# LIQUEFACTION SUSCEPTIBILITY OF THE GREATER TACOMA URBAN AREA, PIERCE AND KING COUNTIES, WASHINGTON

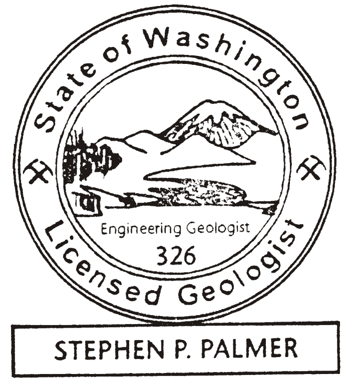
by Stephen P. Palmer,
William J. Perkins,
and W. Paul Grant

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Geologic Map GM-51
June 2003

*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**
**Doug Sutherland** - Commissioner of Public Lands

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5/30/03


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# Liquefaction Susceptibility of the Greater Tacoma Urban Area, Pierce and King Counties, Washington

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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. This report presents the technical evaluation used in generating the accompanying liquefaction susceptibility map of the Greater Tacoma urban area of Pierce and King Counties, Washington. The study area (Fig. 1) consists of the Tacoma South and Puyallup 7.5-minute quadrangles and those portions of the Tacoma North, Gig Harbor, Steilacoom, and Poverty Bay quadrangles east of Puget Sound. The map is intended to provide building officials, land-use planners, emergency-response personnel, engineering consultants, building owners and developers, insurance providers, and private citizens with an estimate of the likelihood the soil will liquefy as a result of strong earthquake shaking.

Liquefaction occurs when water-saturated sandy soil loses strength during severe shaking such as that generated by an earthquake. Below the groundwater 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 grain support. If strong shaking lasts long enough, the grain structure of a loose sandy soil may completely collapse. When grain contact support is lost, pore-water pressure must increase to account for stresses imposed by the weight of the overlying soil. At this stage, 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 within the moving soil mass. Collapse of grain structure can result in settlement of the soil column and loss of weight-bearing capacity, which may cause severe damage to structures. Buoyant forces within a liquefied soil mass can cause flotation of underground tanks, pilings, and other buried structures.

The liquefaction susceptibility map presented in this report is based on available 1:24,000-scale geologic mapping and the analysis of 502 geotechnical borings obtained from local government agencies, the Washington State Department of Transportation, and the database used in a previous liquefaction hazard mapping project in the Tacoma area (Shannon & Wilson, 1993). Six categories of geologic deposits found in the study area are assigned a relative liquefaction hazard rating determined through analysis of the geotechnical data and/or geological characterization. A seventh category composed of areas underlain by Holocene peat is also shown on the liquefaction susceptibility map. Although peat is not susceptible to liquefaction, it can be susceptible to permanent ground deformation and strength loss during earthquake shaking.

Shannon & Wilson (1993) presented an evaluation and map of liquefaction potential for roughly the same area as that characterized in this study. Their liquefaction hazard map was based on 1:63,500-scale geologic mapping performed as part of a water resource study (Walters and Kimmel, 1968). Both Shannon & Wilson (1993) and this study employed a similar approach in categorizing geologic units as to liquefaction hazard and applied a standard engineering methodology to a large

