Liquefaction Susceptibility of the Greater Eastside Area, King County, Washington

by Stephen P. Palmer,
Brian D. Evans,
and Henry W. Schasse

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Geologic Map GM-48
August 2002

The information provided in this map cannot be substituted for a site-specific geotechnical investigation, which must be performed by qualified practitioners and is required to assess the potential for and consequent damage from soil liquefaction.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
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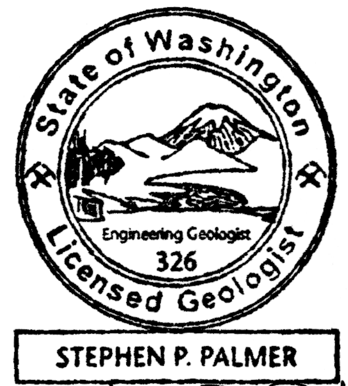

Stephen P. Palmer
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INTRODUCTION

The Washington Division of Geology and Earth Resources is actively investigating earthquake hazards statewide and has concentrated part of its technical program on mapping deposits in the Puget Sound region that are susceptible to seismically induced soil liquefaction.

Liquefaction occurs when water-saturated sandy soil loses strength during severe shaking such as that generated by an earthquake. Below the ground-water table, the pore space between sand grains is filled with water, and the weight of the overlying soil mass is ordinarily supported by grain-to-grain contact. Strong shaking during a large earthquake can disrupt the grain-to-grain contact, causing a decrease in the grain support. If strong shaking lasts long enough, the grain structure of a loose sandy soil may completely collapse. When the grain contact support is lost, the pore-water pressure must increase to account for the stresses imposed by the weight of the overlying soil. At this point, the sandy soil is liquefied and will temporarily behave as a viscous fluid, causing an immediate loss of soil strength. The liquefied soil may then be subject to extreme lateral deformation because it does not provide much resistance to horizontal forces. Such lateral spreading of the soils within and above the zone of liquefaction can cause tremendous damage to buildings and buried utilities located within the moving soil mass. The collapse of the grain structure can result in settlement of the soil column and loss of weight-bearing capacity which may cause severe damage to structures. The buoyant forces within a liquefied soil mass can cause flotation of underground tanks, pilings, and other buried structures.

This report presents the technical evaluation used in generating the accompanying liquefaction susceptibility map of the Greater Eastside area of King County, Washington. The study area (Fig. 1) consists of the Redmond, Kirkland, Issaquah, and Mercer Island 7.5-minute quadrangles. The map is intended to provide building officials, land-use planners, emergency-response personnel, engineering consultants, building owners, developers, insurance providers, and private citizens with an estimate of the likelihood the soil will liquefy as a result of strong earthquake shaking. This study is based on available geologic mapping at 1:24,000 scale (1 in. = 2000 ft, or 1 cm = 240 m) and the analysis of 668 geotechnical borings obtained from the Washington State Department of Transportation and local government agencies. Six categories of geologic deposits found in the study area are assigned a relative liquefaction hazard ranking (ranging from very low to high) determined through analysis of the geotechnical data and geological characterization. Areas mapped as Holocene peat and Tertiary bedrock, not included in the quantitative liquefaction analysis, are shown on the map.

Because of the regional nature of this map, we delineate only generalized areas prone to liquefaction and assign only a relative susceptibility to these areas. *This map cannot be used to determine the presence or absence of liquefiable soils beneath any specific locality*. Likewise, we present no estimate of the damage resulting from liquefaction; in many instances, liq-

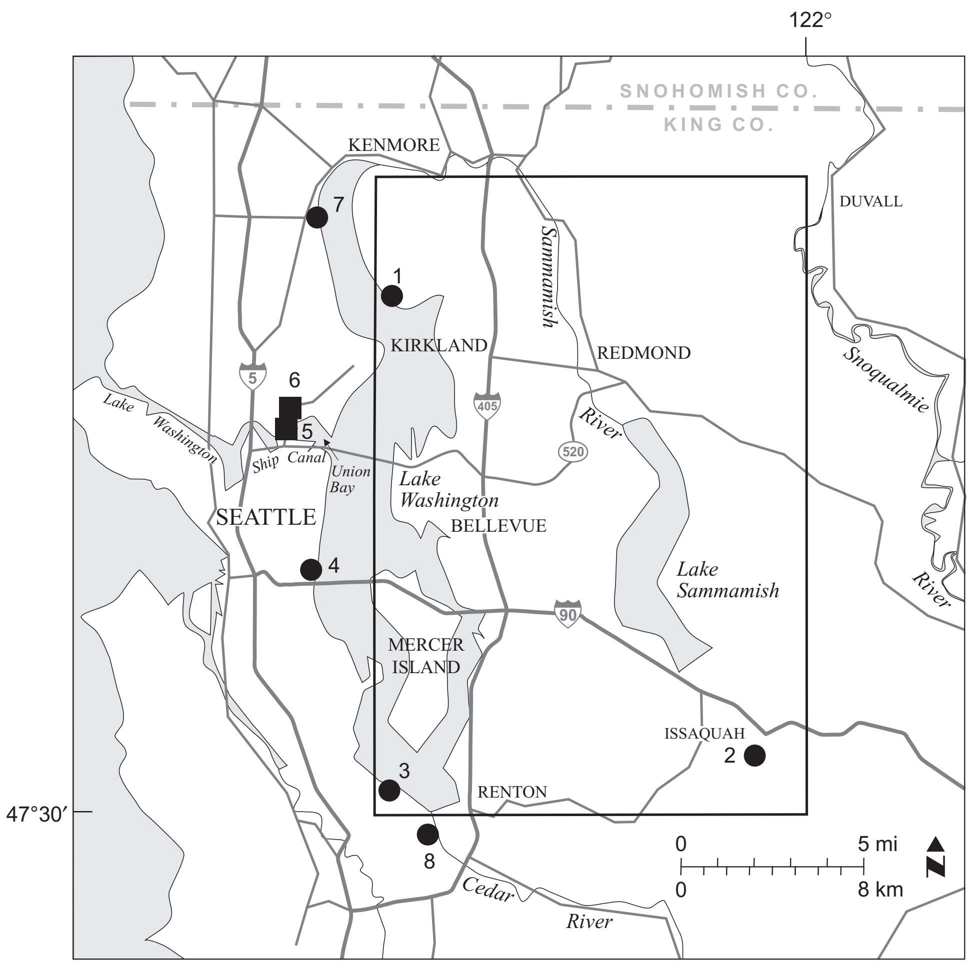

Figure 1. Location map of the Greater Eastside study area showing sites of ground failures that occurred during the 1949 Olympia or 1965 Seattle–Tacoma earthquakes and their corresponding identification numbers (Tables 2 and 3). The black rectangle outlines the study area. Filled squares are sites where the ground failures definitely resulted from liquefaction, and filled circles are sites where liquefaction may have occurred.

uefaction may occur without causing significant ground displacement and consequent damage to structures.

This map cannot be substituted for a site-specific geotechnical investigation, which must be performed by qualified practitioners and is required to assess the potential for liquefaction and consequent damage at a given locality.

