Liquefaction Susceptibility and Site Class Maps of Washington State, By County

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DISCLAIMER

The liquefaction susceptibility and site class maps presented with this report are meant only as a general guide to delineate areas based on their potential for liquefaction or ground shaking enhanced by near-surface soil conditions. Because these maps are developed using regional geologic mapping, they cannot be used to make final determinations of liquefaction susceptibility or site class at any specific locality. They are not a substitute for a site-specific investigation to assess the actual geologic conditions and the potential for liquefaction or amplified ground shaking. These determinations require a site-specific evaluation performed by a qualified practitioner. This product is provided 'as is' without warranty of any kind, either expressed or implied, including, but not limited to, the implied warranties of merchantability and fitness for a particular use. The Washington Department of Natural Resources will not be liable to the user of this product for any activity involving the product with respect to the following: (a) lost profits, lost savings, or any other consequential damages; (b) the fitness of the product for a particular purpose; or (c) use of the product or results obtained from the use of the product.

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Contents

APPENDIXES

FIGURES

TABLES

MAPS

This pamphlet accompanies a set of 78 maps comprising a liquefaction susceptibility map and a site class map for each of the 39 counties in Washington State.

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INTRODUCTION

The Washington State Department of Natural Resources, Division of Geology and Earth Resources received grant funding through the Hazard Mitigation Grant Program (HMGP) following the Nisqually earthquake of February 2001 (FEMA-1361-DRWA). This grant required the Division of Geology and Earth Resources to develop statewide liquefaction susceptibility and NEHRP (National Earthquake Hazards Reduction Program) site class maps. Regional earthquake hazard maps such as these support hazard mitigation, emergency planning and response, planning of local zoning ordinances, and building code enforcement.

The primary reason for producing this series of earthquake hazard maps is to support revisions to the State Hazard Mitigation Plan required in the implementation of final rules 44CFR201.4 and 44CFR201.6. These Federal code regulations require both state and local agencies to describe the location and extent of earthquake hazards that affect their jurisdictions. Additionally, these maps will serve a great variety of end-users that are crucial partners in earthquake hazard mitigation. In specific:

- The Washington Emergency Management Division and local emergency management agencies will be able to implement more accurate HAZUS vulnerability assessments using real map inputs for ground-motion amplification and liquefaction-induced ground failure rather than the HAZUS default values (HAZUS is the Federal Emergency Management Agency's earthquake loss estimation methodology).
- Generation of the NEHRP site class maps will benefit the response efforts of the Pacific Northwest Seismic Network in the near-real-time production of ShakeMap displays of ground shaking following significant earthquakes.
- Local jurisdictions can use these maps to delineate earthquake hazardous areas and enforce Critical Areas ordinances as required by the State Growth Management Act. Also, local building officials will be able to use these maps to help delineate areas requiring thorough geotechnical investigation in their enforcement of state and local building codes.

The liquefaction susceptibility and NEHRP site class maps presented with this report are meant only as a general guide to delineate areas based on their potential for liquefaction or ground shaking enhanced by near-surface soil conditions. Because these maps are developed using regional geologic mapping, they cannot be used to make final determinations of liquefaction susceptibility or site class at any specific locality. They are not a substitute for a site-specific investigation to assess the actual geologic conditions and the potential for liquefaction or amplified ground shaking. These determinations require a site-specific evaluation performed by a qualified practitioner. This product is provided 'as is' without warranty of any kind, either expressed or implied, including, but not limited to, the implied warranties of merchantability and fitness for a particular use. The Washington Department of Natural Resources will not be liable to the user of this product for any activity involving the product with respect to the following: (a) lost profits, lost savings, or any other consequential damages; (b) the fitness of the product for a particular purpose; or (c) use of the product or results obtained from the use of the product.

The following section provides a general discussion of the liquefaction susceptibility and NEHRP site class maps developed during our study, and is intended for a nontechnical reader. The concluding section of the report provides technical documentation of the methodologies used in producing these earthquake hazard maps; this section is written solely for professional engineering geologists and geotechnical engineers with expertise in earthquake hazard assessment.

NONTECHNICAL SUMMARY

Soil liquefaction and the amplification of earthquake shaking caused by near-surface geologic conditions are two earthquake-related phenomena that can result in the damage or destruction of buildings and other structures. Accordingly, map delineation of areas where these phenomena are likely to occur is an important initial step in mitigating these hazards.

Liquefaction Susceptibility

Liquefaction is a phenomenon in which strong earthquake shaking causes a soil to rapidly lose its strength and behave like quicksand. Liquefaction typically occurs in artificial fills and in areas of loose sandy soils that are saturated with water, such as low-lying coastal areas, lakeshores, 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. During the 1989 Loma Prieta earthquake, liquefaction was a contributing factor to severe building damage in the Marina District of San Francisco. Liquefaction-induced ground movements also broke water lines, severely hampering control of the ensuing fires. Damage caused by liquefaction to the port area of Kobe, Japan, during the 1995 earthquake resulted in billions of dollars in reconstruction costs and lost business.

A liquefaction susceptibility map provides an estimate of the likelihood that soil will liquefy as a result of earthquake shaking. The susceptibility is a measure of the physical characteristics of a soil deposit, such as grain texture, compaction, and depth of groundwater, that determine the propensity of the soil to liquefy during earthquake shaking. A liquefaction susceptibility map depicts the relative hazard in terms of high, moderate, low, or very low liquefaction susceptibility, and cannot be used to directly predict the severity of permanent ground deformation resulting from liquefaction. Assessment of ground failure effects depends on local site conditions, such as the configuration of the ground slope. A geotechnical evaluation is necessary for a detailed localized assessment of ground failure effects.

Amplification of Earthquake Ground Shaking

Often the most damaging effect of an earthquake is strong shaking at the ground surface. For more than a century, engineers and seismologists have known that ground shaking during an earthquake is strongest in areas of soft soils, such as in river valleys or along the shorelines of bays and lakes. Measurements of earthquake ground motions made in the last few decades have allowed seismologists to more fully understand the physics of this long-observed phenomenon. Earthquake wave velocity is slower in soils than in the underlying rock of the Earth's crust. It is this difference in wave speed that causes the shaking at the ground surface to be amplified. Generally, the greater the wave velocity difference, the greater the amplification of ground surface shaking. Consequently, ground shaking in areas of soft soils underlain by stiffer soils or rock is generally stronger than in areas where there is little or no variation between the surface and substratum. This has been observed time and again in past earthquakes.

In the mid-1990s, a simplified method for characterizing the ground-motion amplifying effects of soft soils was developed by Roger Borcherdt of the U.S. Geological Survey, based on data collected from the Loma Prieta and Northridge earthquakes in California (Borcherdt, 1994). His empirical study related the average shear wave velocity in the upper 100 feet (30 meters) of the soil–rock column to the amplification of shaking at ground surface. Shear waves are the earthquake waves that create the strongest horizontal shaking and are the most damaging to buildings and structures.