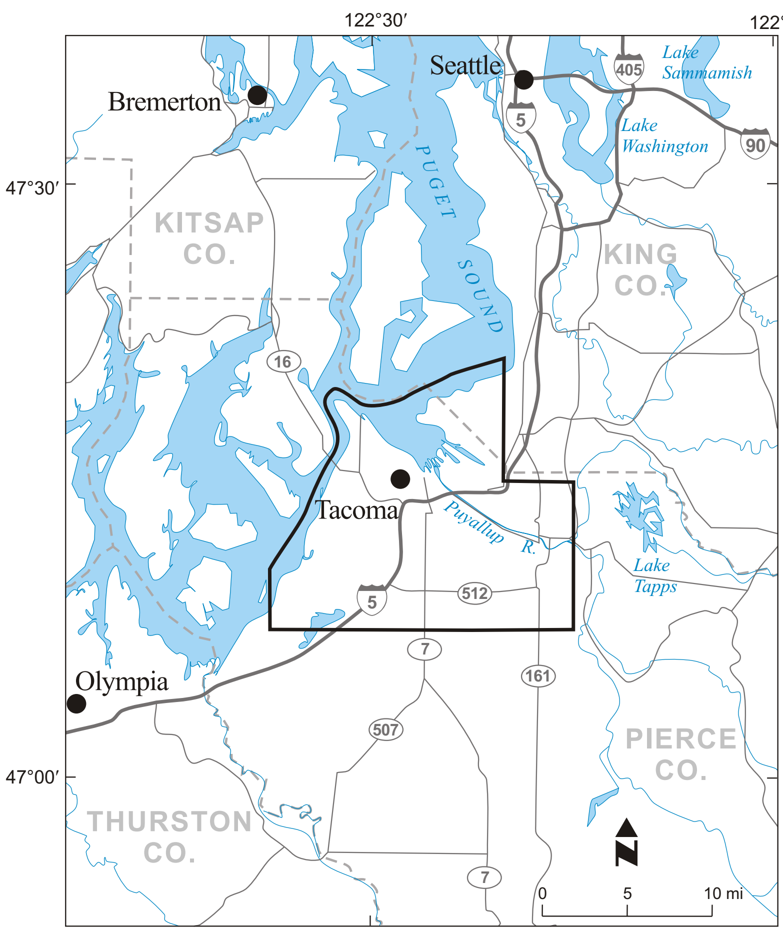


**Figure 1.** Map showing the location of the study area (black outline) within the Greater Tacoma urban area.

data set of geotechnical borings drilled within the study area. In this study, we used larger-scale (1:24,000) geologic mapping to more accurately delineate liquefaction hazard areas and expanded the number of borings within, and provided a higher degree of quality control on, the geotechnical boring database used in the evaluation. In particular, we have compiled a larger geotechnical boring database for the filled tide flats area (using 82 more borings than Shannon & Wilson) and set a minimum drilled depth of 20 ft (6.1 m) for inclusion in the database.

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, liquefaction may occur without causing significant ground displacement or 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 high liquefaction susceptibility is assigned to the fill area covering the former tide flats of Commencement Bay and recent (mid- to late Holocene) alluvial deposits of the Puyallup Valley and Chambers Creek drainage. Areas underlain by Holocene landslide debris and beach deposits are considered to have a low to moderate susceptibility based on results from previous liquefaction hazard mapping in the Puget Sound region. Sandy glacial outwash and ice-contact deposits from the recession of the latest Pleistocene continental glaciation (~13,000 years ago) are also regarded as having a low to moderate liquefaction susceptibility. 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 strength loss and both transient and permanent vertical and lateral displacement caused by ground shaking. Also, sand layers interbedded with the peat deposits may be liquefiable.

## GEOLOGIC MAPPING OF THE GREATER TACOMA URBAN AREA

The primary sources of 1:24,000-scale geologic mapping for this study were provided by Smith (1977), Troost (in press a,b), Troost and Booth (in press), and Troost and others (in press). These geologic maps were compiled into a digital coverage as part of this study. Table 1 presents the correlation between the map units used in Smith (1977), Troost (in press a,b), Troost and Booth (in press), and Troost and others (in press) and the generalized geologic units developed for this study. Minor revisions were made to the digital versions of these authors' map data in the course of the study. Riverine geomorphic features associated with the Puyallup River and Wapato Creek (such as avulsed and abandoned channels or bar and swale topography) were interpreted from aerial photography and included on the accompanying liquefaction susceptibility map.

Wherever possible, we subdivided recessional outwash and ice-contact deposits of the Vashon Stade of the Fraser Glaciation mapped by Smith (1977), Troost (in press a,b), Troost and Booth (in press), and Troost and others (in press) into three textural units: unit Qvrc, which is primarily composed of gravel and sand, unit Qvrs, which is primarily composed of sand, and unit Qvrf, which is primarily composed of silt and clay. This textural breakdown was necessary because previous analyses and historic performance in other parts of the Puget Sound region indicate that unit Qvrs is potentially susceptible to liquefaction in areas with a shallow groundwater table (Palmer and Moses, 1996; Palmer and others, 1995, 1999).

Sandy or silty Vashon recessional and ice-contact deposits (units Qvrs and Qvrl, respectively) were identified using U.S. Department of Agriculture Soil Conservation Service (now Natural Resource Conservation Service) soil maps for the King and Pierce County areas (Snyder and others, 1973; Zulauf, 1979). Digital geologic and agricultural soil coverages were superimposed in order to identify areas of sandy or silty loams falling within areas shown as Vashon recessional outwash (generalized geologic unit Qvr) or ice-contact deposits (generalized geologic unit Qvi) on the geologic source maps; we assigned these areas to the stratigraphic units Qvrs and Qvrf, respectively. Similarly, areas of gravelly loam falling within Vashon recessional outwash or ice-contact deposits were assigned to unit Qvrc. Field checking at spot locations and review of water well and geotechnical boring logs confirmed that this

**Table 1.** Correlation of units from geologic mapping of the Gig Harbor (Smith, 1977), Tacoma North (Troost and others, in press), Tacoma South (Troost, in press b), Steilacoom (Troost and Booth, in press), and Puyallup (Troost, in press a) 7.5-minute quadrangles, and the generalized geologic units used in this study. N/A, not applicable

| Description of unit | Gig Harbor | Tacoma North, Tacoma South, Steilacoom, Puyallup | Generalized unit |
|---|---|---|---|
| Artificial fill, modified land | af | af, m | af |
| Holocene alluvium | Qal | Qal | Qal |
| Holocene alluvial fan deposits | N/A | Qf | Qal |
| Holocene beach deposits | N/A | Qb | Qb |
| Holocene landslide deposits | Qls | Qls | Qls |
| Holocene swamp or wetland deposits | Qp | Qp, Qw | Qp |
| Vashon recessional lacustrine deposits | N/A | Qvrl | Qvrf |
| Vashon recessional outwash | Qvr | Qvr, $Qvs_{p-1}$, $Qvs_{p-2}$, $Qvs_{p-4}$, $Qvs_{cc-1}$, $Qvs_{st-1}$, $Qvs_{st-2}$, $Qvs_{st-3}$, $Qvs_{st-4}$, $Qvs_{b-1}$, $Qvs_{b-2}$, $Qvs_{b-3}$, $Qvs_{b-4}$ | Qvr, Qvrf, Qvrs, Qvrc |
| Vashon ice-contact deposits | N/A | Qvi | Qvi, Qvrf, Qvrs, Qvrc |
| Vashon till | Qvt | Qvt | Qvt |
| Vashon advance outwash | Qva, Qe | Qva, Qvas | Qva, Qvas |
| Pre-Fraser glacial deposits | Qns, Qdr, Qu | Qvlc, $Qob_m$, Qpf, $Qpf_c$, $Qpf_m$, $Qpf_f$, $Qpfn_c$, $Qpfn_f$, Qpo, $Qpo_c$, Qpog, $Qpog_c$, $Qpog_f$, Qpon, $Qpon_c$, $Qpon_d$, $Qpon_f$, Qr, $Qrn_m$ | Qu |

