Supplemental Best Available Science Report For Geological Hazard Areas

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Seattle Fault Zone

Background

A fault is a fracture in the earth along which rocks on one side have moved relative to those on the other side. An earthquake is generated when stress exceeds the available resistance along the fault, resulting in sudden movement and release of energy. When faults occur at the surface, they are called surface faults or shallow crustal faults. If a fault has moved in the past 10,000 years (Holocene) and/or generated an earthquake, it is considered geologically “active”. Some faults are buried deep in the earth and some break through to the ground surface. Not all earthquakes result in surface rupture, and not all surface rupture occurs along pre-existing faults.

Prior to the 1990’s, shallow crustal earthquakes had not been attributed to specific faults in the Puget Sound region, and no evidence of Holocene fault rupture had been observed. Yount and Gower mapped an east-west trending thrust fault in Seattle in 1991. Known as the Seattle Fault, it forms the boundary between uplifted Tertiary bedrock of the Seattle uplift on the south and thick Quaternary strata in the Seattle basin on the north. This offset produces a large gravity anomaly that was first identified by Danes et al. in 1965.

Bucknam et al. (1992) and Atwater and Moore (1992) discovered the first evidence that the Seattle Fault is active and capable of producing earthquakes that may result in ground surface rupture—a magnitude 7.0 or greater earthquake approximately 1100 years ago resulted in as much as 7 meters of uplift at Restoration Point on Bainbridge Island, creating marine terraces; over 4 meters of uplift at Alki Point, creating an uplifted beach platform; and 1 to 1.5 meters of subsidence at West Point. This earthquake also generated a tsunami in Puget Sound.

Effects of Surface Rupture

Surface rupture due to fault movement results in sudden differential movement at the ground surface. Buildings, transportation infrastructure, utilities, and any structures built above or adjacent to the surface rupture can be severely damaged by the changes in ground elevation and the accompanying ground shaking. Previous earthquakes with ground surface rupture have caused loss of ground support beneath portions of buildings, collapsed bridge spans, broken utility lines, and failure of retaining walls. These types of failures contribute to loss of life and hamper emergency response following an earthquake.

Recent Studies of the Seattle Fault Zone

The Seattle Fault was defined as a "zone" by Johnson et al. in 1994 with four south-dipping strands with reverse displacement. Since then, the subsurface geometry and activity of the Seattle Fault Zone has been the subject of a number of recent studies. Many details about its precise location, subsurface geometry, displacement history, and slip rate are still being debated by researchers, and a number of models have been proposed. Table 1 summarizes recent published studies with postulated proposed models of the Seattle Fault Zone available as of January 2007. The most recent research shows the Seattle Fault Zone as a 5 to 7 km-wide east-west trending zone of south-dipping thrust faults, north-dipping backthrusts, and folds.

The earliest models of the Seattle Fault Zone were based on inferences from gravity data and conventional industry seismic reflection data. Subsequently, more detailed studies have been performed that include aeromagnetic surveys, seismic reflection surveys as part of the 1998 Seismic Hazards Investigation in Puget Sound (SHIPS) experiments, geologic evidence from fault trenching, and geologic mapping.

Stratigraphic and geomorphic evidence support the conclusion that strands of the Seattle fault as mapped by Johnson et al. (1999) can be traced on to land at the coast in West Seattle; however, mapping of individual strands much beyond the coast is not yet possible (Booth et al., 2003). Work by Harding et al. (2002) further confirms that at least three of the strands of the Seattle Fault Zone can be identified in the West Seattle coastline based on topographic data and that the frontal strand moved during the ~900 AD event described by Atwater and Moore (1992). Faults are difficult to map in the Puget Lowland because of dense vegetation, water, coverage by surficial deposits and/or fill, and extensive regrading for urban development in many areas.

Recent work by Sherrod (2005), Sherrod et al. (2001), and Nelson et al. (2003) indicate that known active strands of the Seattle Fault in Bellevue and on Bainbridge Island have produced surface rupture, and some strands have been reactivated by multiple earthquake events. Ten Brink et al. (2006) concluded that the surface rupture that occurred 1100 years ago on at least two strands on the Seattle Fault resulted from a moment magnitude (M) 7.5 earthquake.

The estimated probabilities of an earthquake with $M \geq 6.5$ occurring on the Seattle Fault Zone or from a random shallow crustal source in the Puget Sound region are approximately 5 percent in 50 years (recurrence interval of 1000 years) and 15 percent in 50 years, respectively (EERI, 2005b). These probability estimates have large uncertainties (Frankel, 2007). The probability estimate for an $M \geq 6.5$ earthquake on the Seattle Fault Zone is based on trenching studies at a small number of locations as well as a slip rate estimate that has a large uncertainty (Frankel, 2007). The probability estimate of a random shallow earthquake with $M \geq 6.5$ in the Puget Sound region is based on extrapolating the rate of observed earthquakes with magnitudes of 4 and above (Frankel, 2007).