SUMMARY OF RESULTS

A moderate to high liquefaction susceptibility is assigned to artificial fill and recent (mid- to late Holocene) lake and stream deposits in the vicinity of the city of Issaquah and along the Lake Washington and Lake Sammamish shorelines. A low to moderate liquefaction susceptibility is assigned to areas underlain by Holocene river and stream deposits in the Sammamish River valley and Bear and Evans Creek tributaries, landslide debris and thick soil (colluvial and alluvial fan) deposits typically found at the base of steep slopes and drainages, and sandy outwash from the recession of the latest Pleistocene continental glaciation (~13,000 years ago). Quantitative evaluation of geotechnical data obtained from all other Pleistocene deposits indicates a very low susceptibility to liquefaction. Peat deposits cannot liquefy, but may be subject to significant vertical settlement caused by ground shaking (termed 'dynamic compaction'). Also, sand layers interbedded with the peat deposits, such as those along the margins of Mercer Slough, may be liquefiable. Bedrock is not susceptible to liquefaction, but unmapped deposits of fill or thick soils overlying bedrock may be liquefiable.

GEOLOGIC MAPPING OF THE GREATER EASTSIDE AREA

For this study, Minard and Booth (1988), Minard (1983), and Booth and Minard (1992) were the primary sources of 1:24,000-scale geologic mapping of the Redmond, Kirkland, and Issaquah 7.5-minute quadrangles, respectively. This mapping was revised by Booth and incorporated in a digital geologic coverage of King County compiled by the King County Geographic Information Systems Center. This digital coverage also included 1:24,000-scale geologic mapping for the Mercer Island 7.5-minute quadrangle, and was the primary source of geologic mapping used in producing the liquefaction hazard map. We made minor revisions to these map data, including generalization of stratigraphic unit designations presented in these various sources, as shown in Table 1.

We subdivided recessional outwash deposits of the Vashon Stade of the Fraser Glaciation into two textural units: unit Qvrc, which is primarily composed of gravel and sand, and unit Qvrs, which is primarily composed of sand and silt. This textural breakdown was required because previous analyses and historic performance indicate that unit Qvrs deposits are potentially susceptible to liquefaction, especially in areas with a shallow ground-water table (Palmer and Moses, 1996; Palmer and others, 1995, 1999). Sandy Vashon recessional outwash deposits (unit Qvrs) were identified using U.S. Department of Agriculture Soil Conservation Service (now Natural Resource Conservation Service) soil maps for the King County area (Snyder and others, 1973). Digital geologic and agricultural soil coverages were superimposed in order to identify areas of silty or sandy loams falling within areas of Vashon recessional outwash; these areas were assigned to the stratigraphic unit Qvrs. Similarly, areas of gravelly loams falling within Vashon recessional outwash were assigned to unit Qvrc. Field checking at spot locations and review of water well and geotechnical boring logs confirmed that this approach was reasonably accurate in mapping soil texture within the Vashon recessional outwash.

As a result of the construction of the Lake Washington Ship Canal in 1916, the mean water elevation of the lake was lowered by 8.8 ft (2.7 m). The lowered water level exposed near-

Table 1. Correlation of units from geologic mapping of the Redmond (Minard and Booth, 1988), Kirkland (Minard, 1983), Issaquah (Booth and Minard, 1992), and Mercer Island 7.5-minute quadrangles. Digital map coverage for the Mercer Island quadrangle was obtained from the King County Geographic Information Systems Center

Description of unit	Units on 7.5-minute quadrangles				Generalized unit
	Redmond	Kirkland	Issaquah	Mercer Is.	
Modified land, including artificial fill		ml	m	m	ml
Holocene alluvium (younger)	Qyal	Qyal	Qyal	Qyal	Qal
Holocene alluvium (older)	Qoal	Qoal	Qoal		Qal
Holocene alluvial fan	Qaf		Qf	Qf	Qmw
Holocene colluvium	Qc				Qmw
Holocene mass wasting	Qmw		Qmw		Qmw
Holocene landslide	Qls	Qls			Qmw
Holocene swamp or wetland	Qsw		Qw	Qw	Qp
Vashon recessional outwash	Qvr, Qvry, Qvrc, Qvrb, Qvrd	Qvr	Qvr, Qvr_5, Qvr_4, Qvr_3, Qvr_2, Qvr_1	Qvr, Qvrl	Qvrs, Qvrc
Vashon kame terrace or ice-contact deposits	Qvrk		Qvi, Qvi_5, Qvi_4, Qvi_3, Qvi_2, Qvi_1		Qvik
Vashon older recessional outwash	Qvro				Qvrs, Qvrc
Vashon till	Qvt	Qvt	Qvt	Qvt	Qvt
Vashon advance outwash	Qva	Qva	Qva	Qva	Qva
Fraser glaciation and Olympia interglacial transitional beds	Qtb	Qtb	Qtb	Qtb	Qtob
Olympia interglacial beds	Qob	Qog	Qob		Qtob
pre-Fraser glacial deposits		Qtu	Qpf	Qpf	Qu
Thin Vashon till on bedrock			br+Qvt		Qvt
Tertiary sedimentary rock	Ts		Tsc, Tb, Tr, Tt	Tsc, Tb, Tpr, Tpt	Ts
Tertiary volcanic rock			Tv		Tv
Tertiary intrusive rock			Ti		Ti

shore beach platforms and drained a number of fresh-water marshes and sloughs. These areas were then subject to development, mainly in the form of lakefront residences and roadways. The primary 1:24,000-scale geologic maps used in this study did not map these exposed beach platforms and fill areas. Consequently, 1:24,000-scale published mapping of the pre–Ship Canal shoreline and historical wetlands provided by Chrzastowski (1983) was used in identifying these areas. The modern marine and lake shorelines were extracted from Washington Department of Natural Resources hydrographic and hydrologic map data sources.

HISTORIC LIQUEFACTION IN THE GREATER EASTSIDE AREA

The two largest earthquakes in recent historic times in the Puget Sound region are the 1949 Olympia earthquake, with a surface-wave magnitude (M_s) of 7.1, and the 1965 Seattle–Tacoma earthquake, with a body wave magnitude (m_b) of 6.5. Significant portions of the study area were exposed to Modified Mercalli Intensity VII shaking during these events (Murphy and Ulrich, 1951; Roberts and Ulrich, 1951; von Hake and Cloud, 1967). The most thorough documentation of liquefaction-induced ground failures during these earthquakes is presented in Hopper (1981) and Chleborad and Schuster (1998). There were no occurrences of sand boils or other unequivocal evidence of liquefaction in the study area during the 1949 and 1965 earthquakes. However, three sites of ground deformation that may represent surface expression of liquefaction of the underlying soil are located within the study area. Locations of these sites are shown in Figure 1, and descriptions of the ground deformation and earthquake effects are presented in Table 2.

The description given for site 1 (Table 2) at Champaign Point clearly indicates lateral as well as vertical displacement of the shallow soil column. Bathymetric data (U.S. Geological Survey and U.S. National Ocean Service, 1982) indicate that at Champaign Point, the lake bottom has an average slope gradient of 20 percent as measured from the shoreline to the deepest portion of the lake adjacent to the point (water depth of 157 ft [48 m]). The description given for site 3 (Table 2) also indicates lateral displacement as well as vertical settlement. Bathymetric data (U.S. Geological Survey and U.S. National Ocean Service, 1983) indicate that the lake bottom adjacent to the site has an average slope gradient of approximately 6 percent as measured from the shoreline to the 33 ft (10 m) water-depth contour. Landsliding on such shallow slopes, particularly at site 3, strongly indicates that cyclic weakening of the lake bottom soils was an important factor in causing the instability. Damage to the brick school buildings documented at site 2 (Table 2) can be explained by the response of these old, unreinforced masonry structures to the strong ground shaking caused by the 1965 earthquake. The broken concrete walkways indicate ground settlement in the vicinity of the buildings, which may be a manifestation of liquefaction of the underlying soil.

