Geologic Folio of the Olympia–Lacey–Tumwater Urban Area, Washington: Liquefaction Susceptibility Map

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Location of area

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Natural Resources
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INTRODUCTION

The Washington Department of Natural Resources, Geology and Earth Resources Division, is actively investigating earthquake hazards statewide and has concentrated its technical program on mapping deposits in the Puget Sound region that are subject to seismically induced soil liquefaction. The purpose of this report is to present the technical evaluation used in generating the accompanying liquefaction susceptibility map of the Olympia–Lacey–Tumwater urban area. This map encompasses the Olympia–Lacey–Tumwater Urban Growth Area, the alluvial valley along the lower reach of the Nisqually River, and the low-lying tidal marsh and alluvial plain in the vicinity of Mud Bay.

Liquefaction occurs when a water-saturated, sandy soil loses strength during vibratory 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 overlying weight of the soil mass. 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 on the moving soil mass. The collapse of the grain structure can result in settlement of the soil column and loss of soil 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.

The accompanying 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 a relative assessment of the likelihood of soil liquefaction during an earthquake. The various data used in the liquefaction susceptibility assessment

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Errata

There are two mistakes on the accompanying map that are explained in the caption of Figure 1 and in the second paragaph on page 9.

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have been correlated with geological units mapped at 1:24,000 scale (1 in. = 2,000 ft or 1 cm = 240 m). Because of the regional nature of this map, only generalized areas prone to liquefaction can be delineated, and only a relative susceptibility (ranging from very low to high) is assigned to these areas. This map *cannot* be used to determine the presence or absence of liquefiable soils beneath any specific locality. Likewise, no estimate of the damage resulting from liquefaction is presented in this study; in many instances, liquefaction 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.
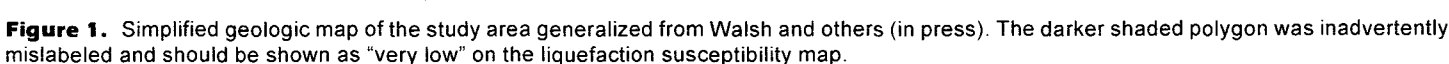
The liquefaction susceptibility map presented in this report is based on recent 1:24,000-scale geologic mapping conducted in support of this project and the analyses of 231 geotechnical borings obtained from the Washington State Department of Transportation and local government agencies. Four categories of geologic deposits found in the study area are assigned a relative liquefaction hazard ranking determined through analysis of the geotechnical data, geological characterization, and historical reports of liquefaction during the 1949 Olympia (magnitude 7.1) and 1965 Seattle–Tacoma (magnitude 6.5) earthquakes.

Artificial fill and Holocene (younger than 10,000 years) alluvium are determined to have a high susceptibility to liquefaction. The high liquefaction hazard in portions of downtown Olympia underlain by fill is well quantified based on the analysis of 91 borings located in this area. The high liquefaction hazard area encompassing the Deschutes River valley is defined using measured shear wave velocities obtained in a boring drilled in Pioneer Park. Analyses of geotechnical borings drilled in the Nisqually River valley and Mud Bay area indicate that liquefiable soils are present, but quantitative characterization of the hazard in these areas cannot be performed because of the limited number of available borings. No geotechnical data were available in other high liquefaction hazard areas located along minor streams and drainages. Consequently, assessment of the liquefaction susceptibility is based on the age and geological setting of these deposits.

Late Pleistocene (12,000–14,000 year old) glaciolacustrine (glacial lake) and glaciofluvial (glacial river) sediments predominantly composed of sand and Holocene landslide deposits are regarded as having a low to moderate liquefaction susceptibility. Geotechnical analyses using ground-water conditions reported at the time of drilling indicate that unit Qvrs deposits

Figure 1. Simplified geologic map of the study area generalized from Walsh and others (in press). The darker shaded polygon was inadvertently mislabeled and should be shown as "very low" on the liquefaction susceptibility map.

have a low to moderate liquefaction susceptibility. Some of the reported occurrences of liquefaction ground failures during the 1949 and 1965 Puget Sound earthquakes are located within this sandy glacial unit.

Quantitative evaluation of geotechnical data obtained from all other Pleistocene deposits indicates a very low susceptibility to liquefaction. The historic record supports the very low susceptibility ranking, as there are no reported instances of liq-

EXPLANATION

QUATERNARY UNCONSOLIDATED DEPOSITS

Holocene Nonglacial Deposits

af **Artificial fill**—Clay, silt, sand, gravel, organic matter, shells, and construction debris; in downtown Olympia, fill generally composed of dredge spoils from Budd Inlet, wood waste from sawmills, and construction debris and is commonly thick (>20 ft/ 6.1 m). In the port area, it is usually capped with a more recent compact structural fill. The fill contact shown for the downtown and port areas of Olympia is based on the ca. 1870 shoreline (Olympia Planning Department, written commun., 1996). Construction fills on the upland are not shown because their extent and thickness are unknown, except for a silty sand and gravel fill placed on peaty soils near Cooper Point Road in the northwestern part of the map.

Qa **Alluvial, estuarine, and beach deposits**—Silt, sand, gravel, and peat deposited in stream beds, estuaries, and on beaches; includes some lacustrine deposits; surface relatively undissected; in the subsurface, includes alluvial and estuarine deposits of Budd Inlet and Moxlie Creek beneath artificial fill.

Qp **Peat**—Organic and mineral sediments deposited in closed depressions in the vicinity of Black Lake; includes peat, muck, silt, and clay. Mapped only where judged to be at least 10 ft (3 m) thick.

Qls **Landslide debris**—Rock fragments, colluvium, soil, and locally organic matter deposited by mass wasting; unstratified and poorly sorted; surface commonly hummocky; landslides not systematically mapped for this study.

Pleistocene Glacial Deposits

Vashon Stade of Fraser Glaciation

Qvrs **Latest Vashon recessional glaciolacustrine and low-energy fluvial sand, silt, and locally gravel or clay**—Reworked recessional and proglacial stratified outwash sand and silt deposited in and around the margins of glacial lakes and low-energy streams; includes Vashon moraines from just south of Nisqually delta southward and southwestward to Pattison Lake; hosts numerous steep-walled lakes interpreted as kettles and rare boulder erratics, evidence that this unit was largely deposited during deglaciation when there was stagnant ice occupying much of south Puget Sound. Near Boston Harbor, where this unit appears to be entirely composed of laminated clay and silt, it is designated unit Qvc and mapped separately because it is thought to be too fine grained to liquefy.

Qvr **Vashon recessional outwash**—Chiefly recessional and proglacial stratified outwash sand and gravel, locally containing boulder erratics, silt, and clay; also contains laminated lacustrine deposits and ice-contact stratified drift.

Qvt **Vashon till**—Gray, unsorted, unstratified to weakly stratified, highly compact mixture of clay, silt, sand, gravel, and boulders deposited directly by glacier ice; locally contains outwash sand and gravel both within and overlying till; age of maximum advance in this area estimated as ~16,950 calendar yr B.P. (Porter and Swanson, 1998).

Qva **Vashon advance outwash**—Outwash sand and gravel and lacustrine clay, silt, and sand deposited during glacial advance, generally underlying till; where till is absent, unit differentiated from recessional outwash on basis of greater compactness due to being overridden by ice; sands commonly thick, well sorted, and fine grained (locally called Colvos Sand), with lenses of coarser sand and gravel; locally contains nonglacial sediments not separately mappable at this scale.

Pre-Vashon Pleistocene Deposits Undivided

Qu **Pre-Vashon sediments**—Glacial and nonglacial sediments beneath Vashon drift. In near-vertical exposures, includes some Vashon advance outwash mapped together with pre-Vashon nonglacial sediments (previously mapped as Kitsap Formation; Noble and Wallace, 1966), consisting of laminated clay and silt, peat, and minor sand and gravel; may also include an older glacial drift consisting of till and outwash sand and gravel.

