GEOLOGIC HAZARDS BEST AVAILABLE SCIENCE 2014

5.0 Introduction

Geologic hazard areas in Seattle include landslide-prone and steep slope areas, peat settlement-prone areas, liquefaction-prone areas, seismic hazard and volcanic hazard areas. These geologic hazards may overlap in some areas of the City.

This chapter will begin with a summary of the geologic and seismic setting of the region. Then for each geologic hazard, we will provide an overview of the hazard, a review of relevant studies, a recommendation for regulation of development in the hazard area, and a list of references.

5.1 Geologic and Seismic Setting

5.1.1 Glacial Geology

Sedimentary deposits make up the bulk of local soil types and can be attributed to several processes. During glaciation cycles over the past two million years, glaciers advanced and retreated out of the Puget Sound region continuing to add and sometimes subtract from sedimentary layers in the Seattle area. This and more recent factors have resulted in a complex regional soil pattern of interbedded, highly permeable soils overlying compacted and relatively impermeable soils.

Approximately 25,000 years ago, alpine glaciers began to form and advance in the mountains of western Washington, and an ice sheet was developing in the mountains of western British Columbia; this marks the beginning of the Fraser Glaciation (Armstrong et al., 1965). Approximately 15,000 years ago, a lobe of Cordilleran ice, the Puget Lobe, pushed south into the Puget Lowland far enough to block the northward-flowing drainage to the Strait of Juan de Fuca. This resulted in a large proglacial lake, which drained southward into Grays Harbor via the lower Chehalis Valley. Water and sediment entered the lake from the glacier, which constituted its northern boundary, and from the highlands on both sides. A widespread deposit of silt and clay was thus created in a lake, which constitutes the Lawton Clay Member of the Vashon Drift (Mullineaux et al., 1965; Yount et al., 1993).

As the Puget Lobe advanced to the south, a thick unit of proglacial fluvial and lacustrine sand was deposited. This unit, the Esperance Sand Member of the Vashon Drift, spread over the Lawton Clay and the hills of older material that protruded through the Lawton Clay. The contact between the Lawton Clay and the Esperance Sand is not generally an abrupt one; there often exists a zone, several meters thick, in which sand is interlayered with silt and clay. This contact zone, as used in this report, is the boundary between the Lawton Clay and the Esperance Sand. Because of its role in slope stability processes, Tubbs (1975) includes the transition zone between these two units to be within the Lawton Formation because of the presence of lower permeable layers within this zone. The transition zone is also described in Mullineaux et al. (1965).

The front of the Puget Lobe continued to advance southward to about 60 miles south of Seattle; at its maximum, the glacial ice thickness in the vicinity of Seattle was probably about 3000 feet. Some of the material eroded by the glacier was redeposited further south as advance outwash and the remainder was incorporated into the ground moraine of the Vashon glacier. This ground moraine is a mixture of sand, silt and gravel known as the Vashon (lodgment) till. Vashon till generally mantles the ridges in Seattle (Galster and Laprade, 1991). As glaciers retreated, sediments trapped in the ice layers were deposited. Ablation till, consisting of assorted gravels with interspersed clay, silt and sand lobes, was deposited locally. These soils tend to be 4 to 10 feet thick and can be found as a top layer blanketing hillsides and valleys in certain areas of the Puget Sound region. However, most top layer soils are the result of weathering of the glacially consolidated soils or deposition since the glacial retreat.

The recession of the Puget Lobe was rapid. By approximately 13,500 years ago (Mullineaux et al., 1965) the ice front had retreated to a latitude north of Seattle, and by 11,000 years ago the ice had retreated up the Fraser Valley. The retreating ice uncovered a glacially-sculptured landscape of uplands and intervening valleys. Meltwater streams often cut large channels and, especially where they emptied into lakes, locally deposited Vashon recessional outwash.

Accompanying worldwide deglaciation, the land rebounded, sea level rose rapidly, and marine water invaded the glacially carved troughs to form the inlets of Puget Sound. Most of the rise in sea level had taken place by about 7,000 years ago, but since then there has been a slow rise of relative sea level in the Puget Lowland amounting to about 10 meters (Biederman, 1967).

Glaciers consolidated underlying sediment with the weight of ice, thousands of feet in height. These glacially overridden soils include Vashon Till, Esperance Sand and Lawton Clay (from the Vashon Stade of the Fraser glaciation) as well as all previous glacial and interglacial sedimentary cycles, of which there are thought to have been as many as seven (Troost and Booth, 2008).

These Pre-Fraser deposits can be subdivided in places into Olympia beds (last interglacial period), and older glacial and non-glacial deposits, all of Pleistocene age. Sedimentary bedrock that comprises the Blakeley Formation is present near the ground surface near Alki Point and in portions of South Seattle (Booth, et al. 2003).

A well-documented summary of the previous decade's research and conclusions was produced in the "Geology of Seattle and the Seattle Area, Washington" (Troost and Booth, 2008).

5.1.2 Postglacial Geologic Processes

The postglacial geologic history of the Seattle area primarily involves natural weathering and erosion of the uplands and resulting infilling of the intervening valleys and inlets with alluvial and colluvial deposits, in addition to human-induced processes. Peat deposits formed in the numerous kettles and closed depressions on the surface of the till uplands and alluvial fill valleys (Galster and Laprade, 1991). Prior to construction of seawalls, the bases of Seattle's bluffs were subject to continual shoreline erosion and oversteepening at the toe of the slope. Once undercut, the slope would slide, thereby undercutting the slope at higher elevations. With urbanization and the subsequent construction of seawalls and other shoreline armoring measures over most (about 90 percent) of the Seattle shoreline, this erosion has been arrested or greatly reduced (Shannon &

Wilson, 2000). Thus, wave action may no longer cause undercutting along much of the coast, but slopes throughout Seattle have not necessarily achieved a stable configuration yet, so landslides continue to occur (Tubbs, 1974).

5.1.3 Regional Seismicity

Sources of seismic hazards include (1) deep earthquakes within the subducting oceanic plate (the Juan de Fuca Plate); (2) large mega-thrust earthquakes occurring at the interface between the oceanic and continental plates; and (3) shallow crustal earthquakes within the continental plate (North American Plate). These three sources pose significant hazards to the Puget Sound Region (Pacific Northwest Seismograph Network, 2003).

The most recent significant earthquakes on record are deep earthquakes occurring in 1946, 1949, 1965, and 2001 with magnitudes up to 7.1. While deep earthquakes could occur beneath the city, these events originate 30 miles or more below the earth's surface and this depth tends to reduce the shaking at the ground surface from these deep earthquakes.

Mega-thrust earthquakes on the subduction zone plate interface have the potential to be devastating, with magnitudes of up to 9, and durations of one to three minutes. The last known massive subduction zone interface earthquake in the region occurred in 1700, which ruptured the entire length of the interface off the coast from northern California to southern British Columbia. The entire interface has ruptured multiple times in the last 10,000 years with recurrence of approximately 500 to 530 years (Goldfinger et al., 2012). The portion of the interface off the coast of Oregon and California appears to rupture more frequently, producing smaller earthquakes with a recurrence interval of approximately 240 years (Goldfinger et al., 2012).The ground shaking from large interface earthquakes would be attenuated by the 100 kilometers or more distance between Seattle and the epicenter of such a temblor.

Shallow earthquakes have the potential to be quite devastating, especially if shallow enough to cause ground rupture. Current seismic research has identified shallow crustal faults in the Puget Lowland on which large, pre-historic earthquakes have occurred, including the Seattle Fault zone. There appears to have been 3 to 4 large ground-surface rupturing earthquakes in the Seattle Fault zone between approximately 1,100 and 2,500 years ago (Nelson et al., 2003a and 2003b), with the largest likely a magnitude 7 or greater event at about 900 A. D. Prior to this most recent cluster, there is evidence for one or two other large events in the Seattle Fault zone over the past 16,000 years. Similarly, the recurrence for large shallow earthquakes on other faults in the Puget Lowland appears to be on the order of thousands of years.

In addition to the various seismic sources, the basin in which the city lies also contributes to the ground shaking hazard posed by these sources. Bedrock is displaced vertically across the Seattle Fault, with bedrock being brought to the surface on the south side of the fault and buried several thousand feet on the north side. Consequently, the city north of the fault is located in a sediment-filled basin. Seismic waves from the various earthquake sources reverberate in the basin causing the ground shaking to be amplified in portions of the basin (Frankel et al., 2007; Frankel et al., 2009).

Regardless of the seismic source and basin effects, records of disturbed sediments in Lake Washington indicate that the Seattle area has been subjected to strong earthquake ground shaking 7 times in the last 3,500 years (Karlin et al., 2004).

5.1.4 The Seattle Area Geologic Mapping Project

The City of Seattle was a sponsor of the Seattle Area Geologic Mapping Project (SGMP), and other efforts, to improve our understanding of the soil conditions in Seattle and how they relate to seismic hazards. The more detailed and accurate geologic maps resulting from this project allowed for upgraded and refined mapping of geologic hazard areas, especially as they relate to geologic contacts between different soil units and the spatial extent of soil units subject to liquefaction. The SGMP was a cooperative project sponsored jointly by the City of Seattle, U.S. Geological Survey, King County, and the Center for Water and Watershed Studies at the University of Washington. The SGMP produced a new generation of geologic maps for the City of Seattle, using the tremendous amount of information acquired by the City, private consultants, and other scientists since Waldron et al. (1962) and Galster and Laprade (1991).

This project developed a detailed understanding and representation of the three-dimensional distribution of geologic materials beneath Seattle and embedded that information in the context of a coherent, regionally integrated geologic framework for the central Puget Sound region. These new maps are the foundation for making modern assessments of geologic hazards, because the distribution of the different geologic materials across the city largely determines where the risks of landslides, liquefaction, and seismic shaking are greatest. Maps produced from the SGMP include:

1. Geologic Map of Northwestern Seattle (part of the Seattle North 7.5’ x 15’ quadrangle, King County), Booth, D.B., Troost, K.G., and Shimel, S.A., 2005.

2. The Geologic Map of Seattle – A Progress Report, Troost, K.G., Booth, D.B., Wisher, A.P., and Shimel, S.A., 2005.

3. Geologic Map of Northeastern Seattle (part of Seattle North 7.5’ x 15’ quadrangle, King County), Booth, D.B., Troost, K.G., Shimel, S.A., 2009.

5.1.5 References

Armstrong, J.E., Crandell, D.R., Easterbrook, D.J., and Noble, J.B., 1965, *Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington*: Geological Society America Bulletin, v. 76, p. 321-330.

Biederman, D. D., 1967, Recent sea-level change in the Pacific Northwest: Masters research paper, Univ. Washington, 24 p.

Booth, Derek B., Troost, Kathy G., Shimel Scott A., 2003, *Geologic Map of the West Part of the Seattle South 7.5X 15-Minute Quadrangle*, Washington, University of Washington, United States Geological Survey.

Booth, D.B., Troost, K.G., Shimel, S.A., 2005, *Geologic Map of Northwestern Seattle (part of Seattle North 7.5’ x 15’ Quadrangle), King County, Washington*: U.S. Geological Survey Scientific Investigations Map SIM-2903, U.S. Geological Survey, Washington, D.C.

