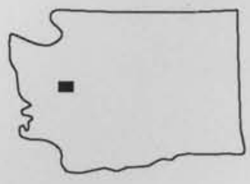
Liquefaction Susceptibility for the Des Moines and Renton 7.5-minute Quadrangles, Washington

by Stephen P. Palmer,
Henry W. Schasse, and
David K. Norman

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Geologic Map GM-41
December 1994

The information provided in these maps 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 for a given project.



Location of quadrangles

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

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Liquefaction Susceptibility for the Des Moines and Renton 7.5-minute Quadrangles, Washington

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SUMMARY

Liquefaction susceptibility maps are presented for the Des Moines and Renton 7.5-minute topographic quadrangles*. These maps are based on analyses of 440 geotechnical borings. The data were obtained from the Washington Department of Transportation, the Cities of Tukwila and Kent, the Port of Seattle (Sea-Tac Airport), Seattle Metro, and the King County Department of Building and Land Development. Four categories of geologic deposits found in the study area are assigned susceptibility rankings determined through analysis of the geotechnical data and historical reports of liquefaction during the 1949 magnitude 7.1 Olympia and 1965 magnitude 6.5 Seattle–Tacoma earthquakes.

These maps are intended to provide land-use planners, emergency-response personnel, geotechnical consultants, building developers and contractors, and private citizens with a qualitative assessment of the likelihood of soil liquefaction during an earthquake. The maps only indicate generalized areas more or less prone to liquefaction and *cannot* be used to determine the presence or absence of liquefiable soils beneath any specific locality. Because of the regional nature of these maps, the data used in the liquefaction susceptibility assessment have been subdivided on the basis of regional geological mapping at the 1:24,000 scale. 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 damage to structures.

These maps 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 for a given project.

Category I deposits, comprising artificial fill, modified land, and Holocene beach deposits as well as alluvium deposited since the end of the Vashon Stade of the Fraser Glaciation, are ranked as having high susceptibility to liquefaction. The Renton quadrangle map shows the historic pre-Lake Washington Ship Canal shoreline of Lake Washington and associated freshwater marshes and delineates the pre-Ship Canal courses of the Black and Cedar Rivers. In addition, abandoned-channel segments of the Green River are mapped in the study area. These particular areas *may* have a locally higher susceptibility to liquefaction, either because they have been filled earlier this century during the development of the Duwamish valley or because they are topographically low areas that likely have a shallow ground-water table compared to the adjacent flood plain.

Category II deposits, consisting of post-Vashon lacustrine deposits, landslides, and colluvium, are ranked as having low to moderate liquefaction susceptibility. There were no geotechnical data available for this category of deposit in the study area. The post-Vashon lacustrine deposits are primarily composed of peat and silt, with only scattered sandy sections, and would typically be considered as having a low liquefaction susceptibility. However, there was one possible instance of liquefaction in a post-Vashon lacustrine deposit in the Big Soos Creek drainage during the 1949 earthquake; from this we conclude that these deposits could liquefy. Colluvium consists primarily of landslide debris and slope wash and, in places, older alluvial terraces. Landslides and ground cracks were reported in colluvial deposits during the 1949 and 1965 earthquakes, and in some instances these ground failures may have been caused by liquefaction. It seems prudent to acknowledge the variations in the observed nature of the lacustrine and colluvial deposits and the historic record of earthquake-induced liquefaction and other ground failures by assigning low to moderate susceptibility to Category II deposits.

Category III deposits include all Vashon and older glacial and nonglacial deposits. Quantitative evaluation of geotechnical data obtained from these deposits indicates a low susceptibility to liquefaction. The historic record supports the low ranking assigned to Category III deposits as there are no reported instances of liquefaction in these deposits during the 1949 and 1965 earthquakes.

Category IV deposits are non-liquefiable Tertiary bedrock; however, small unmapped areas of weathered bedrock soils or other potentially liquefiable deposits (for example, fill) may lie in the areas mapped as bedrock. For this reason, Category IV deposits are ranked as having low to no susceptibility to liquefaction.

* This pamphlet accompanies the liquefaction susceptibility maps for the Des Moines and Renton 7.5-minute topographic quadrangles.

INTRODUCTION

The Washington Department of Natural Resources, Division of Geology and Earth Resources (DGER), is actively investigating earthquake hazards statewide and initially received funding from the National Earthquake Hazards Reduction Program (NEHRP) and subsequently the Federal Emergency Management Agency (FEMA) to conduct earthquake hazard mitigation studies. DGER has concentrated its technical program on mapping deposits in the Puget Sound region that are subject to seismically induced ground liquefaction. The purpose of this work is to present maps showing liquefaction susceptibility in the Des Moines and Renton 7.5-minute quadrangles. These areas encompass the alluvial valley along the lower reach of the Green River and the adjacent drift plains. The liquefaction maps cover areas adjacent to the Seattle North and Seattle South 7.5-minute quadrangles where liquefaction susceptibility was mapped by Grant and others (1991) (Fig. 1).

Liquefaction occurs when a water-saturated, granular (sandy) soil loses strength during vibratory shaking such as that generated by an earthquake. Below the ground-water table, the pore space among sand grains is filled with water. The weight of the overlying soil mass is 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 the liquefiable soil may completely collapse. If the pore water cannot flow out of the collapsing pore space quickly, then the pore-water pressure increases. In the extreme case where the grain support is completely lost, the pore water must bear the entire weight of the overlying soil mass. At this point the granular soil is liquefied and will behave as a viscous fluid. The liquefied soil may then be subject to extreme lateral deformation because it does not provide much resistance to horizontal forces. Additionally, soil liquefaction can result in loss of bearing capacity for large structures, flotation of underground tanks and buried structures, and foundation damage caused by extreme differential settlement.

These maps provide land-use planners, emergency-response personnel, geotechnical consultants, building developers and contractors, and private citizens with a qualitative assessment of the likelihood for soil liquefaction during an earthquake. These maps are meant only as a general guide to delineate areas prone to liquefaction. *These maps are not a substitute for a site-specific investigation to assess the potential for liquefaction and corresponding damage for any development project.* Because of the regional nature of these maps (scale 1:24,000) and because the data used in the liquefaction susceptibility assessment have been subdivided on the basis of regional geological mapping, these maps cannot be used to determine the presence or absence of liquefiable soils beneath any specific locality, nor the potential for damage if liquefaction should occur. *Site-specific geotechnical investigations performed by qualified practitioners are required to make these determinations.*

GEOLOGY OF THE DES MOINES AND RENTON QUADRANGLES

The oldest rocks exposed in the study area are early Tertiary sedimentary rocks termed the Puget Group, subdivided into the Tukwila and Renton Formations, unnamed marine sedimentary rocks containing Narizian (Eocene) shallow-water marine fossils and interbedded volcaniclastic rocks, and unnamed sedimentary rocks of Oligocene age correlative with the Blakeley Formation. Tertiary andesite sills and irregularly shaped bodies intrude the Tukwila Formation. All of these bedrock units crop out only in the northern parts of the Des Moines and Renton quadrangles. Generalized geologic maps for the Des Moines and Renton quadrangles are given in Figures 2b and c, respectively; the explanation for these maps is shown in Figure 2a.

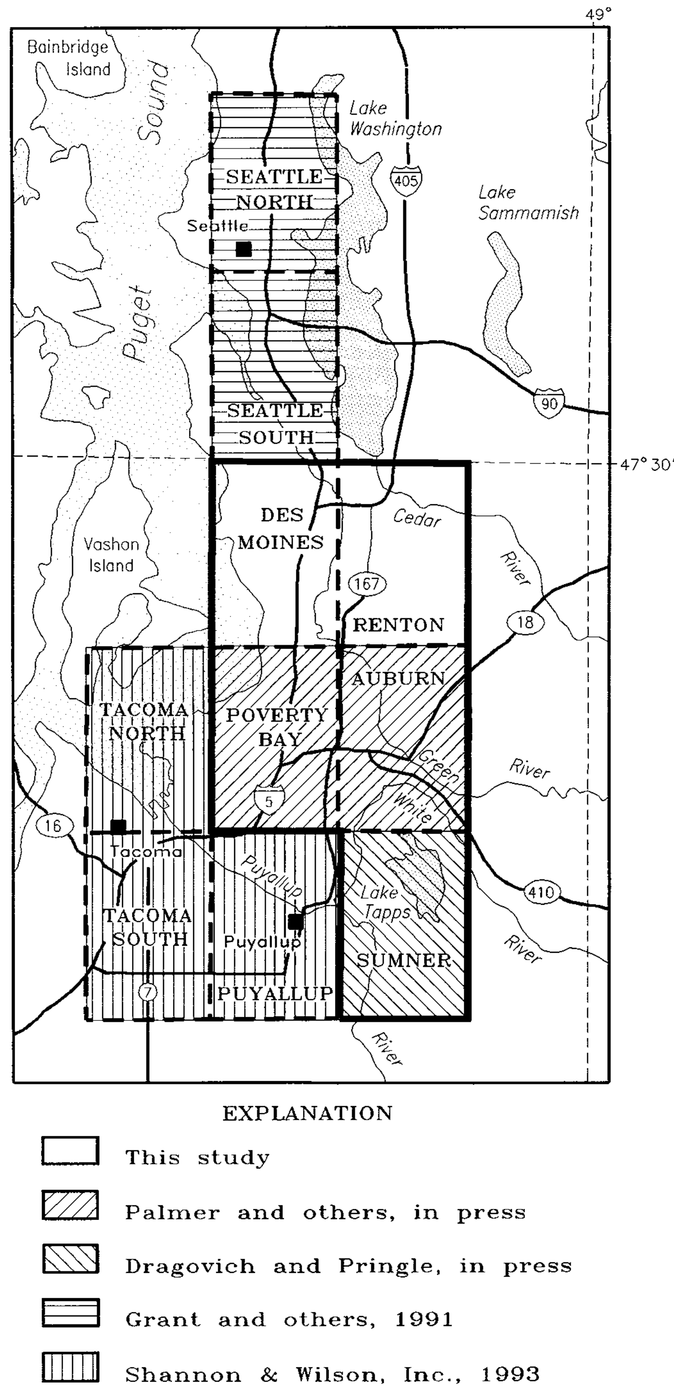

Figure 1. Location map showing the Des Moines and Renton 7.5-minute quadrangles and adjacent quadrangles for which liquefaction studies have been completed or are in progress.

Pleistocene glacial and nonglacial deposits unconformably overlie Tertiary bedrock in the study area (Figs. 2b and c). The youngest of these glacial units was deposited during the Vashon Stade of the Fraser Glaciation (ca. 10,000–15,000 years ago). Vashon till and outwash form a veneer on the broad drift plain that occupies the lowland between the Olympic Mountains and the foothills of the Cascade Range. In the study area, this drift plain stands a few hundred feet above valley floors cut by the major river systems draining into Lake Washington and Puget Sound.

