,000
Pend Oreille	0	$28,000
Spokane	0	$1,498,000
Stevens	0	$89,000
Whitman	0	$215,000
Washington State	0.02	$302,456,000

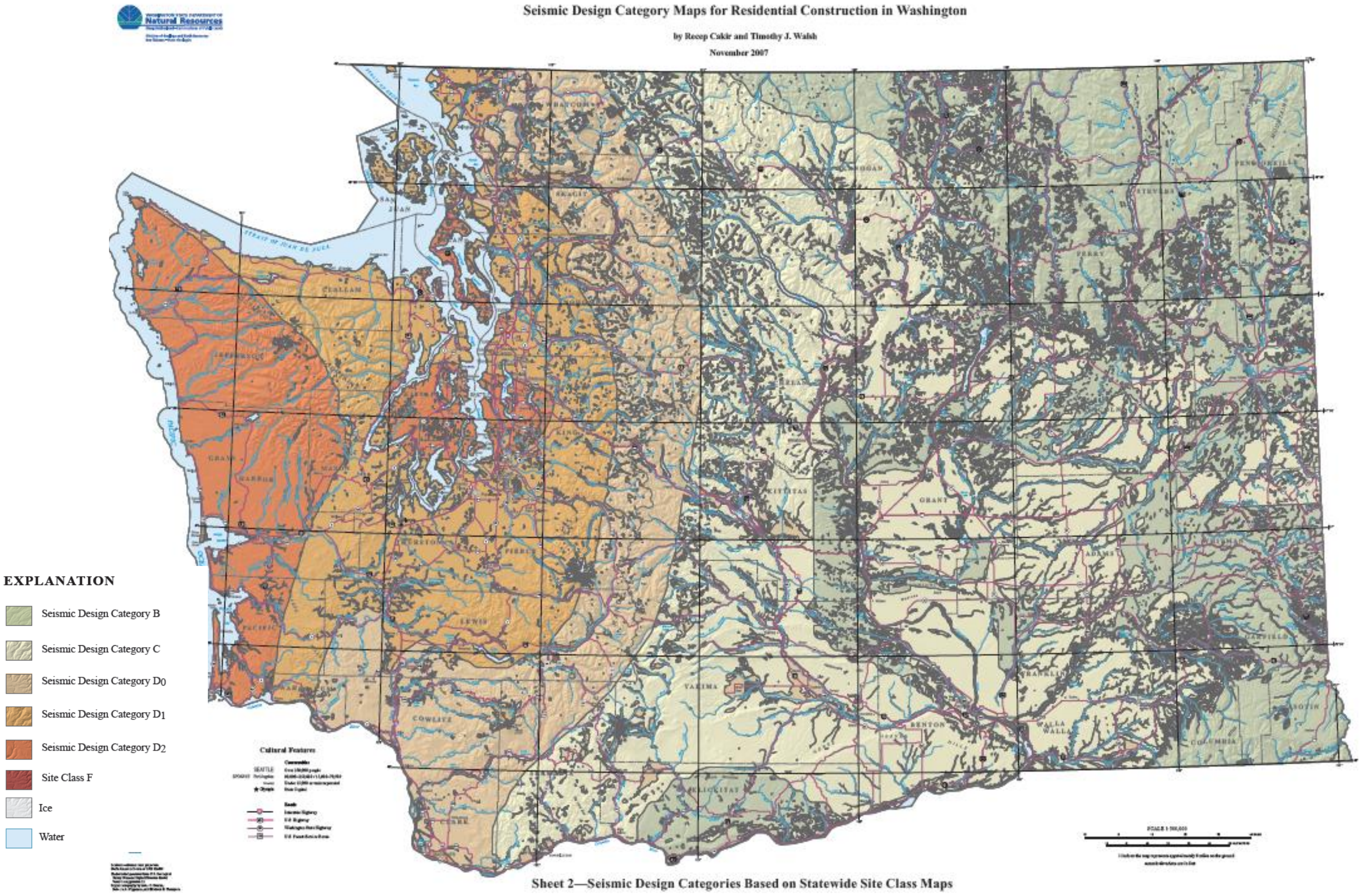
The following figure shows the location of the twenty-five most vulnerable jurisdictions to earthquake.

