5.4 Tsunamis and Seiches

Tsunami

- *Definition*: Tsunamis are water waves caused by earthquakes, volcanic eruptions, or landslides. In deep water tsunamis have long wavelengths, short wave heights, and travel up to 30 mph. As tsunamis enter shallow water they slow down, and the waves increase significantly in height.
- Tsunamis do not have to have large wave heights to be damaging. Tsunami damage is caused by both the forces exerted by flowing water onto structures, and by run-up of the wave onto land that causes flooding and carries debris. Tsunamis can also generate dangerous current speeds that can be hard for vessels to navigate.
- Tsunamis generated in the Pacific Ocean off Washington's coast will not have as great of an effect in Seattle as they will on the Pacific Coast, but low-lying areas may experience flooding, and strong currents will likely be present in Puget Sound for hours after the earthquake.
- Tsunamis can be generated in Puget Sound by both landslides and earthquakes.
- The most frequent cause of Puget Sound tsunamis is landslides. The 1949 Olympia earthquake triggered a landslide in the Tacoma Narrows that caused a 6 to 8-foot tsunami that affected nearby shorelines three days after the earthquake.
- The most damaging tsunami would likely come from a Seattle Fault earthquake, or earthquakes on other local faults. There is evidence that an earthquake on the Seattle Fault that occurred around 900 AD produced a 16-foot tsunami. The National Oceanic and Atmospheric Administration (NOAA) recreated this tsunami using a model.
- The modelled tsunami would flood areas up to one mile inland with depths up to 5 meters. The tsunami would hit immediately after the ground stopped moving. People along the shore would have little time to escape. It would destroy buildings along the shore and flood low-lying areas up to one mile inland. Structures built to modern code would fare better than older ones.
- The 900 AD tsunami was probably a worst-case event. It is more likely (but not certain) that the next Seattle Fault earthquake and tsunami will be smaller.
- The preliminary results from modeling a tsunami generated by an M9.0 megathrust earthquake predict the main impacts to be current speeds of 3 to 5 knots in Elliott Bay and 15 inches of inundation near the Duwamish river.

Seiche

- *Definition*: Seiches are standing waves in waterbodies caused by most often by seismic waves or atmospheric pressure. They can occur at great distances (100s or 1000s of miles away) from an earthquake epicenter. Because they are *standing* waves they move vertically rather than horizontally.
- Lake Union is especially prone to seiches due to its shape. The east and west sides are roughly parallel, and the V-shaped northern end focuses waves. There is a historical report of a seiche or tsunami on Lake Washington, but it is not clear how large seiches on Lake Washington could be.
- Seiches have occurred multiple times in Seattle, but they have not caused extensive damage so far. Large seiches are a danger to the I-90 and SR 520 floating bridges. A large seiche could strain cables anchoring the bridges. The new SR 520 bridge is designed to take about 12-feet of upward motion

and 8-feet of downward motion from a seiche. Based on models the most damaging seiche would probably be caused by a Cascadia subduction zone earthquake.

5 4.1 Context

Tsunami

Tsunamis are water waves produced by an offshore earthquake, volcanic eruption, landslide, or an impact of an object from space. Any event that suddenly displaces a huge volume of water can generate a tsunami.

Tsunamis generated by four sources have the potential to reach Seattle: 1) distant sources, including subduction zones from around the Pacific, 2) Cascadia Subduction Zone megathrust earthquakes, 3) earthquakes on local faults, such as the Seattle Fault, and 4) landslides.

Tsunamis are hard to detect in the deep, open ocean. The wavelengths of tsunamis are between 93 and 155 miles, with amplitudes of three feet or less, and travel at speeds of about 450 (and up to 600) miles per hour.[281] As a wave approaches the shoreline, its front slows, allowing the rest of the wave to ride up and increasing the wave's height dramatically. Tsunamis nearing the coast can rise to 100 feet in height and move at a speed of 30 miles per hour.