Booth, D.B., Troost, K.G., Shimel, S.A., 2009, *Geologic Map of Northeastern Seattle (part of Seattle North 7.5' x 15' Quadrangle), King County, Washington*: U.S. Geological Survey Scientific Investigations Map 3065, U.S. Geological Survey, Washington, D.C.

Frankel, A. D.; Stephenson, W. J.; Carver, D. L.; and others, 2007, Seismic hazard aps for Seattle, Washington, incorporating 3D sedimentary basin effects, nonlinear site response, and rupture directivity: U. S. Geological Survey Open File Report 2007-1175, scale 1:24,000.

Frankel, Arthur; Stephenson, W. J.; and Carver, D. L., 2009, Sedimentary basin effects in Seattle, Washington: ground-motion observations and 3D simulations: Bulletin of the Seismological Society of America, v. 99, no. 3, p. 1579-1611.Gerstel, W.J., M.J. Brunengo, W.S. Lingley, R.L. Logan, H. Shipman, T.J. Walsh. 1997. *Puget Sound Bluffs: The Where, Why, and When of Landslides Following the Holiday 1996/97 Storms*. Washington Geology, vol. 25, no.1, 17-31.

Galster R. W. and Laprade, W. T., 1991 *Geology of Seattle, Washington United States of America*. Bulletin of the Association of Engineering Geologists Vol. XXVII, No. 3.

Goldfinger, Chris; Nelson, C. H.; Morey, A. E.; and others, 2012, Turbidite event history - methods and implications for Holocene paleoseismicity of the Cascadia subduction zone: U. S. Geological Survey Professional Paper P 1661-F, 170 p.

Karlin, R. E.; Holmes, Mark; Abella, S. E. B.; and Silwester, R., 2004, Holocene landslides and a 3500-year record of Pacific Northwest earthquakes from sediments in Lake Washington: Geological Society of America Bulletin, v. 116, no. 1/2, p. 94-108.

Mullineaux, D.R., Waldron, H.H., and Rubin, Meyer, 1965, Stratigraphy and chronology of late interglacial and early Vashon glacial time in the Seattle area, Washington: U.S. Geological Survey Bulletin 1194-O, 10 p.

Nelson, A.R, Johnson, S.Y., Kelsey, H.M., Sherrod, B.L., Wells, R.E., Bradley, L.-A., Okumura, K., and Bogar, R., 2003a, Late Holocene earthquakes on the Waterman Point reverse fault, another ALSM-discovered fault scarp in the Seattle fault zone, Puget Lowland, Washington: Geological Society of America Abstracts with Program (Abstract for talk in topical session on "Earthquake geology in reverse faulting terrains" at the Nov 03 Annual Meeting of The Geological Society of America in Seattle Washington).

Nelson, A.R., Johnson, S.Y., Kelsey, H.M., Wells, R.E., Sherrod, B.L., Pezzopane, S.K., Bradley, L.-A., and Koehler, R.D., III, 2003b, Late Holocene earthquakes on the Toe Jam Hill fault, Seattle fault zone, Bainbridge Island, Washington: Geological Society of America Bulletin, v. 115, 1388-1403.

Pacific Northwest Seismograph Network, 2003, http://www.geophys.washington.edu/SEIS/PNSN/ CascadiaEQs.pdf.

Troost, K.G., Booth, D.B, Wisher, A.P. and Shimel, S.A., 2005, *The Geologic Map of Seattle – A Progress Report*, U.S. Geological Survey Open-File Report 2005-1252, U.S. Geological Survey, Washington, D.C.

Troost, K.G. and Booth, D.B., 2008, *Geology of Seattle and the Seattle Area, Washington*, in Baum, R.L, Godt, J.W., and Highland, L.M., editors, Landslides and Engineering Geology of the Seattle, Washington Area, Geological Society of America Reviews in Engineering Geology XX, p. 1-36

Shannon & Wilson, Inc., W.D. Nashem, W.T. Laprade, T.E. Kirkland, C.A. Robertson. *Seattle Landslide Study*. 2000, Seattle Public Utilities: City of Seattle, Seattle.

Tubbs, D W. 1975 *Causes, Mechanisms and Prediction of Landsliding in Seattle*. PhD. Dissertation. (University of Washington, Seattle).

Waldron, H.H., Liesch, B.A., Mullineaux, D.R., and Crandell, D.R., 1962. *Preliminary geologic map of Seattle and vicinity*. Washington: U.S. Geological Survey Miscellaneous Investigations Map I-354.

Yount, J.C., Minard, J.P., and Dembroff, G.R., 1993. *Geologic map of surficial deposits in the Seattle 30' x 60' Quadrangle*. Washington: U.S. Geological Survey Open File Report 93-233. scale 1:100,000.

5.2. Landslide-prone Areas

5.2.1 Overview

Landslides occur on a frequent basis in the City of Seattle (Baum et al., 2005), and the City has recorded landslides as early as 1890 (Shannon & Wilson, 2000 and 2003). The original areas designated the City as landslide-prone due to “potential slide due to geologic conditions” was based on Class 3 and Class 4 Landslide Hazard Areas by Tubbs (1975). Based on their review of extensive landslide records and their subsequent geologic reconnaissance, Shannon and Wilson (2000) revised the boundaries of “potential slide due to geologic conditions” to include the following from Section 21 of the Seattle Landslide Study:

1. Areas with historical record of landsliding
2. Signs of past landsliding observed in the field, such as landslide scars and deposits.
3. Signs of potential landsliding observed in the field such as springs, groundwater seepage, and bowed or backtilted trees.
4. Topographic expression of runout zones, such as fans and colluvial deposition at the toes of hillsides.
5. Setbacks from very steep slopes or bluffs.
6. Extrapolation of the above factors to areas of similar and contiguous topography and geology.

The history of landslide mapping is chronicled by Laprade and Tubbs (2008).

A number of probable causes and factors related to slope failure were identified (Shannon & Wilson, 2000). Among these are: increased groundwater levels and surface runoff, removing support at the toe of the slope by erosion or by excavation, changes in the soil strength, loading the head of the slope with debris from another landslide or with manmade fills, and seismic loading. Although landslides can occur any time of the year, most occur during the typically wetter winter months, and most occur during or shortly after periods of intense rainfall following the buildup of the water level in the ground (Shannon & Wilson, 2000 and Chleborad, 2001).

Similarly, Tubbs (1975) relates landslides in Seattle to certain geologic, climatic, and human factors. These factors include (1) steep topography; (2) unfavorable geologic characteristics; (3) intense or prolonged rainfall intensity; (4) the products of human activity**;** and (5) ground shaking caused by large earthquake events.

The majority of landslides in Seattle occur in areas of steep slope containing geologic conditions that can lead to instability and loss of soil strength. Such geologic conditions conducive to landsliding include permeable, coarse-grained soils overlying relatively impermeable fine-grained sediments, including interbedding of coarse- and fine-grained soils. This geologic stratification can direct groundwater seepage to the slope face; with buildup of seepage forces and/or hydrostatic pressure at the face of the slope, the effective strength of the soil decreases. Landslides occur where the strength of the soil mass becomes less than the soil strength that is required to maintain stability (Turner and Schuster, 1996).

Past glaciations play a major role in landslide mechanisms in the Seattle area. The steep slopes surrounding many of the upland areas have been affected by weathering of the surficial soils, and some slopes has been affected by shoreline erosion and undercutting for thousands of years (Tubbs and Dunne, 1977). Because of the high strength of the glacially consolidated sediment, deep-seated landslides are often characterized as block movements, which may remain partially intact as they translate downslope. Deep-seated slides are typically associated with high groundwater pressure within the shear zone.

5.2.2 Landslide Studies About Seattle

Three major publications have been prepared concerning landslide mechanisms and inventories in Seattle. These include the following:

1. *Landslides in Seattle.* Donald W. Tubbs. 1974. Department of Natural Resources Division of Geology and Earth Resources, Information Circular No. 52 (United States Geologic Survey, Washington).

2. *Causes, Mechanisms and Prediction of Landsliding in Seattle*. Donald Willis Tubbs. 1975. PhD. Dissertation. (University of Washington, Seattle).

3. *Seattle Landslide Study*. Shannon & Wilson, Inc., W.T. Laprade, W.D. Nashem, T.E. Kirkland, C.A. Robertson. 2000 updated 2003. (Seattle Public Utilities: City of Seattle, Seattle).

References 1 and 2 above were based primarily on the landslide season of 1971/1972. More than three-quarters of the landslides originated as debris slides that could be modeled as infinite-slope failures (Tubbs, 1975).

Reference 3 includes an inventory and evaluation of landslides on record with the City of Seattle, as well as landslides in files maintained by Shannon & Wilson, Inc. The landslide locations were field verified. The study includes recommendations for landslide hazard areas, based on review of the documented landslides, field verification of landslides, and geologic assessment and evaluation of topographic and geologic conditions that are conducive to landslide activity.

More recently, the US Geological Survey prepared a number of landslide studies of the Seattle area. These include the following:

1. Landslide Susceptibility Estimated from Mapping Using Light Detection and Ranging (LiDAR) Imagery and Historical Records, W.H. Schulz, USGS Open-File 2005-1405, 2005.

2. Shallow-Landslide Hazard Map of Seattle, Washington, E.L. Harp, J.A. Michael, W.T. Laprade, USGS Open-File Report 2006-1139.

3. Rainfall Thresholds for Forecasting Landslides in the Seattle, Washington Area – Exceedance and Probability, A.F. Chleborad, R.L. Baum, and J.W. Godt, USGS Open-File Report 2006-1064.

In comparing areas of landslide susceptibility from USGS Reference 1 to the current areas mapped as landslide prone for the City of Seattle, there are some differences, though most of the areas have some overlap. An update of the Seattle Landslide Study with field verification would be needed to decide how or whether to incorporate new areas suggested by Reference 1.

Based on our discussion with the third author of Reference 2, shallow landslide hazards are adequately represented by the current mapping of landslide-prone areas.

The results of Reference 3 are used by SPU, SDOT, and DPD to predict whether City facilities will be impacted and whether City resources will need to be on-call to respond to landslide events.

Additional references can be found on the USGS website (http://pubs.usgs.gov/). Documents include the following:

A Preliminary Finite-Element Analysis of a Shallow Landslide in the Alki Area of Seattle, Washington, S. Debray and W.Z. Savage, USGS Open-File Report 01-0357, 2001.

Preliminary map showing landslide densities, mean recurrence intervals, and exceedance probabilities as determined from historic records, Seattle, Washington, J. A. Coe, J.A. Michael, R.A. Crovelli, and W.Z. Savage, USGS Open-File report 00-303, 2000.

An Account of Preliminary Landslide Damage and Losses Resulting from the February 28, 2001, Nisqually, Washington, Earthquake, by Lynn M. Highland, USGS Open-File Report 03 211, preliminary, no date.

Map Showing Recent and Historic Landslide Activity on Coastal Bluffs of Puget Sound Between Shilshole Bay and Everett, Washington, R.L. Baum, E.L. Harp and W.A. Hultman, Map MF 2346, 2000.

Landslides Mapped Using LiDAR Imagery, Seattle, Washington, W.H. Schulz, USGS Open-File Report 2004-1396, 2004.

