Introduction

Tsunami (soo-NAH-mee): a Japanese word that means harbor wave; a sea wave of local or distant origin that results from large-scale seafloor displacements associated with large earthquakes, major submarine slides, or exploding volcanic islands. [65]

Tsunamis, often incorrectly described as tidal waves, are sea waves usually caused by displacement of the ocean floor. Typically generated by seismic or volcanic activity or by underwater landslides, a tsunami consists of a series of high-energy waves that radiate outward like pond ripples from the area in which the generating event occurred. The arrival of tsunami waves is usually typified by a sudden and unexpected recession of water; the first wave will be followed by additional waves a few minutes or even a few hours later. Wave size typically increases over time, and coastal flooding may often precede the largest waves.

Seiche (saysh): a series of standing waves (sloshing action) of an enclosed body or partially enclosed body of water caused by earthquake shaking. Seiche action can affect harbors, bays, lakes, rivers, and canals. [66]

Tsunami and Seiche events occur only very infrequently in Puget Sound.

High Probability Low Impact	**High Probability Moderate Impact**	**High Probability High Impact**
Moderate Probability Low Impact	**Moderate Probability Moderate Impact**	**Moderate Probability High Impact**
Low Probability Low Impact	**Low Probability Moderate Impact**	**Low Probability High Impact**

Hazard Identification

Normally caused by earthquake activity, tsunamis and seiches can affect harbors, bays, lakes, rivers, and canals. In the majority of instances, earthquake-induced events do not occur close to the epicenter of an earthquake, but hundreds of miles away. Earthquake shock waves close to the epicenter consist of high frequency

[65] Skagit County Natural Hazards Identification Plan, http://www.skagitcounty.net/EmergencyManagement/Documents/2003HazMitFinal/Section%20II%20Final%20Documents/3%20HIVA%20Skagit%20Drought.pdf
[66] Skagit County Natural Hazards Identification Plan, http://www.skagitcounty.net/EmergencyManagement/Documents/2003HazMitFinal/Section%20II%20Final%20Documents/3%20HIVA%20Skagit%20Drought.pdf

vibrations, while those at much greater distances are of lower frequency. It is the low frequency vibrations that move bodies of water. The biggest tsunamis and seiches develop when the period of ground movement matches the frequency of oscillation in the body of water.[67]

Not all earthquakes produce tsunamis. To generate a tsunami, an earthquake must occur underneath or near the ocean, be very large (approximately Richter magnitude 7 or greater), and create vertical movement of the sea floor. All oceanic regions of the world can experience tsunamis, but in the Pacific Ocean there is a much more frequent occurrence of large, destructive tsunamis because of the many large earthquakes along the boundaries of the Pacific Ocean's "Ring of Fire." [68]

Tsunamis can be intensely powerful, as large Pacific Ocean tsunamis typically have wave crest to wave crest distances of 60 miles and can travel about 600 miles per hour in the open ocean, navigating the entire 12,000 to 14,000 miles of the Pacific Ocean in just 24 hours. In deep ocean waters, the length from wave crest to wave crest may be a hundred miles or more but only reaches a wave height of less than a few feet. As a result, tsunamis cannot be felt aboard ships nor can they be seen from the air in the open ocean. [69]

Tsunamis and seiches can be generated by a number of sources:

1. Distant earthquakes along the Pacific Rim.

2. Local earthquakes, such as those generated by local surface faults, those originating in the Benioff zone, or those that occur in the Cascadia Subduction Zone off the coast.

3. Large landslides into bodies of water, such as Puget Sound or area lakes.

4. Submarine landslides in bodies of water like Puget Sound.[70]

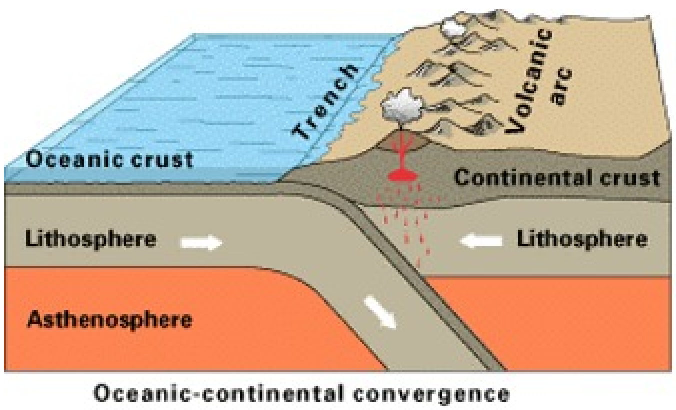
Either a large subduction zone quake off the coast or along the Seattle fault could produce a tsunami, however, while a tsunami generated by a distant or Cascadia subduction earthquake could result in much damage to the coast, it wouldn't create as great of an impact in King County. For in the case of a subduction zone quake, a tsunami would travel from the coast through the Straight of Juan de Fuca into Puget