Tsunamis generated in enclosed bodies of water can be especially large. The collapse of a 3,000-foot tall rock wall in a narrow Alaska fjord stripped vegetation over 1,700 feet high on the opposite shore. While the Seattle area does not have any cliffs nearly that size, it does have steep sea bluffs along enclosed bodies of water, and a high susceptibility for submarine landslides.

While tsunamis are often depicted as one large wave, they are actually a series of waves, with a distance between crests of 60 or more miles. The time between successive waves reaching the shore can vary from 5 to 90 minutes.[282] These waves interact with each other, and with shorelines, which is why a single tsunami event can last for several hours.

Whether a tsunami is generated by a potential trigger depends on the volume of water displacement and the speed of the displacement. Most tsunamis are triggered by earthquakes of magnitude 7 or larger.[283] However, magnitude alone is not sufficient in predicting a tsunami. Along with the vertical movement of the earth during an earthquake, horizontal movement and the bathymetry (underwater topography) of the sea floor influence tsunami generation and size.

Some tsunamis break when they reach land. Some rush ashore as a huge mass of water, like a sudden massive tide. Others break far from land and come ashore as a turbulent cascading mass called a bore. The size and speed of the tsunami as well as the coastal area's form and depth are factors that affect the tsunami's shape. The power of a tsunami comes from the huge amount of water behind the wave's leading edge. Normal waves have a small volume, so they dissipate quickly when they strike the shore. Tsunamis do not. Their huge volume pushes the water far inland. This phenomenon is called "run-up" and its size is what often determines a tsunami's destructiveness.[284] The tide at the time of the tsunami can also influence potential run-up. A tsunami or seiche riding on a high tide presents greater danger than one occurring at low tide.

Tsunamis rarely crash ashore without warning. Though localized coastal flooding may precede the first wave, often the shoreline water recedes before the first tsunami wave arrives. This is dangerous since many people, unaware of the looming danger, venture too close to shore and are caught by subsequent waves. During the Indian Ocean Tsunami, a ten-year-old girl who had studied tsunami recognized this phenomenon and saved more than 100 people.

Three main factors could influence the size, shape, volume, and potential destructiveness of a tsunami generated by the Seattle Fault. These are shallow waters above the Seattle Fault, steep shoreline bathymetry, and the shape of Elliott Bay.

- Since Elliott Bay and Puget Sound are shallower than the open ocean, there would be less water displaced by a Seattle Fault earthquake. The resulting tsunami would be slower and have less volume than one generated in the deep ocean.[285]
- Puget Sound's steeply sloping bathymetry may increase the chance that a tsunami will break on the shore, thus enhancing the tsunami's destructiveness.[286]
- The shape of Elliott Bay could increase damage by funneling waves together, thereby increasing wave height.[287]

Seiches

Seiches are vertical waves in which the largest vertical oscillations are at each end of a body of water with very small oscillations at the center point of the wave.[288] In other words, it is the waves created by the sloshing of water in an enclosed or partially enclosed waterbody, like water sloshing in a bathtub. Pushes from a seismic wave or air pressure cause the water to rock back and forth. Under the right conditions, resonance builds up wave height just like pumping one's legs to make a swing go higher. Since larger bodies of water usually have longer frequencies, it takes longer frequency waves traveling through the ground to create seiches in them. Due to the mechanics of an earthquake, areas close to the epicenter shake at high frequencies. Therefore, seiches tend to occur far from earthquake epicenters.[289] The biggest danger is from subduction zone or megathrust earthquakes that cause powerful, low frequency ground waves.

5 4.2 *History*

Both tsunamis and seiches have occurred in the past 1200 years in Central Puget Sound area.

Tsunami deposits attributed to the Seattle Fault have been found in five locations in Puget Sound, including Seattle.[290] It is not known if they are the result of one event or several closely spaced in time, but the most likely source in an estimated magnitude 7.3 earthquake on the Seattle Fault around 900 AD.