Figure 5.4-16. Jurisdictions Most Vulnerable to Earthquake



Building codes enforced at the time the structure was built does influence the buildings survivability to seismic events.

Figure 5.4-17. Seismic Design Category Map for Residential Construction in Washington State, 2007.



Source: http://pubs.usgs.gov/of/2009/1298/pdf/usgs_of2009-1298_cakir.pdf

Potential Impacts of Earthquakes

Much of the damage in earthquakes occurs from ground shaking that affects buildings and infrastructure. However, there are several other consequences of earthquakes that can result in substantially increased levels of damage in some locations. These consequences include: surface rupture, subsidence or elevation, liquefaction, settlement, lateral spreading, landslides, dam, reservoir or levee failures, tsunamis and seiches. Any of these consequences can result in very severe damage to buildings, up to and including complete destruction, and also a high likelihood of casualties.

Surface Rupture

Surface rupture occurs when the fault plane along which rupture occurs in an earthquake reaches the surface. Surface rupture may be horizontal and/or vertical displacement between the sides of the rupture plane. For a building subject to surface rupture the level of damage is typically very high and generally results in destruction of the building. Horizontal or vertical rupture through a building in a major earthquake means that two parts of the building are displaced by several feet in horizontal or vertical direction or both.

Surface rupture does not occur with interface or intraplate earthquakes on the Cascadia Subduction Zone and does not occur with all crustal earthquakes. Fault rupture for the Cascadia earthquakes and for many crustal earthquakes doesn't reach the earth's surface. However, surface rupture does when crustal earthquake fault ruptures reach and break the ground surface. Faults in Washington where surface rupture is likely include the Seattle Fault System and the Tacoma Fault System.

Subsidence or Uplift

Large interface earthquakes on the Cascadia Subduction Zone are expected to result in subsidence of up to several feet in many coastal locations, while other locations may be uplifted by several feet. For facilities located very near sea level, co-seismic subsidence may result in the facilities being below sea level or low enough so that flooding becomes very frequent. Subsidence may also impede egress by blocking some routes and thus increase the likelihood of casualties from tsunamis.

Subsidence or uplift may be fairly uniform over an area or be uneven due to variations in soil/rock type. Uneven subsidence or uplift may substantially increase building damages in a manner analogous to surface rupture.

Liquefaction, Settlement and Lateral Spreading

Liquefaction is a process where loose, wet sediments lose bearing strength during an earthquake and behave similar to a liquid. Once a soil liquefies, it tends to settle vertically and/or spread laterally. With even very slight slopes, liquefied soils tend to move sideways downhill (lateral spreading). Settling or lateral spreading can cause major damage to buildings and to buried infrastructure such as pipes and cables.

The Washington Department of Natural Resources (DNR) has made statewide estimates of liquefaction potential, based on available geological data. Liquefaction potential varies markedly with location, often over very short distances. Thus, it is not possible to show liquefaction potential maps except at high spatial resolution for small areas.

Landslides

Earthquakes can also induce landslides, especially if an earthquake occurs during the rainy season and soils are saturated with water. The areas prone to earthquake-induced landslides are largely the same as those areas prone to landslides in general. As with all landslides, areas of steep slopes with loose rock or soils and high water tables are most prone to earthquake-induced landslides**.** See Risk Assessment Tab 5.7 for a more detailed discussion of landslides.

Dam, Levee and Reservoir Failures

Earthquakes can also cause dam failures in several ways. The most common mode of earthquake-induced dam failure is slumping or settlement of earthfill dams where the fill has not been properly compacted. If the slumping occurs when the dam is full, then overtopping of the dam, with rapid erosion leading to dam failure is possible. Dam failure is also possible if strong ground motions heavily damage concrete dams. Earthquake induced landslides into reservoirs have also caused dam failures.