Observation of sand and water venting at ground surface (sand blows) is the only unequivocal evidence of liquefaction of the underlying soil column. No sand blows were reported at or near sites 1, 2, and 3 (Table 2); consequently, liquefaction at these sites is a permissible, but not required, explanation of the observed ground deformation. Additional sites of ground failures and liquefaction that occurred within Lake Washington shoreline deposits (Figure 1) but fall outside of the study area are presented in Table 3. The ejection (venting) of sand reported at sites 5 and 6 is unequivocal evidence that liquefaction occurred at these locations. Consideration of all of the ground failures reported in Tables 2 and 3 indicates that liquefaction clearly occurred in the lake deposits exposed as a result of the construction of the Lake Washington Ship Canal.

LIQUEFACTION EVALUATION OF THE GREATER EASTSIDE AREA

The method of analysis used in this study generally follows that used in several previously published liquefaction susceptibility maps for the Puget Sound region (for example, Grant and others, 1998; Palmer, 1995; Palmer and others, 1994, 1995, 1999; Shannon & Wilson, Inc., 1993). We determined the potential for soil liquefaction based on the field evaluation methodology developed by Seed and Idriss (1971) and Seed and others (1983, 1985). We incorporated the modifications to this methodology presented in Youd and others (1997).

Table 2. Descriptions of ground deformation that could be related to liquefaction that occurred within the study area during the 1949 Olympia and 1965 Seattle–Tacoma earthquakes. Site numbers refer to locations shown in Figure 1

Site no.	Reference	Location [earthquake]	Description
1	Hopper (1981); Chleborad and Schuster (1998), location no. 35	Champaign Point, Lake Washington, King Co., Wash. [1949]	"Point moved toward lake; moved rail fence west; dock dropped...This earthquake was felt strongly...over an area of 3 lots located on Champaign Point. Other residents in the neighborhood recorded no damage. Champaign Point is across the lake from the northern end of Sand Point. The cracks in cement have become wider since the shock, and we have noticed occasional creakings in the house (wood) since the 13th. In the front of the house deep cracks in the earth appeared next to the basement walls, and water pipes were broken in the sprinkling system from the lake. The basement floor was cracked and two small cement retaining walls dropped several inches."
2	von Hake and Cloud (1967)	Issaquah, Wash. [1965]	"Both of the old, 2- and 3-story, brick junior high schools were extensively damaged. There were long jagged cracks in the exterior and interior walls. Daylight could be seen through some of the cracks. At ground level there were long, broken separations in concrete walkways."
3	Chleborad and Schuster (1998), location no. 4	Seattle, Wash. [1949 and 1965]	"Quake opens 6 inch [15 cm] cracks in yard...house sank 4 inches [10 cm]." "Similar damage [to that in the 1949 earthquake] occurred as a result of the 1965 earthquake. Cracks appeared in the basement and the dock separated. House next door had settling and yard cracks in the 1949 and 1965 quakes. The area was once the site of the old Taylor Sawmill." (Hale Lowry, oral commun., 1988)

The Seed and Idriss procedure uses standard penetration test (SPT) N-values[1], sample descriptions, grain-size analyses, and ground-water depths obtained from geotechnical borings to estimate the factor of safety (ratio of resisting stresses to driving stresses) for a hypothetical earthquake with a specified magnitude and peak ground acceleration (PGA). Because this study was primarily concerned with evaluating liquefaction that could cause observable effects at the ground surface, the evaluation of liquefaction was limited to the upper 50 ft (15.2 m) of the borings. This depth restriction allows a direct comparison to historic reports of liquefaction exhibiting effects at the ground surface.

Seed and others (1985) noted that variation in drilling methods and sampling procedures used in geotechnical borings can significantly affect the measured SPT N-values and they recommended certain procedures in performing the test. Drilling and sampling procedures for the geotechnical borings available in the study area are poorly documented and rarely comply with Seed and others' (1985) recommended practice. Most notably, many of the borings used in this study were drilled using hollow stem augers, whereas the recommended procedure requires rotary drilling. It would not be possible to perform a defensible evaluation of liquefaction susceptibility using only the sparse boring data set that adhered to all of the recommended procedures. Consequently, we used all available geotechnical boring data where the geotechnical reports or boring logs indicated that the measurement of the SPT N-values conformed to American Society for Testing and Materials (ASTM) standard D 1586 (American Society for Testing and Materials, 1999a). It was assumed that the energy delivered to the sampler was 60 percent of theoretical maximum except in the case of a small number of borings drilled by the Washington Department of Transportation (WSDOT) since the late 1980s. In these WSDOT geotechnical borings, an automatic trip hammer was employed in performing the SPT, and hammer efficiency for these borings was assigned a value of 70 percent (American Society of Civil Engineers, 1995).

The field evaluation methodology of Seed and others (1983, 1985) requires an estimate of the fines fraction (the fraction of a sample that passes a 200-mesh sieve). Measured grain-size data were used to provide this parameter when available; otherwise the fines fraction was estimated from the soil category denoted on the boring log using the Unified Soil Classification System (USCS) as defined by ASTM standard D 2487 (American Society for Testing and Materials, 1999b). If no USCS soil classification was presented on the log, sample descriptions were used to derive the appropriate soil category. The field evaluation methodology of Seed and others (1983, 1985) only considers sand soils (USCS S-type soils) as being potentially liquefiable. Therefore, we did not explicitly consider liquefaction of soils classified as silts even though liquefaction of native silt soils has been observed in past earthquakes (for example, at Ying Kou City [Arulanandan and others, 1986], San Fernando Juvenile Hall [Bennett,1989], and Moss Landing [Boulanger and others, 1998]). Recent investigations indicate that some silt soils will liquefy or undergo cyclic strain weakening during earthquake loading (Prakash and Sandoval, 1992; Vessely and others, 1996).

We made calculations of the factors of safety using the field evaluation methodology of Seed and others (1983, 1985) for a hypothetical earthquake of moment magnitude (M_W) 7.3 that produces a PGA of either 0.15 *g* or 0.30 *g*, where *g* is the acceleration due to gravity. This is consistent with the scenarios

[1] The standard penetration test (SPT) is made in a geotechnical boring as part of soil sampling and is conducted using an American Society of Testing Materials approved procedure. The SPT N-value is the number of blows of a 140 pound hammer dropping 30 inches required to drive a standard soil sampler 12 inches. The number of hammer blows (N-value) is roughly proportional to the compactness and consolidation of the soil. Therefore, loose soils that are potentially liquefiable will have low N-values.