[67] Snohomish County Department of Emergency Management Hazard Identification and Vulnerability Assessment, http://www.snodem.org/HIVA.pdf
[68] Snohomish County Department of Emergency Management Hazard Identification and Vulnerability Assessment, http://www.snodem.org/HIVA.pdf
[69] Skagit County Natural Hazards Identification Plan, http://www.skagitcounty.net/EmergencyManagement/Documents/2003HazMitFinal/Section%20II%20Final%20Documents/3%20HIVA%20Skagit%20Drought.pdf
[70] Washington State Hazard Mitigation Plan, Region 6, http://emd.wa.gov/3-map/mit/mit-pubs-forms/hazmit-plan/reg-6-profile.pdf

Sound, and then south to Seattle. Because of the shielding effects of the Olympic Peninsula and the islands in Puget Sound, the tsunami expected from a magnitude 8.5 quake would be less then 2 feet high when it arrived at Seattle's shores, having lost much of its' velocity.[71] As a result, primary concerns lie with a tsunami or seiche generated by a land movement originating on the Seattle fault, which runs off the northern end of West Seattle through Elliott Bay towards the Kingdome and across toward Bellevue.[72]

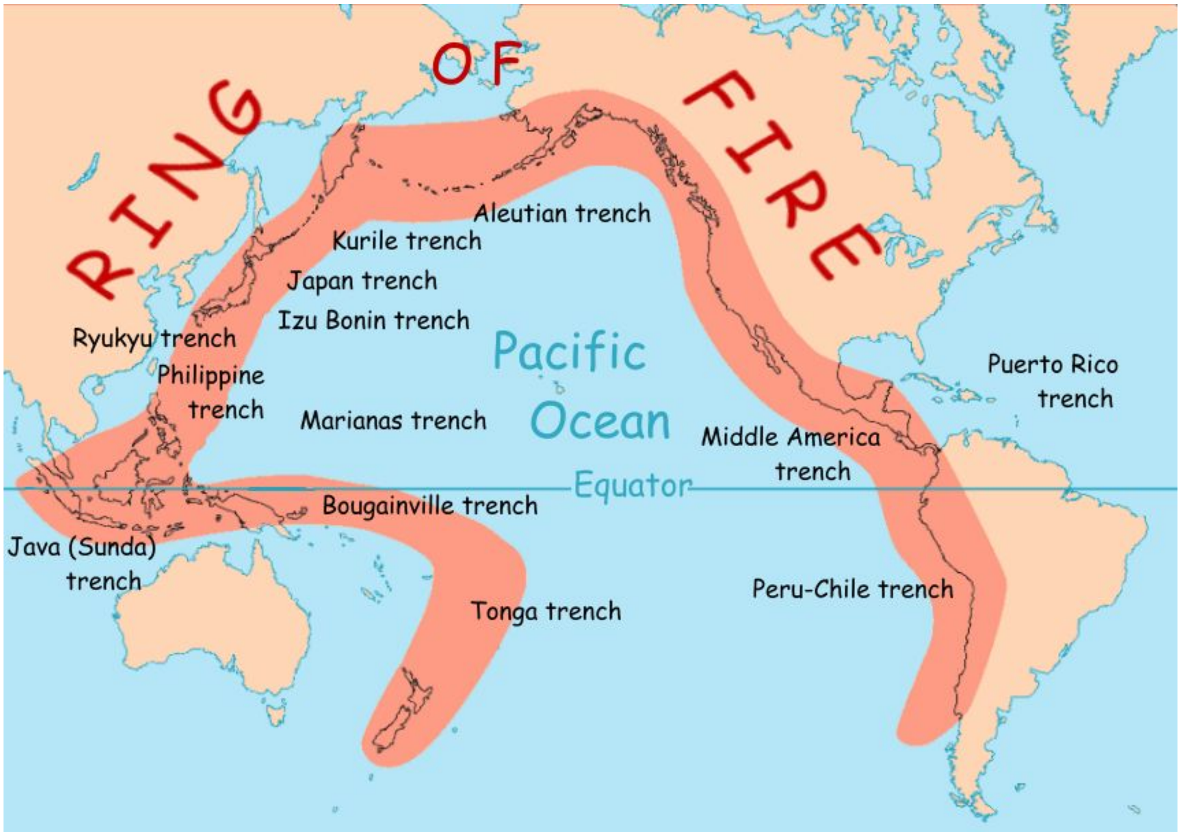
The National Oceanic and Atmospheric Administration (NOAA)'s Center for Tsunami Inundation Mapping Efforts developed a tsunami inundation model for Seattle's Elliott Bay using a magnitude 7.3 Seattle Fault earthquake as an initiating event (this model simulates the earthquake event 1,000 years ago, considered by NOAA to be the credible worst-case scenario.) The area modeled includes communities within one kilometer of the Puget Sound coast, such as portions of Seattle, Riverton-Boulevard Park and White Center, and projects a potential at-risk population of 11,056.[73]