Sedimentary deposits younger than the Vashon Drift are also present in the study area (Figs. 2b and c). Holocene lacustrine deposits mapped by Mullineaux (1965) and Waldron (1962) are primarily peat with some sand, silt, and clay and are found in low areas on the drift plain. Thin, peaty lake deposits have also formed in depressions on the flood plain of the Duwamish valley.

Alluvial sand, silt, and gravel are found in the Duwamish valley, in the valley cut by the Cedar River, and at the mouths of several small drainages where they empty into the Duwamish valley or Puget Sound. Water-well data for the area northwest of Auburn (south of the study area) show that the mid-Holocene Osceola Mudflow (Luzier, 1969) is at a depth of approximately 260–280 ft (79–85 m) below present-day sea level, indicating that the northern portion of the Duwamish valley was formerly an embayment of Puget Sound. Marine shells, reported from several borings in the alluvium at depths of 70 ft (21 m) or more below sea level, also indicate that the valley was an arm of the Puget Sound for some time after retreat of the Vashon ice lobe (Waldron, 1962).

A significant area of northern Renton was filled in the early 1900s as a result of the Lake Washington Ship Canal project. That project also affected the natural river drainage pattern in the study area. Before 1900 (Fig. 3), the Black River drained Lake Washington, and the Cedar River was a tributary of the Black River. The Black River flowed west into the Green River just west of the western edge of the Renton quadrangle. After completion of the Ship Canal project, the outlet feeding the Black River was blocked, and the Cedar River was channelized and redirected into Lake Washington (Fig. 3). Flow in the Black River effectively ceased except for the drainage originating on the adjacent drift plain highland. The level of Lake Washington was lowered approximately 9 ft (3 m) (Chrzastowski, 1983), and in the northern part of Renton both the newly exposed lakebed and surrounding freshwater marshes were filled or otherwise modified by development.

Before 1906, the White River bifurcated as it reached the floor of the Duwamish valley, with the White River flowing northward into the Green River and the Stuck River flowing southward as a tributary of the Puyallup River (Willis and Smith, 1899). After a flood in 1906, most of the flow was directed into the Stuck River, and engineering projects permanently diverted the north-flowing White River into the Stuck River (which was renamed the White River). The city of Auburn has developed on the abandoned channel of the former White River. Figure 3 delineates the current and historic names and courses of rivers traversing the study area.

Modified or filled land is mostly concentrated in alluvial valleys; it includes extensive fill of Lake Washington and embankments for railroad lines, roadways, and water impoundments. However, several small areas of modified and (or) filled land occur at scattered locations on the drift plain in the Des Moines quadrangle. These locations are the sites of schools, public parks, and roadway construction. Filled land at the Des Moines Marina consists of sediments dredged from Puget Sound and placed over Holocene beach deposits. Waldron (1962) mapped an extensive area as modified land in what is now occupied by the Seattle–Tacoma (Sea-Tac) International Airport. Waldron's map unit, however, does not appear on the map of the generalized geology of the Des Moines quadrangle (Fig. 2c). The fill materials in this area were well compacted during emplacement over dense Vashon till and glacial outwash and do not have the same engineering characteristics as the older fills placed over Holocene alluvium, beach deposits, or the drained shoreline of Lake Washington or in abandoned river channels.

Beach deposits consist of gravel, sand, silt, and clay that rim Puget Sound and are derived mostly from material in the adjoining bluffs, but they also include some alluvium reworked by waves and littoral currents. Small alluvial deltas are common at the mouths of streams; most of the silt and clay beaches are adjacent to these deltas. Colluvial deposits mapped by Mullineaux (1965) consist primarily of landslide debris and slope wash and, in some places, alluvium plastered on valley walls. Waldron (1962) mapped large inactive slump blocks (unit Qm) that have formed deep reentrants in the upland slopes about 1 mi (1.6 km) east of Point Pulley on the Des Moines quadrangle.

LIQUEFACTION SUSCEPTIBILITY MAPS FOR THE DES MOINES AND RENTON QUADRANGLES

Geological mapping of the Des Moines and Renton 7.5-minute quadrangles is provided by Mullineaux (1965) and Waldron (1962). We have generalized Mullineaux's and Waldron's map units, on the basis of their engineering properties, into four categories of deposits as follows:

- **Category I:** artificial fill and modified land (excepting most fills along transportation routes), post-Vashon alluvium, and beach deposits;
- **Category II:** post-Vashon lacustrine deposits, landslides, and colluvium;
- **Category III:** all Pleistocene glacial and nonglacial deposits;
- **Category IV:** all Tertiary bedrock.

Table 1 summarizes the four categories of deposits used in this study and the corresponding map units of Mullineaux (1965) and Waldron (1962) for the Des Moines and Renton quadrangles. Plates 1 and 2 show the distribution of the four categories on the basis of Waldron's mapping in the Des Moines quadrangle and Mullineaux's mapping in the Renton quadrangle. The geologic contacts mapped by Waldron (1962) and Mullineaux (1965) were not field checked during this study. The historic shoreline of Lake Washington, the associated freshwater marshes, and the pre-Ship Canal courses of the Black and Cedar Rivers mapped by Chrzastowski (1983) are shown on Plate 2.

Mullineaux (1965) mapped two abandoned channels of the Green River in the Duwamish valley between Kent and Renton. He conjectured that avulsion of these channels was caused by aggradation of the river as the profile was lengthened by construction of a delta in Puget Sound and by slow bank cutting at the outside of meander bends (Mullineaux, 1961). In his model, long segments of the channel were abandoned after aggradation had built up the channel to nearly the level of the adjacent flood plain and the river shifted to a new course. Abandoned channels were not mapped by Waldron (1962) in the Des Moines quadrangle.

U.S. Army Corps of Engineers (USACE) 1944-vintage aerial photo mosaics of the Duwamish valley were reviewed in this study to evaluate the mapping of Mullineaux (1965). Traces of abandoned channels observed on these photo mosaics were transferred to Plates 1 and 2. An example of an USACE aerial photo mosaic (showing the area near the former Longacres Race Track) is given in Figure 4. In addition to the two long abandoned segments mapped by Mullineaux (1965) in the Renton quadrangle, other shorter abandoned segments and meanders were mapped using the USACE photo mosaics. We attempted further mapping using 1976-vintage 1:24,000-scale stereo air photos (Washington Department of Natural Resources Flight Index Symbol NW-C-76). However, development of the Duwamish River valley between 1944 and 1976 has obscured many of the abandoned channels mapped by Mullineaux (1965) and shown on the USACE aerial photo mosaics.

Two types of abandoned channels are mapped on Plates 1 and 2. The hatchured features mark the trace of clearly identifiable abandoned channels that do not appear to contain intermittent streams or support riparian vegetation. The dot-and-dash lines denote drainages and streams that appear to be continuations or parts of abandoned river channels. The overall pattern of these features suggests that the Green River channel changes position both by avulsion of long segments and by meander migration and abandonment, as noted by Mullineaux (1961). It is possible that additional abandoned channels could be mapped if we could obtain pre-1960 aerial photographs.

EXPLANATION

af artificial fill and modified land

Qa Holocene alluvium

Qb Holocene beach deposits

Ql Holocene lacustrine sediments

Qm Holocene mass-wasting deposits (colluvium and landslides)

Qu undifferentiated Pleistocene glacial and nonglacial deposits, including Vashon Stade drift and outwash deposits

Tu undifferentiated Tertiary sedimentary and intrusive igneous rocks

Structures *(dashed where inferred, dotted where concealed; arrows on fault show direction of movement)*

Fault

Anticline

Syncline

Figure 2a. Explanation for the generalized geologic maps of the Des Moines and Renton quadrangles. (See Figs. 2b and c; maps modified from Mullineaux, 1965, and Waldron, 1962).

Note: Two minor faults are shown on the Renton geologic map. These offset only bedrock, and displacement of the overlying Quaternary deposits has not been observed. Thus, these faults are not likely to be seismogenic and are not at this time a particular concern with regard to the overall earthquake hazard in the Renton area.

METHODOLOGY USED TO EVALUATE LIQUEFACTION SUSCEPTIBILITY

The analysis of liquefaction susceptibility in the Des Moines and Renton quadrangles closely follows the methodology of Grant and others (1991) in their study of the Seattle North and Seattle South 7.5-minute quadrangles. Palmer (1992) used this approach in a preliminary liquefaction susceptibility study of the Renton and Auburn 7.5-minute quadrangles. We estimate susceptibility of a soil to liquefy 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 elevations obtained from geotechnical borings to estimate the factor of safety for a hypothetical earthquake with a specified magnitude and peak ground acceleration (PGA).

The SPT N-values and other data are obtained from sampled depths in 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. The procedure used in this study characterizes the liquefaction susceptibility of various Quaternary deposits through the cumulative frequency histogram of the aggregate thickness of liquefiable material penetrated in the borings. This is equivalent to the 'thickness' evaluation performed by Grant and others (1991). In this study, the Quaternary units in the study area are grouped into three categories on the basis of their engineering properties. Tertiary bedrock is treated as a fourth category.

The liquefaction susceptibility of each category is quantified from borings drilled only in geologic units that comprise that category. The four categories of geologic deposits used in this study (Categories I–IV) were discussed in the preceding section.

This study is primarily concerned with evaluating liquefaction that would have potential to cause structural damage at the ground surface. A relationship presented by Ishihara (1985) suggests that for accelerations of 0.30 g or less, liquefaction that occurs at depths greater than approximately 40 ft (12 m) will probably not cause noticeable effects or damage at the surface. Thus, this study limits the evaluation of liquefaction to only the upper 40 ft (12 m) of the borings. In many instances, the borings used in this study are less than 40 ft (12 m) deep—the average depth of all borings is 34.8 ft (10.6 m). Also, restricting the evaluation to these shallow depths allows a more direct comparison to historic reports of liquefaction.