Borcherdt's method subdivides the near-surface geology into a number of site classes where each site class is defined by a unique range of average shear wave velocities in the upper 100 feet (30 meters). A modification of Borcherdt's empirical method was implemented by the Building Seismic Safety Council (BSSC) and the Federal Emergency Management Agency in the 1997 edition of the National Earthquake Hazard Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (BSSC, 1997). Borcherdt's designation of site classes was simplified in BSSC (1997), and these simplified site class groupings are commonly referred to as NEHRP site classes. In 1997, this modified method of accounting for soil-column amplification effects was adopted by the International Conference of Building Officials in the Uniform Building Code (International Conference of Building Officials, 1997). This method of designating site classes for determination of seismic design ground motions is used in the 2003 version of the International Building Code (International Code Council, 2003), which is the current building code adopted for use in Washington State.

Note that from this point forward we refer to NEHRP site class simply as 'site class', which is consistent with the terminology of the 2003 version of the International Building Code.

Ground shaking during an earthquake will generally be stronger on soft soils than stiff soils or bedrock. Therefore, the site class map provides some measure of the potential for strong shaking in a particular area during an earthquake. In the methodology presented by BSSC (1997), site class B represents rock condition, where earthquake shaking is neither amplified nor reduced by the near-surface geology. Site classes C, D, and E represent increasingly softer soil conditions which result in a progressively increasing amplification of ground shaking. Site class F is reserved for unusual soil conditions where prediction of the amplification of earthquake shaking can only be determined by a site-specific evaluation. On the statewide site class maps, we delineate areas of peat soil as site class F. Liquefiable soils also fall into site class F, but are not classified as such on the site class maps; please refer to the liquefaction susceptibility map corresponding to the area of interest for this information. Table 1 shows the site class for given average shear wave velocities in the uppermost 100 feet (30 meters) of the soil column.

A site class map provides only a general guide to areas where shaking will be the strongest and where the potential damage to buildings and other structures may be elevated because of soil effects. A site class map does not incorporate other factors affecting the actual severity of ground shaking. The two most important of these factors are the size of the earthquake and the distance of the area in question from the earthquake's focus (location of the fault rupture that caused the earthquake).

The amount of energy released during a fault rupture, expressed as the earthquake magnitude, can vary tremendously from earthquake to earthquake. The earthquake magnitude scale

Table 1. Site class designations defined in Building Seismic Safety Council (1997).

Site class	Average shear wave velocity in the upper 100 feet (30 m)	Rock or soil category
A	greater than 5000 ft/sec (greater than 1520 m/sec)	Hard rock
B	2500 to 5000 ft/sec (760 to 1520 m/sec)	Rock
C	1200 to 2500 ft/sec (360 to 760 m/sec)	Very stiff soil or soft rock
D	600 to 1200 ft/sec (180 to 360 m/sec)	Stiff soil
E	less than 600 ft/sec (less than 180 m/sec)	Soft soil
F	soils susceptible to potential failure under seismic loading, such as liquefiable soils or sensitive clays, peats, or organic clays thicker than 10 ft (3 m); thick sections of clays	Special category indicating a geotechnical evaluation should be performed to assess amplification potential

is exponential to accommodate this range in earthquake size. An increase of one on the scale represents a thirty to forty times increase in the amount of energy released by the fault rupture. For example, a magnitude 7 earthquake releases about 35 times the energy of a magnitude 6 tremor.

The intensity of ground shaking will generally decrease with increasing distance from the earthquake focus. Comparison of the strength of ground shaking between the 2001 Nisqually earthquake (magnitude 6.8) and the 1995 Kobe, Japan earthquake (magnitude 6.9) demonstrates this point. Ground shaking from the Nisqually earthquake was not particularly violent because the fault rupture was at a depth of 30 miles, so that even the point on the ground surface directly above the earthquake focus was 30 miles away. However, during the Kobe earthquake, the fault rupture was only a mile or two beneath the city; shaking was violent and the damage severe, with the loss of over 5000 lives in a country experienced with and prepared for earthquakes.

Development of Liquefaction Susceptibility and Site Class Maps for Washington State

The liquefaction susceptibility and site class maps are primarily based on 1:100,000-scale geologic mapping produced by the staff of the Division of Geology and Earth Resources and by the U.S. Geological Survey. These map data were compiled into a digital geographic information system (GIS) coverage which allowed for efficient production of the earthquake hazard maps (Washington Division of Geology and Earth Resources staff, 2003). Liquefaction susceptibility and site class maps are produced separately for each of the thirty-nine counties in Washington State. The liquefaction susceptibility and site class maps for Clark County are an exception as they were produced using larger scale geologic mapping (1:24,000-scale) and more detailed quantitative evaluations (see Appendix D).

LIQUEFACTION SUSCEPTIBILITY MAP

The liquefaction susceptibility maps for Washington use assessments presented by Youd and Perkins (1978) which relate liquefaction susceptibility to the age and type of deposit (Table 2). In assigning liquefaction susceptibility, we have drawn on experience gained in producing a number of detailed liquefaction susceptibility maps in the Puget Sound region. We have used our professional judgment to modify the susceptibility assessments in Youd and Perkins (1978) to account for factors such as regional groundwater conditions and over-consolidation of soils due to glacial loading. We have made our own assessment of liquefaction susceptibility for geologic units not evaluated by Youd and Perkins (1978), most notably for the variety of glacial deposits found throughout Washington State.

A number of detailed liquefaction susceptibility maps have been previously published for many of the urbanized portions of the southern Puget Sound region (Grant and others, 1998; Palmer, 1995; Palmer and others, 1994, 1995, 1999a, 2002, 2003). These maps are based on 1:24,000-scale geologic mapping, and employ a quantitative engineering analysis to characterize the liquefaction susceptibility. They have been validated by comparison of calculated susceptibility to reports of liquefaction during the major historic earthquakes that have occurred in the Puget Sound region. These detailed maps have been incorporated into the liquefaction susceptibility maps for King, Pierce, and Thurston Counties. However, the liquefaction susceptibility mapping for the remaining rural portions of these counties is based on the 1:100,000-scale geologic map coverage. Additionally, a detailed liquefaction susceptibility map was developed for Clark County using 1:24,000-scale geologic mapping and based on the analysis of a large database of geotechnical borings and incorporation of a shallow groundwater model (see Appendix D).

Table 2. Correlations of age and type of geologic deposit with liquefaction susceptibility, modified from Youd and Perkins (1978).