Earthquake-induced failures of levees are very similar to failures of earthfill dams. If levee crests slump enough to create overtopping, then rapid erosion leading to levee failure is possible.

Earthquake-induced failures of concrete or steel water storage reservoirs for potable water system are also possible.

For facilities behind levees or with dams or reservoirs upstream, a seismic risk assessment should include evaluation of possible inundation of the facilities from dam, levee or reservoir failures.

See Risk Assessment Tab 5.12 for a more detailed discussion of dam safety.

Tsunamis and Seiches

Tsunamis, which are sometimes incorrectly referred to as “tidal waves,” result from earthquakes that cause a sudden rise or fall of part of the ocean floor. Such movements may produce tsunami waves, which have nothing to do with the ordinary ocean tides. Tsunamis may also be generated by undersea landslides, by terrestrial landslides into bodies of water, and by asteroid impacts. However, earthquakes are the predominant cause of tsunamis.

In the open ocean, far from land and in deep water, tsunami waves may be only a few inches high and thus be virtually undetectable, except by special monitoring instruments. These waves travel across the ocean at speeds of several hundred miles per hour. When such waves reach shallow water near the coastline, they slow down and can gain great heights.

Tsunamis affecting the Washington coast can be produced from very distant earthquakes off the coast of Alaska or elsewhere in the Pacific Ocean. For such tsunamis, the warning time for the Washington coast would be at least several hours. However, interface earthquakes on the Cascadia Subduction Zone can also produce tsunamis. For such earthquakes the warning times would be very short, less than 30 minutes. Because of this extremely short warning time, emergency planning and public education are essential before such an event occurs.

Tsunamis can also be created by crustal earthquakes, such as the Seattle Fault System and the Tacoma Fault System which cross parts of Puget Sound because these earthquakes are likely to include vertical movements of the floor of the sound which will generate tsunamis. The warning times for such tsunamis would be only a few minutes.

A similar earthquake phenomenon is "seiches" which are waves from sloshing of inland bodies of waters such as lakes, reservoirs, or rivers. Seiches may result in damages to docks and other shoreline or near-shore structures. Seiches within reservoirs may also results in roof damage or, in extreme case, rupture of the entire tank with resulting flooding.

See Risk Assessment Tab 5.9 for a more detailed discussion of tsunami.

Potential Impact of Climate Change

With the advent of climate change coming into worldwide focus, it is necessary to take into account the potential effects this emerging climate crisis may have on the dangers associated with natural disasters. The research done so far indicates the potential for unusual or more frequent heavy rainfall and flooding is greater is some areas while the potential for drought is predicted in other areas. Landslide frequency is correlated with heavy rainfall and flooding events. Climate change has not necessarily been associated with increasing risk from earthquake hazards. However, general abnormalities caused by climate change, such as more unstable ground, could exacerbate the impacts of an earthquake.

Recognizing Washington's vulnerability to climate impacts, the Legislature and Governor Chris Gregoire directed state agencies in 2009 to develop an integrated climate change response strategy to help state, tribal and local governments, public and private organizations, businesses and individuals prepare. The state Departments of Agriculture, Commerce, Ecology, Fish and Wildlife, Health, Natural Resources and Transportation worked with a broad range of interested parties to develop recommendations that form the basis for a report by the Department of Ecology: *Preparing for a Changing Climate: Washington State's Integrated Climate Change Response Strategy*.

Over the next 50 - 100 years, the potential exists for significant climate change impacts on Washington's coastal communities, forests, fisheries, agriculture, human health, and natural disasters. These impacts could potentially include increased annual temperatures, rising sea level, increased sea surface temperatures, more intense storms, and changes in precipitation patterns. Therefore, climate change has the potential to impact the occurrence and intensity of natural disasters, potentially leading to additional loss of life and significant economic losses. Recognizing the global, regional, and local implications of climate change, Washington State has shown great leadership in addressing mitigation through the reduction of greenhouse gases.