UNDIFFERENTIATED BEDROCK

b In the western and northwestern part of the map, consists of fine-grained basalt flows and flow breccia of the Crescent Formation; in the southern part of the map, contains marine siltstone and basaltic and feldspathic sandstone of the McIntosh Formation, and an unnamed basaltic andesite intrusion.

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uefaction during the 1949 and 1965 earthquakes in these deposits. Lithified bedrock is not susceptible to liquefaction and should have a nil ranking. However, unmapped deposits of fill soils may occur within areas of mapped bedrock outcrop. Consequently, areas of mapped bedrock are assigned a very low or nil susceptibility to account for the possibility of isolated occurrences of potentially liquefiable fill soils on otherwise nonliquefiable bedrock. Peat soils are included as a separate unit on the accompanying liquefaction susceptibility map. No geotechnical borings penetrated these peat deposits, and consequently no liquefaction assessment is presented. Typically peat soils are not capable of liquefying, but may be subject to significant settlement caused by ground shaking (termed dynamic compaction).

GEOLOGY OF THE OLYMPIA–LACEY–TUMWATER URBAN AREA

The glacial history and geology of south Puget Sound are well summarized by Bretz (1913), who mapped the entire Puget Sound basin in reconnaissance. Noble and Wallace (1966) mapped the geology of Thurston County at a scale of 1:72,400. The Coastal Zone Atlas of Washington (Washington Department of Ecology, 1980), refined Noble and Wallace's mapping at a scale of 1:24,000 for a half-mile-wide strip along the shoreline. Walsh (1987) compiled these data, augmented by reconnaissance mapping, for the southwest quadrant of the Washington State Geologic map (Walsh and others, 1987). Subsequently, Pringle (1990) mapped agricultural soils at a scale of 1:24,000 for all of Thurston County. The geologic map from which the liquefaction susceptibility map is derived (Walsh and others, in press) was compiled from these sources and unpublished mapping of Gerstel and Palmer (1993), supplemented by field inspection of numerous beach bluff and stream channel exposures, construction site excavations, and gravel pits; air photo interpretation; and interpretation of more than 200 geotechnical boreholes and over 1000 water wells (modified from Drost and others, 1998).

Contacts between map units are frequently not exposed and are only approximately located. They are generally located as compiled from previous sources, except where better constrained by newer exposures, geotechnical boreholes, and water wells, or where required by new geological interpretation. Location accuracy of contacts is judged to be ±200 ft (61 m). In addition, the contacts between some units are gradational. We have tried to consider geotechnical significance in the mapping of geological units and have attempted to show units only

where we think they are thicker than about 5 to 10 ft (1.5–3 m) or where they mask the underlying lithology. A generalized geologic map for the study area is shown in Figure 1.

Late Quaternary Geologic History

Because bedrock and older glacial and nonglacial deposits have low susceptibility to liquefaction, the latest glacial and postglacial Quaternary geologic history is most relevant to liquefaction susceptibility mapping. A generalized geologic history of the Puget Sound basin is described by Booth (1994). As ice moved southward from Canada across the Strait of Juan de Fuca, it impounded a lake in the Puget Sound basin. Clay and silt were deposited where the ice front was relatively distant and coarser sediments were deposited nearer the ice, forming thick deposits of advance outwash commonly consisting of a progradational sequence of silt and clay overlain by sand and gravel. Ice eventually flowed south across all of present-day Puget Sound as far as Rochester and Tenino. Ice and subglacial meltwater cut channels into the advance outwash fill and older unconsolidated sediments, carving deep troughs and eroding much of the sediment. Glacial meltwater from the ice sheet flowed southward and southwestward to the Chehalis River, depositing some of this basin fill and other glacial debris as outwash. Areas of dead-ice were left in portions of the study area as glacial ice retreated north from the Olympia area. A large number of kettle lakes, which form around isolated blocks of melting ice, are evidence of the stagnant ice. Glacial meltwater filled the troughs that had been eroded into the earlier Pleistocene tills, outwash deposits, and bedrock and formed interconnected lakes (for instance, glacial Lakes Russell and Nisqually) that lay in present-day Puget Sound.

Drainage reorganized to flow northward between, within, and on top of blocks of ice through the recently deposited outwash into these lakes, as evidenced by paleocurrent indicators in unit Qvrs that are generally northward-directed. Because the streams were lower energy than the outwash streams, only sand and silt (with occasional thin gravel lags) were transported and deposited in streams prograding northward into the arms of the lake, which are presently the southernmost inlets of Puget Sound. (For a more thorough discussion of the subglacial channel network, see Booth, 1994, and Booth and Goldstein, 1994.)

The thickness of unit Qvrs varies substantially throughout the area, reaching more than 100 ft (30 m) in the downtown Olympia area and Deschutes River valley. Lacustrine silts (and rare clays and peats) commonly overlie and are interbedded with unit Qvrs sands, particularly on the uplands dividing the Puget Sound inlets. This unit tends to be better sorted and looser than the outwash sand and grave land behaves differently during earthquake shaking.

After glacial ice retreated from the Puget Lowland, the Puget Sound basin once again became an arm of the sea. Sea level, however, was much lower than the level of any lake that

Table 1. Descriptions of ground failures reported during the 1949 and 1965 earthquakes in the study area that could be related to soil liquefaction. Modified from Chleborad and Schuster (1998)

Site no.	Quotation and (or) comment
1	"Clifford Kyllonen, Olympia tug boat skipper, reported that 150 feet [45 m] of the sandspit of Cooper's point, seven miles [11 km] north of Olympia crumpled and disappeared into Puget Sound during the shock. Kyllonen said he was standing off the spit when the shock occurred, and took color pictures of the mass of land sinking beneath the waves. He said geodetic survey maps showed the spit being five feet [1.5 m] above water at high tide. At high tide yesterday, Kyllonen took soundings and found the spit was now 50 ft [15 m] below the surface." (*Bremerton Sun*, 4/15/49, p. 1) "…it normally extends 300 yds [274 m] and at high tide is partially covered by water. After the quake the middle portion of the point no longer was visible at low tide. Between 100 and 150 feet [30 and 46 m] of the spit had sunk into the bay. About 25 feet (7.6 m) of the north end of the point remained as an island." (*Daily Olympian*, 4/13/49, p. 11)
2	"The entire port area, a man-made fill, settled 5 inches [13 cm]….Evidence of differential settlement around the Port of Olympia Cold Storage Warehouses of 2 inches [5 cm] was seen." (U.S. Army Corps of Engineers, 1949)
3	"Breaks in water mains occurred during the 3 days following the earthquake. In all, 24 breaks were reported. The most serious drop in pressure (from 90 p.s.i. to 20 p.s.i.) resulted in the temporary closing of the business district." (U.S. Army Corps of Engineers, 1949) "…water and gas mains were broken (in Olympia)." (Murphy and Ulrich, 1951)
4	"Shifting earth sent the edge of this highway at Olympia into Capitol Lake behind the state capitol. A half-mile [0.8 km] section was damaged." (*Tacoma News Tribune*, 4/30/65, p. A-6) "Sand boils or 'mud volcanoes' along Capitol Lake in Olympia indicate local soil liquefaction during the 1965 quake. Such features are formed by geysers of muddy water escaping from saturated sediments." (Noson, 1984)
5	(Northern Pacific Railway, Grays Harbor Line) "Mile Post 10½—Embankment slipped out for 45 feet [14 m]." (U.S. Army Corps of Engineers, 1949)
6	"An island has appeared in Moss Lake east of Stevens Field. It obviously came into existence during the big quake Wednesday. Union Pacific Railroad workers said they spotted the new island while repairing quake damage to the tracks. The appearance of the island caused the level of the lake to raise considerably. An overflow eventually brought the lake back to its normal level, however." (*Daily Olympian*, 4/15/49, p. 1)
7	"Thursday morning's seismic shock shook loose part of a Capitol Lake hillside snapping off 40 yards [37 m] of the City of Tumwater's main sewer line and diverting sewage into the lake. Tons of hillside opposite Wildwood Center in the 2800 block of Capitol Boulevard tumbled a hundred yards [91 m] downhill, covering a railroad spur and leaving behind another 50 yards [46 m] of Union Pacific freight line track dangling naked but unbroken." (*Daily Olympian*, 4/29/65, p. 1)
8	"…about 75 feet [23 m] of one lane of the Black Lake road slipped into the lake about a half mile [0.8 km] north of Columbus Park." (*Daily Olympian*, 4/14/49, p. 1). Failure involved a steep lake bank and roadway on west side of Black Lake. The lake bank is approximately 25 ft (7.6 m) high. Cracks in the pavement indicate continued instability at this location (April, 1999).
9	"We really felt it bad on S.E. side of Lake Patterson. As I sat up after the shaking ground threw me, I saw the last cars of a freight train go over the trestle across the lake, then the land slid from under the tracks and at the same time the water rose over dock (10 or 12 inches) [25 or 30 cm]." (Mrs. Harry A. Esborg, written commun., 1949). "Bridge 31—East Approach: Embankment for 275 ft [84 m] slid into Patterson Lake. Repairs by contractor—25,000 CY (19,100 m³) mtl." (U.S. Army Corps of Engineers, 1949)