The 1964 Alaskan Earthquake caused a tsunami that was detected in Seattle, with a sea level rise of 0.8 feet detected on the Elliott Bay tide gauge. The waves were higher on the Pacific coastlines of Washington, Oregon, and California. Friday Harbor and Neah Bay recorded maximum wave heights of 2.3 feet and 4.7 feet, respectively. The tsunami's effect was negligible in Seattle because the wave had lost energy as it traveled up the Strait of Juan de Fuca, and Whidbey Island may have acted as a baffle for the incoming waves. New, nuanced models of a Cascadia event show that the main impact would be increased currents in Puget Sound, and very few areas would experience run-up.

A megathrust earthquake on the Cascadia Subduction Zone in 1700 AD generated a tsunami that impacted the Pacific coastline between Vancouver Island and California, and also sent a damaging tsunami across the Pacific Ocean to Japan.[291] This tsunami probably left deposits of the same age that have been found under the tidal marshes of Discovery Bay and the head of Hood Canal in Washington, but there is no geologic evidence for this tsunami elsewhere in Puget Sound.[292]

Landslides have caused localized tsunamis in at least two locations in Puget Sound since the late 1800s. Other records include oral history from the Snohomish Indian people who describe a deadly tsunami in the early 1800s, a small tsunami or seiche in 1891, and a damaging tsunami in 1894 caused by a submarine landslide in Commencement Bay. The most recent was in 1949 when the Tacoma Narrows experienced a landslide that triggered 6 to 8-foot tsunami following that year's magnitude 7.1

earthquake. The 900 AD Seattle Fault earthquake triggered massive landslides into Lake Washington, but there is no geologic evidence that these slides caused tsunamis in the lake.

The 1964 Alaska megathrust earthquake and 2002 Denali earthquake caused seiches in Lake Union.[293] These seiches damaged boats by battering them against docks and moorings in Lake Washington and Lake Union. Interestingly, the seismic waves that caused them could not be directly felt by humans.

Seiches have been more common than tsunamis and have not caused extensive damage so far. In 1891, an earthquake near Port Angeles caused an 8-foot seiche in Lake Washington, big enough to endanger people along the shore.[294] Both Lake Union and Lake Washington experienced seiches during the 1949 Puget Sound deep earthquake, but they did no damage.[295]

5 4.3 Likelihood of Future Occurrences

Tsunami

Seattle will almost certainly experience tsunami and seiches again, but the question is how often the biggest ones will occur. Seiches and tsunamis from distant earthquakes are the most common instances recorded for Seattle, but they have produced only minor to moderate damage and, to the best of our knowledge, no casualties.

Based on history and the number of landslides in Puget Sound, the most likely source of a tsunami is a large landslide. It is not known how big these waves can get but limited historical evidence suggests at most 6 to 8 feet high, and typically affecting a limited area.

Distant tsunamis originating from around the Pacific Ocean basin (the “Ring of Fire”) are likely, but they will probably have only minor effects on Seattle because they must travel through the Strait of Juan de Fuca then make a 90 degree turn south into Puget Sound and once in the Sound they are disrupted by the many islands and complex shoreline.

Local tsunamis from the Cascadia Subduction zone recur about every 500-600 years on the northern end of the subduction zone. Simulations of a magnitude 9.0 Cascadia earthquake generate a tsunami with wave heights reaching about 4 feet high offshore of Discovery Park and in the channel on the east side of Harbor Island.[296] Despite these wave heights, the simulation predicts almost no inundation of Seattle coastal areas, due in part to steep shorelines.[297] The area most impacted by inundation is Kellogg Island, near the mouth of the Duwamish River, but the model predicts only about 15 inches of inundation there.[298] The greatest predicted hazards are potentially dangerous ocean current velocities off of Discovery Park and Alki Point. Tsunami modeling estimates current speeds of up to 3 knots off of Discovery Park, 3.6 knots off of Alki, and up to 5 knots on the southwest side of Harbor Island.[299] Currents would increase suddenly and potentially last for multiple hours.[300] Such current speeds could make it difficult for maritime traffic, mainly small watercraft, navigate the waters.