Table 1: Recent references on geometry and structure of the Seattle Fault Zone

Factor	**Finding**	**Source**
Seattle Fault Zone geometry	Fault Zone delineated based upon Blakely et al. (2002), Brocher et al. (2004), subsurface stratigraphy, and geologic mapping	Troost, et al., 2005
	Seismic reflection, aeromagnetic, gravity, and geologic data used to interpret the Seattle Fault Zone as a passive-roof duplex associated with the Tacoma Fault Zone. The overlying shallow roof thrust is passive and only slips when the underlying Seattle Fault or Tacoma Fault ruptures. The master floor thrust is the most important thrust beneath Seattle.	Brocher, et al., 2004
	Paper focused on the Tacoma fault. Crustal deformation between Seattle and Tacoma is forced by slip on the deeper Seattle fault. Motion is distributed on the shallow Seattle Fault Zone, Tacoma fault, East Passage Fault Zone and other structures beneath the Seattle uplift.	Johnson et al., 2004
	Shallow velocity structure of the Seattle Fault Zone imaged by tomographic inversion of a very dense data set of seismic reflection profiles shot during the 1998 SHIPS experiments (seismic reflection studies). Along-strike differences in the uplift of Tertiary rocks beneath Puget Sound are likely attributable to the existence of a segment boundary in the Seattle fault system. Segmentation, if present, did not prevent two strands from rupturing across the boundary during the ~AD 900 event.	Calvert et al., 2003
	Used the results of a high-resolution aeromagnetic survey to define four main strands of the Fault Zone over an east-west distance of >50km. These strands coincide with the large gravity anomaly, geologic data, and seismic reflection data presented by previous studies. The magnetic anomalies coincide with steeply dipping bedrock in the hanging wall of the Seattle Fault Zone.	Blakely et al., 2002
	Results from 1998 SHIPS seismic reflection studies confirms newly proposed location for the Seattle Fault Zone in Blakely et al., 2002. Seattle Fault Zone produces a prominent velocity anomaly.	Brocher et al., 2001

	Analyzed high-resolution and conventional industry marine seismic reflection data to characterize the Fault Zone as a 4 to 6 km wide (north-south direction) zone consisting of three or four east-west trending fault strands. Also identified north-trending high-angle strike slip fault zone in Puget Sound that cuts the Seattle Fault Zone into segments.	Johnson et al., 1999
	Used industry seismic reflection data in an initial attempt to define the deep geometry of faults in the Puget Lowland area. Based on this model, most of the faults and folds in the region are related at depth and are components of a north moving thrust sheet. The Seattle fault is interpreted to be a thrust fault dipping southward at an angle of about 20 degrees but steepening to 45 degrees in the near surface. Data indicate >7 km of throw across the fault over the last 40 million years.	Pratt et al., 1997
Known strands of the Seattle Fault	Five trenches across a Holocene fault scarp on Bainbridge Island yield the first radiocarbon-measured earthquake recurrence intervals for a crustal fault in western Washington. The scarp, the first to be revealed by laser (LIDAR) imagery, marks the Toe Jam Hill Fault, a north-dipping backthrust to the Seattle fault. Folded and faulted strata, liquefaction features, and forest soil A horizons buried by hanging-wall-collapse colluvium record three, or possibly four, earthquakes between 2500 and 1000 yr ago. The most recent earthquake is probably the 1050-1020 yr B.P. (A.D. 900-930) earthquake that raised marine terraces and triggered a tsunami in Puget Sound. Vertical deformation estimated from stratigraphic and surface offsets at trench sites suggests late Holocene earthquake magnitudes near M7, corresponding to surface ruptures > 36 km long. Corresponding fault-slip rates are 0.2 mm/yr for the past 16,000 yr and 2 mm/yr for the past 2500 yr. Because the Toe Jam Hill fault is a backthrust to the Seattle fault, it may not have ruptured during every earthquake on the Seattle fault.	Nelson et al., 2003
	At Vasa Park on the west shore of Lake Sammamish, trenching exposed a fault zone. The fault moved at least one time at the very beginning of the Holocene. Only one, limiting, maximum age was obtained.	Sherrod et al., 2001

	Topographic analyses of uplifted marine platforms based on Lidar mapping suggest that activity on the strands of the Seattle fault in West Seattle date to or after the ~900 AD event.	Harding et al., 2002
	Excavation at Vasa Park in Bellevue showed the south side of the fault pushing up and to the north by about 6-1/2 feet during the very beginning of the Holocene. Finding is important because the trench shows that earthquakes on the Seattle fault have occurred on both sides of Puget Sound, provides clear evidence for an earthquake unrelated to the one 1100 years ago, is different from the north side up motions on faults west of Puget Sound.	EERI, 2005a
	Provides a summary of active fault zones in the Puget Lowland. Lidar scarps in the Seattle Fault Zone are north-side-up, opposite the vergence suggested for the Seattle fault. Trenching data reveal as many as three surface rupturing earthquakes in the past 2500 years.	Sherrod, 2005
	Stratigraphic and geomorphic evidence supports that strands of the Seattle fault as mapped by Johnson et al., 1999, can be traced onto land at the coast in West Seattle. Mapping of individual strands much beyond the coast is not yet possible.	Booth et al., 2003