Landslide Hazards in the Seattle, Washington Area, R.L. Baum and L.M. Highland, USGS Fact Sheet FS 2007-3005, 2007.

Modeling 3-D Slope Stability of Coastal Bluffs, Using 3-D Groundwater Flow, Southwestern Seattle, Washington, D.L. Brien and M.E. Reid, USGS Scientific Investigations Report 2007-5092.

Other related topics regarding Seattle landslides included shallow landslide hazards, forecasting landslide occurrence, modeling of landslides, early warning for shallow landslides, the timing of landslides related to rainfall, and the use of digital elevation modeling (Haneberg, 2006 and 2008; Cruz, E.M.B., 2006; Brien and Reid, 2008; Chleborad et al., 2008; Harp et al., 2008; Salciarini et al., 2008; Schulz et al., 2008; Baum el al., 2010a and b.

5.2.3 Landslide Mechanisms

Based on the Seattle Landslide Study (2000), most landslides in Seattle fit into one of the following categories: (1) high bluff peel-off; (2) groundwater blowout; (3) deep-seated; and (4) shallow colluvial (or skin slide; also includes slides involving fill material). It is common for landslides to fit into more than one category listed above. For instance, a landslide may start out as a high bluff peeloff and turn into a shallow colluvial slide in the lower portions of the slope.

Several authors provide detailed descriptions of landslide mechanisms (Tubbs, 1974; Tubbs, 1975; Turner and Schuster, 1996; Shannon and Wilson, 2000). Shannon and Wilson (2000) identify that approximately 68 percent of all documented landslides in the City of Seattle are shallow colluvial. Approximately 20 percent are deep-seated, while, the remaining 12 percent are groundwater blowout, high bluff peel-offs, or unknown (Shannon & Wilson, 2000, fig. 1-10).

The Episodic Nature of Landslide Events

Although landslides can occur at any time of the year, most landslides occur during the typical rainy period from November to May, with only 7 percent occurring outside of the time period (Shannon & Wilson, 2000). Within the typical rainy season, 86 percent of the slides occurred from December to March (Shannon & Wilson, 2000).

Three winter seasons produced a particularly large number of landslides: (1) winter of 1933/1934; (2) winter of 1985/1986; and (3) winter of 1996/1997 (Shannon & Wilson, 2000; Baum et al., 1998). Due to the 1933/1934 landslide season, the Works Progress Administration drainage program was formed in Seattle (Shannon & Wilson, 2000, p. 24). Background information concerning the WPA Landslide Stabilization Projects is contained in the following Evans (1994). The landslides of the winter of 1996/1997 resulted in a state of emergency declared by the mayor, and the subsequent formation of the Seattle Landslide Policy Group. Based on this group's conclusions, the

Landslide Prone Areas (LPA) program was implemented by Seattle Public Utilities to help improve drainage in steep slope/landslide-prone areas in an effort to decrease the risk of landslides.

Shannon &Wilson (2000, p. 24) identifies eleven winter seasons with significantly high numbers of landslide events. These years are (1) 1933/1934; (2) 1955/1956; (3) 1959/1960; (4) 1960/1961; (5) 1966/1967; (6) 1968/1969; (7) 1971/1972; (8) 1973/1974; (9) 1985/1986; (10) 1995/1996; (11) 1996/1997.

Landslide events correspond to high levels of precipitation (Godt, 2004, Godt et al., 2006 a, b, and c; Godt and McKenna, 2008; Godt et al., 2008). A study by the United States Geological Survey (USGS) identifies precipitation thresholds for the initiation of landslides (Chleborad, 2003). The precipitation thresholds are based on the 3-day cumulative rainfall amount following the rainfall amount of the preceding 15 days (antecedent 15-day precipitation). Data for this study was limited to occurrences of three or more landslides within a 3-day period, in order to exclude events that are not related to rainfall (leaking water or sewer lines, improper grading activities, and so forth) (Chleborad et al., 2006). A chart is maintained on the USGS website that allows the public to track precipitation conditions at citywide/regional weather stations in order to predict landslide conditions (Chleborad, 2001).

The Role of Geologic Conditions

The two references cited above by Donald Tubbs include descriptions of geologic conditions that contribute to the potential for landslide activity. In his 1974 study, Tubbs indicates that saturation of surficial debris was a cause, but not necessarily the only cause, of 40 of the 50 landslide events included in the study. In 37 of those landslides, the underlying material was identified as either glacial till, Lawton Clay, or pre-Lawton sediments, all of which have low permeability characteristics. Forty percent of the landslides he studied occurred in proximity to the contact zone between Esperance Sand and Lawton Clay, or the Esperance Sand and pre-Lawton geologic contact. There are a variety of visual indicators for areas of high landslide potential. These include hummocky terrain, groundwater seeps, bowed trees and scarps(Gray and Sotir, 1996).

The role of geologic conditions in landsliding relates to the movement of groundwater within the soil formations. Infiltrating precipitation flows down gradient. Within a highly permeable and unsaturated soil formation percolating groundwater tends to flow downward. Upon contact with a less permeable soil unit, the groundwater seeks the path of least resistance and will flow along the contact between the two soil formations until reaching a terminus. The terminus can be either a lake, pond, creek, or steep slope area (Shannon & Wilson, 2000, p. 13). Saturation of soil at the slope face results in a decrease in resisting shear strength of the soil mass, increasing the possibility of landsliding (Turner and Schuster, 1996).

Tubbs (1975) designates a width of 200 feet horizontally along the trace of Esperance Sand and either the Lawton Clay formation or pre-Lawton sediments as Class 4 Landslide Hazard Area. Slides often occur at the contact zone between the upper sand layer and underlying Lawton Clay or Pre-Vashon Sediments (Tubbs, 1975). This width corresponds to the estimated thickness of the zone of intercalated sand at the top of the Lawton formation that would outcrop along a 15 percent slope. Over three-quarters of the landslides in the Tubbs study occurred in areas directly underlain by either the Lawton Clay or pre-Vashon sediments, and nearly half of the slides occurred along the trace of the contact between one of these units and the overlying Esperance Sand (Tubbs, 1975).

Tubbs designated areas with at least 15 percent slope and underlain by Lawton or pre-Lawton sediments (with the exception of Class 4 Hazard Areas) as Class 3 Landslide Hazard Areas, which are considered of intermediate stability, but less stable than areas underlain by the Esperance Sand or younger sediment. Knowing where the contact zone is located is crucial for determining the propensity for a landslide to occur. The areas of particular risk of slope instability can be readily seen on a map created by statistical analysis of the data from the Seattle Landslide Study (Coe et al., 2000).

5.2.4 The Effect of Large Earthquakes

Seismic shaking can trigger landslides. In fact, some of the most devastating landslides worldwide have been associated with earthquake events. Earthquake-induced landslides have buried entire towns and villages. In the 1964 Alaska earthquake, 56 percent of the total cost of damage was the result of earthquake-induced landslides (Kramer, 1996). Including the effect of large earthquakes in the evaluation of landslide potential and necessary mitigation remains essential for safe development within potential landslide areas, and it requires case-by-case analysis and evaluation by a geotechnical engineer.

Historically, only one seismically induced landslide out of 1,346 had been reported in the Seattle Landslide Study (Shannon & Wilson, 2000). However, the 2001 Nisqually Earthquake triggered many small landslides (Highland, 2003). For ground shaking exceeding historic levels, landslides will be more numerous. Allstadt et al. (2013) studied potential landsliding in Seattle for a M7 Seattle Fault event. They determined that landsliding would be extensive throughout the ECA steep slopes and potential slide areas. Kayen and Barndardt (2007) determined that for earthquakes greater than about M7 and peak ground accelerations of approximately 0.2g or greater, liquefaction of the soils that underlie Duwamish River delta will likely result in flow failure and large submarine landslides along the north side of Harbor Island and adjacent delta front areas.

In Seattle, strong shaking would exacerbate the number and destructiveness of landslides during the wet season. The degree of damage would depend on the time of year, the antecedent precipitation, and the strength and duration of shaking. During dry periods, seismically induced landslide damage could be minor, whereas strong near-surface movement on the Seattle Fault zone during the wet season could be devastating.

5.2.5 The Human Factor

It is usually more difficult to assess the importance of human influences than to determine the geologic and climatic causes of landsliding (Tubbs, 1975). Tubbs (1974) reports that 80 percent of the landslides included in his study were influenced in some way by human activity. Diversion of water into the formation was the most common human factor, noted in more than 40 percent of the landslides. The water was usually the result of runoff from roofs and paved areas, but other sources were occasionally involved (Tubbs, 1975). Other cited human activities included hillside excavation, artificial fill failure, and retaining wall failure. Steepening of slopes by excavation was also recognized in over 40 percent of the landslides (Tubbs, 1975). This can contribute to landsliding either by the removal of lateral support, often resulting in immediate failure, or by the creation of unnaturally steep slopes upon which debris slides are likely at some future date (Tubbs, 1975). Placing artificial fill on a slope can contribute to landsliding, especially on steep slopes underlain by an impermeable substrate (Tubbs, 1975). More than 30 percent of the landslides involved some fill. Ten percent of the landslides were associated with retaining wall failures, due to inadequate design, construction, or maintenance (Tubbs, 1975).

Shannon & Wilson (2000) estimated that on a citywide basis, 84% of all landslides studied had some form of human influence. The identified human factors include broken or leaking pipes, lack of maintenance of drainage facilities, excavation at the toe of a slope, fill placement at the top of a slope, and imprudent cutting of vegetation. Shannon & Wilson (2000) suggest though that the high percentage of landslides with human influence may be explained by the fact that the records contain only reported landslides in developed areas, and that totally natural landslides in parks and other undeveloped areas may have been under reported.

5.2.6 Regulation of Landslide Hazard Areas

Regulation of development of landslide hazard areas, including areas of potential landslide and documented landslide areas, requires site-specific project planning and engineering.

Geologic and/or geotechnical engineering studies should provide evaluations of the geologic hazards affecting the proposed development. Recommendations must be provided to mitigate those hazards on the subject property and prevent adverse and/or cumulative impacts to nearby properties. These recommendations must be incorporated into the project plans. Control of stormwater and seepage collected from subdrainage systems, site stability, and offsite hazards associated with steep slopes and geologic conditions need to be addressed on a case-by-case basis.

Project requirements must be incorporated into the site and building plans, including, but not limited to, limits and configuration of excavation and shoring, surface and subsurface drainage systems, erosion and sediment control plans, staging of construction activities, and structural safeguards (e.g., landslide debris catchment methods). All of these issues must be monitored during construction to ensure compliance with the design.

Potential slide areas due to geologic conditions are mapped by the Seattle Landslide Study (Shannon and Wilson, 2000 and 2003). Known slide areas are based on the database cataloged in the Seattle Landslide Study, updated by recent landslide records documented in the City of Seattle's WebEOC system.

5.2.7 References

Allstadt, K., Vidale, J.E., and Frankel, A.D., 2013, *A Scenario Study of Seismically Induced Landsliding in Seattle Using Broadband Synthetic Seismograms*, Bulletin of the Seimological Society of America, v. 10, no. 6, 22 p.