Type of deposit	General distribution of cohesionless sediments	Likelihood that cohesionless sediments, when saturated, would be susceptible to liquefaction (by age of deposit)			
		< 500 yr	Holocene	Pleistocene	Pre-Pleistocene
river channel	locally variable	very high	high	low	very low
flood plain	locally variable	high	moderate	low	very low
alluvial fan and plain	widespread	moderate	low	low	very low
marine terraces and plains	widespread	--	low	very low	very low
lacustrine and playa	variable	high	moderate	low	very low
colluvium	variable	high	moderate	low	very low
dunes	widespread	high	moderate	low	very low
loess	variable	high	high	high	unknown
glacial till	variable	low	low	very low	very low
tuff	rare	low	low	very low	very low
beach (high wave energy)	widespread	moderate	low	very low	very low
beach (low wave energy)	widespread	high	moderate	low	very low
uncompacted fill	variable	very high	--	--	--
compacted fill	variable	low	--	--	--

SITE CLASS MAP

There are no published correlations of age and type of geologic deposit with site class similar to those presented in Youd and Perkins (1978) for evaluating liquefaction susceptibility. Such correlations are necessary for constructing a statewide site class map using 1:100,000-scale geologic mapping. To establish such correlations, we collected shear wave velocity (V_S) data in a variety of geologic units throughout the state. We also compiled published shear wave velocity data for the Seattle, Olympia, and Portland areas (Wong and others, 2003; Palmer and others, 1999b; Mabey and others, 1993). Also, some unpublished V_S data used in the development of the site class map was obtained from previous V_S surveys we conducted or measurements we compiled from other studies. A database of over 500 separate V_S measurements in nearly 40 different Quaternary and bedrock units was compiled from these various sources.

Typical ranges of shear wave velocity were calculated for individual geologic units or groups of geologic units having the same depositional origin. Site classes for these individual or grouped units were assigned using the site class definitions presented in Table 1. For geologic units not characterized by V_S measurements, site classes were either assigned based on their similarity to units with a quantitatively determined site class, or by using the default site class (D-type soil) as prescribed by the NEHRP methodology (Building Seismic Safety Council, 1997).

The proper application of the NEHRP methodology uses the average V_S in the upper 100 ft (30 m) to determine site class. Our approach assigns a site class to each of the surficial units shown on the 1:100,000-scale digital geologic map coverage. In taking this approach to site class mapping, we make an implicit assumption that the surficial geologic units are 100 ft (30 m) thick. Our approach generally results in a conservative assessment of site class, as V_S generally increases with depth because of the increasing age and induration of the underlying geologic units. Figure 1 provides a graphical example of the differences in assigning site class based on the V_S of the surficial unit versus the average V_S in the upper 100 ft (30 m). In this figure the shear wave velocity of the surface unit would result in an assignment of a site class D. The underlying unit has a higher V_S that falls within the range of a C site class. In this example, the average V_S in the upper 100 ft (30 m) is computed to be in the range corresponding to site class C. Exceptions to the general rule of increasing V_S with depth certainly exist and could result in an under-assessment of site class and the related ground motion amplification parameters.

A more exact site class map for Clark County was developed by calculating the average V_S to a depth of 100 ft (30 m). These average velocity calculations were performed using a three-dimensional geologic model based on 1:24,000-scale surficial geologic mapping and interpretation of water well records and geotechnical boring logs (see Appendix D).

DEVELOPMENT OF THE STATEWIDE LIQUEFACTION SUSCEPTIBILITY AND SITE CLASS MAPS—TECHNICAL DISCUSSION

Development of liquefaction susceptibility and site class maps for the entirety of Washington State presented a significant challenge. It was first necessary to develop a statewide geologic map database that provided the geologic information necessary to assess these particular earthquake-related phenomena. The technical approaches appropriate for assessing liquefaction susceptibility and site class were then determined. The methodology chosen for developing the site class map required the construction of a database of shear wave velocity measurements. This database was created by compiling V_S data from published and unpublished sources, and through the collection of a large number of V_S measurements from seismic refraction surveys conducted for this project. All of these sources of data were then analyzed using the chosen methologies to produce the statewide liquefaction susceptibility and site class maps presented with this report. These statewide maps are presented on 39 countywide coverages rather than one single statewide compilation.

Development of the 1:100,000-scale Geologic Map Database

The largest-scale geologic mapping that covers the entirety of Washington State was developed by the Washington State Department of Natural Resources, Division of Geology and Earth Resources and the U. S. Geological Survey during the

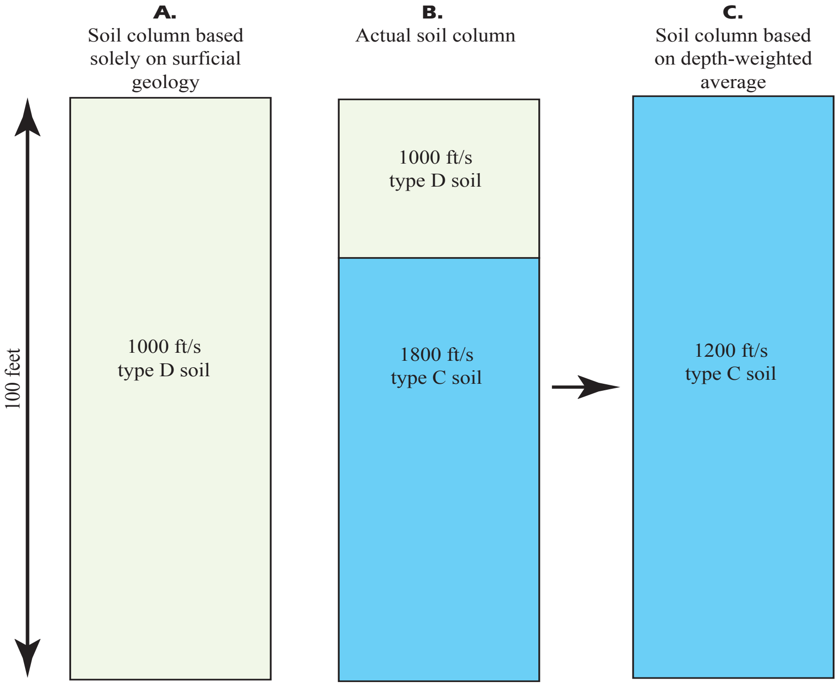

Figure 1. **A.** The assigned D site class is based solely on the surficial geology. A constant shear wave velocity characteristic of the surficial unit is assumed in the first 100 ft (30 m) of the soil column. **B.** In most instances the shear wave velocity increases with depth, and in this example the underlying unit has a shear wave velocity corresponding to a site class C. **C.** The depth-weighted average the shear wave velocity in this example indicates a site class C is the correct assignment based on proper application the NEHRP methodology (Building Seismic Safety Council, 1997). This example shows that in situations where the shear wave velocity increases with depth, a site class assigned solely on the surficial geology may result in an conservative (overstated) site class.

last 20 years. These maps are currently available in a digital geographic information system (GIS) coverage, and the June 2003 version of these map data (Washington Division of Geology and Earth Resources staff, 2003) is used as the geological basis for developing the statewide liquefaction susceptibility and site class maps.