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). We used measured grain-size data when available to provide this required value. If measured data were not available, we estimated the fines fraction of a sample from the soil category as-

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

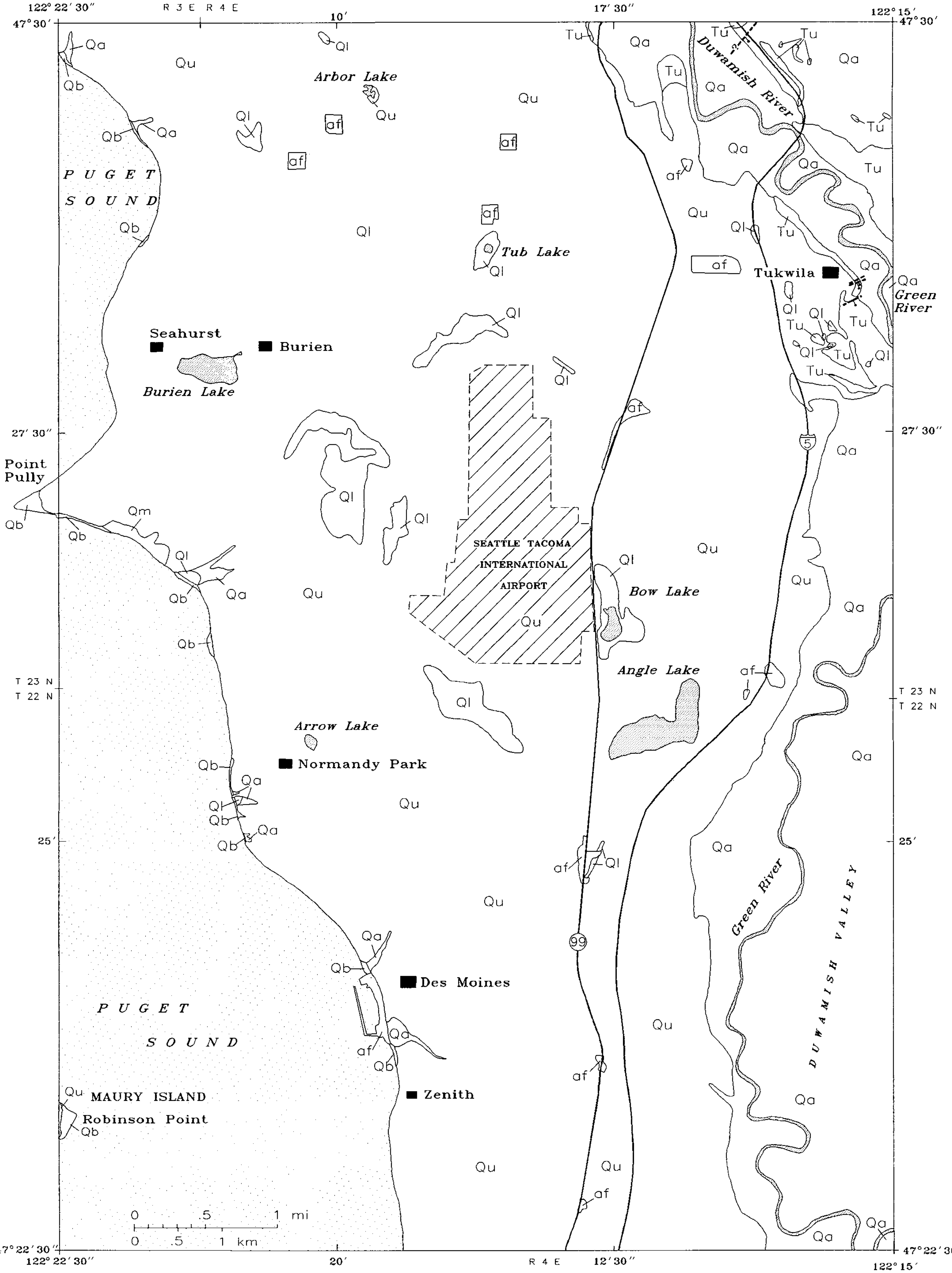

Figure 2b. Generalized geology of the Des Moines quadrangle.

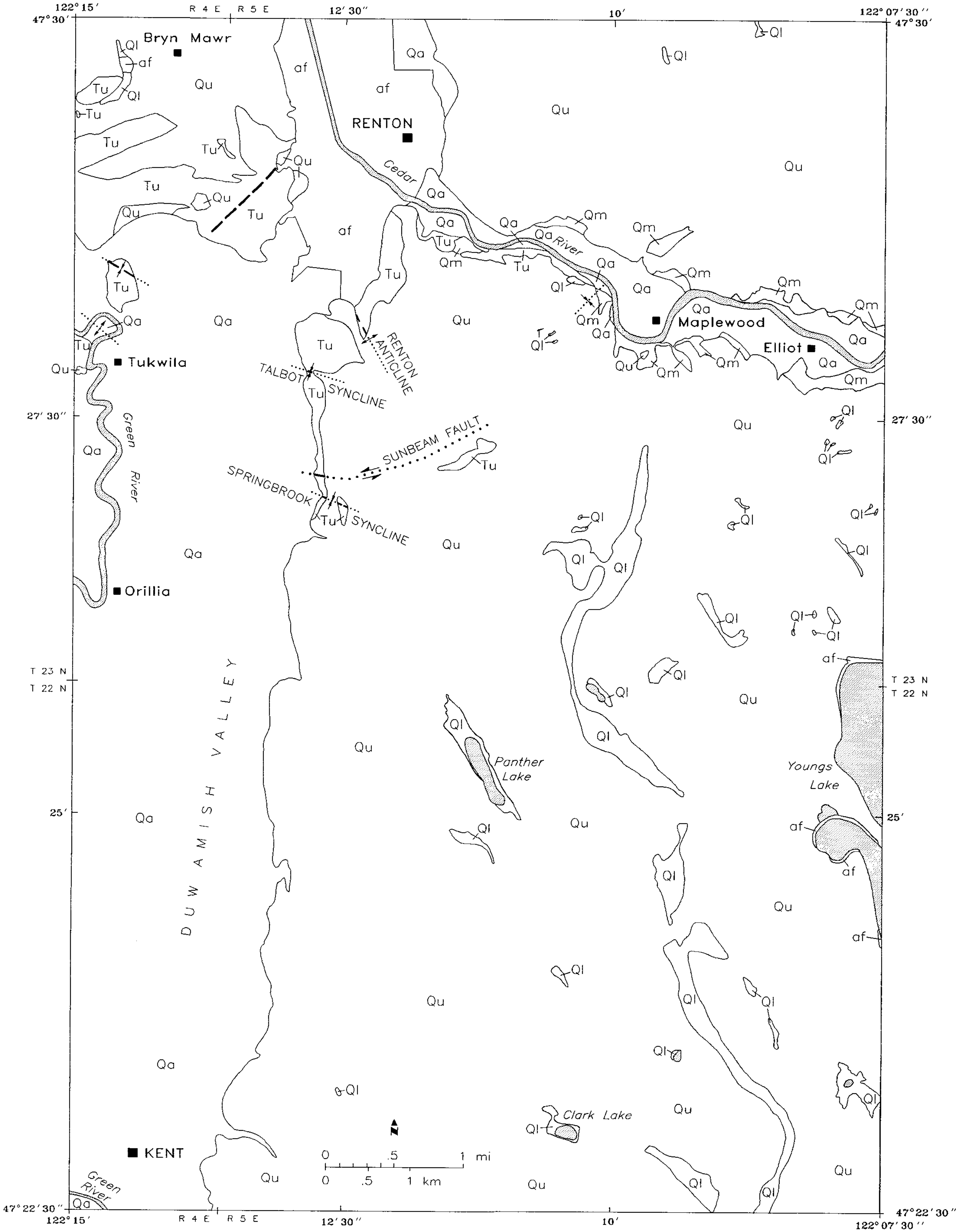

Figure 2c. Generalized geology of the Renton quadrangle.

Table 1. The four categories of geologic deposits used in this study and the corresponding map units of Mullineaux (1965) and Waldron (1962)

Category	Geologic description	Map units in the Des Moines quadrangle (Waldron, 1962)	Map units in the Renton quadrangle (Mullineaux, 1965)
I	fill and modified land, post-Vashon alluvium in the Duwamish and Cedar River valleys, and Holocene beach deposits	Qa, Qb, af, afm	Qac, Qaw, Qas, af, afm
II	post-Vashon lacustrine, colluvial, and landslide deposits	Qpm, Qlc, Qm	Qlp, Qlm, Qmc
III	Vashon and older glacial and nonglacial deposits	Qic, Qit, Qsr, Qg, Qgt, Qsa, Qss, Qpy, Qu	Qik, Qit, Qiv, Qpa, Qis, Qg, Qsr, Qgt, Qss, Qu

signed using the Unified Soil Classification System (ASTM D 2487-90[2]) and the conversions given in Table 2.

Cumulative frequency histograms for Category I and III deposits were 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 by Grant and others (1991) in evaluating liquefaction susceptibility in the Seattle North and Seattle South quadrangles. We could not analyze the Category II deposits using cumulative frequency plots because no boring data were available. Consequently, the liquefaction susceptibility for this category is based primarily on historic reports of liquefaction and generalizations about the engineering properties of Category II deposits.

The scenario earthquakes used in this study are intended to represent a major earthquake similar to the 1949 or 1965 events. We presume that the M_W 7.3 event would represent a large Puget Sound region earthquake occurring within the subducting Juan de Fuca plate at a depth of 30–36 mi (50–60 km) (termed an interface earthquake). 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 interface event. The choice of these scenario earthquakes maintains consistency with the work of Grant and others (1991).

However, recent studies indicate that other earthquake sources have the potential to generate more severe ground motions than the scenario earthquakes chosen for this study. The potential for great (M_W 8 or larger) thrust earthquakes to occur on the Cascadia subduction zone has been recently recognized (Atwater, 1987; Weaver and Shedlock, 1991). Also, evidence for a major earthquake (M_W 7–7.5) on the Seattle fault about 1,000 years ago was recently presented (Bucknam and others, 1992; Atwater and Moore, 1992; Jacoby and others, 1992). This west-trending fault is located approximately 6 mi (10 km) north of the northern boundary of the study area.

Ground motion simulation studies for a M_W 8.0–8.5 subduction zone earthquake were presented by Cohee and others (1991) and Wong and others (1993). These studies indicate that the peak ground accelerations in the Puget Sound region resulting from such an earthquake would be reasonably bounded by the 0.15–0.30-g range of the scenario earthquakes used in this study. However, the duration of strong ground shaking for the 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 and more damage associated with these occurrences than would be indicated from the results of this study. A major earthquake (M_W 7.0) on the Seattle fault would result in PGAs that would exceed 0.30 g, particularly in the northern portion of the study area. This intensity of shaking would produce more numerous and more severe occurrences of liquefaction than are indicated in this study.