Baum, R.L., Coe, J.A., Godt, J.W., Harp, E.L., Reid, M.E., Savage, W.Z., Schulz, W.H., Brien, D.L., Chleborad, A.F., McKenna, J.P., and Michael, J.A., 2005, *Regional Landslide-Hazard Assessment for Seattle, Washington, USA*, Landslides, v. 2, no. 4, p. 266-279.

Baum, R.L., Godt, J.W., and Savage, W.Z., 2010, *Estimating the Timing and Location of Shallow Rainfall-Induced Landslides Using a Model for Transient Unsaturated Infiltration*, Journal of Geophysical Research, v. 115, no. 3.

Baum, R.L., Godt, J.W., and Sassa, K., 2010, *Early Warning of Rainfall-Induced Shallow Landslides and Debris Flows*, Landslides, v. 7, no. 3, p. 259-272.

Baum, R.L., Harp, E.L., and Highland, L.M., 2007, *Landslide Hazards in the Seattle, Washington Area*, U.S. Geological Survey Fact Sheet FS 2007-3005, 4 p.

Brien, D.L. and Reid, M.E., 2007*, Modeling 3-D Slope Stability of Coastal Bluffs, Using 3-D Groundwater Flow, Southwestern Seattle, Washington*, U.S. Geological Survey Scientific Investigations Report 2007-5092, 54 p.

Brien, D.L. and Reid, M.E., 2008, *Assessing Deep-Seated Landslide Susceptibility Using 3-D Groundwater and Slope-Stability Analyses*, in Baum, R.L, Godt, J.W., and Highland, L.M., editors, Landslides and Engineering Geology of the Seattle, Washington Area, Geological Society of America Reviews in Engineering Geology XX, p. 83-101.

Chleborad, A.F. 2001, *Preliminary Method for Anticipating the Occurrence of Precipitation-Induced Landslides in Seattle, Washington - Open-File Report 00-469.*, U.S. Geological Survey Washington D.C..

Chleborad, A. F., 2003, *Precipitation Threshold for Anticipating the Occurrence of Landslides in the Seattle, Washington Area*. "Science for a Changing World" U.S. Geological Survey (USGS) updated 2000. <http://landslides.usgs.gov/html_files/ofr-00.

Chleborad, A.F., Baum, R.L., and Godt, J.W., 2006, *Rainfall Thresholds for Forecasting Landslides in the Seattle, Washington Area – Exceedance and Probability*, U.S. Geological Survey Open-File Report 2006-1064, U.S. Geological Survey, Washington, D.C.

Chleborad, A.F., Baum, R.L., Godt, J.W., and Powers, P.S., 2008, *A Prototype System for Forecasting Landslides in the Seattle, Washington Area, 2008*, in Baum, R.L, Godt, J.W., and Highland, L.M., editors, Landslides and Engineering Geology of the Seattle, Washington Area, Geological Society of America Reviews in Engineering Geology XX, p. 103-120.

Coe, J.A., Michael, J.A., Crovelli, R.A., and Savage, W.Z., 2000, *Preliminary Map Showing Landslide Densities, Mean Recurrence Intervals, and Exceedence Probabilities as Determined from Historic Records, Seattle, Washington*, U.S. Geological Survey Open-File Report 00-0303.

Cruz, E.M.B., 2006, *Modeling Shallow, Precipitation-Triggered Landslides Along Coastal Bluffs in Northwest Seattle, Washington*, Colorado School of Mines, Golden, CO, USA.

Evans, S., 1994, Draining Seattle – WPA Landslide Stabilization Projects, 1935-1941, Washington Geology, Vol. 22, No. 4, December.

Godt, J.W., 2004, *Observed and Modeled Rainfall Conditions for Shallow Landsliding in the Seattle, Washington Area*, University of Colorado at Boulder, Colorado.

Godt, J.W., Baum, R.L., and Chleborad, A.F., 2006, *Rainfall Characteristics for Shallow Landsliding in Seattle, Washington, USA*, Earth Processes and Landforms, p. 97-110.

Godt, J.W., Baum, R.L., and Savage, W.Z., 2006, *Modeling Transient Rainfall Infiltration and Slope Instability for Debris-Flow Initiation; Unsaturated Zone Effects*: U.S. Geological Survey Scientific Investigations Report (2006), U.S. Geological Survey, Washington, D.C., p. 10-11.

Godt, J.W., Baum, R.L., Lu, N. and Savage, W.Z., 2006, *Applying Distributed, Coupled Hydrological Slope-Stability Models for Landslide Hazard Assessments*, in EOS Transactions, American Geophysical Union 2006.

Godt, J.W., and McKenna, J.P., 2008, *Numerical Modeling of Rainfall Thresholds for Shallow Landsliding in the Seattle, Washington Area*, in Baum, R.L, Godt, J.W., and Highland, L.M., editors, Landslides and Engineering Geology of the Seattle, Washington Area, Geological Society of America Reviews in Engineering Geology XX, p. 121-135.

Godt, J.W., Schulz, W.H., Baum, R.L. and Savage, W. Z., 2008, *Modeling Rainfall Conditions for Shallow Landsliding in Seattle, Washington*, in Baum, R.L, Godt, J.W., and Highland, L.M., editors, Landslides and Engineering Geology of the Seattle, Washington Area, Geological Society of America Reviews in Engineering Geology XX, p. 137-152.

Gray D.H. and Sotir R.B. 1996 Biotechnical and Soil Bioengineering Slope Stabilization: a practical guide for erosion control. John Wiley & Sons, Inc. New York, NY.

Haneberg, W.C., 2006, *Effects of Digital Elevation Model Errors on Spatially Distributed Seismic Slope Stability Calculations – An Example from Seattle*, Washington, Environmental and Engineering Geology, v. 12, no. 3, p. 247-260.

Haneberg, W.C., 2008, *Elevation Errors in a LiDAR Digital Model of West Seattle and Their Effects on Slope-Instability Calculations*, in Baum, R.L, Godt, J.W., and Highland, L.M., editors, Landslides and Engineering Geology of the Seattle, Washington Area, Geological Society of America Reviews in Engineering Geology XX, p. 55-65.

Harp, E.L., Michael, J.A., and Laprade, W.T., 2006, *Shallow-Landslide Hazard Map of Seattle, Washington*, U.S. Geological Survey Open-File Report 2006-1139, Washington, D.C.

Harp, E.L., Michael, J.A., and Laprade, W.T., 2008, *Shallow Landslide Hazard Map of Seattle, Washington*, in Baum, R.L, Godt, J.W., and Highland, L.M., editors, Landslides and Engineering Geology of the Seattle, Washington Area, Geological Society of America Reviews in Engineering Geology XX, p. 67-82.

Highland, L.M., 2003, An Account of Preliminary Landslide Damage and Losses Resulting from the February 28, 2001, Nisqually, Washington, Earthquake, U.S. Geological Survey Open-File Report 03-211, Version 1.1**,** http://pubs.usgs.gov/of/2003/ofr-03-211/

Kayen, R. E. and Barnhardt, W. A., 2007, Seismic stability of the Duwamish River delta, Seattle, Washington: U.S. Geological Survey Professional Paper 1661-E, 11 p., available: http://pubs.er.usgs.gov/usgspubs/pp/pp1661E.

Kramer, L. S., 1996. *Geotechnical Earthquake Engineering*, University of Washington, Prentice-Hall.

Laprade, W.T., and Tubbs, D.W., 2008, Landslide mapping in Seattle, Washington, Reviews in Engineering Geology, Reviews in Engineering Geology, vol. 20, no. 0, pp. 37-54

Salciarini, D., Conversini, P, Godt, J.W., Savage, W.Z., and Baum, R.L., 2008, *Modeling Landslide Recurrence in Seattle, Washington*, Engineering Geology, v. 102, no 3-4, p. 227-237.

Schulz, W.H., 2004, *Landslides Mapped Using LiDAR Imagery, Seattle, Washington*, U.S. Geological Survey Open-File Report 2004-1396, U.S. Geological Survey, Washington, D.C.

Schulz, W.H., 2005, *Landslide Susceptibility Estimate from Mapping Using Light Detection and Ranging (LiDAR) Imagery and Historical Records, Seattle, Washington*, U.S. Geological Survey Open-File Report 2005-1405, U.S. Geological Survey, Washington, D.C.

Schulz, W.H., Lidke, D.J., and Godt, J.W., 2008, *Modeling the Spatial Distribution of Landslide-Prone Colluvium and Shallow Groundwater on Hillslopes of Seattle, Washington*, Earth Processes and Landforms, v. 33, no. 1, p. 123-141.

Shannon & Wilson, Inc., W.D. Nashem, W.T. Laprade, T.E. Kirkland, C.A. Robertson. *Seattle Landslide Study*. 2000, Seattle Public Utilities: City of Seattle, Seattle.

Shannon & Wilson, Inc. *Seattle Landslide Study*. (City of Seattle, Seattle Public Utility: Seattle, WA, 2000). And as updated 2003.

Tubbs, D W. 1974 *Landslides in Seattle*. Department of Natural Resources Division of Geology and Earth Resources, Information Circular No. 52 (United States Geologic Survey, Washington).

Tubbs, D W. 1975 *Causes, Mechanisms and Prediction of Landsliding in Seattle*. PhD. Dissertation. (University of Washington, Seattle).

Tubbs, D.W. and Dunne, T., 1977, *Geologic Hazards in Seattle, A field guide for the Geological Society of America Annual Meeting*.

Turner, A.K., R.L. Schuster. (eds.) 1996. *Landslides, Investigation and Mitigation, Special Report No. 247* (National Academy of Sciences: Washington D.C.).

5.3 Steep Slope Areas

5.3.1 Overview

The steepness of slopes is an important factor in both landslide and erosion processes. In Seattle, a steep slope area is defined as a slope 40 percent or steeper within a minimum vertical elevation change of 10 feet. Steep topography increases the potential for adverse impacts related to development activities, including impacts to adjacent properties, public rights-of-way, water bodies, and public natural resources including fish and fish habitat.

5.3.2 Studies and Effects of Erosion

Adequate temporary and permanent control of collected water is essential for safe development, control and prevention of erosion/sedimentation, and reduction of landslide risks on steep slope sites (Gray and Sotir, 1996).

Lack of temporary erosion and sediment control on construction sites is known to increase siltation of streams, lakes, Puget Sound, and other receiving waters, as well as the public stormwater system. The impacts commence as raindrops strike bare soil, such as soil exposed during construction, breaking up soil aggregates, and separating organics and fine soil particles from heavier soil particles (Goldman et al., 1986). This degradation of soil structure can lead to the development of a hard crust, reducing the infiltration rate, and inhibiting plant establishment (Goldman et al., 1986). On a sloping construction site, changes in established drainage patterns can result in concentration of runoff, with associated problems, such as flooding and earth movement (Menashe, 1993; Myers, 1993).

Maintaining vegetation on a slope is critical in reducing the potential for erosion and sedimentation problems (Brennan, 2001; Goldman et al., 1986). This is an important issue, given the difficulty of re-establishing vegetation on a disturbed site.

Vegetated buffers reduce stormwater flows over the steep slope area, reducing erosion on the steep slope and protecting the root system of vegetation on the slope. The buffer also limits the impact of grading and development in close proximity to the steep slope which can affect slope stability.