At Risk State Facilities

A Hazus-MH 2.1 analysis was employed to model building losses for state-owned and state-leased facilities utilizing the Washington State Office of Financial Managements 2012 dataset of state facilities. A total of 9,975 state facilities were analyzed. These buildings have an estimated replacement value of $13,363,228,000. The combined area of the state buildings is estimated at 105,060,000 square feet. Of these buildings, 8,893 were reported as owned and 1,082 were reported as leased. Owned buildings have a combined exposure (building replacement value) of $11,858,700,000, and leased buildings have a combined value of $1,504,528,000. Owned buildings have a combined area of 93,425,000square feet, and leased buildings have a combined area of 11,635,000 square feet.

The OFM data did contain data gaps that needed to be addressed in order to perform the Hazus-MH analysis. Most critically, building type and building replacement value needed attention. For building type, it was assumed that all structures were one story and constructed of wood. Regarding building replacement value, there were both missing and erroneous data in the OFM data. Therefore, 2012 R.S. Means Facilities Construction Cost data was used to determine building replacement value using a combination of the building occupancy (Hazus classification of Government buildings (GOV1)), existing building square footage, year built and the assumed building type. From this updated building inventory, the Advanced Engineering Building Module (AEBM) was used to model each building.

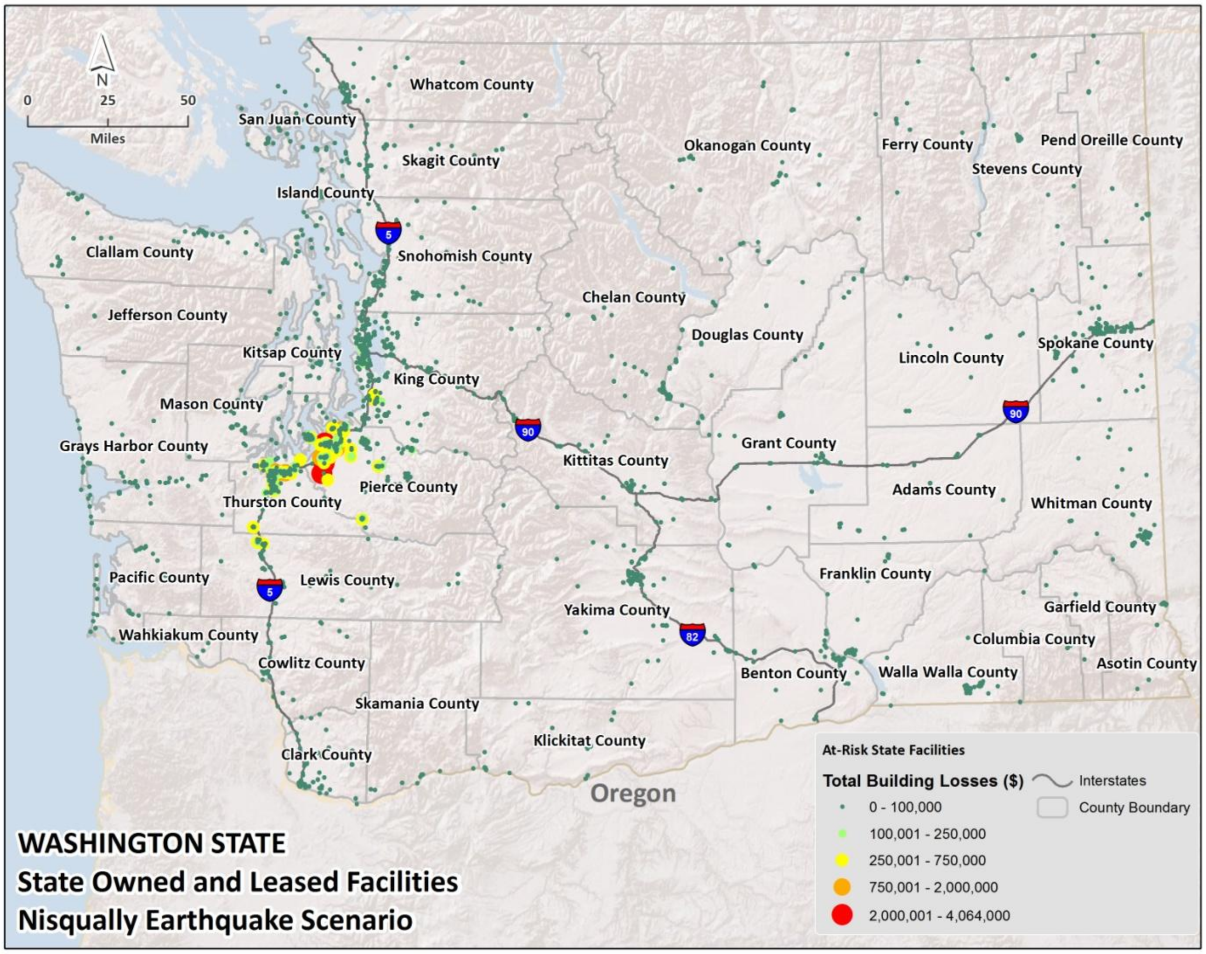
The AEBM is a Hazus-MH component that performs a detailed earthquake analysis and facilitates a site-specific building loss estimation analysis for damages and losses for each building in an inventory. There are many advanced functions, including the ability to input user-specified hazard maps, override the default building fragility curves or create your own building profiles. In this case, an AEBM inventory was developed outside of Hazus using the 2012 OFM dataset of state leased and owned facilities. This dataset was then defined in Hazus as the AEBM Inventory. A set of AEBM Profiles were then entered in Hazus for all possible building occupancies, types and earthquake design level combinations. The AEBM Profiles describe an extensive set of building performance characteristics, including damage and loss function parameters. Each building in the AEBM Inventory is then linked to one of the created AEBM Profiles.