The three most important geologic factors that influence both liquefaction susceptibility and shear wave velocity of a soil deposit are its age, grain texture, and depositional environment. We use the engineering definition of soil as referring to "a natural aggregate of mineral grains that can be separated by such gentle mechanical means as agitation in water" (Terzaghi and Peck, 1967). Quaternary sedimentary deposits can generally be considered to behave as a soil using this definition, whereas most pre-Quaternary deposits are sufficiently indurated that they satisfy the engineering definition of rock. Geologic age can affect the compaction and cementation of a soil, which directly influences its shear strength. The shear strength of a soil determines both its liquefaction susceptibility and shear wave velocity. The grain texture of a soil is an important factor as liquefaction generally occurs only in soils that are composed predominately of sand-sized grains. From our experience we believe that grain texture is also a significant determinant in the shear wave velocity of a soil. Depositional environment is often a controlling factor of grain texture, and it can also have some influence on the soil shear strength.

We determined that the naming convention for geologic units on the statewide digital map coverage (Washington Division of Geology and Earth Resources staff, 2003) was not sufficiently detailed for use in developing liquefaction susceptibility and site class maps. This naming convention only delineates units within the Quaternary period, and does not include definition of their epoch. The methodology presented by Youd and Perkins (1978) for evaluating liquefaction susceptibility uses the epochal age of Quaternary deposits. Also, the naming convention used in the digital map coverage does not typically indicate grain texture for Quaternary units, although in some instances textural information is provided by the unit designation.

We devised a naming convention for Quaternary deposits that satisfies our requirements for developing liquefaction susceptibility and site class maps using the digital geologic map coverage. Our convention provides the epoch of the deposit, and additionally subdivides the Pleistocene into younger and older intervals. A younger Pleistocene age is assigned to deposits that yield a finite radiocarbon age, and an older Pleistocene age to deposits having a radiocarbon-infinite age. Where a deposit either spans the Holocene and Pleistocene epochs, or couldn't be assigned to a specific epoch, its age is specified as undivided Quaternary. Table 3 summarizes our age convention and the designations used to indicate age.

The statewide digital map coverage (Washington Division of Geology and Earth Resources staff, 2003) was compiled from individually published 1:100,000-scale geologic quadrangle maps. We reviewed the description of the Quaternary units in these reports, and developed a series of depositional units that would include all Quaternary sedimentary deposits used in the 1:100,000-scale digital map coverage. Table 4 summarizes our depositional unit convention and the designations used to indicate the depositional environment.

Table 3. Age convention and the age designations used in this investigation.

Age	Definition	Designation
Holocene	Deposits younger than the end of either the Fraser or Wisconsinan glaciations, depending on location	H
younger Pleistocene	Deposits older than Holocene age that would yield a finite radiocarbon date (roughly younger than about 40,000 years before present)	yP
older Pleistocene	Deposits that would yield an infinite radiocarbon date (roughly greater than about 40,000 years before present)	oP
Pleistocene	Deposits where radiocarbon dating is absent and stratigraphic relations are inadequate to discriminate between a younger or older Pleistocene age	P
undivided Quaternary	Deposits that either span the Holocene and Pleistocene epochs, or where the epochal age cannot be determined	Q

Table 4. Depositional convention and the depositional environment designations used in this investigation.

Depositional environment	Designation
artificial fill	afl
alluvium	al
colluvium	cv
alluvial fan deposits	af
beach deposits	b
aeolian deposits	ae
lacustrine deposits	lc
mass-wasting and landslide deposits	ls
peat deposits	pt
terrace deposits	tr
sedimentary deposits	sd
talus deposits	tl
glacial advance outwash	gao
glacial recessional outwash	gro
glacial outwash	go
glaciolacustrine deposits	gl
glacial drift	gd
glacial till	gt
glacial outburst flood deposits	gf
glaciolacustrine and glacial outburst flood deposits	glf
glaciomarine drift	gmd
lahar deposits	lh
tuff and tuff breccias	tf
volcaniclastic deposits	vc

Our grain-texture naming convention differentiates between deposits that are composed primarily of coarse-grained material (gravel and sand), sandy material (sand and silt), and fine-grained material (silt and clay). The deposit is considered texturally undifferentiated if there is insufficient information to determine a dominant grain texture. A unit is also considered texturally undifferentiated if it is a silty, well-graded sand or gravel. Table 5 summarizes our grain texture convention and the designations used to indicate texture.

Our complete designation for a geologic unit is then given by combining the geologic age, depositional environment, and grain texture designations. As examples, the unit yPgros is a younger Pleistocene sandy glacial recessional outwash, the unit Qsdc is an undivided Quaternary coarse sedimentary deposit, and the unit oPgao is an older Pleistocene, texturally undifferentiated glacial advance outwash.

We then reviewed the descriptions of all Quaternary sedimentary units described in the map reports for each of the published 1:100,000-scale geologic quadrangle maps. We classified each of these Quaternary sedimentary units with our naming convention using the report descriptions and our own professional observations and judgment. These assignments were made independently for each quadrangle, and are summarized in Appendix A. This appendix shows the geologic units used in the digital map coverage and our corresponding customized geologic units for each 1:100,000-scale quadrangle.

The digital map coverage (Washington Division of Geology and Earth Resources staff, 2003) was modified in the city of Seattle to separate artificial fill and modified (graded) land in the downtown area. The original 1:100,000-scale geologic mapping (Yount and others, 1993) delineated the filled tide flats in the Duwamish Valley as artificial fill. They mapped the downtown area that was extensively graded in the early 1900's as modified land. Both of these areas are delineated as artificial fill on the digital map coverage, but distinguishing artificial fill from graded land is important in determining liquefaction susceptibility and site class. Consequently, we added the graded area mapped by Yount and others (1993) on the digital map coverage and assigned this area to unit oPgd (older Pleistocene glacial drift) based on our evaluation of the geology in the downtown area. We left the filled tide flat area designation as unit afl (artificial fill), consistent with Yount and others (1993).

Liquefaction Susceptibility Map Methodology

The statewide liquefaction susceptibility map is primarily based on the surficial geologic units shown on the 1:100,000-scale digital map coverage (Washington Division of Geology and Earth Resources staff, 2003). We established the liquefaction susceptibility for each of the 88 customized geologic units that comprise all of the Quaternary sedimentary deposits on the digital map coverage (Appendix A) by using assessments of Youd and Perkins (1978), the results of published larger-scale quantitative liquefaction susceptibility maps and analyses, and our professional judgment. In portions of King, Pierce, and Thurston Counties we replaced the 1:100,000-scale liquefaction susceptibility maps with previously published larger-scale susceptibility maps (Grant and others, 1998; Palmer, 1995; Palmer and others, 1994, 1995, 1999a, 2002, 2003). The liquefaction susceptibility map produced for Clark County is an exception as it is largely based on 1:24,000-scale geologic mapping and a quantitative analysis that incorporates a large database of geotechnical borings and a static groundwater depth model (see Appendix D).