Table 3. Locations and descriptions of liquefaction and ground failure sites that could be related to liquefaction that lie outside of the study area along the Lake Washington shoreline. Site numbers refer to locations shown in Figure 1

Site no.	Reference	Location [earthquake]	Description
4	Chleborad and Schuster (1998), location no. 27	Seattle, Wash. [1949 and 1965]	"...we are on waterfront filled land...foundation cracked, also concrete...one arm of dock broken in two, fell into water; other parallel arm had second of five piles from shore settle, putting swayback in walkway....Basement concrete floor cracked in 1949 [earthquake], opened wider and heaved to different levels." (Steele Lindsay, written commun., 1965)
5	Chleborad and Schuster (1998), location no. 31	Seattle, Wash. [1949 and 1965]	[Photo caption, *Seattle Post-Intelligencer*, April 14, 1949] "NEW 50-YARD LINE?—...The crack, about 100 yards [90 m] from the open end of the Stadium, is about 50 ft [15 m] long by a foot [0.3 m] wide, and about 3 ft [1 m] deep." "...a fissure opened in the practice field at the University. Underground pressure from the shock sent sand spurting in a 100-foot-long [30 m] zig-zag stretch on the lower football field." (von Hake and Cloud, 1967) "Behind the men's pool areas of the ground dropped as much as a foot [0.3 m]. Dirt floor sections in the Hec Edmondson Pavilion also sank slightly." (von Hake and Cloud, 1967)
6	Chleborad and Schuster (1998), location no. 32	Seattle, Wash. [1965]	"North of Union Bay, a broad fill over alluvial and lacustrine sediments subsided and exhibited ground cracks and sand mounds. Subsidence caused minor damage to paving and walks, and an estimated 10 to 30 percent of shelf goods were shaken down in two stores in the shopping center there." (Mullineaux and others, 1967)
7	Chleborad and Schuster (1998), location no. 37; Hopper (1981)	Seattle, Wash. [1965]	"Basement floor-concrete cracks. Rock bulkhead on Lake Washington lowered six (6) inches [15 cm]. Large rocks fell away—ground cracked in flower beds." (Mrs. K. J. Emery, written commun., 1965)
8	von Hake and Cloud (1967)	Renton, Wash. [1965]	"At the Boeing Aircraft Plant, floors settled away from the foundation piling..." (reported by Dr. Gordon B. Oakeshott, California State Division of Mines and Geology)

used in previously published liquefaction susceptibility maps for the Puget Sound region (for example, Grant and others, 1998; Shannon & Wilson, Inc., 1993; Palmer, 1995; Palmer and others, 1994, 1995, 1999). The M_W 7.3 scenario earthquake is intended to represent an intermediate-depth earthquake located within the subducting Juan de Fuca plate (intraplate earthquake), analogous to the 1949 Olympia event. The two values of PGA used as the scenario ground motions are expected to bracket the range predicted for a M_W 7.3 intraplate event. The 0.30 *g* PGA scenario corresponds closely to the value measured in downtown Olympia during the 1949 earthquake. Probabilistic seismic hazard mapping (Frankel and others, 1996) indicates that within much of the study area a PGA of 0.30 *g* has a 10 percent chance of being exceeded in the next 50 years. The 0.15 *g* PGA scenario represents a moderate level of ground shaking within the study area, and would have an approximately 50 percent chance of being exceeded in the next 50 years based on the mapping of Frankel and others (1996).

We obtained SPT N-values and other necessary data (fines contents, ground-water depths, etc.) from the logs of geotechnical borings so that we could estimate the thickness and depth of individual liquefiable soil units and the aggregate thickness of liquefiable soils in each boring. Liquefaction at a particular depth was considered to occur when the factor of safety was less than one for the input sample data and ground motion conditions (M_W and PGA). We obtained the thickness of liquefiable material and total thickness of each hazard category encountered in a boring from this factor-of-safety analysis. We then combined results from all of the borings analyzed to evaluate the overall liquefaction susceptibility for each of the hazard categories.

Studies indicate that other earthquake sources have the potential to generate more severe ground shaking than the scenario earthquake conditions chosen for this study. In the past decade, the potential for M_W 8 or larger earthquakes occurring on the Cascadia subduction zone has been recognized (Atwater, 1987; Weaver and Shedlock, 1991; Atwater and others, 1995). Ground motion simulation studies for a M_W 8.0 to 8.5 subduction-zone earthquake presented by Cohee and others (1991) and Silva and others (1998) suggest that the ground surface PGA values in the Puget Sound region resulting from such an earthquake would be within a range of 0.10 to 0.25 *g*. However, the duration of strong ground shaking for a subduction-zone event would be significantly longer than for the M_W 7.3 scenario event used in this study. The longer duration of shaking could result in more numerous instances of liquefaction (based on the effect of the magnitude scaling factor in the factor-of-safety analysis, for example, Youd and Noble, 1997) and more ground displacement and consequent damage.

There is evidence for a major shallow crustal earthquake (M_W 7–7.5) on the Seattle fault about 1000 years ago (Atwater and Moore, 1992; Bucknam and others, 1992; Jacoby and others, 1992). The eastern section of the Seattle fault traverses the study area roughly parallel to and immediately north of Interstate 90. Also, Johnson and others (1996) suggest that the South Whidbey Island fault should be considered seismogenic based on Quaternary deformation interpreted from marine seismic-reflection data. The eastern end of the South Whidbey Island fault terminates near the town of Duvall, just northeast of the study area. Major earthquakes on either of these two shallow crustal faults could produce PGA values within the study area that are higher than those used in our M_W 7.3 intraplate earthquake scenario.

Our evaluation of liquefaction susceptibility could be viewed as non-conservative because liquefaction of silts was not considered and the range of scenario ground motions does not bracket the most severe earthquake ground motions that can plausibly affect the study area. However, this evaluation does provide a quantitative basis for assessing the relative liquefaction susceptibility of the geologic deposits occurring in the study area. Furthermore, these results can be compared to those used in the development of liquefaction susceptibility maps for the Seattle, Tacoma, and Olympia urban areas to provide a regionally consistent evaluation of the liquefaction hazard.

Liquefaction Susceptibility Map Presentation

The liquefaction susceptibility map that accompanies this report was printed at a scale of 1:36,000 in order to present the entire study area on a single standard-sized plate. However, the printed map was generated using 1:24,000-scale digital coverages of the geologic and liquefaction susceptibility mapping; therefore, digital data are available at the original scale of the hazard mapping on request to the Washington Division of Geology and Earth Resources.

The location accuracy of the digitized contacts of different hazard zones relative to the location of geologic contacts on the original mapping can be reasonably quantified. Contacts between adjacent geologic units on the original 1:24,000-scale mapping are represented by a line with a width of 0.0125 inch (0.318 mm); at map scale this line width represents a distance of 25 ft (7.6 m). Spatial registration of the original 7.5-minute geologic maps during digitization was very good, and probably would not result in shifting of contact locations by more than 5 ft (1.5 m). These two sources of digitization error suggest that the contact location on the accompanying liquefaction susceptibility map is accurate to roughly 30 ft (9.1 m).

The more significant factor affecting map accuracy is the placement of contacts on the original geological mapping. Accuracy of these geologic contacts is influenced by a number of factors that include:

- determination of geologic units and criteria used during field mapping,
- correct identification of the geologic units,
- accurate location of geologic contacts that can be observed and mapped in the field,
- uncertainty in mapping of gradational contacts, and
- inference of contact locations where they cannot be observed and mapped.

Quantification of this source of map inaccuracy is difficult, if not impossible. For the purpose of this study the location of geologic contacts have been accepted at face value from their original sources and used as the basis for delineating areas of different liquefaction susceptibility. This hazard map is not intended to replace a site-specific investigation needed to determine if a particular locality is underlain by liquefiable soils. *Therefore, it is strongly recommended that users of this map consider some level of site-specific investigation commensurate with their concern with mitigating the impact of earthquake-induced liquefaction.*

The entire area at the northern end of Lake Sammamish is mapped as unit Qyal (younger Holocene alluvium) by Minard and Booth (1988) without differentiation between deposits along the shoreline terrace of Lake Sammamish and alluvial deposits of the Sammamish River. Additionally, there were no geotechnical borings available in this transitional area. Consequently, it was not possible to place a definite contact between the low to moderate and moderate to high hazard areas in this vicinity. Therefore, a broad transition in the color shading was used to reflect this inability to place a definite contact between the two different hazard areas. At present this transitional area lies within Marymoor Park and would not likely be subject to significant development projects or major land-use changes.