For example, in addition to Lake Washington, Lakes Sammamish and Union have many watercrafts, houseboats, docks, piers, houses and buildings located on or close to their waterfronts. Our area floating bridges may also be at risk for seiche damage. Additional vulnerabilities to seiche in King County include water storage tanks and containers of liquid hazardous materials, which could be affected by the rhythmic motion of a "sloshing" seiche.



Source: Peninsula Emergency Preparedness Committee, Pacific Northwest Tsunamis Resource Section, http://www.pep-c.org/pacificnorthwesttsunamis/

[71] City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm
[72] City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm
[73] City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm



Source: NOAA National Geophysical Data Center,
http://www.ngdc.noaa.gov/seg/hazard/stratoguide/glossary.html

Hazard Impact

Several factors could influence the size, shape, volume, and potential destructiveness of a tsunami generated by the Seattle Fault. First, since Elliott Bay and Puget Sound are shallow, there is less water to displace; therefore, a resulting tsunami would be slower and have less volume than those generated in the deep ocean. Second, Puget Sound's steeply sloping seabed tends to increase the chance that a tsunami will break on the shore, thus potentially enhancing a tsunami's destructiveness. Finally, the shape of Elliott Bay could increase damage by funneling waves together, increasing wave height. The net result is unclear, as the depth versus shape relationship of Elliot Bay is relatively unknown.[74]

[74] City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm

Estimated recurrence rate of an earthquake on the Seattle fault of the size necessary to generate a tsunami or seiche is estimated at once every 1,100 years. Great earthquakes in the North Pacific or along the Pacific coast of South America that generate tsunamis that sweep through the entire Pacific basin occur at a rate of about six every 100 years.[75]

With regards to seiche threats, both Puget Sound and Lake Washington could experience a seiche as they did in 1891, 1949 and 1964. In those years, there was not as much development near the waterfront as there is now. As a result, since the tsunami and seiche threats were not recognized until recently, most of the structures located near the water were probably not engineered to withstand them.[76]

The potential impact to bridges is expected to be minimal, since the Washington State Department of Transportation anticipates that storm-generated wave forces would exceed the force created by a small to moderate-sized tsunami. As to the possibility of earthquake-induced liquefaction impacting bridge support, bridge design assumes seismic effects to govern.[77]

Additional impacts from a tsunami include floating debris with the potential to batter and damage inland structures. The sheer impact of the waves could even cause breakwaters and piers to collapse. Ships moored in harbors would also be at risk, as they could be swamped, sunk or left battered and stranded high on the shore. In addition, railroad yards and oil tanks situated near the waterfront would also be particularly vulnerable, as resulting oil fires are often spread by waves.

Moreover, port facilities, fishing fleets, and public utilities are frequently the backbone of the economy of the affected areas, and these are the very resources that generally receive the most severe damage. Until debris can be cleared, wharves and piers rebuilt, utilities restored, and the fishing fleets reconstituted, communities may find themselves without fuel, food, and employment. Wherever water transport is a vital means of supply, disruption of coastal systems caused by tsunamis can have far reaching economic effects. For example, Port of Seattle facilities and the Burlington Northern Railway tracks are likely to suffer damage because of their proximity to the shore.[78]

A seiche could affect a larger area because of King County's extensive shoreline, and could also affect the floating bridges across Lake Washington. While, the

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[75] Washington State Hazard Mitigation Plan, Region 6, http://emd.wa.gov/3-map/mit/mit-pubs-forms/hazmit-plan/reg-6-profile.pdf

[76] City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm

[77] City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm

[78] City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm

bridges have withstood waves up to eight feet, waves from a seiche could be much larger. A seiche's rapid onset could also hamper the ability of motorists to exit the bridge before it began.[79] Additionally, the "sloshing" effect of a seiche could cause damage to moored boats, piers and facilities close to the water. Secondary problems, including landslides and floods, are related to accelerated water movements and elevated water levels. Many landslide prone bluff areas are in residential settings, so risk could be quite high in the event of a secondary seiche threat.