LIQUEFACTION SUSCEPTIBILITY BASED ON SURFICIAL GEOLOGIC MAPPING

Youd and Perkins (1978) provided an assessment which relates liquefaction susceptibility to the age and type of deposit based on field observations made after large-magnitude earthquakes; Table 2 summarizes their assessments. They use a qualitative ranking of liquefaction susceptibility that ranges from very low to very high. Table 2 provides rankings for a wide range of sedimentary deposits, but the only glacial deposit shown in this table is till. There are many depositional settings represented in glacial deposits besides till, including fluvial and lacustrine environments. Holocene nonglacial fluvial and lacustrine deposits can have a moderate to high susceptibility based on Youd and Perkins (1978). We infer that glacial deposits of similar texture and only slightly older (latest Pleistocene) age may also be liquefiable and should be considered as a potential hazard.

A number of published large-scale liquefaction susceptibility maps are available for the urbanized areas of the southern Puget Sound region (Grant and others, 1998; Palmer, 1995; Palmer and others, 1994, 1995, 1999a, 2002, 2003). These published maps evaluated liquefaction susceptibility over a wide range of glacial depositional environments. We used these results to determine the liquefaction susceptibility of glacial deposits throughout Washington State, supplementing the susceptibility rankings for a wide range of nonglacial deposits provided by Youd and Perkins (1978).

Our qualitative ranking of liquefaction susceptibility ranges from very low to high; unlike Youd and Perkins (1978) we do not include a very high category. Youd and Perkins (1978) assigned a very high ranking only to river channel and delta deposits less than 500 years old, and to areas of uncompacted fill. Based on the 1:100,000-scale geologic map we can only distinguish the epoch of alluvial or delta deposits, and we cannot determine the state of compaction of a mapped artificial fill. Consequently, the assignment of a very high hazard based on Youd and Perkins (1978) is beyond the accuracy of the 1:100,000-scale geologic map data. We present our assessments of liquefaction susceptibility for our customized geologic units in Appendix B. A detailed explanation of our reasoning in making these

Table 5. Grain texture convention and the textural designations used in this investigation.

Grain texture	Classification	Designation
predominately gravel and sand	coarse	c
predominately sand and silt	sandy	s
predominately silt and clay	fine	f
texture unknown or deposit well-graded and highly variable	texturally undifferentiated	(none)

determinations is provided in this appendix. Appendix A includes these liquefaction susceptibility assignments for all Quaternary sedimentary units occurring in each of the 1:100,000-scale quadrangles composing the statewide digital geologic map coverage (Washington Division of Geology and Earth Resources staff, 2003).

Liquefaction susceptibility is strongly increased by the presence of a shallow groundwater table. The rankings presented by Youd and Perkins (1978) are based on the grain texture and age-related consolidation of a geologic unit, and assume that these deposits are saturated. We only considered groundwater conditions in assigning liquefaction susceptibility to Holocene and Pleistocene aeolian deposits (Appendix B). Youd and Perkins (1978) rank Quaternary dunes and loess as having a low to high susceptibility when saturated. We observed that the groundwater table is typically very deep in the areas of eastern Washington covered by aeolian deposits. Consequently, we chose to assign a low susceptibility to these units, consistent with the lower limit of susceptibility given for these deposits by Youd and Perkins (1978).

All igneous and metamorphic rocks in the digital map coverage are labeled as bedrock, and are not considered susceptible to liquefaction. All pre-Quaternary sedimentary units are also labeled as bedrock as these units are typically indurated and not capable of liquefying. We make an exception for the Troutdale Formation, designated as unit PLMc(t) on the digital geologic map coverage. We acknowledge that this formation could potentially be Pleistocene age where it is mapped in the Vancouver and Mount St. Helens quadrangles. We then designated the Troutdale Formation as unit oPsd (older Pleistocene sedimentary deposit of undifferentiated texture) in our naming convention to account for its possible Pleistocene age and a variable textural facies that ranges from gravel-dominated to silt and sand-dominated. We assign unit oPsd a very low susceptibility based on the detailed evaluation of liquefaction susceptibility performed in producing the liquefaction susceptibility map for Clark County (see Appendix D).

We do not assign a susceptibility to peat deposits (units Hpt and Qpt in our naming convention) as highly organic soils are not capable of liquefying. However, peat soils are capable of undergoing large permanent deformation as a result of strong earthquake shaking. Consequently we delineate these deposits on the liquefaction susceptibility map so that a map user will recognize the potential of these units to undergo significant earthquake-induced ground deformation which could damage structures and disrupt buried utilities.

LARGE-SCALE LIQUEFACTION SUSCEPTIBILITY MAPPING IN THE PUGET SOUND REGION

Large-scale (1:24,000) liquefaction susceptibility maps have been published for the urbanized areas of King, Pierce, and Thurston Counties (Grant and others, 1992, 1998; Palmer, 1995; Palmer and others, 1994, 1995, 1999a, 2002, 2003). In these publications, the determination of susceptibility employed a quantitative engineering analysis using data from a large number of geotechnical borings. Owing to the larger scale and quantitative approach to assigning liquefaction susceptibility, these maps are superior to those generated using the 1:100,000-scale mapping where the susceptibility is determined using only the surficial geologic units. Consequently, we have replaced the 1:100,000-scale susceptibility mapping with these previously published maps in their coincident areas. We revised these larger-scale maps to adopt the convention that areas of bedrock and peat are not assigned a susceptibility, but are specifically labeled as “bedrock” or “peat”.

All of these published maps used large geotechnical boring datasets to calculate liquefaction factors of safety for two magnitude 7.3 earthquake scenarios, one having a 0.15 *g* peak ground acceleration (PGA) and the other a 0.30 *g* PGA (where *g* is the acceleration due to gravity). For each earthquake scenario, the aggregated total thicknesses of liquefiable material within each geologic unit penetrated by each boring were determined. The aggregated thicknesses for all borings were then combined to generate cumulative frequency histograms (one for each earthquake scenario) for each geologic unit, which were then used to determine liquefaction susceptibility assignments.

The earlier of the 1:24,000-scale liquefaction susceptibility maps (Grant and others, 1992, 1998; Palmer, 1995; Palmer and others, 1994, 1995) used the field evaluation methodology described in Seed and others (1983), and only calculated liquefaction factors of safety to a depth of 40 ft (12.2 m). Factor-of-safety calculations in Palmer and others (1999a, 2002, 2003) were made to a depth of 50 ft (15.2 m) using the methodology presented in Youd and others (1997). Furthermore, slightly different methods of assigning liquefaction susceptibility using the cumulative frequency histograms derived from the factor-of-safety analyses were employed. Because of these differences in data analyses and inconsistencies in susceptibility assignment, the liquefaction susceptibility assigned to a particular geologic unit often differs in adjacent maps.

These inconsistencies needed to be corrected so that these detailed maps could be used in our statewide liquefaction susceptibility maps. Table 6 shows the liquefaction susceptibility assigned to all the geologic units (using our categorization scheme) found in the areas covered by these published maps. To clarify the following discussion we will refer to the general areas covered by the liquefaction susceptibility maps rather than using the reference citations, as shown in Table 6. This table shows both the susceptibility assigned in the publications and our proposed revisions. We consider the published maps that cover the Olympia, Eastside, and Tacoma areas to be the standard as they take a consistent approach to the factor-of-safety calculations and the criteria used to assign susceptibility. These factor-of-safety calculations and susceptibility ranking criteria are very different from those used in older published maps covering the Kent Valley and Seattle area. There are no revisions to the susceptibility assignments for the Olympia, Eastside, and Tacoma maps, except that wetland deposits in the Olympia map are classified as Holocene peat.