Liquefaction Analysis

The geologic units in the study area were separated into eight groupings based on their geological and engineering characteristics and geographic distribution. These groupings are:

- artificial fill and Holocene alluvium and lake deposits south of Lake Sammamish in the vicinity of Issaquah,
- artificial fill and Holocene lake deposits along the shorelines of Lakes Washington and Sammamish,
- Holocene alluvium in the Sammamish River valley and the Bear and Evans Creek drainages,
- Holocene mass-wasting deposits,
- Vashon glacial recessional outwash deposits composed primarily of sand (unit Qvrs),
- all other Pleistocene glacial and nonglacial deposits,
- Holocene peat deposits presumed to have a thickness of 10 ft (3 m) or greater, and
- outcrop areas of Tertiary volcanic and sedimentary bedrock.

Detailed geotechnical data analyses for each of the first six groupings were performed in order to quantify their liquefaction susceptibility. No quantitative analyses were performed for the last two groupings (Holocene peat and Tertiary bedrock) because an insufficient number of geotechnical borings were compiled for these two units. The outcrop areas and general liquefaction characteristics of these two groupings are included on the liquefaction susceptibility map.

We used a modified version of the thickness criteria developed by Grant and others (1998) in determining the liquefaction hazard for each of the first six groupings. The thickness criteria and hazard rating scheme used by Grant and others (1998) is based on the total (aggregate) thickness of all liquefiable soil units penetrated by an individual boring. We calculated the aggregate thickness, expressed in absolute units (feet), for both ground motion scenarios. In Grant and others' (1998) approach, the drilled depth is irrelevant, so that a boring drilled to a depth of 20 ft (6.1 m) that encounters a 10 ft (3.0 m) aggregate thickness of liquefiable soil is equivalent in terms of the hazard rating to a 40 ft (12.2 m) deep boring that also encounters an aggregate thickness of 10 ft (3.0 m) of liquefiable soil. We modified the aggregate thickness values by normalizing the aggregate thickness of liquefiable soils encountered in a boring by the total penetrated thickness of that boring and expressing the normalized result as a percentage of the total penetrated thickness. In the above example, the 20 ft (6.1 m) boring would have a normalized aggregate thickness of 50 percent, and the 40 ft (12.2 m) boring would have a normalized aggregate thickness of 25 percent.

We calculated the normalized aggregate thickness of liquefiable soils for all borings and generated cumulative frequency histograms for each geologic grouping (Figs. 2–7). The relative hazard is determined using a liquefaction analysis based on the ground-water depth measured during drilling of the geotechnical borings as well as for the "worst-case" condition where the ground-water table is at ground surface. The histograms show, for each of the two ground motion scenarios and each of the ground-water conditions, the percentage of borings

Table 4. The criteria used in this report to provide a liquefaction hazard rating. For the 0.15 *g* scenario, the hazard is determined by the percentage of borings in a particular geologic unit in which any liquefiable soil was encountered (normalized aggregate thickness exceeds 0 percent). For the 0.30 *g* scenario, the hazard is determined by the percentage of borings in which the normalized aggregate thickness of liquefiable soil exceeds 25 percent

Borings exceeding the normalized aggregate thickness criteria (%)	Hazard rating
> 50	High
25-50	Moderate
5-25	Low
< 5	Very low

Table 5. Summary of thickness criteria hazard rankings for the six geologic groupings in the study area having sufficient geotechnical boring data to perform factor of safety analyses. Also shown are a summary of historical liquefaction, both within and adjoining the study area, and the final assignment of liquefaction susceptibility hazard

Geologic grouping	Thickness criteria ranking: Ground water at time of drilling	Thickness criteria ranking: Ground water at surface	Historical liquefaction: Study area	Historical liquefaction: Adjoining areas	Final liquefaction susceptibility hazard rating
Issaquah vicinity	Moderate	High	Possible	Not applicable	Moderate to high
Shorelines of Lakes Washington and Sammamish	Moderate	High	Possible	Definitive	Moderate to high
Sammamish River valley and Bear and Evans Creek drainages	Low to very low	Moderate	None	Not applicable	Low to moderate
Holocene mass-wasting deposits	Low	Low to moderate	None	None	Low to moderate
Vashon sandy glacial recessional outwash deposits	Low	Low to moderate	None	Definitive	Low to moderate
All other Pleistocene glacial and nonglacial deposits	Very low	Very low	None	None	Very low

that exceed a specific normalized aggregate liquefiable thickness. Normalized cumulative frequency histograms were used by Palmer (1995) and Palmer and others (1994, 1995, 1999) to characterize liquefaction susceptibility in many parts of the Puget Sound region.

The hazard rating scheme used in this study is based on the percentage of borings exceeding certain normalized aggregate thickness criteria (Table 4). For the 0.15 *g* scenario, the relative hazard is determined by the percentage of borings that have any liquefiable soil, and for the 0.30 *g* scenario, by the percentage of borings in which the normalized aggregate thickness of liquefiable soil exceeds 25 percent. The range of hazard determined using the two ground-water conditions was the primary factor used to determine the final liquefaction susceptibility hazard rating presented on the accompanying map. The occurrence of liquefaction during historical earthquakes both within and adjoining the study area is summarized in Table 5, and provides a verification of the hazard rating based on the geotechnical analysis.

ISSAQUAH VICINITY

Using the factor-of-safety evaluation to determine liquefaction susceptibility, we analyzed 63 borings that penetrated Holocene alluvial and lacustrine deposits and artificial fill in the vicinity of Issaquah. Median penetrated thickness of fill and Holocene deposits was 44.0 ft (13.4 m); median depth to ground water reported at the time of drilling was 7.0 ft (2.1 m). The data presented in Figure 2 indicate that for the ground-water depths measured at the time of drilling, 43 percent of these borings encountered some amount of liquefiable soil for the 0.15 *g* scenario and about 48 percent of the borings encountered liquefiable soil exceeding a normalized aggregate thickness of 25 percent for the 0.30 *g* scenario. Based on the thickness criteria presented in Table 4, these values indicate that the Holocene deposits in the Issaquah area have a moderate liquefaction susceptibility. For the condition where ground water is at the ground surface, the histograms indicate a significant increase in the thickness of liquefiable soil compared to those developed using ground-water depths measured at time of drilling. Under this condition, 75 percent of the borings contain some amount of liquefiable soil for the 0.15 *g* ground motion scenario and about 67 percent of these borings contain a normalized aggregate thickness of liquefiable soil that exceeds 25 percent for the 0.30 *g* scenario. These values indicate that the Issaquah area fill and Holocene deposits have a high liquefaction susceptibility when the ground-water table is assumed to be at the ground surface.

The cumulative frequency histograms generated from the Issaquah-area geotechnical data are very similar to those generated in the evaluation of the liquefaction susceptibility of Holocene alluvium and artificial fill in the Kent valley (Palmer and others, 1994, 1995). The histograms used in characterizing the southern part of the Kent valley (Palmer and others, 1995) are presented in Figure 3 for comparison to the Issaquah histograms. These histograms, which illustrate ground-water conditions at the time of drilling, indicate that the liquefaction susceptibility in the Issaquah area is very comparable to that in the southern Kent valley. The artificial fill and Holocene alluvium of the southern Kent valley were assigned a high liquefaction susceptibility based on the cumulative frequency histograms and the abundance of historical liquefaction as described in Palmer and others (1995). Liquefaction was observed in the Kent valley during both the 1949 Olympia and 1965 Seattle–Tacoma earthquakes, but evidence for liquefaction in the Issaquah area during these events is equivocal (see Table 2). Based on these observations and the analyses of the Issaquah-area data, we assign the artificial fill and Holocene deposits in the Issaquah area a moderate to high liquefaction susceptibility hazard rating (Table 5).