approach was reasonably accurate in mapping soil texture within the Vashon recessional deposits. A significant limitation to this textural mapping was that there was no agricultural soil mapping provided in Zulauf (1979) within the Tacoma city limits. Consequently, no textural separation of Vashon recessional deposits was made within the city boundary, and the recessional outwash and ice-contact deposits mapped by Smith (1977), Troost (in press a,b), Troost and Booth (in press), and Troost and others (in press) were generalized into units Qvr and Qvi (Table 1).

## HISTORIC LIQUEFACTION IN THE GREATER TACOMA URBAN AREA

The three largest earthquakes in recent historic times in the Puget Sound region are the 1949 Olympia earthquake (surface wave magnitude [$M_s$] 7.1), the 1965 Seattle–Tacoma earthquake (body wave magnitude [$m_b$] 6.5), and the 2001 Nisqually earthquake (moment magnitude [$M_w$] 6.8). Significant portions of the study area were exposed to Mercalli Modified Intensity (MMI) VIII shaking during the 1949 earthquake, MMI VII intensity during the 1965 earthquake, and MMI VI to VII during the Nisqually earthquake (Murphy and Ulrich, 1951; Roberts and Ulrich, 1951; von Hake and Cloud, 1967; Dewey and others, 2002). The most comprehensive documentation of liquefaction-induced ground failures caused by the 1949 and 1965 earthquakes is presented in Chleborad and Schuster (1998). Most of the information about liquefaction sites in the Puyallup area presented in their publication was originally reported in Shulene (1990).

Table 2 summarizes occurrences of liquefaction reported in Chleborad and Schuster (1998) within the study area during the 1949 Olympia and 1965 Seattle–Tacoma earthquakes, as well as a liquefaction ground failure reported by Palmer and Moses (1996) that occurred during the 1995 magnitude 5.0 Robinson Point earthquake (site 12). Site numbers in Table 2 refer to locations shown on the accompanying liquefaction susceptibility map.

Liquefaction was commonly reported in the Puyallup Valley and filled tide flats during the 1949 earthquake. However, during the 1965 earthquake, liquefaction was observed at only one site in Puyallup (site 9) and one site in the filled tide flats (site 2). The effects observed at site 3 during the 1965 event (ground cracking without associated sand venting) is not unequivocal evidence of liquefaction, as it could be related to other ground-failure mechanisms. No evidence of liquefaction within the study area was observed during the Nisqually earthquake (EERI, 2001) even though five separate groups of investigators made independent reconnaissance of the Puyallup Valley in the week following the earthquake. The lack of liquefaction in the Puyallup Valley during this event was unexpected based on historical behavior and the assessment of a high liquefaction hazard for this area presented in Shannon & Wilson (1993). However, ground shaking in the Tacoma area was anomalously low compared to other areas at comparable hypocentral distances; a peak ground acceleration of only 0.09 *g* (where *g* is the acceleration due to gravity) was measured in the filled tide flats area, whereas ground shaking was two to three times stronger at sites farther north at greater hypocentral distances. Additionally, western Washington was experiencing a severe drought at the time of the Nisqually earthquake, which likely resulted in an unusually low groundwater table beneath the Puyallup Valley. Lowering of the groundwater table reduces the overall liquefaction susceptibility of a soil deposit. The subdued ground shaking, possibly coupled with the low

**Table 2.** Descriptions of liquefaction-induced ground failures that occurred within the study area during the 1949 Olympia, 1965 Seattle–Tacoma, and 1995 Robinson Point earthquakes. Site numbers refer to locations shown on the accompanying liquefaction susceptibility map. Unless otherwise noted by citation, all occurrences were reported in Chleborad and Schuster (1998)