The Holocene alluvium of the Green–Duwamish river system in the Kent valley was originally ranked as having a high susceptibility by Palmer (1995) and Palmer and others (1994, 1995). The Holocene alluvium of the Duwamish River was assigned a moderate liquefaction susceptibility by Grant and others (1992, 1998) in their mapping of the Seattle area. All of these susceptibility maps are based on factor-of-safety calculations using Seed and others (1983) methodology applied to a depth of 40 ft (12.2 m). The difference in the assigned susceptibilities results from application of different criteria to the cumulative frequency histograms developed from these factor-of-safety analyses. Figures 6 and 7 of Palmer and others (1994) demonstrated that the cumulative frequency histograms developed in the northern Kent valley and Seattle

Table 6. Liquefaction susceptibility assigned to all the geologic units (using our categorization scheme) found in the areas covered by published Puget Sound region liquefaction susceptibility maps, including both the susceptibility assigned in the publications and our revisions. The general area covered by each of these published maps is shown below the map citation. – – –, unit does not appear on published map.

		Liquefaction susceptibility as originally assigned in published liquefaction susceptibility maps and as revised in this study						
		Grant and others (1992, 1998)	Palmer and others (1994)	Palmer and others (1995)	Palmer (1995)	Palmer and others (1999a)	Palmer and others (2002)	Palmer and others (2003)
Geologic unit	Suscepti-bility	Seattle area	Kent valley—northern part	Kent valley—central part	Kent valley—Sumner area	Olympia area	Eastside area (areas around Bellevue, Kirkland, Redmond, and Issaquah)	Tacoma area
afl	Original	high	high	high	high	high	– – –	high
	Revised	high	moderate–high	moderate–high	moderate–high	high	– – –	high
Hal	Original	moderate	high	high	high	high	moderate–high or low–moderate, depending on location	high
	Revised	moderate–high	moderate–high	moderate–high	moderate–high	high	moderate–high or low–moderate, depending on location	high
abandoned or filled river and stream channels	Original	– – –	high	high	high	– – –	– – –	high
	Revised	– – –	high	high	high	– – –	– – –	high
Hb	Original	moderate	high	– – –	– – –	high	– – –	low–moderate
	Revised	moderate–high	moderate–high	– – –	– – –	high	– – –	low–moderate
Hpt	Original	moderate	– – –	– – –	– – –	peat	peat	peat
	Revised	moderate–high	– – –	– – –	– – –	peat	peat	peat
wetland	Original	– – –	– – –	– – –	– – –	wetland	– – –	– – –
	Revised	– – –	– – –	– – –	– – –	peat	– – –	– – –
Hlc	Original	moderate	low–high	moderate	low–moderate	– – –	– – –	– – –
	Revised	moderate–high	low–moderate	low–moderate	low–moderate	– – –	– – –	– – –
Hls	Original	very low	low–high	moderate	low–moderate	low–moderate	– – –	low–moderate
	Revised	very low	low–moderate	low–moderate	low–moderate	low–moderate	– – –	low–moderate
Hlh	Original	– – –	– – –	low	low	– – –	– – –	– – –
	Revised	– – –	– – –	very low	very low	– – –	– – –	– – –
yPgl	Original	– – –	– – –	moderate	low–moderate	low–moderate	– – –	low–moderate
	Revised	– – –	– – –	low–moderate	low–moderate	low–moderate	– – –	low–moderate
yPgroc	Original	low	low	low	low	very low	very low	very low
	Revised	low–moderate	very low	very low	very low	very low	very low	very low
yPgros	Original	low	– – –	low	low–moderate	low–moderate	low–moderate	low–moderate
	Revised	low–moderate	– – –	low–moderate	low–moderate	low–moderate	low–moderate	low–moderate
yPgt	Original	very low	low	low	low	very low	very low	very low
	Revised	very low	very low	very low	very low	very low	very low	very low
yPgaoc	Original	very low	low	low	low	very low	very low	very low
	Revised	very low	very low	very low	very low	very low	very low	very low
yPgaos	Original	very low	low	– – –	low	very low	very low	very low
	Revised	very low	very low	very low	very low	very low	very low	very low
oPgd	Original	very low	low	low	low	very low	very low	very low
	Revised	very low	very low	very low	very low	very low	very low	very low
Psd	Original	very low	low	low	low	very low	very low	very low
	Revised	very low	very low	very low	very low	very low	very low	very low
bedrock	Original	very low	low–nil	– – –	– – –	very low–nil	bedrock	– – –
	Revised	bedrock	bedrock	– – –	– – –	bedrock	bedrock	– – –

area investigations are nearly identical. Likewise, figures 5 and 6 of Palmer and others (1995) demonstrated that the cumulative frequency histograms developed in the northern and central parts of the Kent valley are also closely comparable. We concluded that the liquefaction susceptibility for the Holocene alluvium in the Seattle area and Kent valley should be the same, and assigned a moderate to high susceptibility to these deposits in our revised mapping. This assignment spans the susceptibilities assigned to Holocene alluvium in the Seattle area and Kent valley.

In the Seattle area, Holocene beach, lacustrine, and peat deposits were assigned a moderate liquefaction susceptibility by Grant and others (1992, 1998). We revised these to a moderate to high susceptibility consistent with our revised susceptibility for Holocene alluvium in the Seattle area.

Grant and others (1992, 1998) developed cumulative frequency histograms for the extensive fill in the lower Duwamish River valley and Harbor Island area. They determined that these histograms supported assignment of a high susceptibility as the histograms indicated that this fill was substantially more liquefiable than the native Duwamish River alluvium. Consequently we maintained a high susceptibility for this fill area in our revision (Table 6). Geotechnical data and factor-of-safety analyses for fill and alluvium were combined in the liquefaction analyses performed for the Kent valley susceptibility maps. Therefore, artificial fill was assigned a moderate to high susceptibility equivalent to that assigned to alluvium in the Kent valley maps.

In our revision we assigned a very low susceptibility to all Fraser glacial units in the Kent valley maps with the exception of Fraser glaciolacustrine deposits and sandy recessional outwash, consistent with the susceptibilities of these units in the Olympia, Eastside, and Tacoma area maps. Fraser glaciolacustrine deposits and sandy recessional outwash, and Holocene lacustrine and landslide deposits in the Kent valley maps were reassigned a low to moderate susceptibility. In the Seattle area, Grant and others (1992, 1998) did not differentiate the liquefaction susceptibility of Fraser recessional outwash deposits based on grain texture. Consequently, we made a conservative choice to assign all recessional outwash to low to moderate susceptibility, consistent with the susceptibility assigned to sandy recessional outwash in all of the other map areas.