GEOTECHNICAL BORING DATA USED IN EVALUATION OF LIQUEFACTION SUSCEPTIBILITY

The geotechnical boring data used in this study were obtained primarily from the Washington Department of Transportation and the City of Tukwila, with slightly less data supplied by the Port of Seattle (Sea-Tac Airport) and Seattle Metro. The

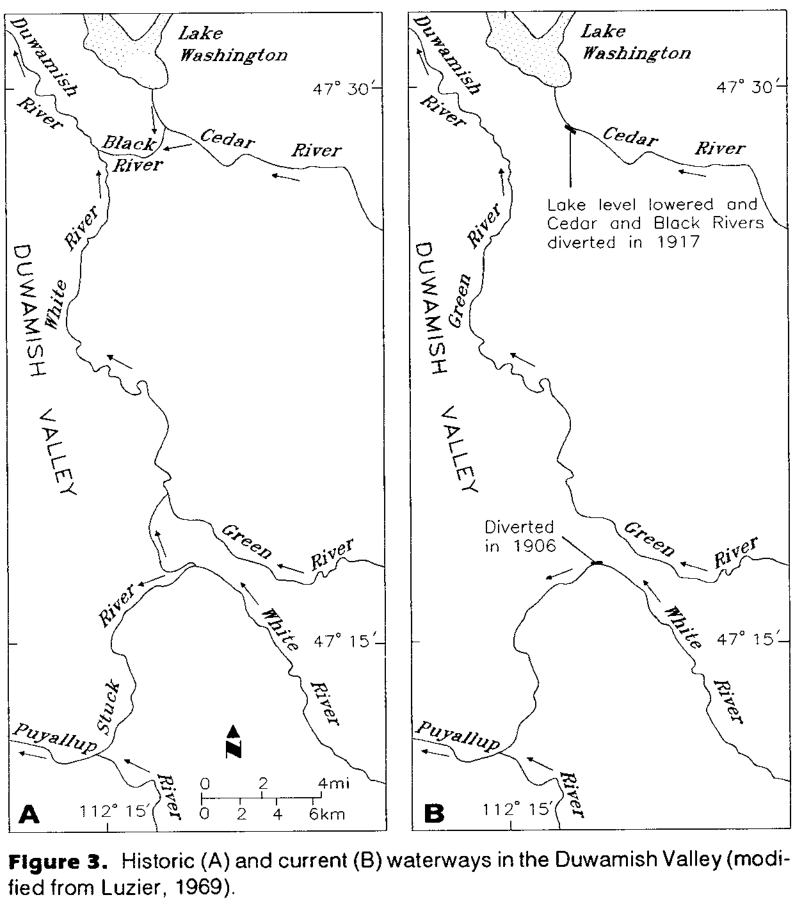

Figure 3. Historic (A) and current (B) waterways in the Duwamish Valley (modified from Luzier, 1969).

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[2] ASTM D 1586-84, also from v. 04.08, p. 309-319. Standard test method for classification of soils for engineering purposes.

remainder of the data was supplied by the City of Kent and the King County Department of Building and Land Development. Data for a total of 440 borings were obtained from these agencies, 244 in the Duwamish valley. Most borings are clustered around state highway routes and construction projects in metropolitan areas and King County that required geotechnical evaluations. On the Des Moines quadrangle, there is a greater density of borings on the drift plain, largely due to subsurface investigations performed during construction of Sea-Tac Airport and Interstate Highway 5. The sparsity of data on the drift plain in the eastern portion of the Renton quadrangle reflects the lack of engineering projects requiring extensive subsurface investigation in this area.

The maximum depth of the 440 borings used in this study is 130 ft (39.4 m). Information from boreholes that were less than 10 ft (3 m) deep was not included in the database. Two hundred sixty-five and 175 borings are located in the Des Moines and Renton quadrangles, respectively. Data for 98 borings were added to the original database generated by Palmer (1992) for the Renton quadrangle. The geologic distribution of borings is as follows: 271 borings in Category I, no borings in Category II, 163 borings in Category III, and 6 borings in Category IV deposits. All boring logs included sample descriptions and SPT N-values; most boring logs or reports contained measured depth to ground water, a general description of drilling and sampling procedures, accessory geotechnical data (such as grain-size analyses), and a site plan showing boring locations.

The variation in drilling methods and sampling procedures used in geotechnical borings can significantly affect the measured SPT N-values (Seed and others, 1984). They suggest that the ideal drilling and sampling practice for obtaining SPT N-values for evaluating liquefaction susceptibility is as follows:

- 4- to 5-in. (10.2–12.7 cm) -diameter rotary boring drilled using an upward-directed flow of bentonite mud (typically a tri-cone bit configuration);
- a sampling tube with 2.00-in. (5.08 cm) O.D. and 1.38-in. (3.50 cm) I.D. without a liner;
- AW drill rods for depths less than 50 ft (15.2 m), and N, BW, or NW rods for greater depths;
- 30 to 40 blows per minute delivered to the sampler;
- SPT N-value measured between 6 in. (15.2 cm) and 18 in. (45.7 cm) penetration of the sampler at the bottom of the hole; and

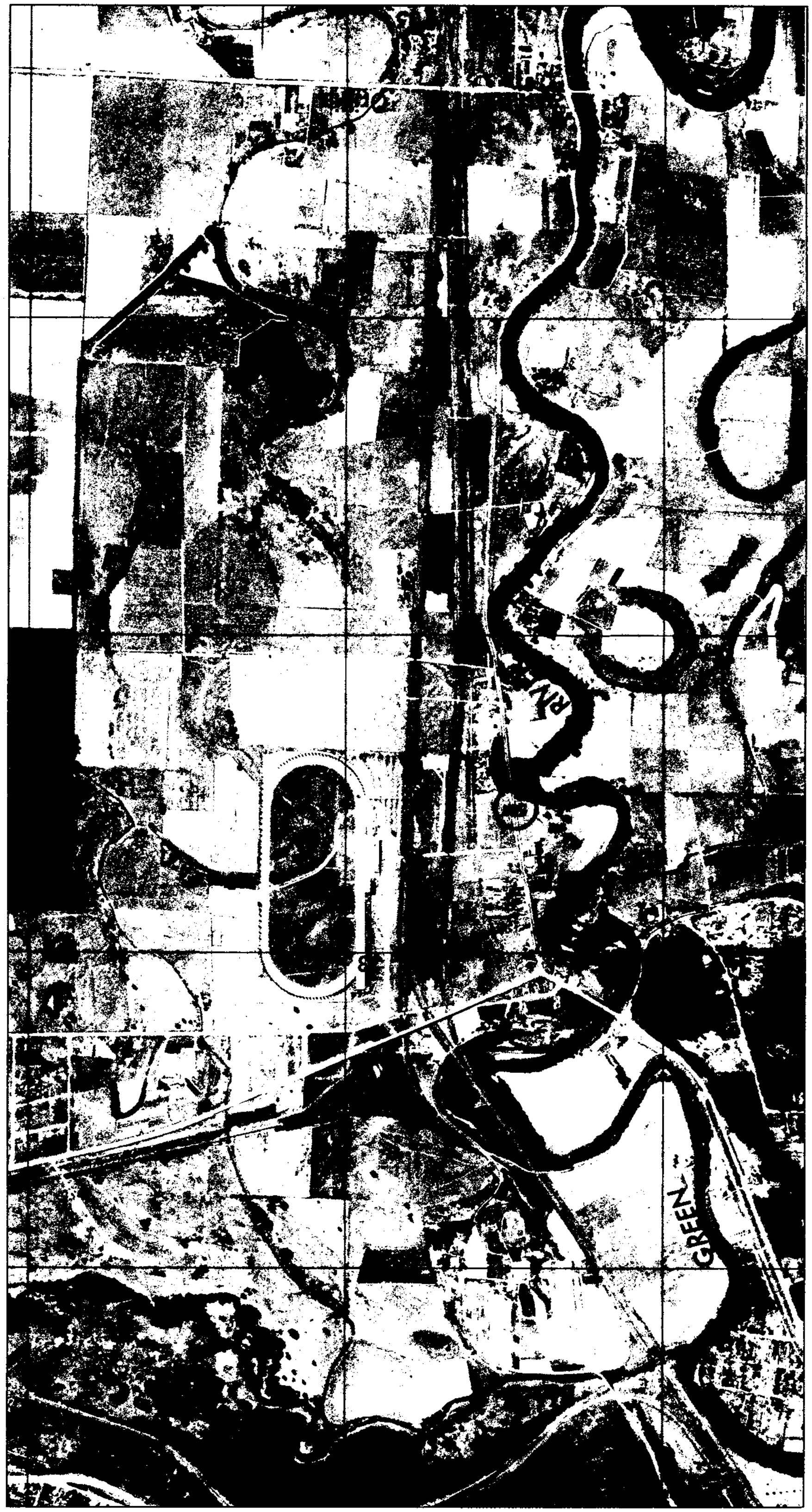

Figure 4. Sample of the U.S. Army Corps of Engineers aerial photo mosaic in the vicinity of the former Longacres Race Track. Dark sinuous band running vertically left of center is the Green River; abandoned channels can be seen on either side of its present course.

- 2,520 in.-lb (2,903 kg-cm) energy delivered to the sampler (60% of theoretical maximum).

The energy delivered to the sampler is typically not measured, but it has been shown to depend on the type of hammer and size of the drill rods used in the penetration testing. In the United States, the most common hammer configuration is a rope and pulley system using a so-called safety hammer (Seed and others, 1984). AW drill rods are typically used in most shallow geotechnical borings drilled in the Puget Sound region; consequently, SPT N-values obtained from these borings follow the recommended practice of Seed and others (1984). Use of a rope and pulley safety hammer system with AW rods would result in a 60 percent transfer of energy to the sampler at depths less than 50 ft (15.2 m) (Seed and others, 1984), which would satisfy the recommended parameters delineated above. It should be noted that N-values reported in borings drilled since the mid-1980s by the Washington Department of Transportation (WDOT) were obtained using an automatic trip hammer, which is reported to have an 80–90 percent efficiency in energy transfer to the drill rods. However, many of the borings obtained from WDOT files probably predate the use of the automatic trip hammer, and more recent WDOT boring logs do not document the type of hammer used in the SPT testing. Thus, we have treated all WDOT SPT blow counts as if the hammer efficiency were 60 percent.

As a minimum criterion, measurement of the SPT-N value in all borings used in this study explicitly adhered to ASTM D 1586-84. Because the use of AW drill rods and the safety hammer is typical practice in drilling and testing conducted by the geotechnical community in the Puget Sound region, we assumed that 60 percent of theoretical maximum energy is transferred to the sampler.

The most significant departure from the recommended procedures of Seed and others (1984) is the regular use of hollow-stem augers instead of rotary methods in drilling geotechnical borings in the Puget Sound region. A standard auger has an 8-in. (20.3 cm) O.D. and a 4-in. (10.2 cm) I.D. and drills a hole larger than the 4- to 5-in. (10.2–12.7 cm) optimal size. Water, rather than bentonite mud, is often used as the drilling fluid, if fluid is used at all during drilling. However, Seed and others (1987) have shown that the type of fluid (drilling mud or water) does not affect the SPT blow counts.