Designation of the Seattle Fault Zone

Mapping by Troost et al. (2005) represents the most current delineation of the area of suspected fault rupture hazard. The Seattle Fault Zone shown in this reference considers the fault models postulated by Blakely et al. (2002) and Brocher et al. (2004), constrained and modified by areas of geologic evidence such as uplifted beach deposits, down-dropped tidal marshes, offset strata, and deformation such as sheared and tightly folded strata near the northern edge of the Fault Zone. Troost et al. (2005) designate the Seattle Fault Zone as a zone, rather than specific lines, because of the uncertainty in the postulated fault models and the uncertainty in precise locations of fault strands; however, all of the postulated models present four or more possible east-west trending strands or a large area over which deformation could possibly occur due to movement on deeper portions of the Seattle Fault. Surface rupture is possible along existing strands within the Seattle Fault Zone and less likely along new faults within the Seattle Fault Zone (Troost, 2007).

It is likely that the State of Washington in conjunction with the U.S. Geological Survey will issue a map of active faults in the State of Washington some time in 2007 (Troost, 2007 and Walsh, 2007).

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Tsunami Inundation Areas

Background

A tsunami is a series of water waves of extremely long period and long wavelength (distance from crest to crest) caused by a sudden disturbance that vertically displaces the water. Sudden offsets in the earth's crust, such as during earthquakes, can cause a tsunami. Landslides and underwater volcanic eruptions can also generate tsunamis.

Washington's outer coast is vulnerable to tsunamis from distant sources (such as earthquakes in Alaska, Japan, or Chile) and from the adjacent Cascadia Subduction Zone (CSZ). The CSZ is a fault located at the boundary between two tectonic plates, and it has generated earthquakes of magnitude 8 or larger at least six times in the past 3,500 years. Computer modeling by Walsh et al. (2000) indicates that a tsunami due to a great earthquake on the CSZ could cause a tsunami up to 30 feet in height that would affect the entire Washington coast.

Washington's inland waters, such as those in the Puget Sound region, are also subject to tsunamis, particularly those generated by local crustal earthquakes or by surface and submarine landslides. Atwater and Moore (1992) showed that a magnitude 7+ earthquake approximately 1100 years ago on the Seattle Fault Zone likely created a tsunami in Puget Sound that deposited sand at West Point and Cultus Bay near Whidbey Island. Karlin et al. (2004) present evidence of earthquake-induced submarine slope failures interspersed throughout Lake Washington that would likely have produced associated tsunamis or seiches. Lander et al. (1993) reported an eight foot wave in Lake Washington resulting from landslides caused by the 1891 Port Angeles Earthquake. Landslide-induced tsunamis in the Puget Sound include the early 1800's Camano Head Tsunami, 1890's Puget Island Tsunami near Cathlamet, 1891 Puget Sound Tsunami, 1894 Commencement Bay Tsunami, and 1949 Puget Sound Tsunami at Point Defiance (Washington State Hazard Mitigation Plan, 2004).

Effects of Tsunami Inundation

Tsunamis typically cause the most severe damage near their source, where the waves are highest because they have not yet lost much energy to friction or spreading. Nearby populations, often disoriented from the earthquake shaking, have little time to react before the tsunami arrives, and persons caught in the tsunami may be crushed by debris or drown.

In the deep ocean, a tsunami is barely noticeable as a small rising and falling of the ocean surface. When the tsunami approaches land and shallow water, the waves slow down, become compressed, and increase in height. A tsunami can come on shore quickly like a rising tide and flood low-lying areas, or it can rush onshore as a wall of turbulent water with great destructive power. Minutes later, the water will drain away as the trough of the tsunami arrives. This destructive cycle may repeat many times before the tsunami dissipates.

The amount of destruction to structures and other facilities depends on wave period, wave height, and wave and current velocities. Tsunamis can cause structural failure, scouring at foundations, erosion, flooding, battering, movement of sediment and objects, and loss of life.

Recent Studies of Tsunami Inundation in the Puget Sound

The City of Seattle may be subject to tsunamis from the following sources: (1) shallow crustal earthquakes that rupture the submarine floor of Puget Sound, (2) shallow crustal earthquakes that rupture the floor of Lake Washington, (3) landslides within or into Puget Sound, (4) landslides within or into Lake Washington, and (5) lateral spreading due to liquefaction producing landslides into or in the Duwamish River and/or Puget Sound. At this time, no marine inundation is expected in the Seattle area from tsunamis generated from subduction zone earthquakes because the waves that deflect around the 90-degree bend to enter central Puget Sound would be small and attenuated by the time they reached the City of Seattle (Walsh, 2007; Murty and Hebenstreit, 1989).