SHORELINES OF LAKES WASHINGTON AND SAMMAMISH

Construction of the Lake Washington Ship Canal and the associated drop in lake elevation resulted in the exposure of nearshore beach deposits along the Lake Washington shoreline. These deposits form a terrace bordering the lake that has been

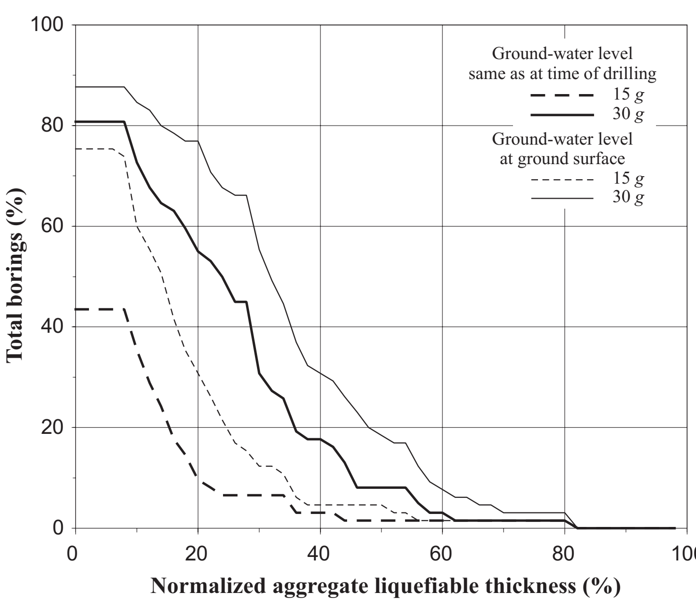

Figure 2. Cumulative frequency histograms developed from 63 geotechnical borings penetrating artificial fill and Holocene alluvium and lake deposits in the vicinity of Issaquah.

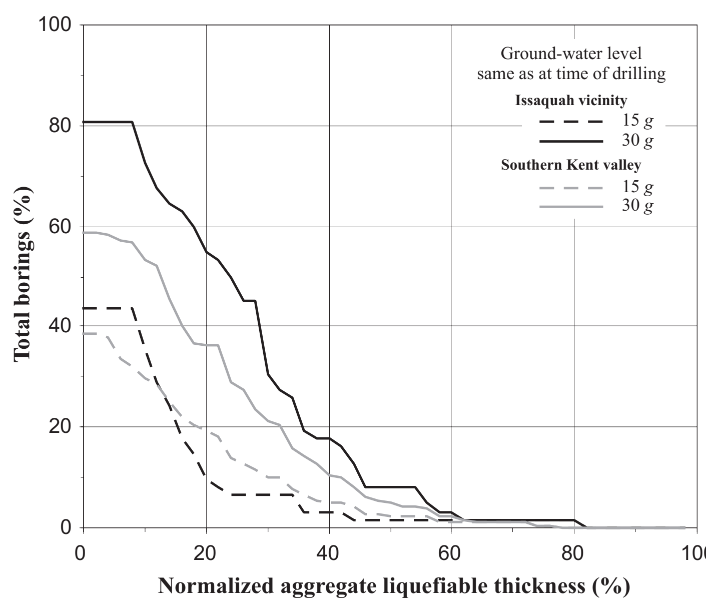

Figure 3. Comparison of cumulative frequency histograms developed for the southern Kent valley (Palmer and others, 1995) with those developed for the alluvium and lake deposits in the vicinity of Issaquah.

subjected to extensive development, often involving the placement of artificial fill. A similar terrace, unrelated to the Ship Canal project, borders Lake Sammamish and possibly represents a prehistoric lake highstand. This terrace is underlain by Holocene lacustrine and alluvial deposits, and many areas of this shoreline terrace have been graded or filled. Data from geotechnical borings located within the shoreline areas of both lakes were combined and evaluated for liquefaction susceptibility.

We developed cumulative frequency histograms from 26 geotechnical borings penetrating these lake shoreline deposits (Fig. 4). Median penetrated thickness of these deposits was 18.8 ft (5.7 m); median depth to ground water reported at the time of drilling was 6.5 ft (2.0 m). For ground-water conditions measured at the time of drilling, the histograms show that approximately 39 percent of these borings contain liquefiable soil for the analysis based on the 0.15 *g* scenario. Likewise, about 31 percent of the borings contain more than a 25 percent normalized aggregate thickness of liquefiable soil for the 0.30 *g* scenario. For ground-water assumed at ground surface, about 62 percent of the borings contain liquefiable soil for the 0.15 *g* scenario, and 70 percent of the borings contain more than a 25 percent normalized aggregate thickness of liquefiable soil for the 0.30 *g* scenario. According to the criteria in Table 4, these deposits have a moderate to high liquefaction susceptibility, depending on the assumed ground-water conditions.

The ground failures documented at sites 1 and 3 (Fig. 1, Table 2) provide only equivocal evidence for liquefaction of these shoreline deposits within the study area. A number of other sites within the emerged shoreline of Lake Washington, but located outside of the study area, experienced significant ground deformation during the 1949 and 1965 earthquakes (Table 3). Sites 5 and 6, located in the Lake Union area, provide unequivocal evidence of liquefaction (ejected sand). The historical ground failures and the results of the analysis of geotechnical boring data justify a moderate to high liquefaction susceptibility hazard rating for these lake deposits and overlying artificial fill (Table 5).

SAMMAMISH RIVER VALLEY AND BEAR AND EVANS CREEK DRAINAGES

The Sammamish River originates at the northern end of Lake Sammamish, traverses the north-central portion of the study area, and flows into the northern end of Lake Washington at Kenmore (Fig. 1). The fall of the Sammamish River is determined by the difference in water surface elevation of the two lakes, which is nominally 13.2 ft (4.0 m) based on topographic data from U.S. Geological Survey and U.S. National Ocean Service (1982). The total channel length of the Sammamish River is approximately 13 mi (21 km), yielding a channel gradient of approximately 1 ft/mi (0.2 m/km). Prior to construction of the Lake Washington Ship Canal, the Sammamish River (then called the Sammamish, or Squak, Slough) was a slow, meandering stream navigable only by shallow draft ships and barges. Construction of the Ship Canal resulted in the lowering of Lake Washington by approximately 8.8 ft (2.7 m), increasing the gradient and causing incision of the channel. By the mid-1960s, the entire length of the Sammamish River had been widened and deepened by dredging and significant lengths of the river had been straightened in order to reduce flooding of adjacent farmland and improve small-craft passage.