had occupied Puget Sound (Thorson, 1981) and lower than present sea level (Dragovich and others, 1994, and references therein). Streams flowing into Puget Sound after deglaciation had a lower base level and cut channels to much below present-day sea level. As sea level rose to its present position, alluvium and estuarine sediments were deposited in these channels. Geotechnical boreholes used in this study show that postglacial sediments in the Nisqually Delta, for instance, extend to at least 100 ft (30 m) below sea level.

Extensive fills have been placed in the Deschutes River and Moxlie Creek drainages within the downtown Olympia area. These have commonly been dredge spoils from Budd Inlet and were not compacted to present-day engineering standards. The fill also contains construction debris and wood waste from sawmills in the port area north of 4th Ave.

HISTORIC LIQUEFACTION IN THE OLYMPIA–LACEY–TUMWATER URBAN AREA

The two largest earthquakes in recent historic times in the Puget Sound region are the 1949 surface wave magnitude (M_s) 7.1 Olympia and the 1965 M_s 6.5 Seattle–Tacoma earthquakes. The study area was exposed to Modified Mercalli Intensity VIII and VII shaking in the 1949 and 1965 events, respectively (Murphy and Ulrich, 1951; Roberts and Ulrich, 1951; von Hake and Cloud, 1967). Sites of ground failures caused by liq-

MODIFIED MERCALLI INTENSITY SCALE

I.   Not felt except by a very few under especially favorable circumstances.

II.   Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III.   Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.

IV.   Felt indoors by many, outdoors by few during the day. At night, some awakened, especially light sleepers. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V.   Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.

VI.   Felt by all; many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.

VII.   Damage negligible in buildings of good construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving motor cars.

VIII.   Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.

IX.   Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.

X.   Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

XI.   Few, if any, [masonry] structures remain standing. Bridges destroyed. Rails bent greatly.

XII.   Damage total. Lines of sight and level distorted. Objects thrown into the air.

uefaction in the study area have been reported by Hopper (1981) and Chleborad and Schuster (1998), and are summarized in Table 1 and shown on the accompanying map. A report of liquefaction near Stevens Field (site 6 in Table 1) was obtained from the *Daily Olympian* newspaper (April 15, 1949, edition).

Site 1 in Table 1 and on the accompanying map is a submarine landslide that occurred at the end of Cooper Point during the 1949 earthquake. Approximately 150 ft (46 m) of the sand spit disappeared, and soundings made after the earthquake (see Table 1) indicated water depths of 50 ft (15 m) in areas where the sand spit was above high tide prior to the earthquake. The disappearance of the spit resulted from a flow slide and is clearly an indicator of liquefaction at the site. No water wave was reported from the flow slide, suggesting that this was a slow-moving failure.

Site 2 of Table 1 is settlement likely caused by liquefaction and (or) dynamic compaction of the fill and native soils underlying the port area of Olympia during the 1949 earthquake. Figure 2A shows wooden piles that have erupted through the asphalt pavement in the port area. The results of the downtown fill area liquefaction analysis discussed below would indicate that the observed settlement is likely liquefaction-induced.

Site 3 of Table 1 documents the breakage of numerous water lines that serviced the downtown and port areas of Olympia during the 1949 earthquake. Pipeline breakages on level ground during an earthquake typically result from movement of the soil in response to liquefaction, either by vertical settlement or lateral spreading. An interesting anecdote is reported in U.S. Army Corps of Engineers (1949).

> "A serious [water main] break near the port area caused an interruption of water service for 13 hours, during which time a grave fire hazard was present in the areas because of 12,000 gallons of gasoline and 5,000 gallons of fuel oil which had escaped from damaged pipe lines. The hazard was controlled by hauling and dumping sand over the area, until water service was restored."

The occurrences discussed in site 4 of Table 1, located in the downtown fill area, are unequivocal instances of soil liquefaction (sand boils and lateral spreading) during the 1965 earthquake. Figures 2B and 2C show lateral spreading and sand blows along the Deschutes Parkway.

Site 5 of Table 1 is a description of an embankment failure along the Northern Pacific railroad line during the 1949 earthquake. This failure is believed to have occurred on the stretch of rail line along Percival Creek west of Capitol Lake. This section of rail line is situated on fill and (or) alluvial deposits that slope down to the creek. Numerous springs and seeps can be observed along the length of the Percival Creek alignment, indicating many areas of shallow ground-water conditions. The limited description provided by the reference source (U.S. Army Corps of Engineers, 1949) indicates that this could either be a landslide or a liquefaction-induced ground failure.

Site 6 of Table 1 appears to be the description of a series of sand boils or blows surfacing in Moss Lake during the 1949 earthquake. These features could be the result of liquefaction of the underlying soils, which in this location are sandy unit Qvrs.

Site 7 of Table 1 is a landslide that occurred during the 1965 earthquake. The failure involved the fill, and possibly the un-