As part of the Tsunami Inundation Modeling Efforts (TIME) within the National Tsunami Hazard Mitigation Program, Titov et al. (2003) have developed a high resolution computer model to estimate potential tsunami inundation along the shores of Seattle. The model is based upon a tsunami generated by a magnitude 7.3 event on the Seattle Fault Zone. The displacements along the Seattle Fault Zone are based upon those reported by Bucknam et al. (1992) from a magnitude 7+ earthquake that occurred approximately 1100 years ago. Walsh et al. (2003) used the results of the modeling by Titov et al. (2003) to produce the most recent tsunami inundation map of the Elliott Bay area. Other tsunami modeling studies (e.g. Koshimura et al., 2002) for tsunamis generated by historical movement on the Seattle Fault Zone have also been performed as part of the National Tsunami Hazard Mitigation Program; however, these studies were done at lower resolution.

At present, no modeling studies of tsunamis in Lake Washington generated by fault rupture in the lake or by landsliding have been performed. Karlin et al. (2004) present evidence of numerous submarine landslides in Lake Washington that were probably caused by earthquakes, but wave heights of any tsunamis generated by these events were not estimated.

Kayen et al. (1999) describe extremely young and thick deposits of sand at the Duwamish delta front, rapidly deposited by geologic processes, which have formed loose deposits that are highly susceptible to liquefaction under expected levels of seismic loading (e.g. from the Seattle Fault Zone, other shallow crustal faults, or the CSZ). Liquefaction-induced lateral spreads or flow slides at the Duwamish delta front along the northern end of Harbor Island could result in a tsunami (Troost, 2007). No modeling of this scenario is currently available, and we do not have evidence of previous occurrences; however, liquefaction-induced landslides have occurred in other areas resulting in water waves. For example, a submarine landslide in the Puyallup delta at Commencement Bay in 1894 (likely the result of static liquefaction) resulted in a 3 to 4.5 meter (9.8 to 14.8 ft) high water wave (Palmer, 2005). It is unlikely that such an event would impact areas outside of those currently delineated in the Walsh et al. (2003) tsunami hazard map (Troost 2007).

A summary of findings from the most significant reviewed references is presented in Table 2.

Table 2: Recent tsunami studies for the Seattle area

Factor	Finding	Source
Tsunami inundation studies for Seattle Fault Zone earthquake	Tsunami inundation map based upon the modeling by Titov et al., 2003 for rupture on the Seattle Fault Zone.	Walsh et al., 2003
	Finite-difference, high resolution computer model used to develop map of potential tsunami inundation along the Puget Sound shores of Seattle Washington. Assumed magnitude 7.3 earthquake on the Seattle Fault with displacements consistent with that reported by Bucknam et al., 1992 from a magnitude 7+ event on the Seattle Fault 1100 years ago (7 m uplift at Restoration Point, 4m uplift at Alki Point, and over 1 meter of subsidence at West Point). Manning coefficient of n=0.025 (mildly rough surface) used for bottom friction in inundation model does not consider buildings and other structures. Vertical datum of Mean High Water was used. Maximum amplitudes of tsunamis approaching shores of Elliott Bay fluctuate around 6 meters. Maximum vertical runup of 10 meters is calculated southwest of Magnolia Bluff. The model shows isolated areas of maximum current speeds that impact land of up to 30 meters/second; however, most of the modeled current speeds range from about 1.5 meters/ second to 10 to 15 meters/second as the waves impact the land. The model shows the first wave crest reaching southwest of Magnolia Bluff 2 minutes 20 seconds after generation. Within half a minute after that, this wave crest reaches all the shores around Elliott Bay. The south shores of Elliott Bay are inundated when a large wave reflected from the northern coasts reaches Harbor Island about 5 minutes after the earthquake.	Titov et al., 2003

	Finite-difference computer model (30 to 90 meter grid spacing) used to model the magnitude 7+ event on the Seattle Fault approximately 1100 years ago. Modeled displacements consistent with Bucknam et al., 1992. Tsunami inundation zone presented for the Cultus Bay area. Tsunami more than 3 meters high strikes the Seattle waterfront.	Koshimura, S., et al., 2002
	Finite-difference low resolution computer model used to develop potential tsunami inundation map for the Seattle waterfront. Assumed magnitude 7.2 on the Seattle Fault deformation of 2.3 meters of maximum uplift at the sea bottom between Bainbridge Island and Elliott Bay. Model grid size is 30 to 90 meters. Inundation of 2 meters at Pier 90/91 and greater than 1 meter at Pier 36 to 77.	Koshimura, S and Mofjeld, H., 2001
Tsunami inundation depth for Cascadia Subduction Zone (CSZ) earthquake	Finite-element model used to develop potential tsunami inundation map for the southern Washington Coast. Assumed earthquake is a magnitude 9.1 CSZ event with a rupture length of 1050 km and rupture width of 70 km. Land surface along the coast was modeled to subside by about 1 to 1.5 meters, consistent with some paleoseismic investigations. One model includes an area of locally greater fault slip along the fault plane; the second model does not. This is the same model adopted for tsunami inundation mapping in Oregon as well. Map only shows inundation for the Washington Coast. A movie file of the tsunami model shows wave heights of up to about 1 meter along the coast of Seattle; however, the model was not set up as an inundation model for Seattle.	Walsh et al., 2000
	No marine inundation is expected in the Seattle area from tsunamis generated from subduction zone earthquakes. Tsunami waves would be expected in Bellingham Bay or the west side of Whidbey Island.	Walsh, 2007
	Tsunami waves from CSZ that deflect around the 90-degree bend into Puget Sound from the Strait of Juan de Fuca will be small and attenuated by the time they reach Seattle. Study does not include inundation modeling for Seattle.	Murty and Hebenstreit, 1989