History of Events

On average, the west coast of the United States experiences a damaging tsunami every 18 years. Geologic evidence shows that the Cascadia Subduction Zone has generated great earthquakes in the past, the most recent about 300 years ago. Any large earthquake has the capability to generate a tsunami or severe seiche action. Recent studies regarding the potential for a great Subduction zone earthquake off the Washington, Oregon, and Northern California coastlines indicate that local tsunami waves may reach nearby coastal communities within minutes of the earthquake thereby giving little or no time to issue warnings.[80]

Local studies of the Seattle Fault indicate a potential for tsunamis. Scientists interpret the evidence of irregular sand sheets in the Northern Puget Sound area found at the West Point Sewer Treatment Plant, Alki, and Restoration Point on Bainbridge as the result of a tsunami generated by an earthquake on the Seattle fault about 1,000 years ago.[81]

Similar evidence in Lake Washington sediments suggests a recurrence interval of 300 to 400 years. Several areas of the Seattle Fault show evidence of episodic fault rupture of about 6 feet that could produce a tsunami. Continued studies of Seattle Fault traces suggest that the fault may have ruptured in different segments and at different times.[82]

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[79] City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm

[80] Skagit County Natural Hazards Identification Plan, http://www.skagitcounty.net/EmergencyManagement/Documents/2003HazMitFinal/Section%20II%20Final%20Documents/3%20HIVA%20Skagit%20Drought.pdf

[81] City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm

[82] City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm

Table 5-15: History of Tsunami and Seiche in King County	
Year	**Conditions**
A.D. 900-930	A magnitude 7 or greater earthquake on the Seattle fault created uplift on the floor of Puget Sound. The uplift generated a tsunami that deposited a sand sheet at West Point and the Duwamish Delta in Seattle. Computer simulations showed the tsunami reached heights of 10 feet or more on the Seattle waterfront.
1891	Water in Lake Washington and Puget Sound surged onto beaches two feet above the high water mark from two earthquake shocks and submarine landslides. This earthquake near Port Angeles also caused an eight-foot seiche in Lake Washington.
1949	Both Lake Union and Lake Washington experienced seiches during the 1949 earthquake (M7.1), but they did no damage.
1964	The tsunami generated by the magnitude 9.2 Alaska earthquake raised the water level 0.1 feet in Elliott Bay, Seattle. Seiches damaged houseboats, buckled moorings, and broke water and sewer lines in Lake Union. However, the tsunami's effect was negligible in Seattle because the complicated shoreline in Puget Sound acted as a baffle for incoming ocean waves.
1965	Due to a local earthquake event (M6.5), sloshing action was observed in area lakes.
2002	Seiches damaged houseboats, buckled moorings, and broke water and sewer lines in Lake Union following an Alaskan earthquake (Denali, M7.9).
Sources: Washington State Hazard Mitigation Plan, Region 6, http://emd.wa.gov/3-map/mit/mit-pubs-forms/hazmit-plan/reg-6-profile.pdf; City of Seattle Emergency Management Natural Hazards, Tsunami and Seiche Section, http://www.cityofseattle.net/emergency_mgt/hazards/tsunamiSeiches.htm	

Past Mitigation Efforts

Since it is known that the speed of tsunamis varies with water depth, the prediction of tsunami arrival times at coastal locations is possible once the epicenter has been determined. But it is not yet possible to predict the wave height at a specific coastal location. Another indeterminable feature of a tsunami is how many successive waves there will be in the series, although there is rarely only one. However, efforts and programs exist to help mitigate the damage wrought by tsunamis and seiches, especially by providing warnings to vulnerable areas.