Figure 2. Earthquake-induced ground failures in the greater Olympia area: **A.** "Subsidence of fill brought this old piling to view through asphalt pavement in Olympia. In other areas, piles not driven to refusal dropped out of sight, while some freestanding piles rose." (Photo and quote from Edwards, 1951.) Site 2 from Table 1. **B.** A liquefaction-induced lateral spread damaged the Deschutes Parkway in Olympia during the 1965 earthquake. (Photo by G. W. Thorsen.) Site 4 from Table 1. **C.** Sand blows along Deschutes Parkway in Olympia indicating liquefaction of the underlying soils during 1965 earthquake. (Photo by G. W. Thorsen.) Site 4 from Table 1. **D.** Landslide along a 400 ft (122 m) long section of a Union Pacific Railway branch line near Olympia during the 1965 earthquake. (Photo by G. W. Thorsen.) Site 7 from Table 1. **E.** "...about 75 feet of one lane of Black Lake Boulevard slipped into the lake about a half mile north of Columbus Park (now Guerin Park)." (*Daily Olympian*, 4/14/49, p. 1). This description of the location of this failure, used in representing this site on the accompanying liquefaction susceptibility map, is incorrect. The actual location on the accompanying map (verified by careful inspection of the photo) is at the letter "v" in the word "Blvd" at the northwest edge of Black Lake. This failure involved the steep lake bank and roadway on west side of Black Lake. (Photo courtesy of Jack Goldsby.)
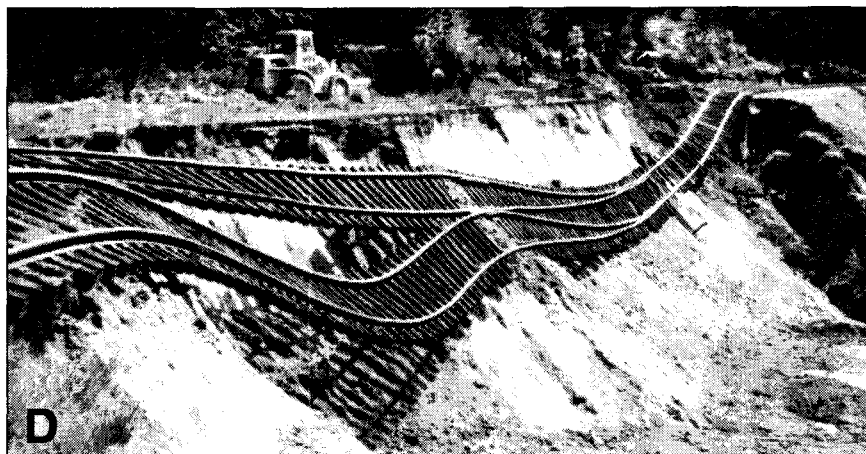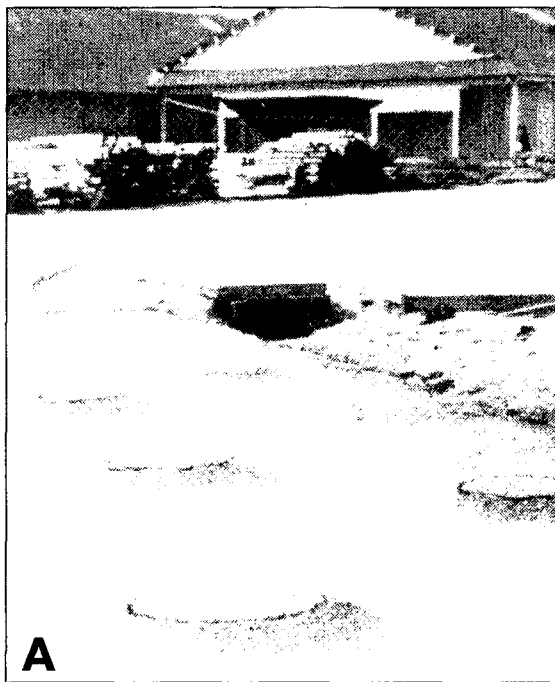
derlying sandy unit Qvrs, supporting the railroad tracks. This failure is shown in Figure 2D; the pipe discharging water in the background is the ruptured sewer line servicing Tumwater. A larger landslide occurred in this location during the winter of 1996–97, again damaging the railroad line and breaking the sewer line, which again spilled raw sewage into Capitol Lake. Loss of soil strength resulting from liquefaction of the fill and (or) sandy unit Qvrs may have been a contributing factor in the 1965 landslide.

Site 8 of Table 1 is a landslide that damaged Black Lake Boulevard during the 1949 earthquake. This ground failure is shown in Figure 2E. Site 8 is mislocated on the accompanying liquefaction susceptibility map; the correct location is near the letter 'v' in the word 'Blvd' at the northwest edge of Black Lake. Geotechnical borings along Black Lake Boulevard approximately 500 to 600 ft (152–183 m) north and south of the 1949 failure indicate that a section of clean to silty sand (unit Qvrs) underlies the road and extends to below lake level. This sand is underlain by a sequence of silt and clay, a glaciolacustrine facies of unit Qvrs. The depth of the ground-water table is controlled by the level of Black Lake, so that the basal portion of the sand unit is saturated. A reasonable interpretation is that liquefaction of the sandy section occurred during the 1949 earthquake. The resulting loss of soil strength at the base of the slope was a likely cause of the ensuing landslide.

Site 9 of Table 1 describes an embankment failure of the railroad line crossing Pattison Lake during the 1949 earthquake. This failure may have resulted from liquefaction of the submerged portion of the embankment or underlying native soil (interpreted as unit Qvrs in this study), similar to the failure mechanism suggested for site 8. Alternatively it could have simply been a landslide failure of the embankment resulting from strong ground shaking.

LIQUEFACTION EVALUATION OF THE OLYMPIA–LACEY–TUMWATER URBAN AREA

The analysis of liquefaction susceptibility in the Olympia–Lacey–Tumwater urban area follows the methodology used by Palmer (1995), Palmer and others (1994; 1995), Grant and others (1998), and Shannon & Wilson, Inc. (1993). The potential for soil liquefaction is estimated using the field evaluation methodology developed by Seed and Idriss (1971) and modified by Seed and others (1983, 1985). This field evaluation procedure uses Standard Penetration Test (SPT) N-values (ASTM D 1586-84[1]), sample descriptions, grain-size analyses, and measured ground-water depths obtained from geotechnical borings to estimate the factor of safety for a hypothetical earthquake with a specified magnitude and peak ground acceleration (PGA). As this study is primarily concerned with evaluating liquefaction that could cause structural damage at the ground surface, the evaluation of liquefaction is limited to the upper 50 ft (15 m) of the borings. This depth restriction also allows a more direct comparison to historic reports of liquefaction.

Seed and others (1985) note that variation in drilling methods and sampling procedures used in geotechnical borings can significantly affect the measured SPT N-values and present recommended procedures for obtaining SPT N-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. For example, 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 did document having followed all the recommended procedures. Consequently, all available geotechnical boring data are used in evaluating liquefaction susceptibility as long as the basic parameters of the Standard Penetration Test have been followed. It is assumed that the energy delivered to the sampler was 60 percent of theoretical maximum.

The 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 are used to provide this parameter when available; otherwise the fines fraction is estimated from the soil category denoted on the boring log using the Unified Soil Classification System (USCS, as defined in ASTM D 2487-90[2]). If no USCS soil classification is presented on the log, sample descriptions are used to derive the appropriate soil category. The methodology of Seed and others (1983, 1985) only considers sand soils (USCS classification) as being potentially liquefiable. Liquefaction of soils classified as silts is not explicitly considered in this study even though liquefaction of native silt soils has been observed in past earthquakes (for example, 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).

Recent studies indicate that other earthquake sources have the potential to generate more severe ground motions than the scenario earthquakes chosen for this study. In the last 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 PGAs in the Puget Sound region resulting from such an earthquake would be reasonably bounded within a range of 0.15 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 event considered in this study. The longer duration of shaking would 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.

Liquefaction Analysis

The geologic units in the study area are grouped into four liquefaction susceptibility categories on the basis of their geological and engineering characteristics. These groupings are:

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[1] American Society for Testing and Materials (ASTM), 1991, D 1586-84, Standard method for penetration test and split-barrel sampling of soils. *In* Annual book of ASTM standards, v. 04.08, Soil and rock; dimension stone; geosynthetics, p. 232-236.

[2] American Society for Testing and Materials (ASTM), 1991, D 2487-90, Standard test method for classification of soils for engineering purposes. *In* Annual book of ASTM standards, v. 04.08, Soil and rock; dimension stone; geosynthetics, p. 309-319.

I artificial fill and Holocene alluvium,

I late Pleistocene glaciolacustrine and glaciofluvial deposits composed chiefly of sand and Holocene landslide deposits,

I all other Pleistocene glacial and nonglacial deposits, and

I outcrop areas of Tertiary volcanic and sedimentary bedrock.

The SPT N-values and other necessary data (fines content, ground-water depth, etc.) are obtained from the log of a geotechnical boring so that the thicknesses and depths of individual liquefiable soil units and the total thickness of liquefiable material in that boring can be estimated. Liquefaction at a particular depth is considered to occur when the factor of safety (ratio of resisting stresses to driving stresses) is less than unity for the input sample data and ground motion conditions (earthquake magnitude and PGA). The thickness of liquefiable material and total thickness of each hazard category encountered in a boring is obtained from this factor of safety analysis. Results from all of the borings analyzed are then combined to evaluate the overall liquefaction susceptibility for each hazard category.

Calculation of the factors of safety using the field evaluation methodology of Seed and others (1983, 1985) are made for a hypothetical earthquake of magnitude 7.3 (M_w 7.3) that produces a PGA of either 0.15 g or 0.30 g. This is consistent with the scenario earthquakes 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). The M_w 7.3 scenario earthquake is intended to represent an intermediate depth (37 mi/60 km) earthquake located within the subducting Juan de Fuca plate (intraplate earthquake) and is analogous to the 1949 Olympia event. The two values of PGA used in the scenario earthquakes are expected to bracket the range of damaging ground motions that would arise from a M_w 7.3 intraplate event. The 0.30 g PGA corresponds closely to the PGA value measured in downtown Olympia during the 1949 earthquake.