Tsunamis due to landslides in Lake Washington	Numerous submarine landslides (large block slides, sediment slumps and debris flows) are present throughout the lake, and are attributed to large earthquakes that have occurred in the Puget Sound region about every 300 to 500 years. Benioff zone (e.g. 1949, 1965, or 2001 Nisqually) earthquakes have not caused large block slides in Lake Washington, so it is clear that the prehistoric earthquakes that triggered these slides had stronger ground motion than any earthquakes this century.	Karlin et al., 2004
	Reported an eight foot wave in Lake Washington resulting from landslides caused by the 1891 Port Angeles Earthquake.	Lander et al., 1993
Tsunamis in Puget Sound due to fault rupture	Large earthquake on the Seattle Fault approximately 1000 to 1100 years ago probably generated a tsunami by causing abrupt uplift south of the fault and complementary subsidence to the north. This movement would have caused water in Puget Sound to surge northward. Found tsunami sand deposits at West Point and Cultus Bay near Whidbey Island.	Atwater and Moore (1992)
Tsunamis in the Duwamish River or Puget Sound due to liquefaction/lateral spreading	At the Duwamish River delta, extremely young and thick deposits of sand that were rapidly deposited by geologic processes have formed a loose deposit that is highly susceptible to liquefaction. Under expected levels of seismic loading, the analysis indicates that a large-strain flow failure may occur at the delta front along the northern end of Harbor Island.	Kayen et al., 1999
	Documented evidence of a submarine landslide occurring on the Puyallup delta at Commencement Bay in 1894 that resulted in a 3 to 4.5 m high water wave that was likely the result of static liquefaction.	Palmer, 2005

Extent of Tsunami Hazard Areas

Mapping by Walsh et al. (2003) represents the most current delineation of the area of suspected tsunami hazard along Seattle’s marine shorelines. Although this map only considers a tsunami that may be generated by a major earthquake on the Seattle Fault Zone, this event is likely to be more severe than other potential tsunamis caused by local landslides or lateral spreading/flow slides into the Duwamish River. Hazard areas for tsunamis from these other sources are likely to be contained within the delineation by Walsh et al. (2003). Thus, this map represents a reasonable boundary for suspected tsunami risks on Seattle’s marine shorelines (Troost, 2007).

There is no available scientific evidence or studies that suggest a risk from tsunamis in Lake Union. Tsunamis are known to occur in Lake Washington, however no scientific studies in any way characterize the extent of this potential hazard. Accordingly, the extent of tsunami hazards surrounding Lake Washington is currently unknown. There are no performance standards presented in the literature to determine tsunami risk on a site by site basis.

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Seiches

Background

Seiches are a series of standing waves contained in an enclosed or partially enclosed body of water and are analogous to the sloshing of water that occurs when a bowl of water is moved back and forth. Seiches can occur in harbors, bays, lakes, rivers, and canals. Locally, Lake Union, Lake Washington, and, to a lesser extent, Elliott Bay hold significant potential for seiche activity.

Seiches are caused commonly by wind, water waves, or tides, but present the greatest threat to public safety when initiated as a result of a tsunami or earthquake. Tsunami-induced seiches represent the continuing oscillation of a waterbody that occurs after the initial originating force of the tsunami. Earthquake-induced seiches occur as the result of low frequency seismic waves that rhythmically oscillate the entire basin of the waterbody. Earthquake-induced seiches frequently occur as a result of distant earthquakes rather than local ones as the frequency of vibration produced by an earthquake decreases with distance from the epicenter and the low frequency vibrations associated with distant earthquakes have the greatest impact on bodies of water (King County, 2005). Earthquake-induced seiches are nearly impossible to predict due to the multiplicity of potential sources and lack of earthquake predicting technology. Their onset can be very rapid, and emergency response may be difficult because they occur coincident with other earthquake impacts.

The potential magnitude of a seiche event occurring from any earthquake is difficult to predict as they depend on the magnitude of the earthquake, frequency of vibrations, natural period of the water body, sediment thicknesses, presence of thrust faults and other geologic factors (Barberopoulou, 2006). The biggest seiches develop when the period of ground movement matches the frequency of oscillation in the body of water. Additionally, constructive interference of the seiche waves with water waves can lead to additional wave action.