We developed cumulative frequency histograms from 75 geotechnical borings penetrating the alluvium in the Sammamish River valley (Fig. 5). A small number of borings located in the Bear and Evans Creek drainages, tributaries to the Sammamish River, were included in this data set and analysis. For ground-water conditions measured at the time of drilling, approximately 4 percent of these borings penetrated some amount of liquefiable soil for the 0.15 *g* ground motion scenario. For the 0.30 *g* scenario about 7 percent of the borings encountered liquefiable soil exceeding a normalized aggregate thickness of 25 percent. These values indicate that the alluvium has a low to very low liquefaction susceptibility (Table 4) under the ground-water conditions described above. For ground-water at ground surface, about 29 percent of the borings contain liquefiable soil for the 0.15 *g* scenario and nearly 48 percent of the borings contain more than a 25 percent normalized

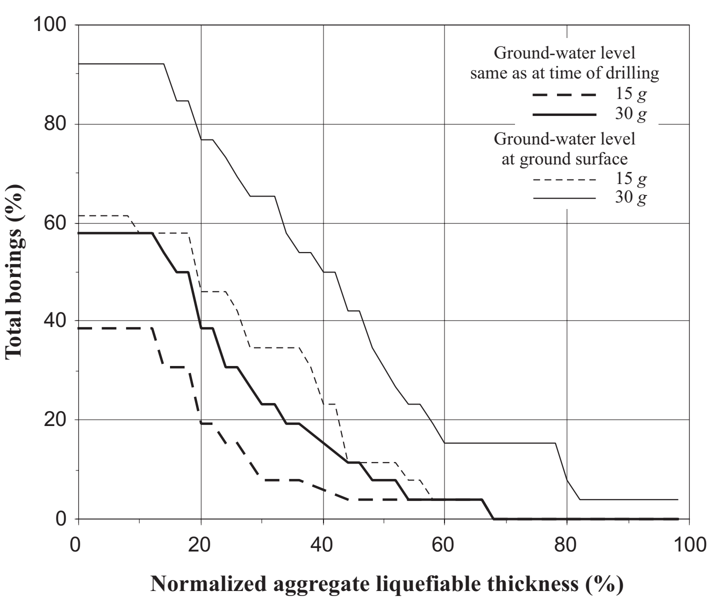

Figure 4. Cumulative frequency histograms developed from 26 geotechnical borings penetrating artificial fill and Holocene lake deposits along the shorelines of Lakes Washington and Sammamish.

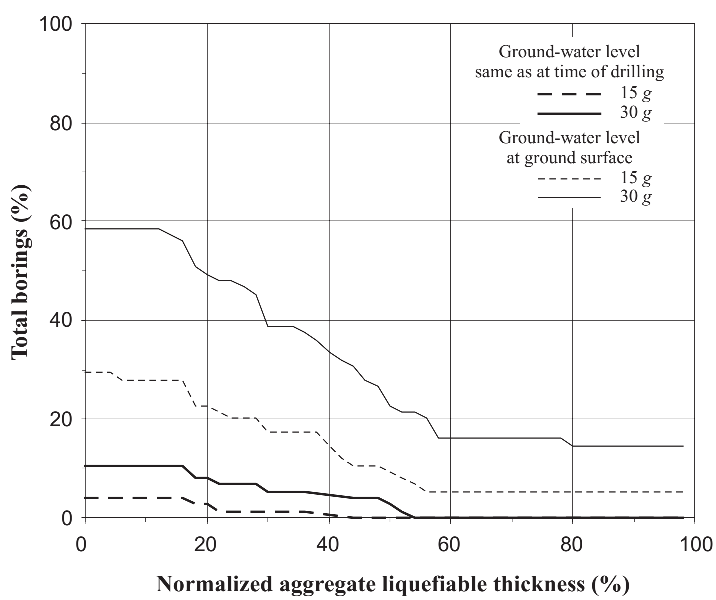

Figure 5. Cumulative frequency histograms developed from 75 geotechnical borings penetrating Holocene alluvium in the Sammamish River valley and Bear and Evans Creek drainages.

aggregate thickness of liquefiable soil for the 0.30 *g* scenario, indicating a moderate liquefaction susceptibility (Table 4).

Review of geotechnical boring logs in the Sammamish River valley (including the Bear and Evans Creek drainages) indicated that the Holocene alluvium is thin (median penetrated thickness of 12.5 ft, or 3.8 m), and the thickest section of Holocene alluvium encountered in the compiled geotechnical borings was approximately 30 ft (9.0 m). The median depth to ground water reported at the time of drilling was 11.5 ft (3.5 m), which nearly equals the median thickness of these deposits. On average, only a relatively thin portion of the Sammamish River alluvium lies below the ground-water table, and consequently would be considered liquefiable. Also, alluvial soils in the Sammamish River valley are predominantly fine-grained or peaty (65% classified as silty sand, silt, clay, or organic soils). The fine-grained composition of these alluvial soils results from the low channel gradient and consequent low current velocity of the Sammamish River.

The liquefiable thickness distributions presented in Figure 5 indicates that these deposits rank as very low to moderate susceptibility. Although there is no report of liquefaction during past earthquakes in the Sammamish River valley, Youd and Perkins (1978) estimate that Holocene flood plain deposits have a moderate liquefaction susceptibility based on worldwide historical observations. We consequently assign the fill and alluvial soils found in the Sammamish River and Bear Creek and Evans Creek drainages a low to moderate liquefaction susceptibility hazard (Table 5).

HOLOCENE MASS-WASTING DEPOSITS

Holocene mass-wasting deposits include areas of mapped landslide deposits, thick colluvium, and alluvial fans deposited on valley floors at the base of steep ravines. Twenty-six geotechnical borings penetrated these geologic units, and the cumulative frequency histograms developed from the data produced by these borings are shown in Figure 6. Median penetrated thickness of the Holocene mass-wasting deposits in these borings is 9.4 ft (2.9 m); median depth to ground-water reported at the time of drilling was 17.8 ft (5.4 m). For ground-water conditions encountered at the time of drilling, approximately 11 percent of these borings contain some amount of liquefiable soil for the 0.15 *g* ground motion scenario. For the 0.30 *g* scenario about 11 percent of the borings encountered liquefiable soil exceeding a normalized aggregate thickness of 25 percent. These values indicate a low liquefaction susceptibility (Table 4). For ground-water at ground surface, about 22 percent of the borings contain liquefiable soil for the 0.15 *g* scenario and over 33 percent of the borings contain more than a 25 percent normalized aggregate thickness of liquefiable soil for the 0.30 *g* scenario, indicating a low to moderate liquefaction susceptibility. The similarity of the cumulative frequency histograms in Figure 6 with those for the fill and alluvial soils found in the Sammamish River and Bear Creek and Evans Creek drainages (Fig. 5) support our assignment of a low to moderate liquefaction susceptibility hazard to the mass-wasting deposits (Table 5).

VASHON SANDY GLACIAL RECESSIONAL OUTWASH DEPOSITS

We separated Vashon recessional outwash deposits predominantly composed of sand and silt (unit Qvrs) from gravelly recessional outwash (unit Qvrc) in the study area using agricultural soils mapping (Snyder and others, 1973). Field-checking and review of water well and geotechnical boring logs indicated that the agricultural soil maps were reasonably accurate in separating these textural units.