The evaluation of liquefaction susceptibility presented in this study is somewhat nonconservative because liquefaction of silt soils is not considered, and the choice of scenario earthquakes does not necessarily represent the most severe earthquake ground motions that can occur in 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 and Tacoma urban areas so that a regional perspective on the relative liquefaction hazard may be obtained.

High Hazard

The results of this investigation show five general areas that are classified as having a high liquefaction susceptibility hazard. These areas include:

I major artificial fill in downtown Olympia,

I the Deschutes River valley upstream of Tumwater Falls,
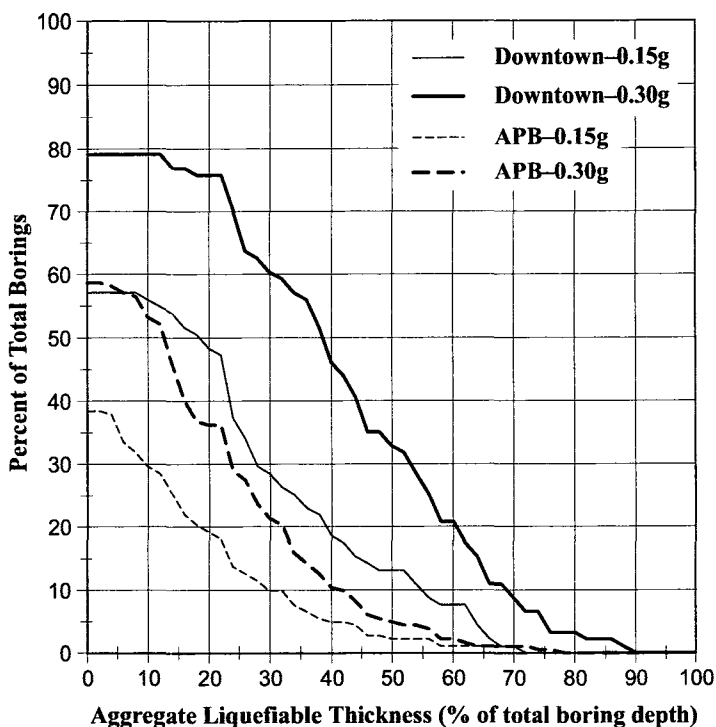
I the Nisqually River valley,

Figure 3. Cumulative frequency histograms showing the percentage of borings penetrating fill and Holocene native soils in the downtown Olympia area that exceed a normalized aggregate liquefiable thickness. Also shown are the cumulative frequency histograms for Duwamish valley alluvium (APB) in the Auburn and Poverty Bay quadrangles (Palmer and others, 1995), which is considered to have a high liquefaction susceptibility.

I the Mud Bay vicinity, and

I major tributary streams of the Black River and smaller streams draining into Puget Sound.

The high hazard area in downtown Olympia is delineated using the circa 1870 shoreline (Olympia Planning Department, written commun., 1996). Significant thicknesses of fill (usually greater than 10 ft or 3 m) were emplaced in areas waterward of the circa 1870 shoreline to provide additional land for development. This fill overlies Holocene estuarine and alluvial deposits that consist of plastic silts and clean to silty sands. Vashon recessional glaciolacustrine and glaciofluvial sands (unit Qvrs) directly underlie these Holocene deposits.

Ninety-one borings that penetrated the downtown Olympia fill and Holocene deposits are analyzed for their liquefaction susceptibility using the factor of safety evaluation discussed previously. The ground-water conditions observed at the time of drilling are used in the liquefaction analysis. For each boring, the aggregate thickness of liquefiable fill and Holocene deposits is combined and normalized as a percentage of the total drilled thickness of these units. The cumulative frequency histogram presented in Figure 3 shows the percentage of downtown Olympia borings that exceed a normalized aggregate liquefiable thickness. These cumulative frequency histograms are used by Grant and others (1998), Shannon & Wilson, Inc. (1993), Palmer (1995), and Palmer and others (1994, 1995) to characterize liquefaction susceptibility in other parts of the Puget Sound region. Average drilled thickness of fill and Holocene deposits in the 91 downtown borings is 24.0 ft (7.3 m). If this average drilled thickness and the cumulative frequency histogram of Figure 3 are combined, then approximately 57

percent of these borings contain at least 1 ft (0.3 m) of liquefiable soil for the 0.15 g scenario. Likewise, about 46 percent of the borings contain at least 10 ft (3.0 m) of liquefiable soil for the 0.30 g scenario. These values verify that the downtown fill and Holocene deposits have a high liquefaction susceptibility using the thickness criterion presented in Grant and others (1998). Figure 3 also shows the cumulative frequency histograms for Duwamish valley alluvium in the Auburn area, considered as having a high liquefaction susceptibility (Palmer and others, 1995).

Figure 4 shows the median corrected SPT N-values ($N_1(60)$) at equally spaced depth intervals for the 91 downtown Olympia borings. Corrected SPT N-values for clean sand ($\leq 15\%$ fines) are binned using 5 ft (1.5 m) depth intervals, and the median value within the binned interval is plotted at the corresponding midpoint depth. The critical $N_1(60)$ value is computed at each midpoint depth for the 0.30 g PGA scenario earthquake for a sand with 15 percent fine content and a ground-water depth of 5 ft (1.5 m), a typical value for the downtown fill area. Liquefaction is predicted wherever measured $N_1(60)$ values at a given depth are less than the corresponding critical $N_1(60)$ values. The median $N_1(60)$ values measured in the 91 downtown Olympia borings are less than the critical $N_1(60)$ values except at midpoint depths of 5 and 30 ft (1.5 and 9.1 m). This characterization places the downtown Olympia fill and Holocene deposits in the high hazard category using the threshold criterion presented by Grant and others (1998).

Both methods of quantifying the liquefaction susceptibility of the fill and Holocene deposits underlying downtown Olympia indicate that these soils have a high liquefaction susceptibility. Occurrences of liquefaction in these deposits during the 1949 and 1965 earthquakes support the high susceptibility ranking. Geotechnical boring data indicate that the thickness of these liquefiable soils in the downtown area varies from 20 ft (6.1 m) to more than 60 ft (18.3 m) and that these liquefiable soils are underlain by a sequence of dense, generally nonliquefiable sand and silt interpreted as unit Qvrs and possibly older glacial sediments.

The soils underlying the Deschutes River valley upstream of Tumwater Falls are composed of 10 to 15 ft (3 to 4.5 m) of silty sandy gravel (Holocene alluvium) underlain by at least 100 ft (30 m) of clean to silty, fine- to medium-grained sand interpreted as unit Qvrs. The modern valley along this stretch of the Deschutes River resulted from erosion of unit Qvrs to a base level determined by the elevation of the bedrock outcrop at Tumwater Falls. The steep bluffs bounding the Deschutes River valley in the vicinity of Pioneer Park and the Tumwater Valley Golf Course are evidence of this Holocene incision. Water well data indicates that this sandy unit Qvrs deposit underlies much of the Deschutes River valley upstream of Tumwater Falls.