The sedimentary basins of the Puget Lowland have been documented to affect the amplitude of seismic waves at long periods, generally increasing the potential for seiche events (Pratt et al., 2003; Barberopoulou, 2004). Lake Union, in particular, has been observed to be prone to earthquake-induced water waves due to its relatively small size and its location in the Seattle basin (Barberopoulou, 2004). Modeling by Barberopoulou (2006) further indicates that Lake Union is particularly prone to wave action in the east-west direction of the main body due to the parallel nature of the east and west shorelines as well as wave action in the northern arms due to the small width of these channels and the redirection of north-south waves by the v-shaped extrusion around Gas Works Park.

Effects of Seiches

Seiches can cause significant impacts due to rapidly changing water levels, particularly along the shoreline where the rhythmic “sloshing” motion can cause damage to moored boats, utilities, piers and facilities close to the water. Common damages resulting from seiches include broken piers, ruptured house boat connections, damaged or disconnected boats, and flooding. The high prevalence of houseboats along Lake Union may make this area particularly prone to damage.

The Lake Washington floating bridges may also be at risk for seiche damage; the bridges have withstood standing waves up to eight feet in height (King County, 2005). A seiche's rapid onset could also prevent motorists from exiting the bridge before a hazardous situation occurs.

There is also the potential for seiches to cause landslides by eroding the base where landslide-prone bluff areas abut the water.

Historic records of Seiches

Seiches occur infrequently in the Puget Sound, but have been observed to accompany many of the high magnitude earthquakes in the recent history of the Pacific Northwest and Alaska. A brief history of recent seiche activity around Seattle is presented below:

Table 3: Historic records of Seiches

Date	**Description**
1949	Both Lake Union and Lake Washington experienced seiches during the 7.1M Queen Charlotte Island earthquake, but no damage was reported.
1964	Seiches in Lake Union damaged houseboats, buckled moorings, and broke water and sewer lines as a result of 9.2M Alaska earthquake. Damage was estimated at $5,000 (Wilson and Torum, 1972). Additionally, a seiche of 0.4 ft (0.12 m) crest to trough lasting 48 minutes was measured at a tide station in Puget Sound (McGarr and Vorhis, 1968).
1965	During the 6.5M Seattle earthquake, seiches were reported in Lake Washington and Lake Union, but no significant damage was observed.
2002	Seiches damaged houseboats, buckled moorings, and broke water and sewer lines in Lake Union following the 7.9M Alaskan earthquake. Damage was limited to about 20 houseboats. While no historic records are available to document the size of waves produced during this event, modeling by Barberopoulou (2006) predicted maximum wave heights of 1.41 ft (0.43 m) as a result of this event.

Little historic data exists as to the height, duration or inland extent of waves generated as a result of these events. Historical data is limited to anecdotal reports collected by local newspapers and the USGS as well as the single recording at a tide station in 1964. None of this data addresses the inland extent of waves generated by a seiche.

Seiche Studies in Seattle

A summary of findings from the most significant reviewed references is presented in Table 4.

Table 4: Recent tsunami studies for the Seattle area

Report	**Findings**
Barberopoulou, 2006	Modeled the seiche activity that is likely to occur as a result of four potential earthquake scenarios. This exercise demonstrated that Lake Union is particularly prone to wave action in the east-west direction of the main body due to the parallel nature of the east and west shorelines as well as wave action in the northern arms due to the small width of these channels and the redirection of north-south waves by the v-shaped extrusion around gas works park. This study also noted the relative potential for different earthquake types to produce seiche activity in Lake Union. Deep Benioff zone earthquakes (e.g. 2001 Nisqually) and earthquakes caused by the Seattle Fault do not seem to have the capability to produce large oscillations in Lake Union. A model based on the 2001 Nisqually earthquake produced maximum water wave heights of 0.46 ft (0.14 m). Instead, Lake Union was found to be particularly prone to earthquakes occurring at extra-regional distances such as the Denali Fault in Alaska or the San Andreas in California. A model of the 2002 Denali earthquake produced maximum wave heights of 1.41 ft (0.43 m) in Lake Union. A model of a subduction zone earthquake was found to have the most dramatic effect in Lake Union with predicted water waves reaching 3.9 ft (1.2 m). The model did not look at impacts to the shoreline or inundation from a seiche event.
Barberopoulou et al., 2004	Documented damage to 20 houseboats in Lake Union from seiche activity resulting from the 2002 Denali earthquake. Their analysis of this event showed substantially increased shear and surface wave amplitudes coincident with the Seattle sedimentary basin, indicating that size of the water waves may have been increased by local amplification of the seismic waves by the basin.
Karlin et al., 1992	Found evidence that suggests a number of simultaneous landslides occurred in Lake Washington about 1100 years ago that correlate with other indications of earthquake activity from other parts of the state.
Karlin et al., 2004	Numerous submarine landslides (large block slides, sediment slumps and debris flows) are present throughout the lake, and are attributed to large earthquakes that have occurred in the Puget Sound region about every 300 to 500 years. Benioff zone (e.g. 1949, 1965, or 2001 Nisqually) earthquakes have not caused large

	block slides in Lake Washington, so it is clear that the prehistoric earthquakes that triggered these slides had stronger ground motion than any earthquakes this century.
McGarr and Vorhis, 1968	Documented seismic seiches occurring throughout the United States as a result of the 1964 Alaskan earthquake. Documented a seiche of 0.4 ft (0.12 m) crest to trough lasting 48 minutes occurring in Puget Sound as a result the 1964 Alaskan earthquake.
Pratt et al., 2003	Presented evidence that the Seattle Basin causes local amplification of seismic waves based on records of past earthquakes
Wilson and Torum, 1972	Noted occurrence of seiche in Lake Union resulting in $5,000 of damage to several pleasure crafts, houseboats, floats that broke their mooring due to 1964 Alaskan earthquake. No damage to shorelines was noted.