After the AEBM Inventory and Profiles were developed, the Hazus Earthquake model was employed to generate building losses based on certain scenario earthquakes, or an earthquake with a specified magnitude and location. The resulting loss estimate generally will describe the scale and extent of damage that may result from a potential earthquake. Quantitative estimates of losses were then reported in terms of direct costs for repair and replacement of damaged buildings.

The first scenario earthquake (deterministic hazard) that was run was the February 28, 2001, Nisqually earthquake event which a Magnitude 6.8. Similar to the methodology employed for Average Annualized Losses above, two user-supplied data layers for liquefaction and soil class were added to Hazus-MH to more accurately model the effects of the earthquake at each site-specific state facility. These maps allow Hazus-MH to model the conditions present at each of the building sites.

The Nisqually M6.8 earthquake resulted in $122,589,000 potential total building losses to the 9,975 state owned facilities. Of this $90,719,000 were total building losses to the 8,893 state owned buildings and $31,871,000 were total building losses to 1,082 state leased facilities. As a percentage this represents a loss ratio of 0.91 percent of total state facility exposure (including .68 percent for state owned buildings and 0.24 percent for state leased buildings). Figure 5.4-18 below shows an overview of buildings and their associated losses.

Figure 5.4-18. State Facility Hazus-MH Earthquake Losses



Appendix A

Utilizing Enhanced Hazus-MH Input Data

It is important to note that the default Hazus-MH inventory datasets is not current to calendar year 2013. This is crucial to understand because any of the loss estimates that are generated by a Hazus-MH analysis will be portrayed with out-of-date information. As such, the losses may not be accurate to current building replacement costs or may not accurately reflect present-day population from which Hazus-MH estimates building square foot totals by tract and by block. At the time this plan was completed (May 2013), Hazus-MH version 2.1 software utilized U.S. Census 2000 data as the default primary geographic unit of analysis. To quantify building and demographic distribution across Census block and tracts, Hazus-MH uses Census 2000 data for RES1 and RES2; Building replacement costs were derived from Means Square Foot Costs 2002, for Residential, Commercial, Industrial, and Institutional buildings; to calculate business economic losses, aggregated information on total number of employees, total annual sales and total square footage by census tract is provided by 2006 Dunn and Bradstreet. Much of this default data can be enhanced with more current or local data through the use of FEMA's Comprehensive Data Management System (CDMS).

Comprehensive Data Management System (CDMS) can be used to update a variety of Hazus-MH inputs using local data (such as tax assessor or regional planning data). CDMS is a complementary tool to Hazus-MH. This software streamlines the inventory update process, allowing a user to update the entire statewide dataset with Hazus-MH, as opposed to a single study region. This permits for repeated analysis and the creation of new study regions with updated Hazus inventory. There are two main areas of Hazus-MH inventory that can be updated via CDMS. These are aggregate data sets (such as building values and counts) and site-specific data sets (Such as essential facilities. Unfortunately, local data could not be fully updated into Hazus for this plan update, but some improvements were made.

The Washington State Hazard Mitigation Plan was able to benefit from work coordinated by the Washington Hazus User Group (WAHUG). The WAHUG coordinated and completed the local data updates for the state GBS geodatabases utilizing CDMS. Local data from these counties was used to replace the default Hazus-MH data, therefore providing a more accurate and representative loss estimation. The following counties were updated using local data: Snohomish, September, 2010; Yakima, June, 2010; Lewis, June, 2010; Grays Harbor, June, 2010; and Cowlitz, June, 2010. Hazus-MH default data was used in Washington's 34 other counties. These enhanced datasets were used for the statewide General Building Stock (GBS) Average Annualized Loss (AAL) analysis in the five counties.

It is likely that future version of Hazus-MH will use 2010 or newer Census data as a default. Until then it is advisable that in any future Hazus-MH analysis technicians attempt to use the most current data available. Following are examples of sources of inventory data that can be accessed to enhance the Hazus building data:

- Locations of government facilities, ex. military installations and government offices
- Databases of hazardous buildings, Tax assessor's files
- School district or university system facilities
- Databases of fire stations or police stations
- Databases of historical buildings
- Databases of churches and other religious facilities

- Postal facilities (ATC-26, 1992)
- Hospitals (The AHA Guide of the American Hospital Association; ATC-23A, 1991A)
- Public and private utility facility databases
- Department of transportation bridge inventory
- Dun and Bradstreet database of business establishments
- Insurance Services Office databases used for fire assessment of large buildings

Updating the Washington state-owned facilities for use in a User Defined Facilities (UDF) or in an Advanced Engineering Building Module (AEBM) analysis is important as well. In a UDF analysis User-defined facilities are those facilities, other than essential facilities or high potential loss facilities, which the user may wish to analyze on a site-specific basis. Critical pieces of data that must be collected are:

- Building Type (wood, steel, masonry, etc.)
- Building Replacement Value
- Building Contents Value
- Building Occupancy Type
- Floor Area
- Number of Stories
- Latitude and Longitude
- Year Built

For detailed descriptions and Hazus-MH accepted values and domains please refer to the CDMS Data Dictionary.

References

---

[1] Earthquakes in Washington. Washington State Department of Natural Resources. Available at: http://www.dnr.wa.gov/researchscience/topics/geologichazardsmapping/pages/earthquakes.aspx

[2] *Washington State 2001 Hazard Identification and Vulnerability Assessment*, Washington State Military Department, Emergency Management Division, April 2001.