Evaluation of the liquefaction susceptibility of alluvial and underlying unit Qvrs deposits in the Deschutes River valley upstream of Tumwater Falls is based on surface-to-downhole shear wave velocity measurements made in a boring drilled in Pioneer Park. A constant shear wave velocity of 660 ft/sec (200 m/sec) was measured in the upper 50 ft (15 m) of this boring (S. P. Palmer, 1999, Washington Department of Natural Resources, unpub. data). Shear wave velocity corrected for effective stress (Andrus and Stokoe, 1997) ranges from 565 to
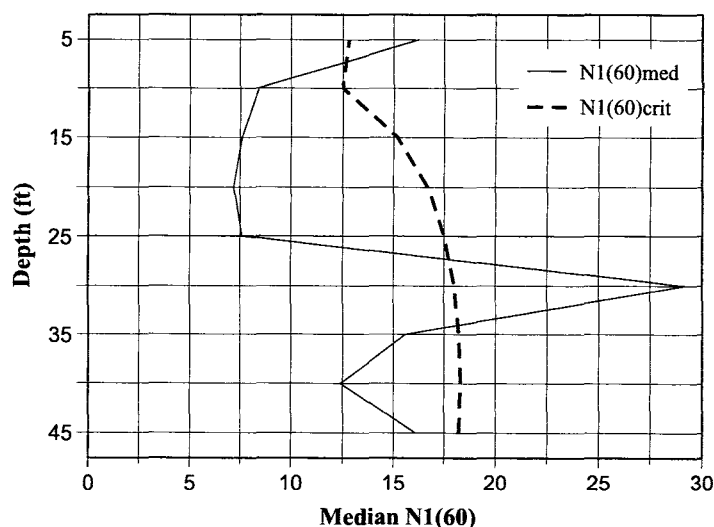

Figure 4. Median $N_1(60)$ values binned using 5 ft (1.5 m) depth intervals for the 91 downtown Olympia borings. Also shown are the corresponding critical $N_1(60)$ values computed for the 0.30 g PGA scenario earthquake. Liquefaction is predicted wherever measured $N_1(60)$ value is less than the corresponding critical $N_1(60)$ value.

710 ft/sec (172–217 m/sec) in the depth interval from 15 to 50 ft (4.5–15 m). This interval is composed of saturated clean to slightly silty sand, based on disturbed samples and drilling returns from the boring in which the shear wave velocity measurements were made. Empirical relations presented in Andrus and Stokoe (1997) indicate that this interval would be susceptible to liquefaction for cyclic stresses generated by the 0.3 g scenario earthquake, but would not liquefy for the 0.15 g scenario event.

Evaluation of liquefaction susceptibility in the Nisqually River valley and Mud Bay vicinity is limited by a lack of geotechnical borings drilled in these deposits. Only 11 borings in the Nisqually River valley and 6 in the area of Mud Bay were collected for this study, which is not a sufficient number of borings to quantify liquefaction susceptibility using cumulative frequency histograms (thickness criterion) or median $N_1(60)$ values (threshold criterion). However, intervals of liquefiable soils are identified in many of the borings located in these areas as indicated in Table 2. The presence of liquefiable intervals in many of these boring provides the basis for rating these areas as having a high liquefaction susceptibility.

No geotechnical borings located in areas surrounding major tributary streams of the Black River and smaller streams draining into Puget Sound were found for this study. Assignment of a high liquefaction susceptibility to these areas is based solely on the inferred age of these deposits (Holocene, with near-surface soils deposited in the last 500 years) and depositional environment (river channel and flood plain). Relations of age and depositional environment to liquefaction susceptibility presented by Youd and Perkins (1978) indicate that the distribution of liquefiable sediments in these depositional environments is locally variable, and that the liquefaction susceptibility of these deposits ranges from moderate to very high.

Low to Moderate Hazard

Late Pleistocene (12,000–14,000 year old) glaciolacustrine and glaciofluvial deposits predominantly composed of sand and silt (unit Qvrs) and Holocene landslide deposits are re-

Table 2. Summary of results of liquefaction analyses of geotechnical borings located in the Nisqually River valley and Mud Bay area

Site report no.	Boring no.	Soil unit thickness (ft)	Soil unit thickness (m)	0.15 g PGA		0.30 g PGA	
				Liquefiable thickness (ft)	Liquefiable thickness (m)	Liquefiable thickness (ft)	Liquefiable thickness (m)
Nisqually River valley							
T-39	B-1	50.0	15.2	5.5	1.7	23.5	7.2
T-40	B-1	38.0	11.6	2.0	0.6	8.0	2.4
T-40	B-2	32.0	9.8	0.0	0.0	8.0	2.4
T-56	C9-1	50.0	15.2	0.0	0.0	19.0	5.8
T-56	C9-2	50.0	15.2	10.0	3.0	18.0	5.5
T-56	H-3	50.0	15.2	7.0	2.1	25.0	7.6
T-56	H-4	50.0	15.2	6.0	1.8	15.0	4.6
T-56	H-5	50.0	15.2	12.0	3.7	22.0	6.7
T-56	H-6	50.0	15.2	5.0	1.5	10.0	3.0
T-56	H-W-1	40.0	12.2	0.0	0.0	11.0	3.4
T-56	H-W-2	30.0	9.1	0.0	0.0	5.0	1.5
Mud Bay vicinity							
T-43	M-1	40.0	12.2	5.0	1.5	5.0	1.5
T-43	M-1A	50.0	15.2	0.0	0.0	0.0	0.0
T-43	M-2	50.0	15.2	0.0	0.0	5.0	1.5
T-55	B-1	50.0	15.2	0.0	0.0	5.0	1.5
T-55	B-2	50.0	15.2	0.0	0.0	16.0	4.9
T-55	B-3	50.0	15.2	18.0	5.5	37.0	11.3

garded as having a low to moderate liquefaction susceptibility. Mapping of landslide deposits used in this study (Noble and Wallace, 1966) is not a comprehensive depiction of the distribution of landslide deposits in the study area. A significant effort was directed to mapping the extent and thickness of unit Qvrs using agricultural soil maps (Pringle, 1990), water well and geotechnical boring logs, and field review.

Quantitative evaluation of the liquefaction susceptibility of unit Qvrs is based on analysis of 77 geotechnical borings drilled in this unit. These analyses use the measured SPT N-values, fines content based on actual gradations or estimated from USCS soil type, and ground-water depths measured at time of drilling for the two scenario earthquakes (M_w 7.3, 0.15 g or 0.30 g PGA). Figure 5 presents a cumulative frequency histogram for unit Qvrs based on analysis of the boring data. Average drilled thickness of unit Qvrs in the 77 borings is 30.5 ft (9.3 m). If this average drilled thickness and the cumulative frequency histogram of Figure 5 are combined, then approximately 9 percent of these borings contains at least 1 ft (0.3 m) of liquefiable soil for the 0.15 g scenario. Likewise, about 15 percent contain at least 10 ft (3.0 m) of liquefiable soil for the 0.30 g scenario. These values suggest that unit Qvrs has a low liquefaction susceptibility using the thickness criterion presented in Grant and others (1998).

The cumulative frequency histograms shown in Figure 5 are comparable to those presented in Palmer and others (1995) for late Pleistocene sandy glaciolacustrine deposits occurring in southwestern King County. These glaciolacustrine deposits are similar in age, depositional environment, and USCS soil classification to the unit Qvrs described in this study. Palmer and others (1995) assigned the sandy glaciolacustrine deposits found southwestern King County to a moderate liquefaction susceptibility based only on the thickness criterion.

Figure 6 shows the median and 25th percentile of the $N_1(60)$ values for clean sand ($\leq$15% fines) at equally spaced depth intervals for the 77 borings penetrating unit Qvrs. $N_1(60)$ values are binned using 5 ft (1.5 m) depth intervals, and the me-
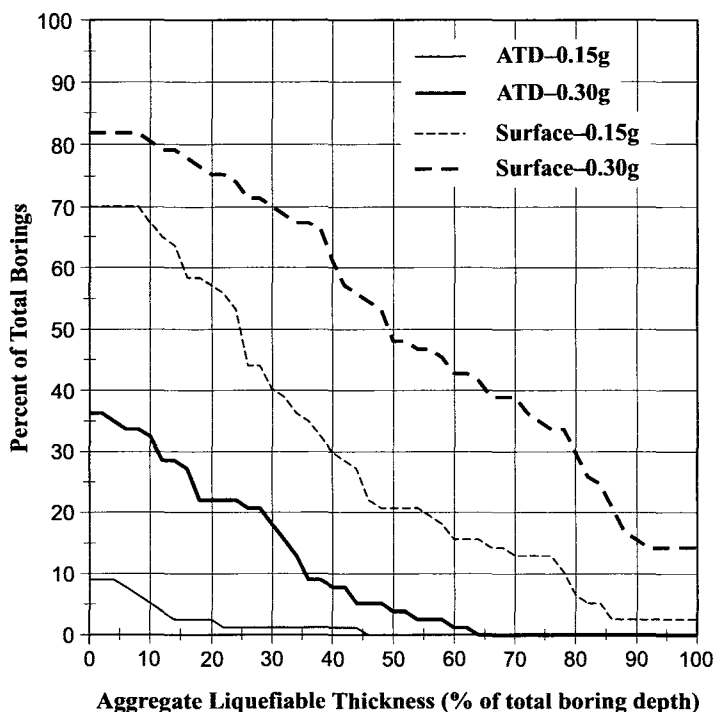