5.3.3 Regulation of Steep Slope Areas

The preferred method of preventing harm to the environment from development activity on steep slopes, and harm to the drainage systems and basins in which the steep slopes are located, is to minimize disturbance, to maintain and enhance existing vegetative cover, and enact effective temporary erosion control methods during construction activities.

The steep slope layer in the City of Seattle database is based upon aerial topography circa 1956, digitized by hand and transferred to the City's GIS system. The City is working to update the steep slope layer so that it is based more recent topographic surveys and LIDAR mapping.

5.3.4 References

Brennan, J.A., 2001, *Native Plantings and Vegetating Slopes around Puget Sound*, American Society of Civil Engineers, Seattle Section, Geotechnical Group and University of Washington Department of Civil Engineering, Spring Seminar, 16 p.

Goldman, S.J., Jackson, K., Bursztynsky, T.A. 1986, *Erosion and Sediment Control Handbook.* McGraw Hill.

Gray D.H. and Sotir R.B. 1996 Biotechnical and Soil Bioengineering Slope Stabilization: a practical guide for erosion control. John Wiley Et Sons, Inc. New York, NY.

Menashe, E., 1993, *Vegetation Management: A Guide for Puget Sound Bluff Property Owners. Publication 93 31*, Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia, WA.

Myers, Rian D., 1993, Slope Stabilization and Erosion Control Using Vegetation: A Manual of Practice for Coastal Property Owners. Publication 93-30, Shorelands and Coastal Zone Management Program, Washington Department of Ecology. Olympia, WA.

The geologic and seismic setting, landslide hazards, and steep slope sections were originally prepared by Dean Griswold, P.E. and updated by Bill Laprade, L.E.G. and Bill Perkins, P.E., L.E.G. in 2014.

5.4 Peat Settlement-Prone Areas

5.4.1 Overview

Peat is an accumulation of partially decayed organic plant material that typically forms in wetlands where lack of oxygen and acidic conditions inhibit complete decay. Unconsolidated peat deposits are generally characterized by a fibrous structure exhibiting weak compressive strength and high void ratios (i.e., containing significant void space).

Peat deposits are subject to settlement when loaded with additional weight or when groundwater levels are lowered. Lowering of the groundwater level reduces the buoyancy of overlying soils, thus increasing the pressure on the peat deposit and potentially resulting in compression. Settlement can occur where new fill or structures load soil or where groundwater levels are lowered due to sump pumps, temporary construction dewatering withdrawals, trenching, or other drainage projects. Because settlement can be induced by lowering of the groundwater table as well as by direct loading of the soil, settlement of peat deposits can occur a significant distance from the originating development activity because water withdrawals can influence the water table off-site.

5.4.1.1 Seattle Context

In the City of Seattle, peat deposits have typically formed in topographic depressions created during the most recent glacial retreat and in the nearshore areas of lakes, the floodplains of the Duwamish River, depressions along modern streams, and marine estuaries. The lowering of Lake Washington by nine feet in 1916 also exposed significant areas of former lake bottom that contain peat deposits. As the City developed, these boggy areas were commonly filled to reclaim marshy areas considered to be a nuisance due to standing water and odors as well as to provide more developable land. Consequently, many peat deposits have been buried and now support development throughout the City.

Urban development in these areas has led to further alterations which have impacted the peat deposits and their settlement potential. Drainage projects were initiated in some areas of the City to drain wet areas and redirect stream flows. Installation of storm drains and sewer systems, sump pumps, and impervious surface have reduced the amount of groundwater recharge through diversion of stormwater and groundwater inflow. Regrading projects and public utilities may also have changed water flow directions and created new flow corridors where granular fill has created new pathways of increased permeability. Together, these modifications have led to significant cumulative impacts where altered hydrology has created new equilibrium states, as well as acute impacts where individual development projects adversely affected nearby properties.

5.4.1.2 Mechanics of Peat Settlement

The magnitude of settlement occurring in a particular location is based on a number of factors including:

- Geotechnical characteristics of the peat
- Thickness of the peat deposit
- Existing pressure on the peat
- Change in pressure on the peat
- Historic loading of the peat

The expected total settlement is made up of three components: immediate settlement, primary consolidation, and secondary compression. Immediate settlement is only of concern during fill or structure loading. Because these concerns are adequately addressed by existing building code standards, they are not a topic for this section, which remains focused on potential off-site impacts.

Primary consolidation is a time-dependent settlement process that occurs in saturated fine-grained soils that have low permeability. The settlement is due to water slowly being forced from the void spaces of the soil due to increases in load on the soil. For soils such as peat and other highly organic soils with high natural water content and high void ratios, primary consolidation settlements can be large. Primary consolidation settlement can take several months to complete.

Secondary compression is a continuation of the volume change that starts during primary consolidation, but it occurs at a much slower rate. It constitutes a major part of the total settlement of peats and other highly organic soils, and it may continue for years, creating a continuing hazard.

Once settlement has occurred, peat deposits will never return to their original state, although minimal rebound is possible if weight is removed or the water level increases.

5.4.1.3 Effects of Settlement

The impacts of settlement can be significant, particularly where differential settlement occurs due to a peat deposit having variable thickness, groundwater flow directions, slopes, differential loading, or previous loads. Common damages from settlement include uneven or cracked foundations, cracks in the interior finishes, sticking windows and doors, broken underground utilities, and uneven sidewalks and roads. These problems may cause existing structures to become more prone to damage during earthquakes. Flooding may also occur both as pipes break and settlement lowers the elevation of yards and structures, creating ponding, or even lowering areas below the water table. Because settlement occurs gradually, the impacts of additional loading or groundwater withdrawals may appear gradually after an initial modification.

As an example of the effect of lowering the groundwater table on settlement of peat, we developed estimates, shown in Tables 1 and 2, based upon the following assumptions:

(1) consolidation parameters from the WSDOT Geotechnical Design Manual of $C_{c\varepsilon} = C_c/(1+e_o) = 0.4$ and $C_{\alpha\varepsilon} = 0.06 * C_{c\varepsilon}$ (note that geotechnical properties of peat can be highly variable)
(2) initial water table at 2 feet below the ground surface drawn down to 7 feet below the ground surface

Table 1: Estimated primary consolidation settlement (in inches) expected due to groundwater table drawdown from 2 feet below surface to 7 feet below surface.

Depth to top of peat deposit (ft)	Vertical Thickness of Peat Deposit			
	2 ft thickness	3 ft thickness	5 ft thickness	10 ft thickness
0	0	½	1½	11
5	2	3	5	9
10	1½	2	3½	6½
20	1	1	2	4

Table 2: Estimated total settlement (in inches) expected due to groundwater table drawdown from 2 feet below surface to 7 feet below surface.

Depth to top of peat deposit (ft)	Vertical Thickness of Peat Deposit			
	2 ft thickness	3 ft thickness	5 ft thickness	10 ft thickness
0	0	½	4	16
5	3	4½	7½	14
10	2½	3½	6	11
20	2	2½	4½	9

5.4.1.4 Historic Settlement in Seattle

Evidence of gradual settlement has been found in many localized areas of Seattle. Areas in Greenwood, the most studied area of peat-rich soils, have been experiencing documented settlement of roads and structures as far back as 1958 (Shannon and Wilson, 2004). Union Bay, one of the deepest known peat deposits in Washington State, has also experienced significant recorded settlement (Montlake Landfill Work Group, 1999).

In 2001, sections of the Greenwood neighborhood began to experience unexpected acute settlement. Developed on the location of historic wetlands, substantial subsurface peat deposits have been found under portions of Greenwood including part of the Greenwood business district and the residential area north and west of NW 85th Street and Greenwood Avenue North. This area, commonly referred to as the "Greenwood Bog," constitutes a topographical depression bordered by Phinney Ridge to the east and Crown Hill and Blue Ridge to the west. Lowered groundwater levels resulting from development along Greenwood Avenue North appear to be a cause of this settlement, although insufficient data exists to pinpoint an exact source (Shannon and Wilson, 2004).

Data for assessing the effects of settlement in other parts of the City are not readily available.

5.4.2 Peat Studies in Seattle

Studies conducted for the City of Seattle have added to the knowledge of peat and peat settlement occurring within the City including the Map of Seattle Identified Bogs (Troost, 2007), Map of Organic-Rich Deposits (Troost, 2006) and the Shannon and Wilson Greenwood Subsurface Characterization Study (2004).

The Map of Organic-Rich Deposits (GeoMapNW, 2006) project compiled and analyzed boring logs submitted to the City of Seattle in conjunction with permit applications between 1914 and 2006. Thirty three thousand two hundred and seventy reports were compiled and analyzed to identify subsurface deposits of peat greater than one foot in thickness. These results were then extrapolated based on historic geomorphology and hydrology to estimate the extent of peat deposits as well as other organic-rich geologic units, including wetland, lake, tideflat, and Vashon recessional lake deposits.

Follow-up work completed in June 2007 refined the earlier map and identified discrete bogs. This 2007 map, City of Seattle Identified Bogs, dated June 19, 2007, relied on 34,909 data points. The map shows both discrete bogs and individual borings/data points that indicate a presence of peat in the subsurface. This analysis summarized each of the peat deposits based on four factors that indicate potential risk due to settlement: thickness of peat, depth to peat, depth to groundwater level, and location of groundwater level in relation to peat. This characterization provides a critical resource for determining where much of the City's peat settlement hazards exist. The map relies on available borehole data, geologic mapping, and geologic interpretation.

Another important study of peat settlement within Seattle is the Greenwood Subsurface Characterization Study (Shannon and Wilson, 2004). This study was commissioned by Seattle Public Utilities in response to acute settlement occurring in the neighborhood to determine underlying geologic conditions. The study developed a map that delineates the former peat bog area and identifies the depth and thickness of the peat throughout the area. Shannon and Wilson also tested the peat to determine the potential to re-introduce water into the substrata and placed monitoring devices in several locations for a long-term assessment of groundwater flows and levels in the area. The study concluded that settlement in the neighborhood was "likely the result of groundwater removal" occurring due to multiple factors including construction of impervious surface, diversion of stormwater, installation of the 1970s storm drain system, natural groundwater fluctuations, climate change, construction dewatering and permanent drainage systems in subsurface structures. Shannon and Wilson warned that the “continued groundwater removal and the removal of groundwater from other locations within the study area could contribute to additional or new settlement, and should be avoided where settlement could impact structures, utilities, roadways and other improvements.” (Shannon and Wilson, 2004)

Although not located within the Seattle city limits, Badger’s (2008) study of peat in the Mercer Slough bog in Bellevue presents keen insights into the engineering properties and peat settlement and lateral movement in deposits similar to those in Seattle.

5.4.3 Regulation of Peat Settlement-Prone Areas

Development in areas containing peat deposits can result in settlement where new structures or fill compress underlying peat soils or where modification of the groundwater table increases the effective pressure on underlying peat soils.

To avoid negative impacts from development, it is necessary to ensure both that new structures are designed to prevent or accommodate settlement and that they do not cause settlement off-site through modification of the groundwater table. Regulations should specifically seek to minimize modification of the existing groundwater regime because any modification of existing groundwater regime that removes or redirects groundwater even for a short period may lead to local groundwater depressions resulting in settlement. Alternatively, modifications of the groundwater table that increase groundwater levels, although they would not lead to settlement, may also be undesirable as they cannot significantly reverse previous settlement activity and may lead to flooding.