| Site no. | Year of earthquake | Summary of reports |
|---|---|---|
| 1 | 1949 | During the earthquake, white sand was reported to have boiled out of ground cracking that initiated the Tacoma Narrow landslide. Chleborad and Schuster (1998) interpret this report as documenting a sand boil developed during earthquake shaking, which is generally accepted as evidence of soil liquefaction. An alternate explanation is that the vented sand may have been the result of piping along the incipient landslide failure surface due to high pore water pressures, which may or may not have been earthquake induced. |
| 2 | 1949, 1965 | During the 1949 earthquake an approximately 1000 ft (305 m) long ground crack developed along a line paralleling 11th Street with 6 in (15 cm) of vertical displacement. Sand boils appeared in the tide flats along Alexander Avenue between 11th Street and Lincoln Avenue during the 1965 event. |
| 3 | 1949, 1965 | Sand boils and ground settlement were observed at several points in the tide flats, and numerous water line breaks were reported after the 1949 earthquake. A 500 ft (152 m) long ground crack formed along Thorne Road in the port industrial area during the 1965 event. |
| 4 | 1949 | Sand boils were observed near East 23rd and G Streets during the earthquake. |
| 5 | 1949 | Sand boils appeared along the North Levee Road. |
| 6 | 1949 | Sand boils appeared along 44th Street East. |
| 7 | 1949 | Ground cracking, settlement, and lateral spreading and slumping were observed along Clarks Creek. |
| 8 | 1949 | Sand boils were observed at numerous localities north of the Puyallup in the vicinity of Freeman Road. |
| 9 | 1949, 1965 | A large number of sand boils and ground cracks were observed in the city of Puyallup during the 1949 earthquake in the area near Stewart Avenue. Reports included basements filled with 4 ft (1.2 m) of sand, broken concrete foundations, and groundwater flooding. Sand boils were observed at only one site, Aylen Junior High School, during the 1965 earthquake. |
| 10 | 1949 | Sand boils were reported in the field west of the Western Washington Fair Grounds. |
| 11 | 1949 | Sand boils were observed along 7th Avenue SE. |
| 12 | 1995 | Small sand boils were observed at a residence in the western part of Federal Way after the Robinson Point earthquake. Maximum vertical and horizontal ground displacements were approximately 2 in (5 cm). Movement resulted in through-going cracks in foundation stem wall and footing, and severe wracking of residence's framing (Palmer and Moses, 1996). |

groundwater table resulting from the dry winter is the most likely explanation for the lack of liquefaction observed in the study area during the Nisqually earthquake.

Site 1 in Table 2 describes sand venting from a 2 in. (5 cm) wide ground crack that developed during the 1949 earthquake behind the top of a 400 ft (122 m) high bluff at Salmon Beach. The bluff failed three days after the earthquake, and had an estimated volume of 1,000,000 $yd^3$ (760,000 $m^3$). Geologic reconnaissance of this landslide indicates that it occurred in Vashon gravelly recessional and advance outwash overlying older Pleistocene glacial and nonglacial deposits (Chleborad, 1994). These geologic units were found in this report to have a very low liquefaction susceptibility, so this reported occurrence is unusual. An alternate explanation is that the vented sand may have been the result of piping along the incipient landslide failure surface due to high pore-water pressures, which may or may not have been induced by liquefaction.

## LIQUEFACTION EVALUATION OF THE GREATER TACOMA URBAN 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, 2002; Shannon & Wilson, 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).

The Seed and Idriss procedure uses standard penetration test (SPT) N-values[1], sample descriptions, grain-size analyses, and groundwater 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 for obtaining those values. 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 mud-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 1586-84 (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). 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. This is a somewhat conservative value, as testing of CME automatic hammers on two WSDOT drill rigs indicated hammer efficiencies of 73 and 81 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 2487-90 (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) considers only 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 used in previously published liquefaction susceptibility maps for the Puget Sound region (for example, Grant and others, 1998; Shannon & Wilson, 1993; Palmer, 1995; Palmer and others, 1994, 1995, 1999, 2002). 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) indicate 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 approximately a 50 percent chance of being exceeded in the next 50 years based on the mapping of Frankel and others (1996).

[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 of the soil. Therefore, loose soils that are potentially liquefiable will have low SPT N-values.

We obtained SPT N-values and other necessary data (fines contents, groundwater 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.

Recent studies indicate that other earthquake sources have the potential to generate more severe ground shaking than the scenario earthquake conditions chosen for this study. The potential for $M_W$ 8 or larger earthquakes occurring on the Cascadia subduction zone has been recognized (Atwater, 1987; Weaver and Shedlock, 1996; Atwater and others, 1995) and is generally accepted in the engineering and earth-science communities. 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 damage.

A steep, east–west-trending Bouguer gravity gradient crossing the western portion of Pierce County was interpreted as a probable fault by Gower and others (1985). Brocher and others (2001) use a tomographic inversion of the 1998 SHIPS (Seismic Hazards Investigations in the Puget Sound) data to infer a steep bedrock fault, which they termed the Tacoma fault, in roughly the same location as the probable fault mapped by Gower and others (1985). Sherrod and others (2002) summarize evidence of sudden changes in land level about 1000 years ago that they attribute to coseismic uplift during an earthquake on the Tacoma fault. A large earthquake on the Tacoma fault might result in stronger ground shaking within the study area than that considered by the scenario earthquake conditions used in our liquefaction analysis.

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, Greater Eastside, and Olympia urban areas to provide a regionally consistent evaluation of the liquefaction hazard.

## Liquefaction Susceptibility Map Presentation and Accuracy

The liquefaction susceptibility map that accompanies this report was printed at a scale of 1:30,000 in order to present the entire study area on a single standard-size plate. However, the printed map was generated using 1:24,000-scale digital coverages of the geologic and liquefaction susceptibility mapping; therefore, the digital data reflect the original 1:24,000-scale of the hazard mapping.

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 in. (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 relative to the original geologic mapping 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 has 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 potential users of this map consider consultation with qualified practitioners commensurate with the level of risk they are willing to accept regarding the possible impact of earthquake-induced liquefaction.