Extent of Seiche Hazards Risk

Historical records and scientific studies document a known hazard from seiche activity within the waters of Lake Union, Lake Washington, and the Puget Sound. Documentation of seiches in 1949, 1964, 1965 and 2002 clearly identifies a seiche hazard that exists within the submerged portions of these waterbodies; however, the potential hazard that these events pose to adjacent shorelines is unknown.

Historical records do not document any damage to Seattle shorelines due to seiche activity, although the 1964 Alaska earthquake produced a seiche in the reservoir at Aberdeen that caused an embankment failure so impacts are clearly possible (Troost, 2007). Scientific studies on this subject also remain insufficient to characterize the potential impact of seiche activity on shorelines as they lack any analysis of land inundation. However, since seiches are standing waves rather than moving water flows, potential inundation of the surrounding shorelines is considered to be a minimal risk.

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Lahar Hazard Zones

Background

A lahar is a gravity-driven mixture of sediment and water that originates from the flanks of a volcano. Such flows are analogous to debris flows, but typically are very large in size due to the high elevations, steep slopes, and abundance of loose or hydrothermally weakened material associated with volcanoes. Lahars can initiate as a result of; (1) melting of snow and ice by radiant heat or pyroclastic flows generated during an eruption, (2) collapse of the steep sides of a volcano, (3) heavy rainfall eroding volcanic deposits, (4) seismically induced landslides, (5) magmatic intrusion or (6) floods generated by lake or glacial outburst. Lahars not associated with volcanic eruption pose a particular problem because they can occur spontaneously without any of the warning signs accompanying an eruption such as increased tremor activity.

Lahars can vary in character with time and distance from their source. Lahars generally flow in one of three types of phases: debris-flow phase, transitional or hyperconcentrated-flow phase and stream-flow phase. In the debris-flow phase, the solid and liquid fractions of the lahar are in roughly equal volume and are mixed through the vertical section. Due to the mix of water and debris, lahars in this phase generally look and behave like flowing concrete. In the stream-flow phase, water transports fine-grained sediment in suspension and coarse-grained sediment along the bed at discrete intervals. Transitional flow occurs between these stages as a lahar carries higher sediment loads than stream-flow, but vertical sorting differentiates it from debris-flow (Vallance, 2000).

Lahars represent a significant hazard for communities located downstream of volcanoes because of their ability to travel long distances quickly, transport large debris such as logs and boulders, and bury floodplains under tens of feet of sediment. They can travel tens of miles at speeds of tens to hundreds of miles per hour, although energy generally decreases with distance from the source. The pathway of a lahar is defined by the topography, generally following river channels and other depressions.

Mount Rainier represents the only active volcano that may pose a hazard to the City of Seattle from lahar activity. Three river networks (White, Carbon, and Puyallup) provide potential pathways for lahar activity from Rainier, which could connect with the Duwamish River valley and impact areas of Seattle (Hoblitt et al., 1998). Mount Rainier readily generates lahars. It has a large volume of snow and glacier ice (more than the combined volume of glacier ice on the other Cascade volcanoes) available for melting during an eruption and a large volume of hydrothermally altered rock. It also stores water beneath its glaciers, which is sometimes released as outburst floods.

Four classes of lahars are defined in Hoblitt et al. (1998). In order of decreasing size and increasing frequency, these are called Case M, Case I, Case II, and Case III lahars.

Case M: Case M flows are low-probability, high-consequence lahars, such as the largest lahar to occur at Mount Rainier in the past 10,000 years. These lahars are associated with volcanic activity and sometimes collapse of portions of the volcano. The Washington State Hazard Mitigation Plan (2004) reports that flows of Case M magnitude occur far less frequently than once every 1000 years.

Case I: Case I flows are smaller than Case M flows, and they generally originate from debris avalanches of hydrothermally altered rock. Case I flows are not necessarily associated with volcanic eruptions. They occur about once every 500 to 1000 years.

Case II: Case II flows have relatively low clay content and the most common origin for this type of flow is the melting of snow and glacier ice by hot rock fragments during a volcanic eruption. However, Case II flows can also be triggered by heavy rains or other non-eruptive origins. Case II flows have recurrence intervals on the lower end of the 100- to 500-year range.