Shannon & Wilson, Inc., (1990) suggested that SPT N-values measured in borings drilled using hollow-stem augers are consistently lower than those measured in rotary-drilled borings. The certainty of this observation is obscured by the mixed use of safety- and donut-type hammers in obtaining the SPT N-values used in their study. Shannon & Wilson, Inc., (1993) drilled paired rotary and hollow-stem auger borings with the same drill rig at three sites in the Puyallup valley and reported no significant bias in measuring SPT N-values with the type of drilling method. Only 78 borings in this study's data set are known to have been drilled using rotary methods; this amounts to less than 18 percent of the borings available for use in the Des Moines–Renton liquefaction analysis. The majority of the available borings were drilled using hollow-stem augers. Thus, this study ignores the postulated bias introduced into SPT N-values measured in hollow-stem auger borings on pragmatic grounds: it would not be possible to perform a defensible evaluation of liquefaction susceptibility using only the sparse data set provided by rotary-drilled borings.

Table 2. Conversion of Unified Soil Classification System (USCS) soil class to fines fraction used as input to the liquefaction susceptibility analysis

USCS soil category	Fines fraction (%)
SP	5
SM	30
SP–SM	15
SW	20

HISTORIC LIQUEFACTION

The two largest earthquakes in recent historic times in the Puget Sound region are the 1949 magnitude 7.1 Olympia and the 1965 magnitude 6.5 Seattle–Tacoma earthquakes. The study area was exposed to Mercalli Modified 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). Locations of ground failures caused by liquefaction in the study area have been summarized by Hopper (1981) and Chleborad and Schuster (1990). Six sites where liquefaction may have occurred and that are identified by the reference number used in Chleborad and Schuster (1990) are shown on Plates 1 and 2. The location and description of a seventh site were obtained by T. J. Walsh, DGER; it is labeled site 107A on Plate 2 and in Table 3 because of its proximity to site 107 of Chleborad and Schuster (1990). Table 3 reproduces the quotations and comments given for the sites identified in Chleborad and Schuster (1990) and for site 107A.

Five of the seven possible liquefaction sites are located in the Duwamish valley in post-Vashon alluvial deposits. A sixth site is located along the retaining dikes at Lake Youngs. The remaining site lies in a post-Vashon lacustrine deposit in the Big Soos Creek valley. Thus, six of the seven historical liquefaction sites are in Category I deposits, and the remaining historical site occurs in a Category II deposit.

Locations 106, 107, 107A, and 110 appear to be bona fide liquefaction sites on the basis of the descriptions cited in Table 3. We can reasonably infer that the slumping and cracking of the retaining dikes and damage to the gate chamber casting at loc. 114 was the result of lateral spreading, although no definitive evidence of liquefaction was observed at this site. The differential ground settlement at the Shattuck Street residence described in loc. 111 may have been caused by liquefaction of the underlying soils. Similar cracking of foundations and ground disruptions were observed in Puyallup during the 1949 earthquake near well-documented liquefaction sites (Chleborad and Schuster, 1990). However, the settlement along Burnett Street and Seventh Avenue (loc. 111, Table 3) is along the route of the Metro sewer line and may simply be the result of dynamic compaction of the fill used in closing the sewer line excavation.

The interpretation of liquefaction at loc. 105 (Table 3) is somewhat more equivocal. The primary effect described appears to be a sudden increase in the flow of the numerous springs at this locality. An increase of water flow is not necessarily an indication of liquefaction; sudden increases (and decreases) in water flow into wells and from springs are commonly reported after large earthquakes. The cracking above the reservoir is clearly a slope failure caused by the earth-

Table 3. Descriptions of selected ground failures in the Des Moines and Renton 7.5-minute quadrangles (excerpted verbatim from table 2 of Chleborad and Schuster, 1990; information for site 107A from other sources). Location numbers correspond to ground-failure location numbers found on Plate 2. Location accuracy: A, available information allows accurate relocation; B, available information allows relocation to within a kilometer; C, available information allows relocation to within a few kilometers; D, information insufficient to locate accurately. Quotations referenced as "written commun., 1949", or "written commun., 1965", are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colorado. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents

Loc. No.	Failure Type; (year of quake)	Reference Municipality or Geographic Location; County	Location Accuracy	Quotation and (or) Comment
105	Slump (49) Sandboils (49) Misc. effects (49)	Kent, Wash. (NE on Big Soos Creek); King County	A	"Water system is gravity line taken from springs east side of creek, 2 and 3 inch [5.1 and 7.6 cm] wooden pipe—about 950 feet [298.6 m]. Went to inspect pipelines 1 hour after quake, nearly all were leaking where line crosses creek and swamp, emitting white water (water mixed with clay). Water reservoir (earth constructed) all white and all springs giving more water. Above reservoir crack in earth about 100 feet [30.5 m] long north and south. At that time lower, or west side of crack, had slipped about 3 inches [8 cm] but after 24 hrs it was about 8 inches [20 cm] and appeared to be slowly settling. At one spot that was dry I could slip my hand into the crack. I went to inspect other springs, one on adjoining property about 1000 ft [300 m] north of my reservoir was emitting white water with about 4 times the volume as before the quake and brought up considerable fine sand and clay. Between this spring and mine there were numerous spots where seepage of new water occurred in spots that were dry." (John Haverinen, written commun., 1949). The reservoir mentioned in the letter [above] was located on hillside just east of Big Soos Creek and below the powerlines that cross the upper part of the hillside. The reservoir was very small, not more than a few tens of feet across. (John Haverinen Jr., personal commun., 1988).
106	Sand boil (65) Ground crack (65)	Kent, Wash. (208th St. near O'brien); King County	A	"Cracked cement driveway * * * water and sand spurted through cement driveway—several ground cracks and erosions of water and sand." (Mrs. Milton Botts, written commun., 1965).
107	Sand boils (65)	Kent, Wash. (212 St. just west of Green River); King County	A	[Photo caption] "BOIL AND BUBBLE—Thursday morning's earthquake created an odd phenomena in a field near O'Brien being worked by Albert Dreisow. * ** [Dreisow] found numerous "mud pots" [sand boils] in the field, similar to the fissure he is examining here." (Kent News-Journal, 5/5/65, p. 2-3). "Two sand boils appeared in the fields; one on each side of 212th Street." (Albert Dreisow, personal commun., 1988).
107A	Sand boils (65)	Kent, Wash. (just south of 204 St. and west of the Green River); King County	A	Numerous sand and water eruptions (sand boils) "that looked like worm holes" appeared in a farm field. (Ralph Omlid, personal commun., 1994).
110	Slide (65)	Seattle, Wash., (Tukwila); King County	B	The 1965 earthquake triggered a landslide on the Foster golf course along the Duwamish. The slide involved fluvial sands and silts and was probably induced by liquefaction (Seed, 1968).
111	Settlement (65)	Renton, Wash. (Burnett and Seventh Streets); King County	B	"Mayor Custer said filling and paving to repair settling of the entire length of Burnett Street and Seventh Avenue would cost an estimated $15,000 to $20,000. Custer said the settling was along the route of the Metro sewer line, but Robert Hillis of Metro reported there was no damage to the line. * * * City Engineer Jack Wilson said Burnett and Seventh had dropped as much as two feet [0.6 m] in some places." (The Record-Chronicle, 5/5/65, p. 1,2).
	Settlement (65)	Renton, Wash. (Shattuck Street between S. 6th and S. 7th Streets); King County	A	"Foundation cracked open under house. Cement walk from street to house cracked open. House settled about 2-1/2 inches [6 cm]. Front and back-yard upheaved and sunken in spots." (A. F. Salisbury, written commun., 1965).
114	Slides (49) Ground cracks (65)	Mapel Valley, Wash. (Lake Youngs; King County	C	"It has been determined * * * that [due to the 1949 earthquake] 575 yards of material were required to repair slumping in one of the retaining dikes at Lake Youngs. Also, one gate chamber casting was broken due to soil displacement. * * * Dike around Lake Youngs – cracks in three places [as a result of the 1965 earthquake]." (Kennedy-Jenks-Chilton Consultants, 1990).

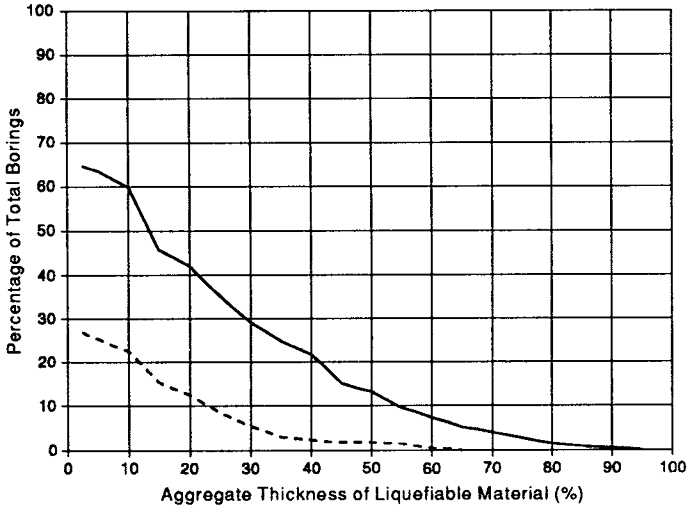

Figure 5. Cumulative frequency histogram for Category I deposits, M 7.3 event. Dashed line is data for 0.15 g PGA; solid line is data for 0.30 g PGA.

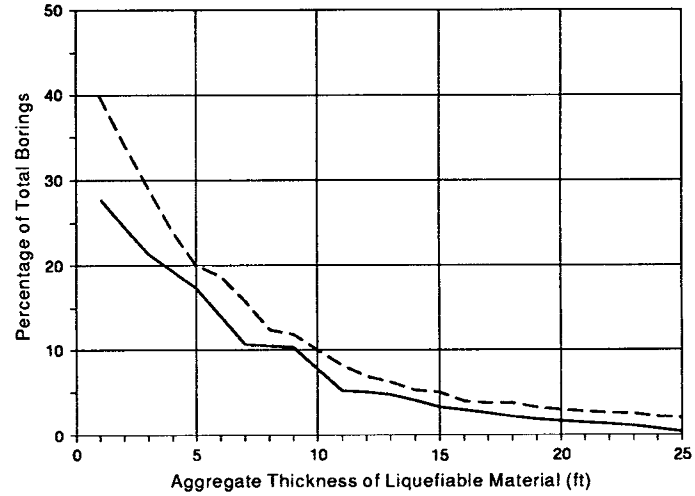

Figure 6. Comparison of data for Category I deposits, this study (solid line) and for Holocene alluvium, Grant and others, 1991 (dashed line), for M 7.3, 0.15 g events.