[3] *Earthquakes in Washington*, Washington Department of Natural Resources Division of Geology and Earth Resources, May 5, 2003. Accessed 9 October 2012. Available at http://www.dnr.wa.gov/ResearchScience/Topics/GeologicHazardsMapping/Pages/earthquakes.aspx

[4] The Nisqually Earthquake Information Clearinghouse, University of Washington. Accessed 9 October 2012. Available at http://www.ce.washington.edu/~nisqually/index.html

[5] Tectonic Plates of the World, figure. Accessed 26 March 2013. Available at: http://johomaps.com/world/worldtecton.html

[6] Washington State Department of Natural Resources

[7] United States Geological Survey (2013). Largest Earthquakes in the World Since 1900. Available at: http://earthquake.usgs.gov/earthquakes/world/10_largest_world.php

[8] University of Washington (2002). Map and List of Significant Quakes in WA and OR, The Pacific Northwest Seismograph Network. University of Washington Department of Earth Sciences.

[9] *Earthquake Hazards in Washington and Oregon – Three Zones*, U.. Geological Survey fact sheet, <http://www.ess.washington.edu/SEIS/PNSN/CascadiaEQs.pdf>, (July 28, 2003).

[10] Ibid.

[11] Current approximate recurrence rates of M9.0 Cascadia Subduction Zone, M≥6.5 Seattle Fault, Deep M≥6.5, and random shallow M≥6.5 earthquakes provided by Arthur D. Frankel, U.. Geological Survey, in an oral presentation at the *Workshop On Geologic Research In The Seattle Area*, University of Washington, October 20, 2003.

[12] Ibid.

[13] William J. Stephenson and Arthur D. Frankel, *Preliminary Simulation of a M6.5 Earthquake on the Seattle Fault Using 3D Finite-Difference Modeling*, U.. Geological Survey Open-File Report 00-339, U.. Department of the Interior, 2000.

[14] S.Y. Johnson, et al., *Active Tectonics of the Seattle Fault and Central Puget Sound, Washington: Implications for Earthquake Hazards,* Geological Society of America Bulletin, v. 111, no. 7, p. 1042-1053, 1999, <http://earthquake.usgs.gov/regional/pacnw/activefaults/sfz/>, (May 1, 2003).

[15] *The Southern Whidbey Island Fault*, U.. Geological Survey Earthquake Hazards Program, <http://earthquake.usgs.gov/regional/pacnw/activefaults/whidbey/>, (May 1, 2003).

[16] Preliminary Estimates of Damages and Loss from a run of Hazus 99-SR2 by Kircher Associates Consulting Engineers for the Seattle Fault Scenario project funded in part by the EERI Foundation, May 2003. The figures

---

developed from a Level 1 analysis of Hazus default data adjusted for the year 2005 for a five county region – King, Kitsap, Pierce, Snohomish, and Thurston Counties.

[17] Samuel Y. Johnson, et al., Active Tectonics of the Devils Mountain Fault and Related Structures, Northern Puget Lowland and Eastern Strait of Juan de Fuca Region, Pacific Northwest, U.S. Geological Survey Professional Paper 1643, U.S. Department of the Interior, <http://earthquake.usgs.gov/regional/pacnw/activefaults/dmf/>, (May 1, 2003).

[18] Washington State Department of Natural Resources (2013). Available at: https://fortress.wa.gov/geology?Theme-wigm

[19] Robert E. Derkey and Michael M. Hamilton, *Spokane Earthquakes Point to Latah Fault?*, Washington Geology, Volume 29, No.1/2, Washington Department of Natural Resources, Division of Geology and Earth Resources, September 2001.

[20] S.P. Reidel, et al., *Late Cenozoic Structure and Stratigraphy of South-Central Washington*, Regional Geology of Washington State, Bulletin 80, Washington Division of Geology and Earth Resources, 1994.

[21] Oral communication from Craig Weaver, Seismologist and Pacific Northwest Coordinator, National Earthquake Program, U.. Geological Survey, July 17, 2003.

[22] Ruth Ludwin, *Earthquake Prediction*, Washington Geology, vol. 28, no. 3, page 27, Washington Department of Natural Resources, Division of Geology and Earth Resources, May 2001.