The worst tsunami for Seattle would be triggered by a Seattle Fault earthquake.[301] The Seattle Fault runs through Bainbridge Island, across Puget Sound, through West Seattle, Sodo, Beacon Hill and then east to Bellevue (see Figure [Nisqually Shaking Intensity] for a map). The biggest earthquake possible on the Seattle Fault is magnitude 7.3. The frequency estimates for Seattle Fault Earthquakes are difficult to estimate due to lack of data about past events. USGS recurrence interval estimates range between 200 and 12,000 years for any Seattle Fault earthquake.[302] Other local earthquake scientists predict a recurrence interval for M7.2 or larger Seattle Fault earthquakes to be every 5,000 to 15,000 years.[303]

It is likely that the next Seattle Fault earthquake will be smaller than the one in 900 AD. A team of seismologists and earthquake engineers chose to model a magnitude 6.7 Seattle Fault earthquake that they consider more likely than a magnitude 7.3. A magnitude 6.7 earthquake would probably trigger a smaller tsunami than the one that happened in 900 AD. The Seattle Fault shows evidence of episodic fault rupture of about 6 feet, enough to produce a tsunami.[304]

The size of a tsunami depends on the amount of uplift caused by an earthquake. The 900 AD earthquake caused over 15 feet of uplift. If the fault movement is purely vertical, a magnitude 6.7 earthquake would likely cause about 1 meter (3 feet) or less of displacement on the fault plane, which translates to about 0.5 meters (1.5 feet) of uplift on a 40-degree thrust fault. A tsunami generated by a magnitude 6.7 Seattle Fault earthquake has not been modeled. It would probably cause a fraction of the damage of the NOAA-modeled tsunami following a magnitude7.3 earthquake or the earthquake-generated tsunami in 900 AD.[305]

Other faults potentially capable of producing tsunamis in Puget Sound include the Tacoma Fault, the South Whidbey Island Fault, the Strawberry Point Fault, the Utsalady Point Fault, and the Darrington-Devils Mountain Fault Zone.[306]

Seiches

Seiches are more common than tsunamis. Both Puget Sound and Lake Washington experienced them in 1891, 1949, and 1964. These events caused light to moderate damage. It is very likely that similar seiches will happen again. A Cascadia megathrust earthquake may cause a much more dangerous seiche than past occurrences in Lake Union and possibly Lake Washington.[307] Cascadia megathrust earthquakes happen, on average, every 500 years. See the chapter on earthquakes for more details.

5 4.4 *Vulnerability*

Further tsunami modeling is in progress for the tsunami impact to Seattle from magnitude 9.0 Cascadia Subduction Zone earthquake, but preliminary results suggest that the Seattle Fault earthquake presents the greatest tsunami danger to Seattle.[308] Figure [Worst Case Tsunami Inundation Area from M7.3 Seattle Fault Earthquake] shows the worst-case Seattle Fault inundation area.