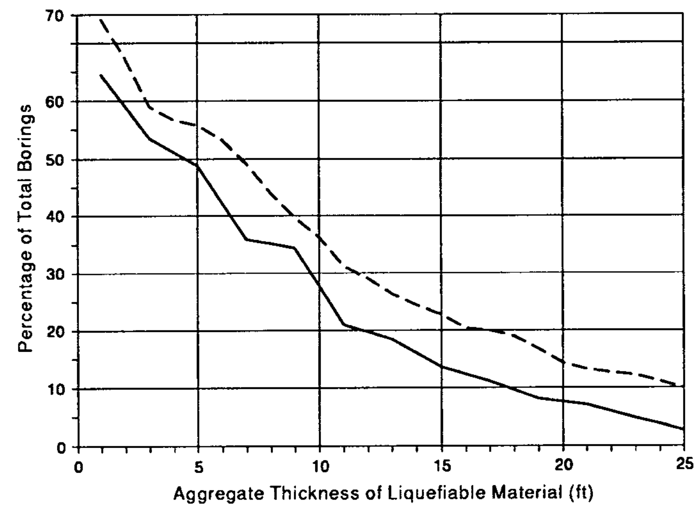

Figure 7. Comparison of data for Category I deposits, this study (solid line), and for Holocene alluvium, Grant and others, 1991 (dashed line), for M 7.3, 0.30 g events.

quake, but again, it need not be the result of liquefaction. Finally, the leaking water pipelines at creek and swamp crossings likely indicate ground settlement that might not have been caused by liquefaction of the underlying soils.

LIQUEFACTION ANALYSIS

Figure 5 is a cumulative frequency histogram for each scenario earthquake showing the percentage of the total borings located in Category I deposits that equal or exceed an aggregate thickness of liquefiable soils expressed as a percentage of the total boring depth. The aggregate thickness is the sum of the thicknesses of all soil units that would liquefy at the magnitude and PGA value chosen for the scenario earthquake. Figure 5 shows the histograms for M_W 7.3 earthquakes that produce a PGA of either 0.15 g or 0.30 g at the boring site. The abscissa of the histograms measures the aggregate thickness of liquefiable material in a boring (expressed as a percentage of the depth of the boring). For borings drilled deeper than 40 ft (12 m), only the upper 40 ft (12 m) were analyzed for susceptibility to liquefaction. The ordinate delineates the percentage of the total number of borings that contain a percentage of liquefiable material greater than or equal to the abscissa value.

Figures 6 and 7 present the cumulative histograms produced by Grant and others (1991) and this study for the two scenario earthquakes. These figures illustrate results from Category I deposits in the Des Moines and Renton quadrangles and Holocene alluvium in the Seattle North and Seattle South quadrangles. Grant and others (1991) did not normalize the aggregate thickness of liquefiable material by the depth of the boring; rather, they report their aggregate thickness in feet. Thus, the abscissa in these figures measures the aggregate thickness in feet rather than as a percentage of total boring depth. Comparison of unnormalized thicknesses is strictly valid only if the average depth of borings in the two studies is equivalent. The average depth of the borings drilled in Category I deposits (this study) is 39.4 ft (11.9 m). Grant and others (1991) restricted their liquefaction analyses to the upper 50 ft (15.2 m); consequently the average depth of the Holocene alluvium borings is estimated to range from 40–50 ft (12.1–15.2 m) (W. J. Perkins, Shannon & Wilson, Inc., personal commun., 1994).

Figures 6 and 7 indicate that the liquefaction susceptibility of the Category I deposits in the Des Moines and Renton quadrangles is less than the susceptibility of the Holocene alluvium, although these cumulative frequency histograms are generally similar. The differences could be partly the result of differences in the average depth of the borings used in the two separate studies.

Table 4 presents the thickness criteria used by Grant and others (1991) to rank the relative liquefaction susceptibility of the various soil units in their study area. Figure 6 shows that for Category I deposits, 28 percent of the borings in the Des Moines and Renton quadrangles had at least 1 ft (0.3 m) of liquefiable material for the 0.15 g earthquake, and 28 percent (coincidentally) had at least 10 ft (3 m) of liquefiable soils for the 0.30 g event. Using these criteria, Category I deposits fall at the lower end of a moderate rating.

A second method of ranking the liquefaction susceptibility of a soil deposit is presented by Youd and Perkins (1987).

Table 4. Criteria used by Grant and others (1991) for rating the hazard due to liquefaction based on analysis of geotechnical boring data in the Seattle North and Seattle South quadrangles

Percentage of borings in geographic location with thickness of liquefied sediment ≥: (a) 10 ft (3.05 m) for a 0.30 g event, and, (b) 1 ft (0.305 m) for a 0.15 g event	Hazard rating
>50	high
25–50	moderate
<25	low

They calculate relative susceptibility to liquefaction using the following equation:

Relative susceptibility (%) = [(A x B x C)/10] x 100, *where,*

A = percent of sandy soils expressed as a decimal fraction;

B = percent of these soils that are liquefiable if saturated, expressed as a decimal fraction;

C = percent of these soils that are saturated, expressed as a decimal fraction.

Their hazard rating scheme is based on the relative susceptibility, which is summarized in Table 5.

Youd and Perkins (1987) evaluate the liquefaction susceptibility of soil in San Mateo County, California, using a scenario earthquake of magnitude range 6.5 to 6.75 that produces a PGA of 0.20 g (Youd and others, 1975). The liquefaction analysis of Seed and others (1983, 1985) treats this scenario earthquake as roughly equivalent to a magnitude 7.3 earthquake with a PGA of 0.15 g. The methodology of Seed and others (1983, 1985) is used by Youd and Perkins (1987), Grant and others (1991), and in this study.

For the 271 borings drilled in Category I deposits, an average of 65.6 percent of the total drilled depth above 40 ft (12 m) was composed of sandy soils. This value is the factor A in the relative susceptibility calculation of Youd and Perkins (1987). Figure 5 shows that 28 percent of the borings contained some amount of liquefiable material (sandy soils that are liquefiable and are saturated). This value is the product of factors B and C of Youd and Perkins (1987). Thus, the relative susceptibility for the Category I deposits is 1.84 percent, which corresponds to a high rating. For comparison, the highest relative susceptibility estimated by Youd and Perkins (1987) for stream alluvium with a shallow (<10 ft, 3 m) ground-water table was 2.1.

Table 6 summarizes the calculation of relative susceptibility from the data presented in Grant and others (1991) for the Duwamish tideflats fill and the Duwamish alluvium. The relative susceptibilities of these deposits would result in a high susceptibility rating using the criteria of Youd and Perkins (1991). However, the rating criteria used by Grant and others (1991) gives the Duwamish tideflats fill a high rating, and the Duwamish alluvium a moderate rating.

It is necessary to maintain consistent regional criteria when rating the severity of the liquefaction hazard. Ideally, all liquefaction susceptibility maps should use the same criteria. However, the rating system developed by Grant and others (1991) would consider all Category I deposits in the study area as having a moderate hazard, which to us seems contradicted by the numerous observations of liquefaction. Their only high liquefaction hazard is located in the 6.1 mi^2 (16.9 km^2) of fill areas of the Seattle North and Seattle South quadrangles in which a total of 26 instances of liquefaction was reported during the 1949 and 1965 earthquakes (W. J. Perkins, Shannon & Wilson, Inc., written commun., 1994). Other Holocene deposits in Grant and others' (1991) study area where liquefaction was also reported are assigned a moderate rating.

Table 5. Relative (liquefaction) susceptibility and associated hazard rating from Youd and Perkins (1987)

Relative susceptibility (%)	Hazard rating
1.0 to 10.0	high
0.1 to 1.0	moderate
0.01 to 0.1	low

Five of the six historical liquefaction sites within our study area occurred in Category I deposits. The two methods of ranking liquefaction susceptibility discussed previously indicate that Category I deposits rank from the lower end of the moderate hazard to the lower end of the high hazard ratings. The cumulative frequency analysis indicates that liquefaction could occur at a large number of sites within Category I deposits, an observation supported by the historical record.

We have chosen to rank the Category I deposits in the Des Moines and Renton area as having a high liquefaction susceptibility on the basis of the historical record and the relative liquefaction susceptibility and associated hazard rating obtained using the criteria of Youd and Perkins (1987). *The high hazard rating does not indicate that any specific locality within a Category I deposit will be underlain by liquefiable soils; the presence or absence of liquefiable material can only be determined by a site-specific geotechnical investigation performed by a qualified practitioner.*

Abandoned channels mapped in Plates 1 and 2 *may* represent areas of locally higher liquefaction susceptibility. Three of the historic liquefaction sites in the Duwamish valley south of the Renton quadrangle are close to abandoned channels (Palmer and others, in press). In addition, three of the historic liquefaction sites in the Sumner area also close to abandoned channels (Dragovich and Pringle, in press). Many of those abandoned channels are low points in the local topography and would consequently have higher ground-water tables than the adjacent flood plain. Because loose, near-surface sandy soils are common throughout the Duwamish and Puyallup valleys, the presence of a high ground-water table would increase the liquefaction susceptibility. Also, many of these abandoned channels have been filled during the urbanization of the Duwamish valley. For example, a filled channel is located on the grounds of the former Longacres Race Track (section 24, T23N, R4E; Mullineaux, 1965; also see Fig. 4). Any or all of these factors could result in a locally higher susceptibility to liquefaction within these abandoned channels.

The decision to delete the fill mapped as modified land (unit afm) by Waldron (1962) near Sea-Tac Airport from the generalized geologic map (Figure 2c) of the Des Moines quadrangle and the liquefaction susceptibility map of the Des Moines quadrangle (Plate 1) warrants further discussion. Before construction of the runways and buildings, engineered fill was placed directly on compact Vashon-age till and glacial outwash. Seventy borings were located in the geological unit mapped as afm by Waldron (1962). Fifty-eight of these borings penetrated fill that had an average thickness of approximately 6 ft (2 m) and ranged in thickness from 1 ft (0.3 m) to

Table 6. Relative (liquefaction) susceptibility and associated hazard ratings using the criteria of Youd and Perkins (1987) and Grant and others (1991) for Duwamish tideflats fill and alluvium, and Holocene beach deposits (Grant and others, 1991), and Category I deposits (this study)

Deposit	Relative susceptibility using the method of Youd and Perkins (1987)	Hazard rating based on relative susceptibility rating of Youd and Perkins (1987)	Hazard rating based on criteria of Grant and others (1991)
Duwamish tideflat fill	4.76	high	high
Duwamish alluvium	2.40	high	moderate
Holocene beach deposits	2.52*	high	moderate
Category I deposits	1.84	high	moderate

* Assumes 70 percent of Holocene beach deposits are composed of sandy soils

21 ft (6.4 m). Standard penetration tests averaged 70 blows/ft in 42 of the 70 boreholes. Only seven borings at three separate sites recorded blow counts that were significantly less (averaging 13 blows/ft). Of those, only four borings at a single site appear to have potentially liquefiable fill.