Figure 5. Cumulative frequency histograms showing the percentage of borings penetrating the unit Qvrs that exceed a normalized aggregate liquefiable thickness. Histograms correspond to liquefaction analyses performed for both depth of ground water at the time of drilling (ATD) and ground water assumed to be at ground surface.

dian and 25th percentile values within the binned intervals are plotted at the corresponding midpoint depth. The critical $N_1(60)$ value is computed at each midpoint depth for the 0.30 g PGA scenario earthquake for a sand with 15 percent fine content and a ground-water depth of 15 ft (4.6 m). Liquefaction is predicted wherever measured $N_1(60)$ values at a given depth are less than the corresponding critical $N_1(60)$ values. The median $N_1(60)$ values measured in the borings penetrating unit Qvrs are greater than the critical $N_1(60)$ values except at a mid-

point depth of 5 ft (1.5 m). However, the 25th percentile of the measured $N_1(60)$ values are less than the critical $N_1(60)$ values at all depths. This characterization places unit Qvrs deposits in the moderate hazard category using the threshold criterion presented by Grant and others (1998).

The two approaches to quantifying liquefaction susceptibility (thickness and threshold criteria) for unit Qvrs yield different relative hazard ratings (low or moderate). The explanation for this apparent disagreement is that unit Qvrs deposits locally contain thick sections of nonliquefiable silt that affect only the thickness criterion. The threshold criterion is not affected by the occurrence of these thick silt intervals as it only depends on the distribution of $N_1(60)$ values for sands containing 15 percent or less fines. The unit Qvrs is ranked as having a low to moderate liquefaction hazard to give equal weight to both the thickness and threshold criteria. This low to moderate susceptibility rating is supported by the infrequent occurrence of liquefaction during the 1949 and 1965 Puget Sound earthquakes within unit Qvrs.

Depth to the ground-water table in unit Qvrs is both geographically and seasonally variable and is determined by a combination of perching conditions on an underlying impermeable stratum and the regional recharge and flow geometry of the unconfined ground-water system. Although unit Qvrs is typically a well-drained soil, ground water in many areas within this deposit may be quite shallow (within 10 ft or 3 m below ground surface). Ground-water flooding (where the ground-water table rises above the ground surface) has occurred at numerous locations within unit Qvrs in the last few winters in response to greater than average rainfall. In many other locations, no significant ground-water flooding has occurred because the regional unconfined ground-water table is deep (below 50 ft or 15 m) and there are no perched aquifers.

A cumulative frequency histogram for unit Qvrs is generated from the available geotechnical boring data in which the ground-water table is assumed to be at ground surface in the liquefaction factor of safety analysis. Results from this analysis (shown in Figure 5) indicate a significant increase in the thickness and frequency of liquefiable soils compared to the analyses performed using ground-water depths measured at time of drilling. The occurrence of ground-water flooding is a reasonable proxy for determining which areas within the unit Qvrs have a shallow ground-water table and accordingly an elevated susceptibility to liquefaction. Also, areas designated as wetlands (Washington Department of Natural Resources Hydrography Data Layer, 1998) are presented on the liquefaction susceptibility map accompanying this report. Wetlands are usually indicative of shallow ground-water conditions, and their occurrence provides a proxy for determining which areas within the unit Qvrs have an elevated liquefaction susceptibility.

Liquefaction occurred at a site in southwestern King County underlain by a late Pleistocene sandy glaciolacustrine deposit 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 was very shallow as a result of heavy precipitation in the weeks preceding the earthquake. Vertical and horizontal ground displacement on the or-
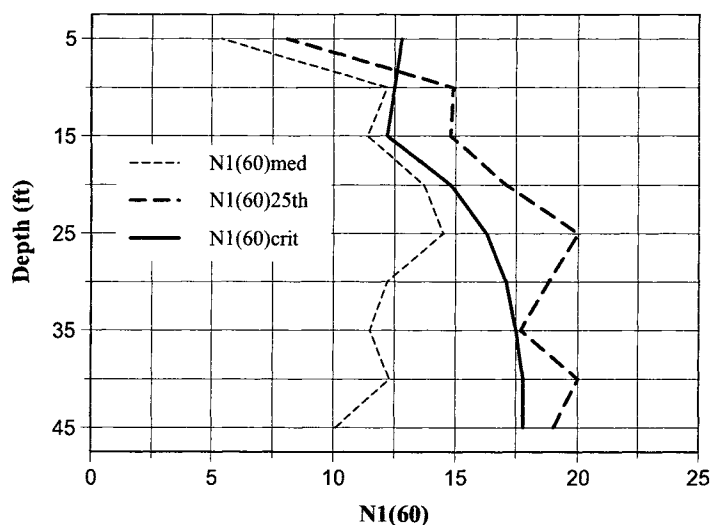

Figure 6. Median and 25th percentile $N_1(60)$ values binned using 5 ft (1.5 m) depth intervals for the 77 borings penetrating unit Qvrs. Also shown are the corresponding critical $N_1(60)$ values computed for the 0.30 g PGA scenario earthquake. Liquefaction is predicted wherever measured $N_1(60)$ value is less than the corresponding critical $N_1(60)$ values.

der of 2 in. (5 cm) caused significant damage to the residential structure located at this site. This occurrence of liquefaction confirmed the assessment presented in Palmer and others (1995) that similar late Pleistocene sandy glaciolacustrine deposits, such as unit Qvrs, are susceptible to liquefaction and cannot be ignored in assessing earthquake hazards in the Puget Sound region.

Liquefaction was determined to be a geotechnical design consideration for the replacement of the Trosper Road overpass on Interstate 5 in Tumwater (Rittenhouse-Zeman & Associates, 1987). Foundation soils beneath the Trosper Road overpass are loose to medium dense, clean to silty sands and are mapped as unit Qvrs. A vertical seam of sand observed from a disturbed sample at a depth of 19 ft (5.8 m) was interpreted as evidence of past liquefaction at the site (Steven Lowell, Washington Department of Transportation, oral commun., 1998).

Very Low Hazard

All Pleistocene glacial and nonglacial deposits (with the exception of unit Qvrs) are assigned a very low hazard rating based on analysis of 93 boring penetrating these units. Liquefiable intervals were identified in only 3 of these borings, and these intervals were 5 ft (1.5 m) or less in thickness. Factors contributing to the very low liquefaction hazard of these units include:

I predominance of a silty and (or) gravelly texture that retards the occurrence of liquefaction,

I significant consolidation of these units (with the exception of unit Qvr) because of glacial ice loading, and

I a typically deep ground-water table (30 ft or 9.1 m).

Further support for the assignment of a very low hazard to these deposits is the lack of historical occurrences of liquefaction during the 1949 and 1965 earthquakes.

Very Low to Nil Hazard

Outcrop areas of Tertiary volcanic and sedimentary bedrock are assigned a very low to nil liquefaction hazard. Lithified bedrock is not susceptible to liquefaction. However, unrecognized fill soils placed during building or road construction may occur within the areas mapped as bedrock. These fill soils may be liquefiable if they are composed of loose sand and are water saturated. Consequently the areas of mapped bedrock outcrop are designated as having a very low or nil susceptibility to account for the possibility of isolated occurrences of potentially liquefiable fill soils emplaced on otherwise nonliquefiable bedrock.