## Liquefaction Analysis

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

- artificial fill and Holocene alluvium deposited at the mouth of the Puyallup River in the area of the intensely developed former tidal marsh and adjacent uplands (termed the 'filled tide flats'),
- artificial fill and Holocene alluvium deposited in the Puyallup Valley upstream from the filled tide flats,

- artificial fill and Holocene alluvium within the Chambers Creek drainage,
- Pleistocene Vashon glacial recessional outwash and ice-contact deposits composed primarily of sand (unit Qvrs),
- Holocene beach and landslide deposits,
- all other Pleistocene glacial and nonglacial deposits, and
- Holocene peat deposits presumed to have a thickness of 10 ft (3 m) or greater.

We used a modified version of the thickness criteria developed by Grant and others (1998) in determining the liquefaction hazard for five of the seven groupings. (We did not analyze Holocene beach and landslide deposits or peat, as no borings in our database encountered these deposits.) 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 or meters), 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.

Assuming the depth to groundwater to be the same as that at the time of drilling, we calculated the normalized aggregate thickness of liquefiable soils for all borings and generated cumulative frequency histograms for each of the first four of the geologic groupings (see Figs. 2–5). Histograms are not presented for the fifth grouping because the liquefaction response of this grouping was inconsequential. The histograms show, for each of the two ground motion scenarios, the percentage of borings that exceed a specific normalized aggregate liquefiable thickness. Normalized cumulative frequency histograms were used by Palmer (1995) and Palmer and others (1994, 1995, 1999, 2002) 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 3). 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 thickness criterion of 25 percent that we used in the 0.30 *g* scenario corresponds to that used by Grant and others (1998), who considered liquefaction to be significant where, in the upper 40 ft (13 m) of a boring, "a minimum of 10 ft (3 m) of soil (cumulative thickness) would liquefy in the 0.30 *g* earthquake".

In our final hazard determination, we also considered the historic occurrences of liquefaction for each geologic grouping. The thickness criteria hazard ratings for the five geologic groupings and the occurrence of liquefaction during historical earthquakes within the study area are summarized in Table 4.

## Results

### FILL AND HOLOCENE ALLUVIUM OF THE FILLED TIDE FLATS

Since the late 1800s, the marsh and intertidal area at the mouth of the Puyallup River have been covered with fill to allow the development of the Port of Tacoma and surrounding industrial facilities. The approximate outline of the filled tide flats is depicted on the accompanying map. Much of the fill was emplaced without any engineering design or inspection, and liquefaction of this unconsolidated fill and the underlying native soil has been observed during historic earthquakes.

We analyzed 284 geotechnical borings that penetrated fill and Holocene alluvium within the filled tide flats. The cumulative frequency histograms developed from these data are shown in Figure 2. The median penetrated thickness of the fill and alluvium in these borings is 50.0 ft (15.2 m); median depth to groundwater reported at the time of drilling was 6.5 ft (2.0

**Table 3.** 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 4.** Summary of thickness-criteria hazard ratings for the five 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 within the study area and the final assignment of liquefaction susceptibility hazard rating. N/A, analysis not performed for this ground-water condition

| Geologic grouping | Thickness criteria rating | | Historical liquefaction (Table 2) | Final liquefaction susceptibility hazard rating |
|---|---|---|---|---|
| | Ground-water depth at time of drilling | Ground water assumed at ground surface | | |
| Fill and Holocene alluvium of the filled tide flats | High | N/A | sites 2, 3 and 4 | High |
| Fill and Holocene alluvium of Puyallup Valley | Moderate | N/A | sites 5, 6, 7, 8, 9, 10, and 11 | High |
| Fill and Holocene alluvium of Chambers Creek | High | N/A | none observed | High |
| Sandy Vashon recessional outwash and ice-contact deposits (unit Qvrs) | Very low | Low to moderate | site 12 | Low t moderate |
| All other Pleistocene glacial and nonglacial deposits | Very low | Very low | possible occurrence at site 1 | Very low |

m). For groundwater depths measured at the time of drilling, approximately 54 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 52 percent of the borings encountered liquefiable soil exceeding an aggregate thickness of 25 percent. These values indicate that the fill and Holocene alluvium underlying the filled tide flats have a high liquefaction susceptibility (Table 4), based on the thickness criteria presented in Table 3. This rating is supported by the number of historic occurrences of liquefaction in this area (sites 2–4 in Table 2 and on the accompanying map).

### FILL AND HOLOCENE ALLUVIUM OF THE PUYALLUP VALLEY

The Puyallup Valley is a glacially carved trough that has been filled with a thick section of alluvial sediments during the mid- and late Holocene. Other than the filled tide flats discussed above, there are only small areas of artificial fill in the Puyallup Valley.

We analyzed 81 geotechnical borings that penetrated minor fill and Holocene alluvium in the Puyallup Valley. The cumulative frequency histograms developed from these data are shown in Figure 3. The median penetrated thickness of the fill and alluvium in these borings is 41.5 ft (12.6 m); median depth to groundwater reported at the time of drilling was 8.0 ft (2.4 m). For groundwater conditions encountered at the time of drilling, approximately 48 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 45 percent of the borings encountered liquefiable soil exceeding an aggregate thickness of 25 percent. By strictly applying the criteria in Table 3, these values indicate that the fill and Holocene alluvium underlying the Puyallup Valley have a moderate liquefaction susceptibility. However, we note that the aggregate thicknesses are within a few percent of a high hazard rating. The significant number of historic occurrences of liquefaction in this area (sites 5–11 in Table 2 and on the accompanying map) supports our assignment of a high liquefaction susceptibility hazard rating to the Puyallup Valley (Table 4).