Holocene lahar deposits in the Kent valley maps were revised from a low susceptibility to a very low susceptibility, consistent with the revised assignment of other low susceptibility units in these map areas. In the Seattle area, landslide deposits were assigned a very low susceptibility by Grant and others (1992, 1998), which was kept unchanged in our revision.

Site Class Map Methodology

The statewide site class map is based on a 1:100,000-scale digital map coverage (Washington Division of Geology and Earth Resources staff, 2003). Ideally we would establish a site class for each of the surficial geologic units in the map coverage using measured shear wave velocity (V_S) data. However, there is a large number of unique geologic units and collecting a comprehensive V_S dataset for all of them was well beyond the scope of this project. We narrowed the focus of our investigation by assuming that all pre-Quaternary units and all Quaternary igneous units could be assigned to site class B, which is termed "rock" in the NEHRP methodology (Building Seismic Safety Council, 1997). After excluding these bedrock units we were left with the same 88 customized geologic units that were evaluated for the statewide liquefaction susceptibility map.

To construct the statewide site class map, we created a database of shear wave velocities for these Quaternary sedimentary units. We then used this database to determine a statistical range of shear wave velocities for each of these units. Given a range of V_S, we then assigned a site class (or combination of site classes) to each unit using Table 1. We correlated the site class or classes determined for each geologic unit to the outcrop areas of each unit on the statewide digital map coverage. This produced a statewide site class map based on the pattern of the surficial geology. In assigning the site class based on the surficial unit, we assume that the V_S values determined for each geologic unit represent the average shear wave velocity in the upper 100 ft (30 m).

Our approach generally results in a conservative assessment of site class, as V_S generally increases with depth because of the increasing age and induration of the underlying geologic units. Figure 1 provides a graphical example of the differences in assigning site class based on the V_S of the surficial unit or the average V_S in the upper 100 ft (30 m). Exceptions to the general rule of increasing V_S with depth certainly exist and could result in an under-assessment of site class and the related ground motion amplification parameters.

Unlike all other countywide site class maps, the map produced for Clark County is based on larger-scale geologic mapping and computation of the average V_S in the upper 100 ft (30 m) using a three-dimensional geologic model (see Appendix D). This is the approach required in the NEHRP methodology (Building Seismic Safety Council, 1997) for determining site class.

SHEAR WAVE VELOCITY DATABASE

To establish the correlations between our customized map units and site class, we collected V_S data in a variety of geologic units throughout the state. We primarily used shear wave refraction surveys to obtain these V_S data. We also compiled published shear wave velocity data for the Seattle, Olympia, and Portland areas (Wong and others, 2003; Palmer and others, 1999b; Mabey and others, 1993). Additional unpublished V_S data from the Portland and Vancouver areas were obtained and used in this study (Matthew Mabey, Oregon Dept. of Transportation, written commun., 2003). A collection of unpublished V_S data from various locations in western Washington was compiled from a variety of sources. This compilation of western Washington V_S data is referred to as the 'Miscellaneous' database in Appendix C. In all of these individual V_S databases, a geologic unit was correlated with each velocity measurement. This enabled us to relate these measurements to our customized geologic naming convention.

We refer to the V_S dataset collected as part of this project as 'HMGP 2003', for data collected during the 2003 field season, and 'HMGP 2004', for data collected during the 2004 field season. We have a high degree of confidence in these data because we have direct knowledge of the data quality, the details of the data analysis, and the designation of the geologic units at each of the sites where the V_S data were acquired. Consequently we use all V_S values from these data sources in our determinations of site class.

Mabey and others (1993) provided a V_S dataset for Quaternary sedimentary units found in the Portland metropolitan area. These units are laterally continuous, and are found across the Columbia River in Clark County. This dataset includes measurements for artificial fill, Columbia River alluvium, both the sandy and gravelly facies of the Missoula glacial outburst flood deposits, and both the fine and coarse facies of the Troutdale Formation. These data, supplemented by our own measurements in an older Pleistocene silt unit found north of the East Fork Lewis River, were the basis for the Clark County site class map (see Appendix D).

Wong and others (2003) provided a large dataset of V_S measurements for a variety of glacial and nonglacial units in the Seattle area. The geologic unit assignments for the V_S data presented by Wong and others (2003) are based primarily on the geological mapping of Waldron and others (1962). Recent geologic mapping in the Seattle area indicates that large areas mapped by Waldron and others (1962) as Fraser till are actually Fraser advance or recessional outwash (Kathy Troost and Derek Booth, Univ. of Washington, written commun., 2004). We did not revise the geologic unit assignments for the V_S measurements presented in Wong and others (2003) likely to be affected by these new mapping results. Examination of the map data provided by Troost and Booth indicated that the V_S measurements in Fraser glacial till provided in Wong and others (2003) should be excluded from consideration in our site class determinations. The HMGP 2003 and HMGP 2004 datasets contain an adequate number of V_S measurements in Fraser glacial till in order to determine site class for this unit.

We were provided with a large unpublished V_S dataset for the Portland and Vancouver areas to use in our study (Matthew Mabey, Oregon Dept. of Transportation, written commun., 2003). This dataset, referred to as ‘Mabey 2003’, contains a large number of V_S measurements in artificial fill, Columbia River alluvium, both the sandy and gravelly facies of the Missoula glacial outburst flood deposits, both the fine and coarse facies of the Troutdale Formation, and late Pleistocene loess deposits. We excluded the V_S measurements presented in Mabey and others (1993) included in the Mabey 2003 dataset to avoid redundancy. We had completed our analysis of Clark County by the time that we had received these data (see Appendix D), and did not use the V_S measurements in the sandy and gravelly facies of the Missoula glacial outburst flood deposits and the fine and coarse facies of the Troutdale Formation for any other part of our study. We did use the V_S data in the artificial fill, alluvium, and loess to supplement the overall V_S dataset used in this study. In reviewing these data, we found a number of instances where the reported velocity was exactly 250 m/sec. We were suspicious of these data, and found that this was the default velocity value in an automated velocity analysis calculation used in constructing the V_S database (Matthew Mabey, Oregon Dept. of Transportation, oral commun., 2004). Consequently, we did not use any values from Mabey’s 2003 dataset that had an exact value of 250 m/sec. We also excluded values of 0 m/sec.

For each measurement in these shear wave velocity databases, we interpreted a corresponding geologic unit using our customized naming convention. For the HMGP 2003 and HMGP 2004 databases, these customized geologic unit interpretations were based on review of the available geologic mapping and subsurface data and field observations at each measurement location. For the other V_S databases, we reviewed the geologic interpretations provided by the database author using available geologic mapping. We then assigned a customized geologic unit to each V_S measurement based on our review. All V_S measurements in these databases and our geologic unit assignments were compiled into a single shear wave velocity database that was the basis for the development of the statewide site class maps.

SITE CLASS DETERMINATION AND MAP PRODUCTION

In order to narrow the scope of this project into a manageable amount of work for the time and resources available to us, we made the assumption that all pre-Quaternary units and Quaternary igneous units would be assigned to site class B. This reduced our analyses to determining the site class of the same 88 customized geologic units that were evaluated for the statewide liquefaction susceptibility map.