Sixty-four of the 70 Sea-Tac boreholes penetrated till and glacial outwash beneath the fill. The drill holes penetrated 2 to 47 ft (0.6–14.2 m) of glacial materials; the average thickness was slightly more than 15 ft (4.5 m). Standard penetration tests typically recorded blow counts greater than 50 (refusal) in the glacial materials. Because of the sporadic occurrence of loose fill soils and the presence of the underlying dense glacial deposits, we determined that the fill associated with the construction of Sea-Tac Airport has a low liquefaction susceptibility. We felt it appropriate to show the glacial drift beneath the fill as the geologic unit representing the Sea-Tac Airport area. Consequently, we consider that Sea-Tac Airport lies on Category III deposits for the purposes of this regional mapping study. However, we emphasize that liquefiable soils were found in some of the Sea-Tac borings and that further study of the earthquake vulnerability of the airport's operational capability is justified.

Several other small scattered areas of modified land and fills north of the Sea-Tac Airport were treated as Category I. These sites also are situated on the drift plain and on the same materials that form the native soils at Sea-Tac airport. However, because there were no boring data to characterize the fills in these areas, we made a conservative decision in classifying these areas as Category I deposits.

Holocene beach deposits were mapped by Waldron (1962) along Puget Sound in the western part of the Des Moines quadrangle. No boring data were available to characterize these deposits in the study area. However, Grant and others (1991) had boring data for beach deposits near Alki Point in the Seattle South quadrangle. Liquefaction in Holocene beach deposits was reported in that area during the 1949 and 1965 Puget Sound earthquakes (Chleborad and Schuster, 1990). Grant and others (1991) ranked the beach deposits as having moderate liquefaction susceptibility. However, using Youd and Perkins' (1987) rating methodology and data from Grant and others (1991), the Holocene beach deposits have a high liquefaction susceptibility. (See Table 6.) Again, we chose a conservative approach because of the historic observation of liquefaction, and we classify the beach deposits in the Des Moines quadrangle as Category I.

Category II deposits include post-Vashon lacustrine deposits and colluvium. We could not locate any borings in areas mapped as Category II deposits. Post-Vashon lacustrine deposits are primarily composed of peat and silt in which there are a few sandy interbeds (Mullineaux, 1965) and would typically be considered as having a low liquefaction susceptibility. However, at loc. 105, in a post-Vashon lacustrine deposit in the Big Soos Creek drainage, liquefaction might have occurred during the 1949 earthquake. From this report we conclude that loose sandy portions of these deposits may be susceptible to liquefaction.

Mullineaux (1970) and Waldron (1962) mapped only thick and continuous colluvial deposits in the Des Moines and Renton quadrangles. These typically occur on the lower parts of steep slopes and primarily consist of landslide debris and slope wash. This composition reflects a diversity of source deposits. Chleborad and Schuster (1990) report several landslides and associated ground cracks along steep slopes underlain by colluvium in the study area; however, the failure mechanisms of these reported downslope movements are unknown. Without a thorough geotechnical investigation we cannot ascertain if an earthquake-induced slope failure resulted from soil liquefaction or the additional dynamic load imposed by strong ground shaking. Two slope failures they describe occurred during the 1965 earthquake within the inactive landslide mapped by Waldron (1962), approximately 1 mi (1.6 km) east of Point Pully.

The geologic descriptions given in Waldron (1962) and Mullineaux (1965) for Category II deposits indicate the they should have low susceptibility to liquefaction. Numerous earthquake-induced ground failures occurred in Category II

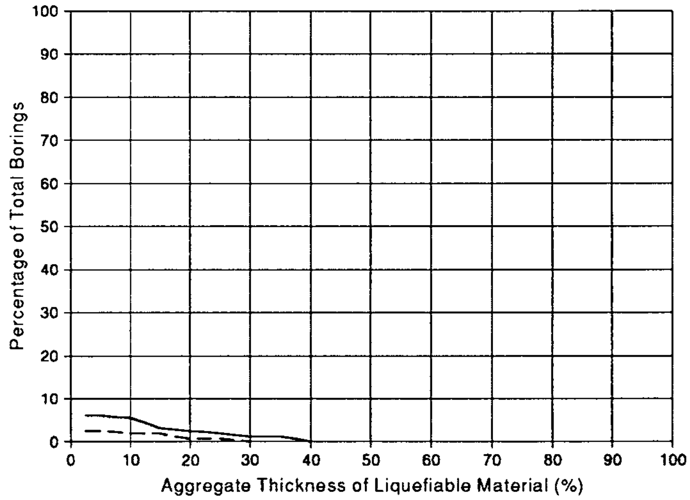

Figure 8. Cumulative frequency histogram for Category III deposits, M 7.3 event. Dashed line is for a 0.15 g PGA, solid line is data for 0.30 g PGA.

Table 7. Liquefaction susceptibility ranking of the four categories of geologic deposits found in the Des Moines and Renton quadrangles

Category	Liquefaction susceptibility rating
I	high
II	low to moderate
III	low
IV	low to nil

deposits, although there is no unequivocal evidence demonstrating that liquefaction did occur. We decided to express the variability in the observed soil types occurring in lacustrine and colluvial deposits and the historic record of liquefaction and slope failures in these units by assigning a low to moderate susceptibility to Category II deposits.

Figure 8 presents the cumulative frequency histograms for Category III deposits; 163 borings drilled in Vashon and older glacial and nonglacial deposits were available for constructing these histograms. These deposits are typically quite dense and provide excellent foundation stability (Mullineaux, 1970). The relative susceptibility for Category III deposits is 0.15 percent, which falls at the lower end of the moderate liquefaction hazard rating of Youd and Perkins (1987). No instances of liquefaction were observed in Category III deposits during the 1949 and 1965 Puget Sound earthquakes. The geologic descriptions, geotechnical analyses, and historical record indicate that Category III deposits have little susceptibility for liquefaction. Consequently, we assign them a low susceptibility.

The Tertiary bedrock (Category IV deposits) in the study area consists of sedimentary and igneous rocks; rock will not liquefy during an earthquake. Six borings penetrating a part of the Tertiary sedimentary section indicated that the sedimentary bedrock is well indurated except where it has weathered into a soft residual soil. There are no historical reports of liquefaction in areas mapped as bedrock by Mullineaux (1965) and Waldron (1962). There may be unmapped soil deposits of limited extent in areas of Category IV deposits that might be susceptible to liquefaction (for example, an unmapped uncompacted fill). To account for this unlikely situation, Category IV deposits are considered to have low to no susceptibility to liquefaction.

CONCLUSIONS

Table 7 summarizes this study's ranking of the liquefaction susceptibility in the Des Moines and Renton quadrangles. The Holocene alluvial deposits in the Duwamish and Cedar River valleys and Holocene beach deposits along Puget Sound are ranked as having high liquefaction susceptibility. Although there are no borings in this study area in Holocene colluvial or lacustrine soils (Category II deposits), descriptions of these deposits (Mullineaux, 1965; Waldron, 1962) indicate that they are composed of materials having a low susceptibility to liquefaction. An equivocal historical example of liquefaction in a Holocene lacustrine unit shows that liquefaction might be possible in Category II deposits. Some of the numerous ground failures (cracking, slumping, etc.) in colluvium during the 1949 and 1965 earthquakes may have been the result of liquefaction, but no definitive evidence supporting liquefaction as the primary cause of these failures is available. We conservatively rank Category II deposits as having low to moderate liquefaction susceptibility. Areas underlain by Vashon and older glacial and nonglacial deposits (Category III deposits) have been assessed as having low liquefaction susceptibility. Category IV deposits comprise all Tertiary bedrock, which is typically well indurated and not susceptible to liquefaction. However, unmapped liquefiable soil deposits of limited extent may overlie Category IV units. For this reason, Category IV deposits have been assigned low to no liquefaction susceptibility.

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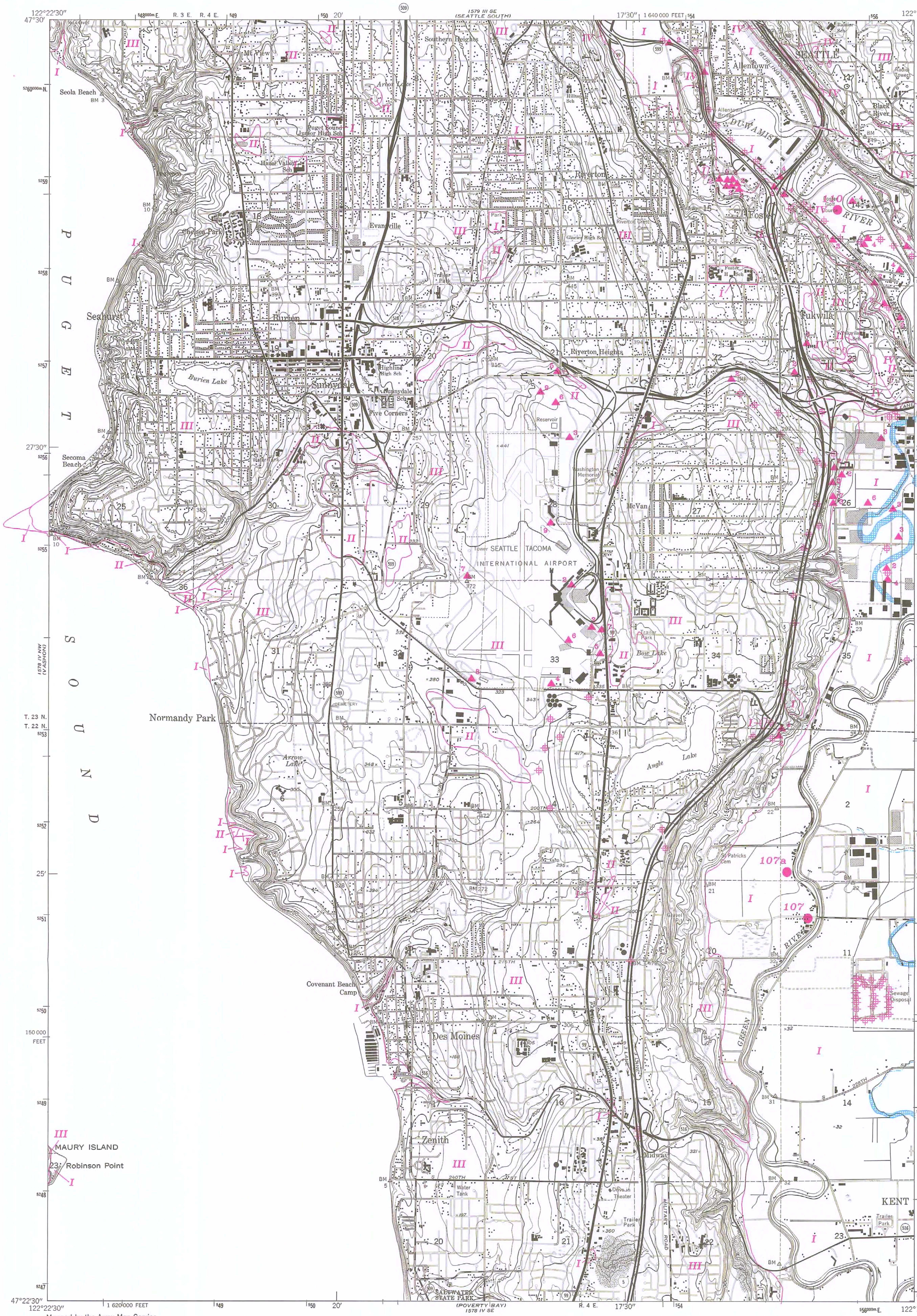
WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
Raymond Lasmanis, State Geologist