Quantitative evaluation of the liquefaction susceptibility of unit Qvrs was based on analysis of 108 geotechnical borings drilled in this unit (Fig. 7). Median drilled thickness of unit Qvrs in the borings is 19.0 ft (5.8 m); median ground-water depth at the time of drilling was 10.0 ft (3.0 m). Figure 7 shows that for ground-water conditions reported during drilling, approximately 5 percent of the borings contain some amount of liquefiable soil for the 0.15 *g* ground motion scenario and approximately 13 percent of these borings contain more than a 25 percent normalized aggregate thickness of liquefiable soil

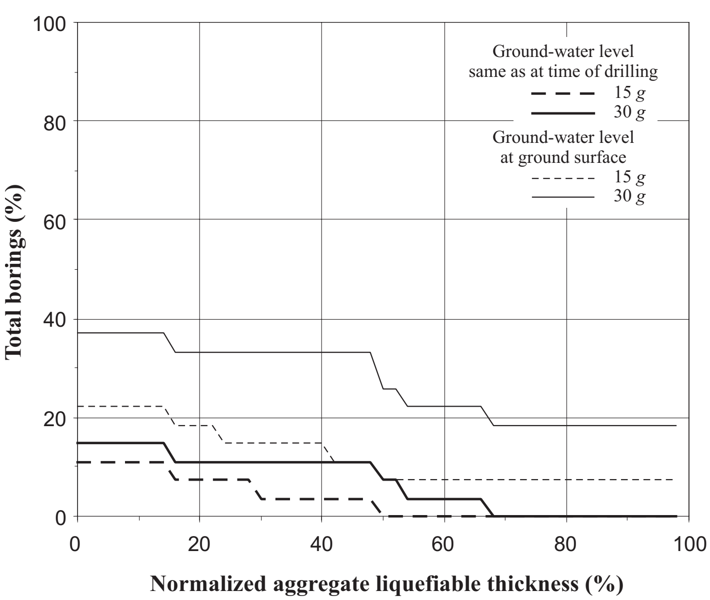

Figure 6. Cumulative frequency histograms developed from 26 geotechnical borings penetrating Holocene mass-wasting deposits.

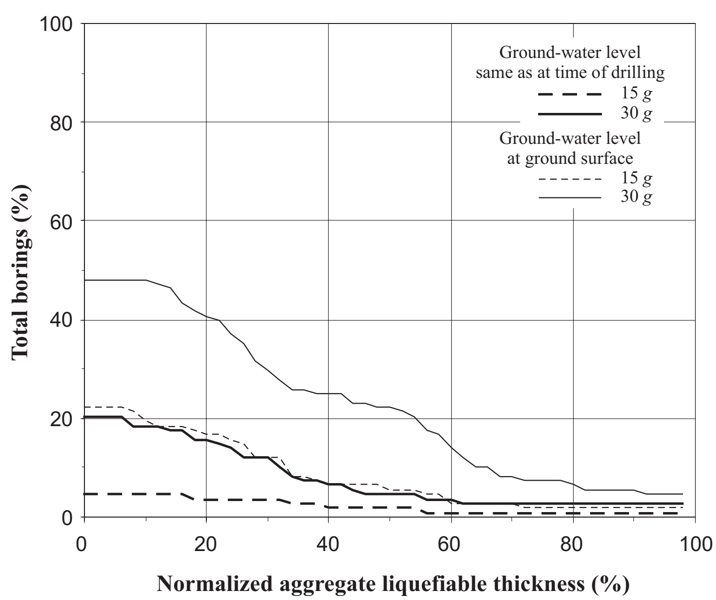

Figure 7. Cumulative frequency histograms developed from 108 geotechnical borings penetrating Vashon glacial recessional outwash deposits composed primarily of sand and silt (unit Qvrs).

for the 0.30 *g* scenario. These values suggest that unit Qvrs has a low liquefaction susceptibility for ground-water conditions observed during drilling.

The cumulative frequency histograms for unit Qvrs where the ground-water table was assumed to be at ground surface indicate a significant increase in the thickness of liquefiable soil compared to those developed using ground-water depths measured at time of drilling. Figure 7 shows that 22 percent of these borings contain some amount of liquefiable soil for the 0.15 *g* ground motion scenario. Nearly 36 percent of these borings contain a normalized aggregate thickness of liquefiable soil that exceeds 25 percent for the 0.30 *g* scenario. These values suggest that unit Qvrs has a low to moderate liquefaction susceptibility when the ground-water table is assumed to be at ground surface.

Liquefaction occurred at a site in southwestern King County underlain by sandy Vashon glacial outwash during the 1995 Robinson Point earthquake (Palmer and Moses, 1996). The occurrence of liquefaction during a magnitude 5.0 earthquake such as the Robinson Point event is unusual but not unprecedented. The liquefaction site was located in an area where the ground-water table was very shallow as a result of heavy precipitation in the weeks preceding the earthquake. Vertical and horizontal ground displacement, on the order of 2 in. (5 cm), caused significant damage to the residential structure located at this site. Similar assessments of sandy Vashon glacial outwash in the southwestern King County and Olympia areas (Palmer and others, 1995, 1999) indicated that these deposits are susceptible to liquefaction, particularly in areas with a shallow ground-water table. These assessments are supported by the reported occurrence of liquefaction in unit Qvrs deposits during the 1949 and 1965 Puget Sound earthquakes (Palmer and others, 1999).

The histograms for unit Qvrs (Fig. 7) are very similar to those of the Sammamish River valley alluvium (Fig. 5) and the Holocene mass-wasting deposits (Fig. 6). Consideration of these similarities in conjunction with the occurrence of liquefaction during past Puget Sound earthquakes in similar deposits outside of the study area supports our assignment of a low to moderate liquefaction susceptibility hazard rating for the unit Qvrs deposits (Table 5).

OTHER PLEISTOCENE GLACIAL AND NONGLACIAL DEPOSITS

All Pleistocene glacial and nonglacial deposits (with the exception of unit Qvrs) were combined into a single geologic grouping. There were 474 geotechnical borings penetrating the units composing this grouping. Only three borings (0.6% of the total number penetrating these units) encountered any liquefiable soil for the 0.15 *g* ground motion scenario or more than 10 ft (3.0 m) of liquefiable soil for the 0.30 *g* scenario. This represents an insignificant number of occurrences of predicted liquefaction, and indicates that this geologic grouping has a very low liquefaction susceptibility hazard.

Factors contributing to the very low liquefaction hazard of these geologic units include:

- predominance of a silty and (or) gravelly texture, which retards the occurrence of liquefaction;
- significant consolidation of these units (except unit Qvrc) because of glacial ice loading;
- a typically deep ground-water table (deeper than 30 ft or 9.1 m).

Further support for the assignment of a very low susceptibility hazard is the lack of historical occurrences of liquefaction in these deposits during the 1949 and 1965 earthquakes throughout the Puget Sound region.

PEAT

Peat deposits are included as a separate unit on the accompanying liquefaction susceptibility map and are composed of organic and mineral sediments deposited during the late Pleistocene and Holocene. Soil types occurring in the mapped peat deposits include peat, muck, silt, and clay. These deposits are judged to be at least 10 ft (3.0 m) thick and consequently would be significant from an engineering perspective. The soils composing the mapped peat unit are generally not liquefiable, but may be susceptible to differential settlement resulting from dynamic compaction during earthquake ground shaking. Localized sand beds within the peat deposits may be liquefiable, such as those identified along the margins of Mercer Slough (Kramer, 1993).

BEDROCK

Outcrop areas of Tertiary volcanic and sedimentary bedrock are included as a separate map unit because lithified rock is not susceptible to liquefaction. However, unrecognized fill soils placed during building or road construction may occur within the areas mapped as bedrock outcrop. Of particular concern in the southern portion of the study area are unmapped spoils piles associated with past coal mining. These fill soils, as well as thick colluvial deposits, may be liquefiable if they are composed of loose sand and are water saturated. Therefore, we designated the areas of mapped bedrock outcrop as having a very low to nil susceptibility to account for the possibility of isolated occurrences of potentially liquefiable fill or thick colluvial soils overlying bedrock.

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