Determination of areas that should be included in potential regulations should consider all the variables impacting settlement potential discussed earlier, including geotechnical characteristics of the peat, peat thickness, existing pressure on the peat, potential changes in pressure on the peat (including groundwater levels), and historic loading of the peat. Within regulated areas, protections should be applied even where geotechnical explorations fail to reveal peat deposits on the site of a proposed development because peat deposits may be present on nearby parcels.

5.4.4 References

Badger, T.C., 2008, Peat Flow in Mercer Slough, Lake Washington, in Baum, R.L.; Godt, J.W.; Highland, L.M., editors, Landslides and Engineering Geology of the Seattle, Washington Area: Geological Society of America Reviews in Engineering Geology XX, p. 153-166.

Badger, T.C., 2008, *Peat Flow in Mercer Slough, Lake Washington*, in Baum, R.L, Godt, J.W., and Highland, L.M., editors, Landslides and Engineering Geology of the Seattle, Washington Area, Geological Society of America Reviews in Engineering Geology XX, p. 83-101.

Berry, P.L., and Vickers, B., 1975, *Consolidation of Fibrous Peat*, Journal of the Geotechnical Engineering Division, ASCE vol. 101, GT 8, August p. 741-753.

City of Seattle Peat Settlement Technical Review Committee, 2007, *Consensus Statements*.

Fox, P.J., et al., 1992, *C sub alpha/C sub c Concept Applied to Compression of Peat*, Journal of the Geotechnical Engineering Division, ASCE vol. 118, GT 8, August, p. 1256-1263.

Holtz, R. D. and Kovacs, W. D., 1981, *An Introduction to Geotechnical Engineering*, Prentice-Hall.

Landva, A.O., and Pheeney, P.E., 1980, *Peat Fabric and Structure*, Canadian Geotechnical Journal, vol. 17, no. 3, August, p. 416-435.

Montlake Landfill Work Group, 1999, *Montlake Landfill Information Summary*, January.

Rigg, George B., 1958, *Peat Resources of Washington*, State of Washington, Division of Mines and Geology Bulletin 44, State Printing Plant, Olympia, WA.

Shannon & Wilson, 2004, *Greenwood Subsurface Characterization Study: Seattle, Washington*, April 21.

Troost, Kathy, 2006, *Map of Organic-Rich Deposits in Seattle*, GeoMapNW, University of Washington, June 14.

Troost, Kathy, 2007, *City of Seattle Identified Bogs*, GeoMapNW, University of Washington, June 29.

Washington State Department of Transportation, 2006, *Publication M 46-03: Geotechnical Design Manual*, Environmental and Engineering Programs, State Materials Laboratory, Chapter 5, p. 21-22, December, <http://www.wsdot.wa.gov/fasc/EngineeringPublications/Manuals/GDM/GDM.htm>.

The original Peat ECA section was prepared by Brennon Staley, MUP in Urban Planning and edited by Susan Chang, Ph.D., P.E.

Technical Review Committee

Steve Erickson; Frosty Hollow Ecological Restoration
Steve Greene; HWA Geosciences
Thomas Kinney; HWA Geosciences
Kathy Troost; University of Washington, GeoMapNW
Mark Varljen; SCS Engineers

The section was updated by Bill Laprade, L.E.G. and Bill Perkins, L.E.G., P.E. of Shannon & Wilson Inc., in 2014.

5.5 Liquefaction-Prone Areas

5.5.1 Overview

Liquefaction occurs in relatively loose, cohesionless, saturated soils when these soils are temporarily transformed into a quicksand-like state, most commonly as a result of earthquake-induced ground shaking. Liquefaction occurs due to a build-up of excess pore water pressure in the soil during ground shaking. When subjected to ground shaking, the soil particles in a loose soil will tend to re-arrange into a dense or more compact condition, decreasing the amount of void space between the soil particles. If void spaces between the particles are filled with water (i.e., if the soil is saturated), the decrease in void space will increase the water pressure between the soil particles in the voids. As the water pressure in the voids (i.e., the pore water pressure) increases and approaches the pressure caused by the weight of the overlying soils, the soil in the zone of increased pore pressure loses most of its shear strength and is temporarily transformed into a quicksand-like condition.

Where the excess pore water pressure is relieved or vented at the ground surface, sand boils or “volcanoes” commonly develop as the fluidized sand and water is ejected on to the ground surface. The vented water may cause localized flooding, and the voids created by the vented sand may cause sinkholes nearby in addition to ground settlement that typically occurs as a result of the earthquake ground shaking.

The reduced shear strength of the liquefied soil can also result in permanent lateral ground displacements. Where the ground is level, the “crust” of non-saturated soil at the ground surface may crack, forming blocks that oscillate or jostle between each other. While there may not be any overall sense of permanent lateral ground displacement, the displacement between individual blocks may be several inches or feet. On sloping ground (slopes as little as 0.1%) or where a “free-face” is nearby, the soil may move as a lateral spread or flow failure down slope or toward the free-face, with permanent ground displacement up to several tens of feet.

5.5.1.1 Effects of Liquefaction

Structures or infrastructure located above or within liquefiable soils can be more susceptible to damage if liquefaction and its associated effects (loss of shear strength, bearing capacity failures, loss of lateral support, ground oscillation, lateral spreading, flow failure, etc.) are not considered in design. Historic types of failures due to liquefied soil include settlement and overturned buildings on shallow foundations (due to reduction in soil bearing capacity), broken piling and lateral and vertical displacement of buildings and bridges on deep foundations (due to loss of lateral support and lateral spreading), rise or floatation of buried structures such as tanks and tunnels, and damage to underground utilities and pavements (e.g., roads and airport runways).

Historically, earthquake-induced liquefaction and related ground failures have caused casualties and substantial property loss. For example, losses in excess of $800 million have been attributed to liquefaction-related ground failures during the 1964 Niigata, Japan Earthquake and over $200 million from the 1964 Great Alaskan Earthquake (Keefer, 1983). More recently, the 2010 Canterbury, New Zealand and 2011 Christchurch, New Zealand earthquakes resulted in substantial liquefaction-induced damage to the Central Business District of Christchurch and its eastern suburbs (Cubrinovsky et al., 2011).

5.5.1.2 Historic Liquefaction in Seattle

Liquefaction has occurred in Seattle in each of the largest historic earthquakes to affect the area (1949 Olympia, 1965 SeaTac, and 2001 Nisqually earthquakes). Chleborad and Schuster (1998) documented more than 26 instances of liquefaction, which typically resulted in differential settlement of buildings, lateral movement of bulkheads and bridge foundations, and cracking of basement walls. Most of the liquefaction and related damages occurred in the soils in the Duwamish River Valley. To a lesser extent, liquefaction and related damages occurred in other areas of the city in soils with high to moderate liquefaction potential.

The 2001 Nisqually earthquake resulted in significant damage from liquefaction-induced settlement in the Duwamish River Valley south of downtown Seattle (Bray et al., 2001 and Nisqually Earthquake Clearinghouse Group, 2001). Areas with liquefaction induced damage correlate well with mapped areas of liquefaction hazard in the City.

5.5.2 Liquefaction Studies

Geologic units that are moderately to highly susceptible to liquefaction typically include Holocene (less than about 10,000 years old) delta, estuarine, beach and lacustrine deposits and non-engineered artificial fills (Youd and Perkins, 1978). The U.S. Geological Survey conducted analytical studies of the liquefaction potential of these soil types in the Seattle area (Grant et al., 1998). The study determined that the artificial fills and Holocene alluvium in the Duwamish River Valley are highly susceptible to liquefaction. While not as susceptible to liquefaction, this study determined that the liquefaction potential of the Holocene alluvium, lacustrine and beach deposits and artificial fill elsewhere in the city is significant. The results of the study were also used to assess the potential for lateral spreading for the soils identified as moderately to highly susceptible to liquefaction (Mabey and Youd, 1991).

The results of the Grant et al.(1998) study were incorporated into a liquefaction susceptibility map for Washington state published by the Department of Natural Resources (Palmer et al., 2004).

5.5.3 Regulation of Liquefaction-Prone Areas

Geotechnical engineering studies should be required of all proposed new development in areas subject to liquefaction to determine the physical properties of the surficial soils, especially the thickness of unconsolidated deposits, and their liquefaction potential. If it is determined that the site is subject to liquefaction, the effects of liquefaction on the site and the proposed development should be evaluated and mitigation measures should be recommended as needed. In addition, engineering studies should be carried out and engineering solutions, such as soil improvement or deep foundations, should be incorporated into project design.

More detailed studies and more extensive engineering solutions should be required in areas subject to high potential for liquefaction, and for critical and high occupancy facilities such as fire stations, hospitals, and high occupancy residential development.

5.5.4 References

Bray, J.D., Sancio, R.B., Kammerer, A., Merry, S., Rodriguez-Marek, A., Khazai, B., Chang, S., Bastani, A., Collins, B., Hausler, E., Dreger, D., Perkins, W.J., Nykamp, M., 2001, Some *Observations of Geotechnical Aspects of the February 28, 2001, Nisqually Earthquake in Olympia, South Seattle, and Tacoma, Washington*, report sponsored by the National Science Foundation, Pacific Earthquake Engineering Research Center, University of California at Berkeley, University of Arizona, Washington State University, Shannon & Wilson, Inc., and Leighton and Associates March 8, 2001 http://peer.berkeley.edu/publications/nisqually/geotech/index.html

Chleborad, A.F., and Schuster, R.L., 1998, *Ground failure associated with the Puget Sound region earthquakes of April 13, 1949, and April 29, 1965, in* Rogers, A.M., Walsh, T.J., and Priest, G.R., eds., Assessing earthquake hazards and reducing risk in the Pacific Northwest, Volume 2: U.S. Geological Survey Professional Paper 1560, p. 373-439.

M. Cubrinovski, R. Green, and L. Wotherspoon (editors). 2011, *Geotechnical Reconnaissance of the 2011 Christchurch, New Zealand Earthquake*, version 1, http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Christchurch_2011/Index_Christchurch_2011.html

Grant, W.P., Perkins, W.J., and Youd, T.L., 1998, *Evaluation of liquefaction potential in Seattle, Washington*, Rogers, A.M., Walsh, T.J., and Priest, G.R., eds., Assessing earthquake hazards and reducing risk in the Pacific Northwest, Volume 2: U.S. Geological Survey Professional Paper 1560, p. 441

Keefer, D.K., 1983, *Landslides, soil liquefaction, and related ground failures in the Puget Sound earthquakes, in* Yount, J.C., and Crosson, R.S., eds., Proceedings of Workshop XIV, Earthquake hazards of the Puget Sound region, Washington, October 13-15, 1980, Lake Wilderness, Wash.: U.S. Geological Survey Open-File Report 83-19, p. 280-299.

Mabey, M.A. and Youd, T.L., 1991, *Liquefaction Hazard Mapping for the Seattle, Washington Urban Region Using LSI (Liquefaction Severity Index)*. United States Geological Survey, Technical Report CEG-91-01.