GEOLOGIC MAP GM-41

LIQUEFACTION SUSCEPTIBILITY OF THE
DES MOINES AND RENTON QUADRANGLES, WASHINGTON

PLATE 1



Mapped by the Army Map Service
Published for civil use by the Geological Survey

Control by USC&GS and King County Engineer Office

Topography from aerial photographs by multiplex methods
Aerial photographs taken 1943. Field check 1949

Polyconic projection. 1927 North American datum
10,000-foot grid based on Washington coordinate system, north zone

UTM GRID AND 1973 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24000

CONTOUR INTERVAL 25 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
THE AVERAGE RANGE OF TIDE IS APPROXIMATELY 12 FEET

QUADRANGLE LOCATION

LIQUEFACTION SUSCEPTIBILITY OF THE DES MOINES QUADRANGLE, WASHINGTON

by

Stephen P. Palmer, Henry W. Schasse, and
David K. Norman

1994

EXPLANATION

Geologic map units from Waldron, 1962.

I	CATEGORY I includes post-Vashon alluvium, manmade fill, modified land (except most fills along roadways) and Holocene beach deposits. LIQUEFACTION SUSCEPTIBILITY : HIGH
II	CATEGORY II includes post-Vashon lacustrine deposits and mass-wasting deposits. LIQUEFACTION SUSCEPTIBILITY : LOW TO HIGH
III	CATEGORY III includes all Pleistocene glacial and nonglacial deposits. LIQUEFACTION SUSCEPTIBILITY : LOW
IV	CATEGORY IV includes all Tertiary bedrock. LIQUEFACTION SUSCEPTIBILITY : LOW TO NIL
	Contacts between liquefaction susceptibility categories.
	Location of geotechnical borings used in this study.
5	Location of multiple geotechnical borings used in this study (with number of borings indicated).
107	Historic liquefaction sites identified by the corresponding reference number in Chleborad and Schuster, 1990; Table 3 reproduces the quotations and comments given for the sites in Table 2 of Chleborad and Schuster, 1990.
	Abandoned channels of the Green River that do not appear to contain intermittent streams or support riparian vegetation.
	Drainages and streams that appear to be abandoned channels of the Green River.

This map is meant only as a general guide to delineate areas prone to liquefaction. This map is not a substitute for a site-specific investigation to assess the potential for liquefaction for any development project. Because of the regional nature of this map and 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 liquifiable soils beneath any specific locality. To make this determination requires a site-specific geotechnical investigation performed by qualified practitioners.

Base is from U.S. Geological Survey 7.5 minute Des Moines quadrangle, 1949, photorevised 1968 and 1973.

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

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
Raymond Lasmanis, State Geologist

GEOLOGIC MAP GM-41

LIQUEFACTION SUSCEPTIBILITY OF THE
DES MOINES AND RENTON QUADRANGLES, WASHINGTON

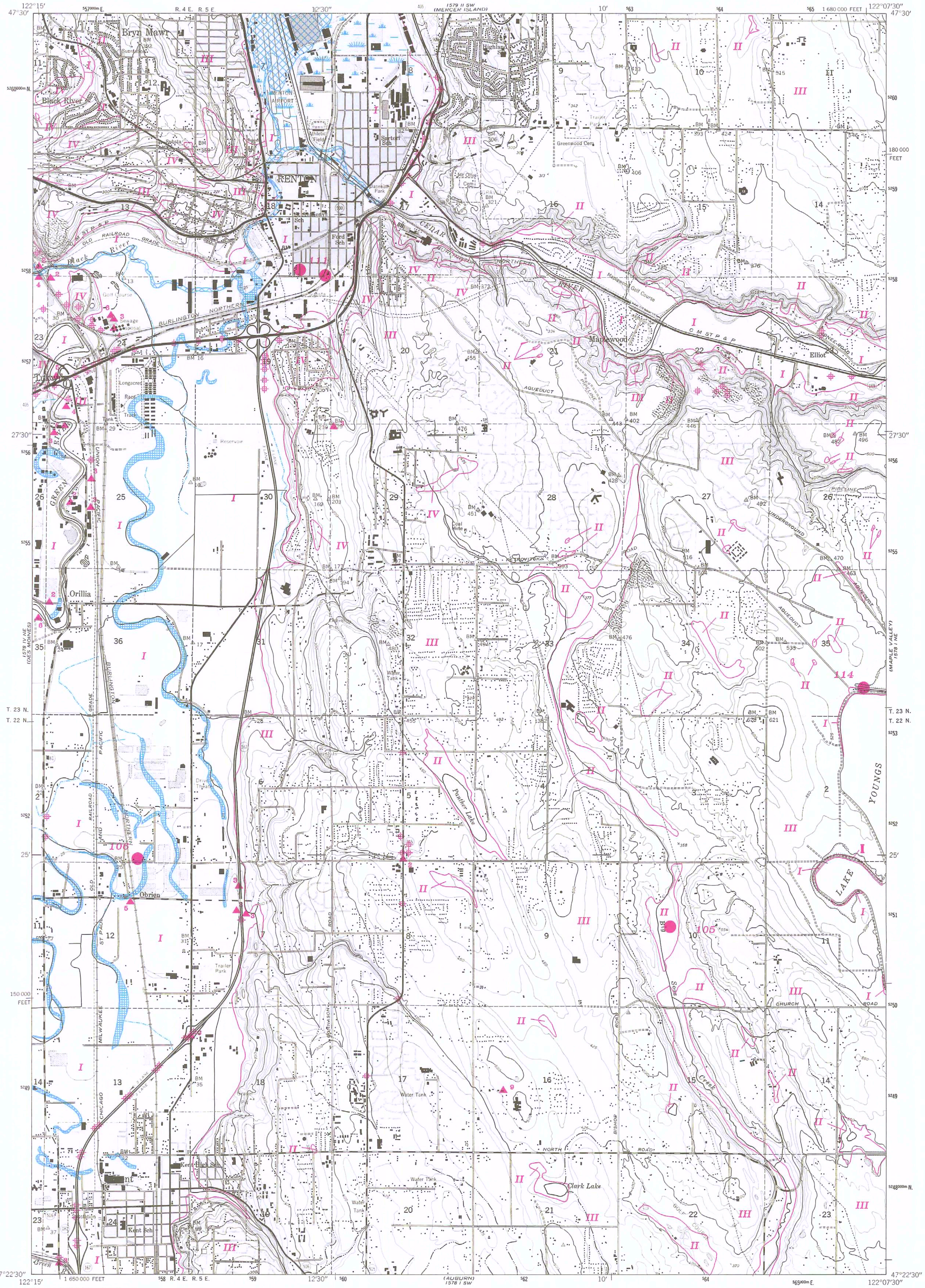
PLATE 2

LIQUEFACTION SUSCEPTIBILITY OF THE RENTON QUADRANGLE, WASHINGTON

by

Stephen P. Palmer, Henry W. Schasse, and David K. Norman

1994



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Topography from aerial photographs by multiplex methods
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Polyconic projection. 1927 North American datum
10,000-foot grid based on Washington coordinate system, north zone

UTM GRID AND 1973 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24000

CONTOUR INTERVAL 25 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

QUADRANGLE LOCATION

EXPLANATION

Geologic map units derived from Mullineaux, 1965.

I — CATEGORY I includes post-Vashon alluvium, manmade fill, and modified land (except most fills along roadways).
LIQUEFACTION SUSCEPTIBILITY : HIGH

II — CATEGORY II includes post-Vashon lacustrine deposits, mass-wasting deposits and colluvium.
LIQUEFACTION SUSCEPTIBILITY : LOW TO HIGH

III — CATEGORY III includes all Pleistocene glacial and nonglacial deposits.
LIQUEFACTION SUSCEPTIBILITY : LOW

IV — CATEGORY IV includes all Tertiary bedrock.
LIQUEFACTION SUSCEPTIBILITY : LOW TO NIL

Contacts between liquefaction susceptibility categories.

Location of geotechnical borings used in this study.

Location of multiple geotechnical borings used in this study (with number of borings indicated).

105 — Historic liquefaction sites identified by the corresponding reference number in Chleborad and Schuster, 1990; Table 3 reproduces the quotations and comments given for the sites in Table 2 of Chleborad and Schuster, 1990.

Historic extent of Lake Washington and the pre-Ship Canal courses of the Black and Cedar Rivers mapped by Chrzastowski, 1983.

Historic fresh-water marshes of Lake Washington.

Abandoned channels of the Green River that do not appear to contain intermittent streams or support riparian vegetation.

Drainages and streams that appear to be abandoned channels of the Green River.

This map is meant only as a general guide to delineate areas prone to liquefaction. This map is not a substitute for a site-specific investigation to assess the potential for liquefaction for any development project. Because of the regional nature of this map and 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 liquifiable soils beneath any specific locality. To make this determination requires a site-specific geotechnical investigation performed by qualified practitioners.

Base map from U.S. Geological Survey 7.5 minute Renton quadrangle, 1949, photorevised 1968 and 1973.

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