[23] From *Map and List of selected significant quakes in WA and OR* , The Pacific Northwest Seismograph Network, University of Washington Department of Earth and Space Sciences, September 9, 2002, < http://www.pnsn.org/earthquakes/recent >, (March 26, 2013).

[24] Abridged from *Seismicity of the United States, 1568-1989 (Revised),* by Carl W. Stover and Jerry L. Coffman, U.. Geological Survey Professional Paper 1527, United States Government Printing Office, Washington: 1993.

[25] Frank Neumann, *United States Earthquakes 1936*, U.S. Department of Commerce, Coast and Geodetic Survey, Serial Number 610, U.S. Government Printing Office, pp. 19-23, <http://www.ess.washington.edu/SEIS/PNSN/HIST_CAT/1936.html>, (July 18, 2003).

[26] Woodward-Clyde Consultants, 1980, Seismological review of the July 16, 1936 Milton-Freewater earthquake source region: Woodward-Clyde Consultants [under contract to] Washington Public Power Supply System, 1 v.

[27] Benj. H. Brown, *The State Line Earthquake at Milton and Walla Walla*, Bulletin of the Seismological Society of America, vol. 27 no. 3, July 1937.

[28] Ibid.

[29] Linda Lawrence Noson, Anthony Qamar and Gerald W. Thorson, *Washington State Earthquake Hazards*, Information Circular 85, Washington State Department of Natural Resource, Division of Geology and Earth Resources, 1988.

[30] Abridged from *Seismicity of the United States, 1568-1989 (Revised),* by Carl W. Stover and Jerry L. Coffman, U.. Geological Survey Professional Paper 1527, United States Government Printing Office, Washington: 1993.

---

[31] Linda Lawrence Noson, Anthony Qamar and Gerald W. Thorson, *Washington State Earthquake Hazards*, Information Circular 85, Washington State Department of Natural Resource, Division of Geology and Earth Resources, 1988.

[32] *Hazard Mitigation Survey Team Report, Nisqually Earthquake, February 28, 2001, DR-1361-WA*, Federal Emergency Management Agency and Washington Military Department, Emergency Management Division.

[33] *The Nisqually Earthquake of 28 February 2001, Preliminary Reconnaissance Report*, Nisqually Earthquake Clearinghouse Group, University of Washington, March 2001.

[34] *Nisqually Quake Damaged Nearly 300,000 Puget Sound Households*, news release posted on UWNews.org, November 19, 2002, <http://uwnews.org/article.asp?articleid=2517>, (May 1, 2003).

[35] Washington State Departmetn of Natural Resources. Seismogenic Features. Accessed on 13 Feb 2013. Available at: http://www.dnr.wa.gov/ResearchScience/Topics/GeosciencesData/Pages/gis_data.aspx

[36] Oregon Seismic Safety Policy Advisory Commission (2013). The Oregon Resilience Plan.

[37] Seattle Toacoma Bremerton MSA Consumer Price Index, All Items. U.S. Department of Labor, Bureau of Labor Statistics. Available at: http://www.bls.gov/ro9/9250.pdf

[38] For detailed information on the calculation of Earthquake Annualized Loss and Earthquake Annualized Loss Ratios using Hazus-MH MR4, see *Hazus-MH MR4 – Technical Manual, Chapter 15 and 17* and *Hazus-MH MR4 – User Manual, Chapter 9*. <www.fema.gov/plan/prevent/hazus/hz_manuals.shtm>

[39] *The Washington State Earthquake Hazards Scenario Catalog*, Washington State Department of Natural Resources (WADNR), the Washington Military Department Emergency Management Division (EMD), Western Washington University (WWU), Huxley College of the Environment, Federal Emergency Management Agency (FEMA), US Geological Survey (USGS) and URS Corporation. Accessed 8 November 2012. Available at https://fortress.wa.gov/dnr/seismicscenarios/