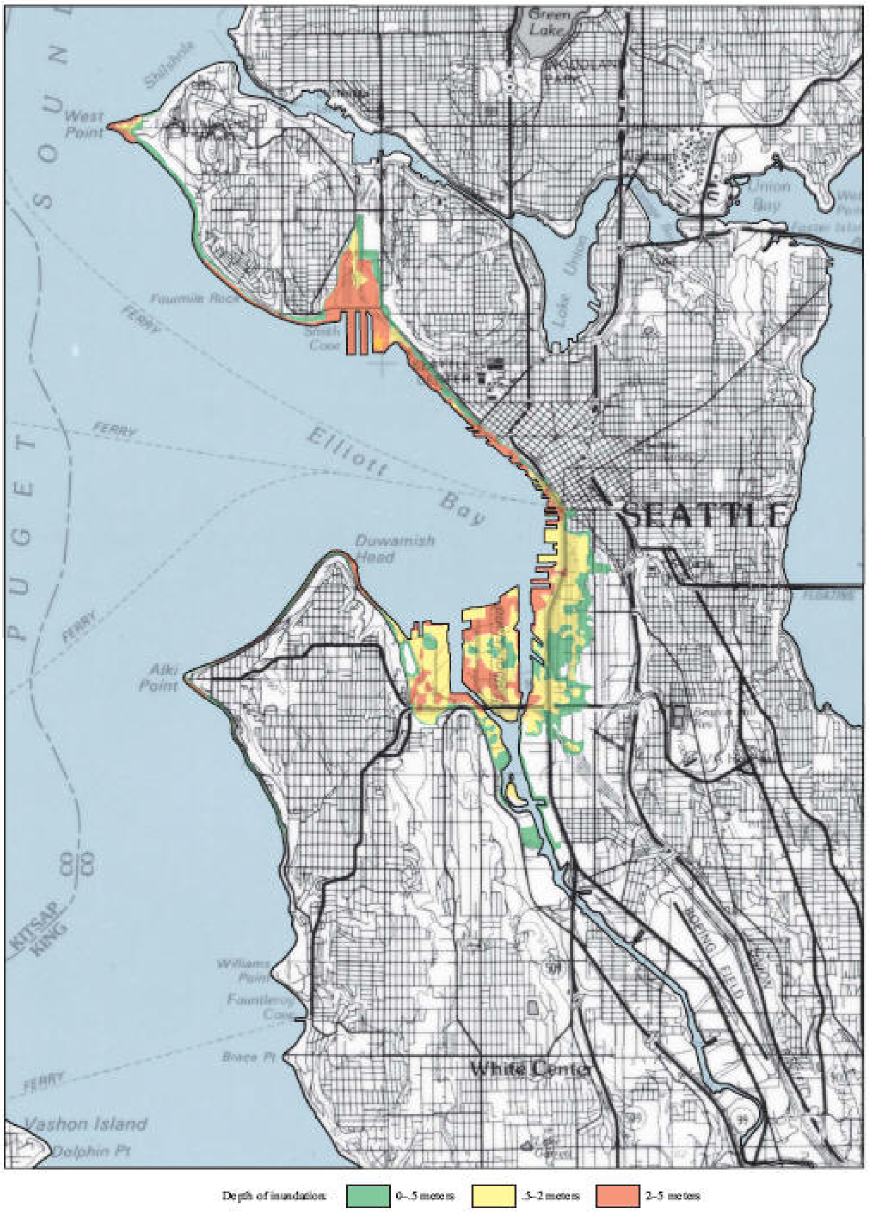
Seattle has a highly developed shoreline that makes it vulnerable to tsunami and seiche damage. Large numbers of people work, play, and live near the water. Major port facilities, tourist attractions, and housing ring Elliott Bay. Lake Union’s shoreline is home to houseboats, businesses (including Amazon), parks, and museums.

The short time between a triggering event (e.g. earthquake, landslide) and arrival of the wave train (30 seconds to 5 minutes) would not permit many people to escape.[309] The only possible escape would be trying to get to higher floors in multi-story buildings. Some of these buildings are likely to be severely damaged if the trigger is a Seattle Fault earthquake. Most engineered structures performed fairly well in recent tsunamis.[310] Steel frame and modern concrete frame buildings built to seismic codes fared best in the tsunami following the 2011 Tohoku earthquake in Japan.[311] Likewise, the low death toll in the 2010 Chilean earthquake and tsunami was attributed to the country’s strict adherence to building codes.[312] Structures already damaged by a landslide or earthquake would be especially susceptible to more damage from a tsunami.