The Puyallup River has been channelized along its reach west of the city of Puyallup for flood control purposes. The former course of the river has been mapped using aerial photography, and the former channels and meander bend cut-offs, as well as areas of bar and swale topography, are shown on the accompanying map. These abandoned courses of the Puyallup River and associated bar and swale topography may represent areas of locally higher liquefaction susceptibility. The abandoned channels are topographically low areas, and would consequently have a higher groundwater table than the surrounding flood plain. Also, areas of bar and swale topography are typically rich in clean sand with respect to overbank deposits, which are commonly composed of silt or silty sand. In a review of liquefaction caused by the Loma Prieta earthquake in the Monterey Bay region of California, Dupré and Tinsley (1998) found that liquefaction was concentrated in areas mapped as abandoned channel fill and point-bars within younger fluvial deposits.

### FILL AND HOLOCENE ALLUVIUM OF CHAMBERS CREEK

Chambers Creek is a large stream that flows directly into the Puget Sound near Steilacoom. The drainage basin for Chambers Creek is predominantly underlain by Vashon glacial outwash composed of sand and gravel; consequently the alluvium of Chambers Creek is largely composed of sand and gravel.

We analyzed 24 geotechnical borings that penetrated fill and Holocene alluvium in the Chambers Creek drainage, and show the cumulative frequency histograms developed from these data in Figure 4. The median penetrated thickness of the fill and Holocene alluvium in these borings is 34.5 ft (10.5 m); median depth to groundwater reported at the time of drilling was 5.8 ft (1.8 m). For groundwater conditions encountered at the time of drilling, approximately 58 percent of these borings contain some amount of liquefiable soil for the 0.15 *g* ground

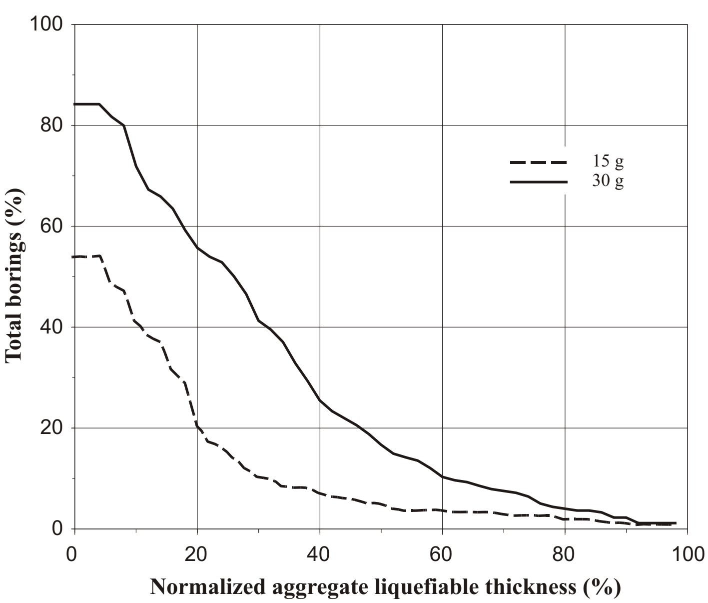


**Figure 2.** Cumulative frequency histograms developed from 284 geotechnical borings penetrating artificial fill and Holocene alluvium in the filled tide flats of Tacoma. Groundwater depth at the time of the scenario earthquake is assumed to be the same as the depth measured during drilling.

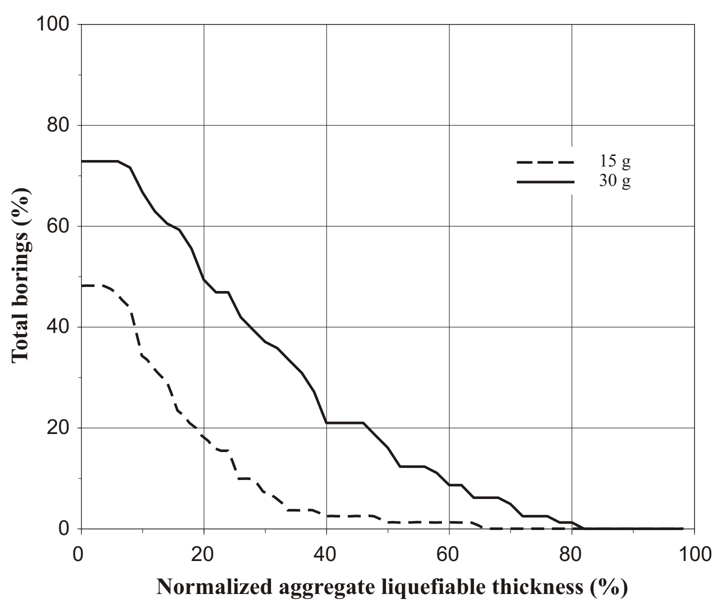


**Figure 3.** Cumulative frequency histograms developed from 81 geotechnical borings penetrating artificial fill and Holocene alluvium underlying the Puyallup Valley upstream from the filled tide flats. Groundwater depth at the time of the scenario earthquake is assumed to be the same as the depth measured during drilling.

motion scenario. For the 0.30 *g* scenario about 63 percent of the borings encountered liquefiable soil exceeding an aggregate thickness of 25 percent. These values indicate that the fill and Holocene alluvium underlying the Chambers Creek drainage have a high liquefaction susceptibility using the thickness criteria presented in Table 3. There are no reports of historic liquefaction in this area, so we assign this geologic category a high liquefaction susceptibility rating (Table 4) based solely on the results of the geotechnical boring analysis.