Nisqually Earthquake Clearinghouse Group, 2001, *The Nisqually Earthquake of 28 February 2001, Preliminary Reconnaissance Report*, University of Washington, Seattle, WA. https://www.eeri.org/lfe/pdf/usa_nisqually_preliminary_report.pdf

Palmer, S.P., Magsino, S.L., Bilderback, E.L., Poelstra, J.L., Folger, D.S., and Niggemann, R.A., 2004, *Liquefaction Susceptibility and Site Class Maps of Washington State, By County*, Depart of Natural Resources Open File Report 2004-20. http://www.dnr.wa.gov/ResearchScience/Topics/GeologyPublicationsLibrary/Pages/pub_ofr04-20.aspx

Youd, T.L., and Perkins, D.M., 1978, *Mapping liquefaction-induced ground failure potential*, Journal of the Geotechnical Engineering Division, American Society of Civil Engineers, v. 104, no. GT4, p. 433-466.

5.6 Seismic Hazard Areas

5.6.1 Seattle Fault Zone

5.6.1.1 *Overview*

A fault is a fracture in the earth along which rock on one side has moved relative to that 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.

5.6.1.2 *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 buildings and 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.

5.6.1.3 *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 3 summarizes recent published studies with postulated proposed models of the Seattle Fault Zone available as of

December 2013. 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.

Work by Sherrod (2005), Sherrod et al. (2001), and Nelson et al. (2003a and 2003b) indicate that known active strands of the Seattle Fault in Bellevue, Bainbridge Island, and Point Glover Peninsula near Port Orchard 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 3: Recent references on geometry and structure of the Seattle Fault Zone

Factor	Finding	Source
Seattle Fault Zone	Identification of high-angle, oblique fault systems crossing the Seattle Fault Zone and basin.	Mace and Keranen, 2012

geometry	Characterization of the Seattle Fault Zone east of Lake Washington based on seismic reflection data. East of Lake Washington, the data does not support a passive-roof duplex model of Brocher et al (2004). Data suggest a north-verging thrust fault with a blind tip beneath the deformation front, a forelimb breakthrough, and a large backthrust.	Liberty and Pratt, 2008
	Fault subsurface structure imaged. 40-degree south dipping fault plane in the upper 5km of the crust.	Fisher, et al., 2005
	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 a cluster of 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. No data to indicate fault rupture for 12,000 years prior to the 1000-2500 yr ago cluster. 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., 2003b
	Three trenches excavated across 1- to 5-m high Holocene fault scarps showing surface faulting and folding events as recent as approximately 1000 yr ago.	Nelson et al., 2003a

	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

5.6.1.4 *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).

An interactive Quaternary fault map of the State of Washington has been compiled by the U.S. Geological survey. It can be found at the following address: http://earthquake.usgs.gov/hazards/qfaults/wa/.

5.6.1.5 *References*

Atwater, B.F., 1999, *Radiocarbon dating of a Seattle earthquake to AD 900-930*, Seismological Research Letters, v. 70, p. 232.

Atwater, B.F., and Moore, A.L., 1992, *A tsunami about 1000 years ago in Puget Sound Washington*, Science, December 4.

Blakely, R.J., Wells, R.E., Weaver, C.S., and Johnson, S.Y., 2002, *Location, structure, and seismicity of the Seattle fault zone, Washington: Evidence from aeromagnetic anomalies, geologic mapping, and seismic reflection data*, GSA Bulletin, vol. 114 no. 2, p. 169-177, February.

Booth, D.B., Troost, K.G., and Shimel, S.A., 2003, *Landfall of the Seattle Fault Zone, West Seattle, WA*: Abstracts with Program, Geological Society of America, Annual Meeting, Seattle, November 2-5, 2003, p.479.

Brocher, T.M., Blakely, R.J., and Wells, R.E., 2004, *Interpretation of the Seattle Uplift, Washington as Passive-Roof Duplex*, Bulletin of the Seismological Society of America, vol. 94, no. 4, 1379-1401.

Brocher, T.M., Parsons, T., Blakely, R.J., Christensen, N.I., Fisher, M.A., Wells, R.E., and the SHIPS Working Group, 2001, *Upper crustal structure in Puget Lowland, Washington: Results from the 1998 Seismic Hazards Investigation in Puget Sound*, Journal of Geophysical Research, vol. 106 no. 7, p. 13541-13564, July.

Bucknam, R.C., Hemphill-Haley, E., and Leopold, E.B., 1992, *Abrupt uplift within the past 1700 years at southern Puget Sound, Washington*, Science, v. 258, p. 1611-1614.

Calvert, A.J., Fisher, M.A., and Johnson, S.Y., 2003, *Along-strike variations in the shallow seismic velocity structure of the Seattle fault zone: Evidence for fault segmentation beneath Puget Sound*, Journal of Geophysical Research, vol. 108 no. B1.

Danes, Z.F., and nine others, 1965, *Geophysical investigations of the southern Puget Sound area, Washington*: Journal of Geophysical Research, v. 70, p. 5573-5579.

Earthquake Engineering Research Institute (EERI) and Washington Military Department Emergency Management Division, 2005a, *Scenario for a Magnitude 6.7 earthquake on the Seattle Fault*, Mark Stewart, editor.

Earthquake Engineering Research Institute (EERI) and Washington Military Department Emergency Management Division, 2005b, *Scenario for a Magnitude 6.7 earthquake on the Seattle Fault*, scenario presentations available from http://seattlescenario.eeri.org/documents.php, downloaded on January 29, 2007.

Frankel, A.F., 2007, personal communication.

Harding, D.J., Johnson, S.Y., and Haugerud, R.A., 2002, *Folding and rupture of an uplifted Holocene marine platform in the Seattle Fault Zone, Washington, revealed by airborne laser swath mapping*, abstract, GSA Cordilleran Section Meeting.

Johnson, S. Y., Potter, C. J., and Armentrout, J. M., 1994, *Origin and evolution of the Seattle fault and Seattle basin, Washington*, Geology, v. 22, p. 71-74.

Johnson, S.Y., Blakely, R.J., Stephenson, W.J., and Dadisman, S.V., 2004, *Active shortening of the Cascadia forearc and implications for seismic hazards of the Puget Lowland*, Tectonics, v. 23, TC1011.

Johnson, S.Y., Dadisman, C.V., Childs, J.R., and Stanley, W.D., 1999, *Active tectonics of the Seattle fault and central Puget Sound, Washington—implications for earthquake hazards*: Geological Society of America Bulletin, v. 111, no. 7, p. 1042-1053.

Liberty, L. M. and Pratt, T. L., 2008, Structure of the eastern Seattle fault zone, Washington State: new insights from seismic reflection data: Bulletin of the Seismological Society of America, v. 98, no. 4, p. 1681-1695.

Mace, C. G. and Keranen, K. M., 2012, Oblique fault systems crossing the Seattle basin--Geophysical evidence for additional shallow fault systems in the central Puget Lowland: Journal of Geophysical Research, v. 117, no. B3, 19 p.

Nelson, A. R.; Johnson, S. Y.; Wells, R. E. and others, 2003a, Field and laboratory data from an earthquake history study of the Waterman Point Fault, Kitsap County, Washington: U.S. Geologic Survey Miscellaneous Field Studies Map MF-2423, 11 p., 1 sheet, scale 1:3,000, available: http://pubs.usgs.gov/mf/2003/mf-2423/.

Nelson, A.R., Johnson, S.Y., Kelsey, H.M., Wells, R.E., Sherrod, B.L., Pezzopane, S.K., Bradley, L., Koehler, R.D., and Bucknam, R.C., 2003b, *Late Holocene earthquakes on the Toe Jam Hill fault, Seattle fault zone, Bainbridge Island, Washington*, Geological Society of America Bulletin, 115, 1388-1403.

Pratt, T.L., Johnson, S.Y., Potter, C., Stephenson, W, and Finn, C., 1997, *Seismic reflection images beneath Puget Sound, western Washington state: The Puget Lowland thrust sheet hypothesis*, Journal of Geophysical Research, v. 102, p. 27469-27489.

Sherrod, B.L., Haeussler, P.J., Wells, R., Troost, K., and Haugerud, R., 2001, *Surface rupture in the Seattle fault zone near Bellevue, Washington*, Seismological Research Letters, v.72, no. 2, p. 253.

Sherrod, B.L., 2002, *Late Quaternary surface rupture along the Seattle fault zone near Bellevue, Washington*: EOS (Transactions, American Geophysical Union), v.83 (47), abstract S21C-12.

Sherrod, B.L., 2005, *Prehistoric earthquakes in the Puget Lowland, Washington*: EOS (Transactions, American Geophysical Union), Fall Meeting abstract S54A-05.

ten Brink, U.S., Song, J., and Bucknam, R.C., 2006, *Rupture models for the A.D. 900-930 Seattle fault earthquake from uplifted shorelines*, Geology, v. 34, no. 7, p. 585-588, July.

Troost, K.G., Booth, D.B., Wisher, A.P., and Shimel, S.A., 2005, *The geologic map of Seattle, a progress report*, U.S. Geological Survey, Open-file report 2005-1252, scale 1:24,000.

Troost, K.G., 2007, personal communication

U.S. Conference on Lifeline Earthquake Engineering, “How Vulnerable are Seattle Area Lifelines?”

Washington State, Military Department, Emergency Management Division, *Washington State Hazard Mitigation Plan*, July 2004, http://emd.wa.gov/6-mrr/mit-rec/mit/mit-pubs-forms/hazmit-plan/hazmit-plan-idx.htm (12 January 2007).

Yount, J. C., and Gower, H. D., 1991, Bedrock geologic map of the Seattle 30' by 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 91-147, scale 1:100,000.

5.6.2 Tsunami Inundation Areas

5.6.2.1 *Overview*

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).

5.6.2.2 *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.

5.6.2.3 *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 4.

Table 4: Recent tsunami studies for the Seattle area

Factor	**Finding**	**Source**
Tsunami	Tsunami inundation map based upon the modeling by Titov et al., 2003 for rupture on the Seattle Fault Zone.	Walsh et al., 2003

inundation studies for Seattle Fault Zone earthquake	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

5.6.2.4 *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.

5.6.2.5 *References*

Atwater, B.F., and Moore, A.L., 1992, *A tsunami about 1000 years ago in Puget Sound Washington*, Science, December 4.

Bucknam, R.C., Hemphill-Haley, E., and Leopold, E.B., 1992, *Abrupt uplift within the past 1700 years at southern Puget Sound, Washington*, Science, v. 258, p. 1611-1614.

Geist, E.L. 2005, *Local tsunami hazards in the Pacific Northwest from Cascadia Subduction Zone earthquakes, in Earthquake Hazards of the Pacific Northwest Coastal and Marine Regions*, Robert Kayen editor, U.S. Geological Survey Professional Paper 1661-B.

Karlin, R.E., Holmes, M., Abella, S.E.B., and Sylwester, R., 2004, *Holocene landslides and a 3500-year record of Pacific Northwest earthquakes from sediments in Lake Washington*, Geological Society of America bulletin, v. 116, n. 1-2, p. 94-108.