Case III: Case III flows are relatively small but have recurrence intervals of 1 to 100 years. These types of flows are not triggered by volcanic eruptions. On Mount Rainier, they rarely move beyond the National Park boundary.

Historic Records of Lahars on Mount Rainier

The Mount Rainier volcano has produced 60 lahars of various sizes and numerous large lahars during the past 10,000 years that flowed down the White River as far as the site of the cities of Auburn and Kent. The most well-documented such flow is the Osceola Mudflow, which left deposits nearly as far north as the city of Renton approximately 5,700 years ago (Dragovich et al., 1994; Vallance and Scott, 1997). The Osceola Mudflow was at least 10 times larger than any other known lahar from Mount Rainier. Deposits from this event are estimated at 0.89 mi^3 and covered an area of about 200 square miles in the Puget Sound lowlands (Hoblitt et al., 1998; Dragovich et al., 1994). Flows of the size of the Osceola Mudflow are termed Case M flows by Hoblitt et al. (1998).

Lahars that have occurred since the Osceola Mudflow played an important role in shaping the landscape in the Duwamish Valley. At the time of the Osceola Mudflow, the Duwamish Valley between Auburn and Seattle existed as an arm of Puget Sound. The Osceola Mudflow contributed to filling of that arm between Renton and Auburn. Since the Osceola Mudflow, at least four lahars from Mount Rainier either reached the Duwamish Valley or transported sediment that was then rapidly reworked and redeposited by post-lahar floods (Zehfuss, et al., 2003 and Zehfuss, 2005). As a result, a layer of lahar-derived sand and silt from post-Osceola events underlies much of the floor of the Duwamish Valley at Seattle to depths of up to 60 feet (Troost, 2007).

Other significant recent Mount Rainier lahars include:

- The Electron Mudflow which occurred about 600 years ago and produced an estimated 300 million cubic yards of debris. This event is considered to be characteristic of Case I lahars which have occurred on average about once every 500 to 1000 years during the last 5,600 years.

- In 1947 in Kautz Creek, at least four lahars were triggered by heavy rain and release of water stored within a glacier. These events deposited a total of about 50 million cubic yards of debris, though each individual flow of the 1947 sequence probably did not exceed 21 million cubic yards. The 1947 sequence of lahars is considered to be the most recent example of Case II lahars. For planning purposes, Case II flows are analogous to the 100-year flood commonly considered in engineering practice. The National Lahar, which occurred less than two thousand years ago and inundated the Nisqually River valley, is considered by Hoblitt et al. (1998) as a characteristic Case II flow for the purposes of identifying inundation areas.

Effects of Lahars

The direct flow of a lahar contains tremendous energy that can easily destroy buildings and almost anything it its path. Buildings and valuable land may become partially or completely buried by the layers of debris. Lahars can also trap people in areas vulnerable to other volcanic hazards by destroying bridges and key roads or burying them in often hot and unstable debris.

Due to its significant distance from Mount Rainier and the long recurrence interval for Case M lahars, however, the City of Seattle is more likely to experience the impacts of post-lahar sedimentation than direct flow (Hoblitt et al., 1998). Post-lahar sedimentation can occur well beyond the direct pathway of a lahar as the water and sediment released by a lahar fill up river channels, reroute water courses, and raise river levels. Other secondary effects of a lahar include loss of storage at dams, destruction of existing dams or the creation of temporary sediment dams. These effects result in significant damage to infrastructure, but may also lead to additional flood events as dams burst or are unable to hold secondary flooding activities (Hoblitt et al., 1998).

The distance between Mount Rainier and the City of Seattle also creates a considerable delay between the formation of a lahar and its arrival in Seattle. A lahar originating in the Sunset Amphitheater at the top of the Puyallup Glacier is projected to reach Auburn about 96 minutes after the lahar warning system sounds an alarm and the warning time to Seattle would be even longer (Washington State Hazard Mitigation Plan, 2004). This time delay would give citizens time to evacuate the area provided that warning systems are in place.

Extent of Lahar Hazard Areas

Hoblitt et al. (1998) maps an inundation zone for Case M lahars that reaches Harbor Island and surrounding areas via the Duwamish River.

Hoblitt et al. (1998) also maps potential areas at risk from Case I and Case II lahars. The City of Seattle is at significantly reduced risk of inundation from Case I lahars, and post-lahar sedimentation is more probable. The Green River valley and the Duwamish River valley (including the City of Seattle) could be at significant risk to a Case II lahar and post-lahar sedimentation if one of two conditions occurs:

(1) The available storage of Mud Mountain Reservoir is reduced significantly by a lahar or post-lahar sedimentation.

(2) The profile of the lower White River valley south of Auburn is changed sufficiently by a lahar or post-lahar sedimentation to cause the White and Puyallup Rivers to drain northward into the Green and Duwamish River valleys.

Without one of these conditions, the City of Seattle's risk from Case II lahars is primarily from post-lahar sedimentation.

The maps by Hoblitt et al (1998) represent the most current delineation of areas of potential lahar inundation and post-lahar sedimentation hazard.

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