The Tsunami Warning System (TWS) in the Pacific, comprised of 26 participating international member states, monitors seismological and tidal stations throughout the Pacific Basin. The System evaluates potentially tsunami-generating earthquakes and disseminates tsunami warning information. The Pacific Tsunami Warning Center (PTWC) is the operational center of the Pacific TWS.[83]

The PTWC was instituted in 1948 following the extensive damage and loss of life in Hawaii caused by a tsunami generated by the great Aleutian Islands earthquake of 1946.[84] The PTWC is comprised of member nations and states that seek to coordinate tsunami detection and warning efforts within the area. The PTWC is responsible for providing warnings to international authorities, Hawaii, and U.S. territories within the Pacific basin.

Another mitigation program is the West Coast/Alaska Tsunami Warning Center (WC/ATWC), responsible for tsunami warnings for California, Oregon, Washington, British Columbia, and Alaska.[85] The devastation associated with the 1964 Alaskan earthquake and tsunami, led to the institution of the WC/ATWC in 1967. It serves as the regional warning center for Alaska, British Columbia, Washington, Oregon and California. This system is intended to detect, locate and calculate the magnitude of earthquakes in the region as quickly as possible and issue warnings to communities close to the epicenter.

The PTWC and WC/ATWC may issue the following bulletins:

WARNING: A tsunami was or may have been generated, which could cause damage; therefore, people in the warned area are strongly advised to evacuate. This notification also gives time of arrival estimations to the vulnerable areas in question.

WATCH: A tsunami was or may have been generated, but is at least two hours travel time to the area in watch status. Local officials should prepare for possible evacuation if their area is upgraded to a warning.

ADVISORY: An earthquake has occurred in the Pacific basin, which might generate a tsunami. WC/ATWC and PTWC will issue hourly bulletins advising of the situation.

[83] Snohomish County Department of Emergency Management Hazard Identification and Vulnerability Assessment, http://www.snodem.org/HIVA.pdf
[84] Snohomish County Department of Emergency Management Hazard Identification and Vulnerability Assessment, http://www.snodem.org/HIVA.pdf
[85] Peninsula Emergency Preparedness Committee, Tsunami Warning Resource Section, http://www.pep-c.org/pacificnorthwesttsunamis/

INFORMATION: A message with information about an earthquake that is not expected to generate a tsunami. Usually only one bulletin is issued.[86]

Recent revelations about the potential for a great subduction zone earthquake off the Washington, Oregon, and Northern California coastlines have led to several studies about the effect of a local tsunami generated in this source area. FEMA estimates that a Cascadia Subduction Zone earthquake-generated tsunami could cost $25-125 billion in damages to the region. If one assumes that the tsunami would cause 5% of these losses, then the tsunami losses would total between $1.25 and 6.25 billion. More significantly, the population directly at risk from a Cascadia tsunami is significant. About 300,000 people live or work in coastal regions that could be affected and at least as many tourists travel through these areas each year. Some tourism and financial corporations already plan for and educate employees about tsunamis. Others are interested but do not know where to begin and are unaware of the potential losses in terms of lives, operations, and clients.[87]

Early warning, coupled with education of the affected populations, proper zoning, and suitable structural design can aid in reducing the disastrous effect of this natural hazard. If warning is received early enough (2 to 5 hours), which is possible for tsunamis generated at a distance, hasty preventive action can be taken: people can be evacuated, ships can clear harbors or seek safer anchorage, planes and rolling stock can be moved, buildings can be closed, shuttered, and sandbagged. For tsunamis generated by local events, however, the time from initiation of a tsunami to its arrival at shore can be as little as a couple of minutes. Residents in areas susceptible to tsunamis should be made aware of the need to seek high ground if they feel strong ground shaking. Coastal communities should identify evacuation routes even if they do not have good information about potential inundation areas.

Seiches that occur in King County also have the potential to cause property damage and casualties. Although much work has been done on disaster preparedness for the public, local governments, emergency planners and the citizenry need to recognize the dangers and effects of seiches as an important component of the earthquake/tsunami hazard.

Because King County is most vulnerable to tsunamis and seiches produced by a local quake, comprehensive educational programs that keep the public informed of the dangers and steps to be taken for personal protection are especially important. In these instances, there may not be enough time between the triggering event and the arrival of the first wave for effective warning.

[86] American Red Cross Tsunami Resource Section, http://www.redcross.org/services/disaster/0,1082,0_592_,00.html#cause

[87] Snohomish County Department of Emergency Management Hazard Identification and Vulnerability Assessment, http://www.snodem.org/HIVA.pdf