**VASHON SANDY RECESSIONAL OUTWASH**

Vashon recessional outwash and ice-contact deposits predominantly composed of sand (unit Qvrs) were separated from both silty or gravelly (units Qvrf and Qvrc, respectively) recessional outwash, glacial lake, and ice-contact deposits using agricultural soils mapping available for the study area (Snyder and others, 1973; Zulauf, 1979). Quantitative evaluation of the liquefaction susceptibility of unit Qvrs was based on our analysis of 22 geotechnical borings drilled in this deposit. The median drilled thickness of unit Qvrs in the borings is 19.9 ft (6.1 m); median groundwater depth at the time of drilling was 17.5 ft (5.3 m). Figure 5 presents cumulative frequency histograms for unit Qvrs based on analyses of these data. No borings encountered any liquefiable soil for the 0.15 *g* ground motion scenario using the groundwater depth measured at the time of drilling. Likewise, for this groundwater condition no borings contain more than a 25 percent aggregate thickness of liquefiable soil for the 0.30 *g* scenario. Therefore, unit Qvrs would have a very low hazard rating based on the thickness criteria presented in Table 3 and would not be particularly susceptible to liquefaction in its native state.

Previous assessments of sandy Vashon glacial outwash in the southwestern King County and the Olympia areas (Palmer and others, 1995, 1999) indicated that above a depth of approximately 20 ft (6.1 m) these deposits are susceptible to liquefaction in their native state, particularly in areas with a shallow groundwater table. These assessments were supported by the reported occurrences of liquefaction in unit Qvrs deposits during the 1949 and 1965 Puget Sound earthquakes (Palmer and others, 1995, 1999). Consequently, our finding that unit Qvrs has a very low susceptibility in the Tacoma study area contradicts the results of past assessments.

However, the median drilled depth for borings penetrating unit Qvrs is only slightly greater than the median groundwater depth measured during drilling, and the shallowest groundwater depth measured in any of the borings used in the analysis was 10 ft (3.0 m). Consequently, the very low hazard rating may not be representative of the actual hazard in areas where groundwater is shallow. To evaluate the liquefaction hazard for shallow groundwater conditions, we analyzed the geotechnical boring data assuming that groundwater was at the ground surface. The cumulative frequency histograms for this groundwater condition are shown in Figure 5. For groundwater at the ground surface, approximately 5 percent of the borings contain some amount of liquefiable soil for the 0.15 *g* ground motion scenario and about 35 percent of the borings contain more than a 25 percent aggregate thickness of liquefiable soil for the 0.30 *g* scenario. This corresponds to a low to moderate hazard rating based on the criteria presented in Table 3.

Liquefaction occurred at a site underlain by sandy Vashon glacial outwash in southwestern King County (site 12 in Table 2 and on the accompanying liquefaction susceptibility map) 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 (for example, Audemard and de Santis, 1991). The site was located in an area where the groundwater was very shallow as a result of heavy precipitation in the weeks preceding the earthquake, a condition that likely contributed to liquefaction. The residence was constructed on a cut-and-fill pad on a slope with a natural grade of approximately 10 percent. It is likely that disturbance of the native soil during grad-

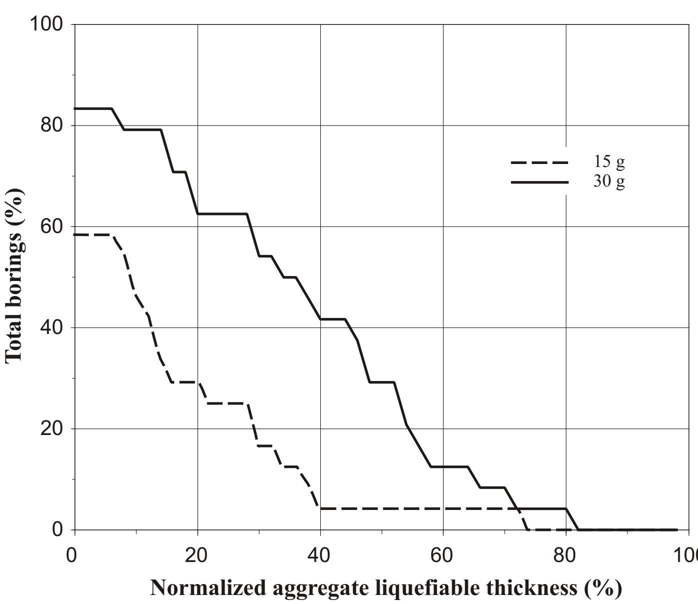


**Figure 4.** Cumulative frequency histograms developed from 24 geotechnical borings penetrating artificial fill and Holocene alluvium in the Chambers Creek drainage. Groundwater depth at the time of the scenario earthquake is assumed to be the same as the depth measured during drilling.