The effect of the built environment is also important. Sea walls line most of Elliot Bay and the Duwamish Waterway. They provide some protection against waves whether they are storm waves, seiche waves, or tsunami waves. Buildings also affect the propagation of waves inland. The first layer of buildings acts as a barrier and tends to decrease wave velocity, but they can also add debris to the storm water. The worst-case tsunami scenario modeled for Seattle does not include the effects of the built environment. In 2017, Seattle replaced its weak, aging seawall to meet current seismic standards. The new seawall is built to withstand a M6.7 Seattle Fault earthquake and subsequent tsunami. However, waves are expected to top the seawall in the M7.3 worst-case Seattle Fault scenario.

The primary impacts are likely to be from the earthquake itself. The new 520 floating bridge is built to withstand waves in a 100-year wind event. The Washington State Department of Transportation anticipates that these storm-generated wave forces would exceed the forces from a small to moderate-sized tsunami.

Figure 5-20. Worst Case Tsunami Inundation Area from M7.3 Seattle Fault Earthquake



Tsunami Lifeline Exposures:

- None of Seattle's water supply lines travel through the worst-case tsunami inundation area, but feeder and distribution mains run along the shore from Interbay to Sodo, under 1st Ave South and along the West Seattle Bridge.
- The BP Olympic pipeline which carries fuel runs through the area from Harbor Island and along the West Seattle Bridge and the Spokane Street Viaduct.

- Seattle City Light power transmission lines enter the area near the Port of Seattle. 30 transmission towers are in the area.
- Sewer mains run through the Interbay area to Myrtle Edwards Park and in the south, from downtown through the rail corridor serving the Port and along the West Seattle Bridge. In West Seattle a sewer main runs along Harbor Ave SW to the Duwamish Head.
- Enwave's steam plant is located in the area, at Western Avenue and Union Street.

Tsunami Transportation Exposures:

- Most of Seattle's marine terminals sit in the tsunami inundation area.
- BSNF's Sodo railyards and about half of its Interbay railyard are in the area; all Seattle's north-south rail corridors touch the area.
- The southern entrance to the new SR 99 tunnel is in the area. See the consequences section below for more on its exposure.
- SR 99, 1st Ave S, and the West Seattle Bridge cross the area.
- The King County International Airport is *not* in the inundation area.

5 4.5 Consequences

Tsunamis

Tsunamis have the potential to cause extreme damage and high casualties. The worst tsunami for Seattle would be a repeat of the one that occurred in 900 AD and modelled by the National Oceanic and Atmospheric Administration (NOAA). It is likely that the next Seattle Fault earthquake and tsunami will be smaller, because earthquake occurrence has a power law distribution. In other words, as earthquake frequency increases, magnitude decreases exponentially, meaning there are many very small earthquakes and a few very large earthquakes. Since the 900 AD event was a very high magnitude, we would expect the next one to be smaller based on the high probability of small magnitude earthquakes (see page 22 for additional discussion on power law distribution).

The NOAA model (see Figure [Worst Case Tsunami Inundation Area from M7.3 Seattle Fault Earthquake]) assumes a maximum of 7 meters of uplift on the Seattle Fault's south side (on Bainbridge Island), 4 meters uplift at Alki Point and 1-meter subsidence on the north side at West Point (Magnolia). The model assumes the earthquake happens at high tide. It does not account for the effects of sea walls or buildings. It adjusts for their absence by using a greater bottom friction parameter. Doing so has the effect of decreasing the amount of flooding in flat areas.

The largest part of a Seattle Fault tsunami would be in Puget Sound between Seattle and Bainbridge Island. Most of this part would miss Seattle. Inside Elliott Bay the first wave crest would form a bore with an amplitude of 6 meters (i.e., 6 meters above the normal water level). The biggest wave would form on the northern edge of the fault. It would move north, striking Magnolia, Interbay, Myrtle Edwards Park, and the Downtown Waterfront in two minutes and 20 seconds. It would reflect off the steep bluffs of Magnolia and move south reaching Harbor Island about 5 minutes after the earthquake.