Peat

Peat deposits are included as a separate unit on the accompanying liquefaction susceptibility map and are composed of organic and mineral sediments deposited in closed depressions, including peat, muck, silt, and clay. These deposits are judged to be at least 10 ft (3 m) thick and consequently would be significant from an engineering perspective. The peat deposits are not liquefiable, but may be susceptible to differential settlement resulting from earthquake ground shaking. Differential settlement of peaty soils may have occurred in Olympia during the 1949 earthquake based on the following excerpt (U.S. Army Corps of Engineers, 1949):

> "A residential area three to eight blocks east of the capitol is founded on a peat soil and appears to be undergoing delayed settlement. The major portion of residential damages are centered in this area."

CONCLUSIONS

The fill area of downtown Olympia has a well-documented liquefaction hazard as demonstrated by the quantitative analysis performed as part of this study and the historic record of the 1949 and 1965 earthquakes. The Holocene alluvium and unit Qvrs underlying the Deschutes River valley are predominantly clean to silty sands that are saturated because of shallow ground-water conditions. Shear wave velocity data supports the high liquefaction susceptibility ranking of this area. The high liquefaction susceptibility assigned to the Nisqually River valley, Mud Bay vicinity, and smaller streams and drainages within the study area is less certain and is based primarily on their geologic setting. Liquefiable intervals identified in borings drilled in the Nisqually River valley and Mud Bay vicinity provide some support for the high susceptibility rating.

The low to moderate liquefaction susceptibility determined for the sandy late Pleistocene glaciolacustrine and glaciofluvial sediments (unit Qvrs) is supported by analyses of geotechnical borings penetrating this unit and by the occurrence of liquefaction in this unit during the 1949 and 1965 earthquakes. Areas within unit Qvrs having a shallow ground-water table have a substantially higher liquefaction hazard compared to areas with a deep ground-water table. However, the sparse coverage of geotechnical borings drilled in unit Qvrs precludes delineating areas of shallow and deep ground-water. The occurrence of ground-water flooding and locations of mapped wetlands are reasonable proxies for determining areas having a shallow ground-water table. The very low susceptibility of all older Pleistocene deposits and areas of bedrock outcrop is sub-stantiated by analysis of geotechnical boring data and the lack of historic liquefaction in these units.

Further refinement of the liquefaction susceptibility map accompanying this report will require additional data and investigation. Additional geotechnical boring data for the Nisqually and Deschutes River valleys, Mud Bay vicinity, and smaller streams and drainages in the study area are needed to better assess the high liquefaction hazard presently assigned to these areas. A regional model of the unconfined ground-water system would assist in delineating areas of elevated liquefaction hazard in unit Qvrs. Additional geotechnical boring data within areas having a shallow ground-water table would also improve the assessment of liquefaction susceptibility in unit Qvrs. The availability of new geotechnical information and more detailed geologic mapping will undoubtedly refine and improve the ranking and distribution of liquefaction susceptibility presented in this report and the accompanying map.

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WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
Raymond Lasmanis, State Geologist
GEOLOGIC FOLIO OF THE
OLYMPIA-LACEY-TUMWATER URBAN AREA, WASHINGTON:
LIQUEFACTION SUSCEPTIBILITY MAP
GM-47

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Jennifer M. Belcher - Commissioner of Public Lands

This liquefaction susceptibility map is one in a folio of Olympia-Lacey-Tumwater area maps showing geology, geomorphology, and geologic hazards.

GEOLOGIC FOLIO
OF THE
OLYMPIA-LACEY-TUMWATER URBAN AREA, WASHINGTON:
LIQUEFACTION SUSCEPTIBILITY MAP

by

Stephen P. Palmer, Timothy J. Walsh, and Wendy J. Gerstel

WHAT IS LIQUEFACTION?

LIQUEFACTION is a phenomenon in which strong earthquake shaking causes a soil to rapidly lose its strength and to behave like quicksand. Liquefaction typically occurs in artificially filled areas and loose sandy soils that are saturated with water, such as low-lying coastal areas, lake shores, and river valleys. When soil strength is lost during liquefaction, the consequences can be catastrophic. Movement of liquefied soils can rupture pipelines, move bridge abutments and road and railway alignments, and pull apart the foundations and walls of buildings.

Ground movement resulting from liquefaction caused massive damage to highways and railways throughout southern Alaska during the 1964 Good Friday earthquake. Liquefaction was a contributing factor to the severe building damage that occurred in the Marina District of San Francisco during the 1989 Loma Prieta earthquake. Control of the ensuing fires in the Marina District was severely hampered because water lines in the area were broken by liquefaction-induced ground movement. Damage to the port area of Kobe, Japan, caused by liquefaction during the 1995 earthquake resulted in billions of dollars of reconstruction costs and lost business.

WHAT IS A LIQUEFACTION SUSCEPTIBILITY MAP?

A LIQUEFACTION SUSCEPTIBILITY MAP provides an estimate of the likelihood of the soil to liquefy as a result of earthquake shaking. This type of map depicts the relative hazard in terms of high, moderate, or low liquefaction susceptibility. The hazard zones shown on this map are determined using geological mapping and quantitative analysis of data from more than 200 geotechnical borings drilled in the study area. Ground truth for this hazard map is provided by the locations of liquefaction sites resulting from the 1949 and 1965 Puget Sound earthquakes.

HOW CAN THIS MAP BE USED?

LIQUEFACTION HAZARD MAPS such as this can be used for many different purposes by a variety of users. For example:

Emergency managers can determine which critical facilities and lifelines are located in hazardous areas;

Building officials and engineers can select areas where detailed geotechnical studies should be performed for new construction or retrofitting older structures;

Facilities managers can assess vulnerability of corporate and public facilities, including schools, and recommend actions required to minimize earthquake damage and loss;

Insurance providers can determine relative seismic risk in the assessment of insurance ratings and premiums;

Land-use planners can recommend appropriate zoning and land-use in higher hazard areas to promote long-term mitigation of earthquake losses by reducing vulnerability;

Private property owners can guide their decisions on retrofitting, purchasing, and upgrading of their properties.

EXPLANATION

■ Liquefaction susceptibility: HIGH

■ Liquefaction susceptibility: LOW to MODERATE

■ Liquefaction susceptibility: VERY LOW

■ Liquefaction susceptibility: VERY LOW to NIL

■ Peat deposits

■ Major open water features

▦ Wetlands

● Historic earthquake-induced ground deformation that may have been caused by liquefaction. (See text for explanation.)

- - - Urban Growth Boundary (1998)

LIQUEFACTION SUSCEPTIBILITY

HIGH — Areas underlain by artificial fill, modified land, and Holocene alluvial, estuarine, and beach deposits.

LOW to MODERATE — Areas underlain by late Vashon proglacial lake and fluvial sediments composed predominantly of sand and silt, and Holocene landslide deposits. Liquefaction susceptibility of these geologic units can be higher when the ground-water table is shallow.

VERY LOW — Areas underlain by Vashon advance and recessional outwash and till, and older Pleistocene glacial and non-glacial deposits. The very low liquefaction susceptibility of these geologic units is a result of their compaction due to glacial ice loading, and/or their predominantly gravelly or silty composition.

VERY LOW to NIL — Areas underlain by Tertiary volcanic or sedimentary bedrock. True bedrock is not susceptible to liquefaction, but unmapped areas of thick soils or artificial fill overlying bedrock may be liquefiable.

PEAT DEPOSITS — Areas underlain by Holocene peat deposits that may have a thickness of 10 feet or greater. Peaty soils are not susceptible to liquefaction, but may undergo settlement as a result of earthquake shaking. Sand beds within the peat deposits may be liquefiable.

1:48,000

Scale

0 0.5 1 1.5 2 2.5 3
MILES

N
W · E
S

This map is meant only as a general guide to delineate areas prone to liquefaction. This map is not a substitute for site-specific investigation to assess the potential for liquefaction for any development project. Because the data used in the liquefaction susceptibility assessment have been subdivided on the basis of regional geologic mapping, this map cannot be used to determine the presence or absence of liquefiable soils beneath any specific locality. This determination requires a site-specific geotechnical investigation performed by qualified practitioners.