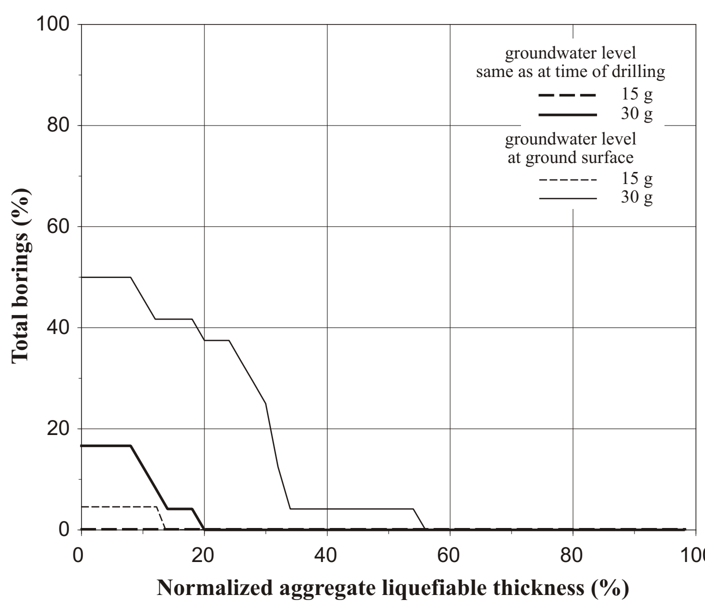


**Figure 5.** Cumulative frequency histograms developed from 22 geotechnical borings penetrating sandy Vashon recessional outwash and ice-contact deposits (unit Qvrs). Shown are results from two groundwater conditions at the time of the scenario earthquake: groundwater depth the same as that measured during drilling, and groundwater at the ground surface.

ing may have left it in a loose condition, which may have been another significant factor in the 1995 ground failure.

The liquefaction occurrence at site 12 indicates that groundwater near or at the ground surface does occur in unit Qvrs in the study area. Furthermore, our analysis assuming groundwater at the ground surface indicates that unit Qvrs is susceptible to liquefaction in areas of shallow groundwater. We conservatively choose to assign unit Qvrs a low to moderate liquefaction susceptibility rating based on the results of the analyses for both groundwater conditions, the historical occurrence of liquefaction at site 12 and within deposits of unit Qvrs outside of the study area, and the hazard rating given to unit Qvrs in other areas of the Puget Sound region (Palmer and others, 1995, 1999, 2002). Finally, we note that the liquefaction susceptibility of unit Qvrs may be substantially increased in areas of poorly engineered grading and fill.

#### HOLOCENE LANDSLIDE AND BEACH DEPOSITS

None of the borings compiled for this study penetrated Holocene landslide or beach deposits, and no quantitative analysis of the liquefaction susceptibility of these geologic units could be performed. We assign these deposits a low to moderate hazard based on previous liquefaction susceptibility assessments made in Palmer and others (1995, 2002) and Grant and others (1998) where limited geotechnical boring data was available for these geologic units.

#### 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 based on the following factors:

- predominance of a silty and (or) gravelly texture;
- significant consolidation of these units (with the exception of units Qvrc and Qvrf) because of glacial ice loading;
- a typically deep groundwater table (>30 ft or 9.1 m).

All of these factors tend to retard the liquefaction process, and consequently these deposits have been found to have a very low liquefaction hazard in previous studies (for example, Grant and others, 1998; Palmer and others, 1999).

We analyzed 106 geotechnical borings penetrating the units composing this grouping. We found that no borings encountered any liquefiable soil for the 0.15 *g* ground motion scenario using the groundwater depth measured at the time of drilling, and less than 2 percent of the borings had any liquefiable soil for the 0.30 *g* scenario. We also performed the liquefaction analysis for groundwater at the ground surface in order to determine if the typically deep groundwater tables documented in the boring database were a significant factor in inhibiting liquefaction. For groundwater at the ground surface, less than 1 percent of the borings contain liquefiable soil for the 0.15 *g* scenario, and only 0.4 percent of the borings contain more than a 25 percent aggregate thickness of liquefiable soil for the 0.30 *g* scenario. This corresponds to a very low rating using the thickness criteria shown in Table 3.

Only a single possible instance of liquefaction in these deposits (site 1 in Table 2) occurred in the Puget Sound region during the 1949, 1965, and 2001 earthquakes, and the interpretation of this instance as a bona fide liquefaction occurrence is equivocal. Based on the results of our analysis of the geotechnical boring data, we assign a very low susceptibility hazard rating to this group of geologic units (Table 4).

#### 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. Most of the peat deposits shown on the accompanying liquefaction susceptibility map encircle small kettle lakes developed on the outwash plain or occur along the margins of the Puyallup Valley. The soils composing the mapped peat unit are generally not liquefiable, but may be subject to significant strength loss and both transient and permanent vertical and lateral displacement caused by ground shaking. The collapse of the Struve Slough bridges in California during the 1989 Loma Prieta earthquake, caused by severe tilting of the support columns, provides an example of the types of ground deformation that can occur in peaty soils (Chieruzzi and others, 1990; Buckle and others, 1990). Also, sand layers interbedded within the peat deposits may be liquefiable.

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