The wave would flood an area up to 1 mile inland around the Duwamish River's mouth. Figure [Worst Case Tsunami Inundation Area from M7.3 Seattle Fault Earthquake] shows the extent and depth of the inundation. The highest vertical run-ups are about 10 meters along Magnolia, Alki Beach, and east of Alki Point.[313]

The consequences of a worst-case tsunami would be catastrophic. Depending on the time of year and day, the shores ringing Elliott Bay are some of the most densely populated parts of Seattle. Survivors of the triggering earthquake would have minutes to reach higher ground. Many people would be trapped in collapsed or damaged buildings. Roads would be blocked by debris. The best evacuation strategy would be to seek shelter in the upper stories of buildings. Normally, it would be inadvisable to enter potentially severely damaged buildings but doing so it safer than facing a tsunami in the open.

The tsunami would impact most of Seattle's port facilities including critical fuel terminals. Prolonged disruption to the Port would have economic impacts for the city, as essential trade operations would be slowed or halted. The tsunami would also inundate major roadways (SR 99, Elliott Avenue, and the area under the West Seattle Bridge) and railways.

The NOAA tsunami model predicts ½ to 2 meters of inundation in the area surrounding the south portal to the SR99 tunnel. The model is based on a magnitude 7.3 Seattle Fault earthquake that is estimated to have a 1% chance of happening in the next 50 years. The extent of flooding in the tunnel depends not only on the flood depth, but also the total volume of water, the flow rate, the direction of flow and the grade of the entrance, the wavelength of the tsunami, and the co-seismic subsidence. The tunnel was built with possible flooding in mind. It has six feet of space under the lower roadway where water can collect and a pumping system to remove it. Emergency exits are spaced every 650 feet. Sea level rise could increase the reach and depth of a future tsunami.[314]

The tsunami would probably cause many landslides on the south side of Magnolia and the area east of Alki point. It would likely also trigger fires and hazardous materials spills in the port and industrial areas around Harbor Island. Inundation could affect downtown steam systems. If Enwave Seattle (previously Seattle Steam) loses generating capacity, Seattle's major hospitals could lose their ability to sterilize medical instruments.

Seiches

Seiches would cause moderate to severe damage to structures on or adjacent to the shore of Seattle's lakes and Puget Sound. Lake Union is likely to experience the most severe consequences. According to Barberopoulou's 2009 modelling, Lake Union would experience wave heights of up to 6 feet (measured trough to crest) for minutes following the earthquake. Ships, boats, floating docks, and houseboats would pound violently against each other. Power, water, sewer, gas, and communications lines would be severed. People standing on vessels or near the shore could easily fall into the violently sloshing water. Wave motion would be more up and down than side to side because seiches are standing waves. This lack of horizontal movement means that major inland flooding would not occur (See Figure [Area Exposed to Lake Union Seiche]).

The likelihood of a seiche on other local waterbodies is not as well understood, but seiches in these bodies will probably be smaller than those on Lake Union. The consequences of a Lake Washington seiche could include people near the shore being knocked into the water, residential and commercial property damage, and damage to the two floating bridges. A seiche in Elliot Bay could include damage to port and industrial facilities. If a seiche damages buildings over or near the water, it is possible that the building could catch fire or release hazardous materials.

5 4.6 Conclusions

Seattle has an extensive and well-developed coastline. Many recreational and economic activities occur near the shoreline. Both tsunami and seiches would occur with little or no warning. These factors give Seattle an inherent vulnerability to tsunami and seiche hazards. Despite this vulnerability, Seattle's risk is mitigated due to the infrequency of incidents that generate truly powerful tsunami and seiches.

Because of their greater frequency in Puget Sound, landslide-caused tsunamis are the greatest overall risk to Seattle. Landslide-caused tsunami can be very large and can be triggered by cumulative events like small to moderate earthquakes and heavy rainfall.

Figure 5-21. Area Exposed to Lake Union Seiche