Kayen, R.E., Barnhardt, W.A., and Palmer, S.P., 1999, *Geomorphological and geotechnical issues affecting the seismic slope stability of the Duwamish river delta, Port of Seattle, Washington*, in W.M. Elliott and P. McDonough, eds., Optimizing Post-Earthquake Lifeline System Reliability, American Society of Civil Engineers, Lifeline Earthquake Engineering Monograph No. 16, p. 482-492.

Koshimura, S. and Mofjeld, H.O., 2001, *Puget Sound Tsunami Inundation Modeling Preliminary Report: Phase 2*, PMEL/NOAA, Tsunami Research Program, Center for TIME, http://nctr.pmel.noaa.gov/pugetsound/pre2 (accessed January 12, 2007).

Koshimura, S., Mofjeld, H.O., Gonzalez, F.I., and Moore, A.L, 2002, *Modeling the 1100 bp paleotsunami in Puget Sound, Washington*, Geophysical Research Letters, v. 29, n. 20, p. 1948.

Lander, J., Lockridge, P., and Kozuch, M., 1993, *Tsunamis Affecting the West Coast of the United States, 1806-1992*, Out of Print.

Murty, T.S. and Hebenstreit, G.T. (1989), *Tsunami amplitudes from local earthquakes in the Pacific Northwest region of North America, Part 2: Strait of Georgia, Juan de Fuca Strait, and Puget Sound*, Mar. Geodesy *13*, 189–209

National Oceanic and Atmospheric Administration, “NOAA and Tsunamis”, *National Tsunami Hazard Mitigation Project*, http://www.publicaffairs.noaa.gov/grounders/tsunamis.html (accessed January 21, 2007).

National Oceanic and Atmospheric Administration, Pacific Marine Laboratory, “Tsunamis: Frequently Asked Questions”, *NOAA Center for Tsunami Research*, http://nctr.pmel.noaa.gov/faq.php (accessed January 19, 2007).

National Oceanic and Atmospheric Administration, National Tsunami Hazard Mitigation Program Center for Tsunami Inundation Mapping Efforts, 2003, *Puget Sound Tsunami Sources—2002 Workshop Report*, Frank I. Gonzalez, compiler.

Palmer, S., 2005, *Submarine Landslides in Commencement Bay* in: Troost, K., Hopkins, T., Palmer, S., Sherrod, B., and Wells, R., 2005, Coastal geology of Tacoma, Fieldtrip Guidebook, 5th Washington Hydrogeology Symposium, April 13, 2005, Tacoma, WA.

ten Brink, U.S., Molzer, P.C., Fisher, M.A., Blakely, R. J., Bucknam, R.C., Parsons, T., Crosson, R.S., and Creager, K.C., 2002, *Subsurface geometry and evolution of the Seattle fault zone and the Seattle Basin, Washington*, Bulletin of the Seismological Society of America, June 2002, v. 92, n. 5, p.1737-1753.

ten Brink, U.S., Song, J., and Bucknam, R.J., 2006, *Rupture Models for the A.D. 900-930 Seattle fault earthquake from uplifted shorelines*, Geology, v. 34, p.585-588.

Titov, V.V., Gonzalez, F.I., Mofjeld, H.O., and Venturato, A.J., 2003, *NOAA TIME Seattle Tsunami Mapping Project: Procedures, Data Sources, and Products*, NOAA Technical Memorandum OAR PMEL-124.

Walsh, T.J., 2007, personal communication, January 2007.

Walsh, T.J., Caruthers, C.G., Heinitz, A.C., Myers III, E.P., Baptista, A.M., Erdakos, B.G., and Kamphaus, R.A, 2000, *Tsunami hazard map of the southern Washington coast: Modeled tsunami inundation from a Cascadia Subduction Zone Earthquake, Washington,* Division of Geology and Earth Resources, Geologic Map GM-49.

Walsh, T.J., Titov, V.V., Venturato, A.J., Mofjeld, H.O., and Gonzalez, F.I., 2003, *Tsunami hazard map of the Elliott Bay area, Seattle, Washington: Modeled tsunami inundation from a Seattle Fault earthquake*, Washington State Department of Natural Resources and National Oceanic and Atmospheric Administration. Washington Division of Geology and Earth Resources Open File Report 2003-14.

Washington State. Military Department. Emergency Management Division. 2004, *Washington State Hazard Mitigation Plan*. July 2004. http://emd.wa.gov/6-mrr/mit-rec/mit/mit-pubs-forms/hazmit-plan/hazmit-plan-idx.htm (accessed January 12, 2007).

Whitmore, P. M., 1993, *Expected tsunami amplitudes and currents along the North American coast for Cascadia subduction zone earthquakes*, Natural Hazards, v. 8, p. 59-73.

Williams, H.F.L, Hutchinson, I., and Nelson, A.R., 2005, *Multiple sources for late Holocene tsunamis at Discovery Bay, Washington State, USA*, The Holocene, v. 15, n. 1, p. 60-73.

5.6.3 Seiches

5.6.3.1 *Overview*

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, 2008) 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.

5.6.3.2 *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.

5.6.3.3 *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 5: 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.

5.6.3.4 *Seiche Studies in Seattle*

A summary of findings from the most significant reviewed references is presented in Table 6.

Table 6: Recent seiche studies for the Seattle area

Report	Findings
Barberopoulou, 2006 and 2008	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.

5.6.3.5 *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.

5.6.3.6 *References*

Barberopoulou, Aggeliki, 2008, A seiche hazard study for Lake Union, Seattle, Washington: Bulletin of the Seismological Society of America, v. 98, no. 4, p. 1837-1848.

Barberopoulou, A, 2006, *Investigating the damage potential of seismic seiches: a case study of the Puget Lowland, Washington State,* [Ph.D. thesis]: University of Washington. Seattle, Washington.

Barberopoulou, A., Qamar, A., Pratt, T.L., Creager, K.C., and Steele W.P., 2004, *Local amplification of seismic waves from the Mw7.9 Alaska earthquake and damaging seiches in Lake Union, Seattle, Washington*, Geophysical Research Letters, v. 31.

Karlin, R.E., and Abella, S.E.B., 1992, Paleoearthquakes in the Puget Sound region recorded in sediments from Lake Washington, U.S.A.: Science, v. 258, p. 1617-1620.

Karlin, R.E., Holmes, M., Abella, S.E.B., and Sylester, R., 2004, *Holocene landslides and a 3500-year record of Pacific Northwest earthquakes from sediments in Lake Washington,* GSA Bulletin, v. 116, no. ½, p. 94-108.

King County Office of Emergency Management, 2005, *Regional Hazard Mitigation Plan*, December 15th, http://www.metrokc.gov/prepare/kcrhmp (downloaded January 12, 2007).

Lander, J.F., P.A. Lockridge, and M.J. Kozuch,1993, *Tsunamis Affecting the West Coast of the United States 1806-1992*, National Geophysical Data Center Key to Geophysical Record Documentation No. 29.

Malone, S.D., Crosson, R.S., Creager, K.C., Qamar, A., Thomas, G.C., Ludwin, R., Troost, K.G., Booth, D.B., and Haugerud, R.A., 2001, *Preliminary report on the MW=6.8 Nisqually, Washington earthquake of 28 February 2001,* Seismology Research Letters, v. 72, p. 353-362.

McGarr, A. and Vorhis, R. C., 1968, *Seismic Seiches from the March 1964 Alaska Earthquake,* USGS Professional Paper 544E, E1-E43.

Pratt, Thomas L., Brocher, Thomas M., Weaver, Craig S., Creager, Kenneth C., Snelson, Catherine M., Crosson, Robert S., Miller, Kate C., and Tre´hu, Anne M., 2003, *Amplification of Seismic Waves by the Seattle Basin, Washington State*, Bulletin of the Seismological Society of America, v. 93, n. 2, p. 533–545, April 2003.

Washington State, Military Department, Emergency Management Division, Washington State Hazard Mitigation Plan, July 2004, http://emd.wa.gov/6-mrr/mit-rec/mit/mit-pubs-forms/hazmit-plan/hazmit-plan-idx.htm (accessed January 12, 2007).

Wilson, B. W.; Torum, A. F., 1972, *Effects of the tsunamis-An engineering study*, In National Research Council Committee on the Alaska Earthquake, 1972, The great Alaska earthquake of 1964- Oceanography and coastal engineering, National Academy of Sciences, Washington, D.C., p. 361-523.

5.7 Volcanic Hazard Areas

5.7.1 Lahar Hazard Zones

5.7.1.1 *Overview*

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.

5.7.1.2 *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.

5.7.1.3 *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.

5.7.1.4 *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.

5.7.1.5 *References*

Dragovich, J.D., Pringle, P.T., and Walsh, T.J., 1994, *Extent and geometry of the mid-Holocene Osceola Mudflow in the Puget Lowland: Implications for Holocene sedimentation and paleogeography*: Washington Geology, v. 22, p. 3-26.

Pringle, P.T., 1994, *Volcanic Hazards in Washington--A Growth Management Perspective*, Washington Geology, v. 22, n. 2, July.

Hoblitt, R.P., Walder, J.S., Driedger, C.L., Scott, K.M., Pringle, P.T., and Vallance, J.W., 1998, *Volcano Hazards from Mount Rainier, Washington*, U.S. Geological Survey Open-File Report 98-428.

United States Geological Survey, "Fact Sheet on Mount Rainier", United States Geological Survey website, http://pubs.usgs.gov/fs/2002/fs034-02/ (accessed January 21, 2007).

Vallance, J.W. and Scott, K.M., 1997, *The Osceola mudflow from Mount Rainier: Sedimentology and hazard implications of a huge clay-rich debris flow*, GSA Bulletin, v. 109, n. 2, p. 143-163, February.

Vallance, J.W., 2000, *Lahars*: in Sigurdsson, H., Houghton, B., McNutt, S., Rymer, H., and Stix, J., Encyclopedia of Volcanoes, Academic Press, San Diego, p. 601-616.

Vallance, J.W., Cunico, M.L., and Schilling, S.P., 2003, *Debris-flow hazards caused by hydrologic events at Mount Rainier, Washington*, U.S. Geological Survey Open File Report 03-368.

Washington State, Military Department, Emergency Management Division, *Washington State Hazard Mitigation Plan*. July 2004. http://emd.wa.gov/6-mrr/mit-rec/mit/mit-pubs-forms/hazmit-plan/hazmit-plan-idx.htm (accessed January 12, 2007).

Zehfuss, P.H., 2005, *Distal records of sandy Holocene lahars from Mount Rainier, Washington*, [Ph.D. thesis]: University of Washington, Seattle, WA.

Zehfuss, P.H., Atwater, B.F., Vallance, J.W., Brenniman, H., and Brown, T.A., 2003, *Holocene lahars and their by-products along the historical path of the White River between Mount Rainier and Seattle,* in Swanson, T.W., ed., Western Cordillera and adjacent areas, Boulder, Colorado, Geological Society of America Field Guide 4, p. 209-223.

The Seismic Hazard Areas sections were prepared by Susan Chang Ph.D. in Civil Engineering, P.E. and Brennon Staley MUP in urban planning, and reviewed by Dr. Kathy Troost, research scientist in Earth and space sciences, University of Washington. The section was updated in 2014 by William J. Perkins, L.E.G., P.E., and reviewed by Susan Chang, Ph.D., P.E.