Based on a large number of shear wave velocity measurements, Wills and others (2000) showed that the assumption that bedrock units can be assumed to fall in site class B is generally valid for plutonic and metamorphic rocks, most volcanic rocks, and coarse sedimentary rocks of Mesozoic age and older. However, they note that fine-grained sedimentary rocks of Miocene age and younger can fall into a C, and even D, site class based on their measured shear wave velocity data.

We made some effort to measure shear wave velocities in a number of fine-grained Miocene and Pliocene sedimentary rocks in eastern Washington. These measurements were made in the Ringold Formation, Latah Formation, and the Vantage Member of the Ellensburg Formation. A summary of these V_S data and their corresponding site class is presented in Table 7. This table

Table 7. Shear wave velocity data for sedimentary bedrock units measured as part of this investigation.

Geologic unit	1:100,00-scale geologic map unit	Age	Shear wave velocity (ft/sec)	Shear wave velocity (m/sec)	Site class
Ringold Formation	PLMc(r)	Pliocene	1342	409	C
Latah Formation	Mc(l)	Miocene	1627	496	C
Latah Formation	Mc(l)	Miocene	1978	603	C
Ellensberg Formation, Vantage Member	Mc(ev)	Miocene	1467	447	C
Ellensberg Formation, Vantage Member	Mc(ev)	Miocene	1962	598	C

indicates that these sedimentary bedrock units fall into site class C based on the limited number of V_S measurements. These results are not surprising based on the conclusions of Wills and others (2000), but they do indicate that our assumption that all bedrock units can be considered site class B has exceptions. These bedrock units were assigned a site class C on the statewide site class map and these assignments are summarized in Appendix A.

We reviewed our compiled database and determined that we had V_S measurements available in 35 of the 88 customized geologic units. We queried the database to extract V_S measurements for each depositional type, and aggregated these values by geologic age and/or texture depending on the number of available measurements and our judgment on the most appropriate use of the data. We calculated mean and median values and the standard deviation for each of the queried V_S datasets. We then calculated a quantity that we term the "lower bound", which is the mean velocity minus its standard deviation. This is very similar to the approach used by Wills and others (2000) in developing a statewide site conditions (site class) map for California. Appendix C presents a tabulation of our groupings of geologic units, the queried data sets, the mean, median, and lower bound values for each grouping, and the number of V_S measurements used in the calculation of these quantities.

We also assigned a site class using the mean and median value and the lower bound value for each grouping using Table 1; these results are also tabulated in Appendix C. We considered both the mean and median values in case there was a strong asymmetry in the distribution of the V_S data for that grouping. In cases where there was a significant difference in the mean and median values, we inspected the velocity data set to determine the cause of the skew, and used our professional judgment in the assignment of the appropriate site class.

We assigned site classes to those groupings with measured V_S data by combining the site classes determined for the mean or median values and for the lower bound value. Where the mean/median and lower bound site classes were the same, we simply assigned that site class to the grouping. If the site classes determined for the mean/median and lower bound values were different, then we assigned a range of site classes. We believe that this was a reasonable approach to characterizing the effect of uncertainties in the velocity data on the site class assigned to the grouping, and is similar to the approach of Wills and others (2000). Using this procedure we quantitatively characterized the site class of 25 groupings of geologic units with a common depositional type. These 25 groupings are composed of the 35 separate customized geologic units that had measured V_S data.

We then assigned site classes to the remaining 53 customized geologic units that did not have measured V_S values using our professional judgment to determine appropriate comparisons and justifications. Our reasons and justifications for making these assignments are summarized in Appendix C. In certain cases we felt that there was no appropriate justification for assigning a site class, and in these situations we assigned the geologic unit the default site class (D) based on the NEHRP methodology (Building Seismic Safety Council, 1997).

Construction of the statewide site class map was based on the translation of the site class designations presented in Appendix C to specific assignments of site class for each of the geologic units shown in Appendix A. The site class assignments shown in Appendix A were used to assign the appropriate values to the digital map coverage and to produce site class maps based on the outcrop pattern of the various geologic units.

Although we had V_S measurements in peat soils (units Hpt and Qpt) that indicated they were consistent with a site class E designation, we assigned these units to an F site class according to NEHRP requirements (Building Seismic Safety Council, 1997). The special study site class designation (F) should be applied to peat soils that are over 10 ft (3.0 m) thick (Table 1). Our assumption is that peat units mapped on the 1:100,000-scale geologic quadrangle maps are significant accumulations of organic soils, and are likely over 10 ft (3.0 m) in thickness. The NEHRP methodology also requires that liquefiable soils be assigned to site class F (Building Seismic Safety Council, 1997). The definition of the conditions under which liquefaction would require a site class F designation are vague, and we could not determine the level of liquefaction susceptibility requiring a special study designation. However, if our site class map is used to provide an estimate of the potential site class for any construction project, then our liquefaction susceptibility map should be reviewed in conjunction with our site class map to determine if a special study (site class F) designation is warranted.

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Appendix A. Geologic units used in the digital map coverage.

The geologic units used in the digital map coverage and our corresponding customized geologic units for each 1:100,000-scale quadrangle in Washington State. Also included are the liquefaction susceptibility and site classes assigned for each of the non-bedrock geologic units in the statewide digital map coverage. The term 'bdC' is used to identify the pre-Quaternary sedimentary units where shear wave velocity measurements indicated a site class C designation (Table 7).

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
ASTORIA	Qa	Hal	D-E	moderate–high
ASTORIA	Qoa	Qal	D-E	moderate–high
ASTORIA	Qls	Qls	D	low–moderate
ASTORIA	Qt	Qtr	C	very low–low
BANKS LAKE	PLMc(r)	bdC	C	bedrock
BANKS LAKE	Qd	Qae	D	low
BANKS LAKE	Qf	Qae	D	low
BANKS LAKE	Ql	Qae	D	low
BANKS LAKE	Qa	Qal	D-E	moderate–high
BANKS LAKE	Qls	Qls	D	low–moderate
BANKS LAKE	Qgd	yPgd	C-D	very low–low
BANKS LAKE	Qfg	yPgfc	C	very low
BANKS LAKE	Qfs	yPgfs	D	low–moderate
BANKS LAKE	Qgl	yPgl	D	very low
BANKS LAKE	Qgo	yPgo	C-D	low
BANKS LAKE	Qgt	yPgt	C	very low
BELLINGHAM	Qf	afl	E	high
BELLINGHAM	Qaf	Haf	D	low–moderate
BELLINGHAM	Qa	Hal	D-E	moderate–high
BELLINGHAM	Qoa	Hal	D-E	moderate–high
BELLINGHAM	Qb	Hb	D	moderate–high
BELLINGHAM	Qvl(k)	Hlh	D-E	moderate–high
BELLINGHAM	Qvl(m)	Hlh	D-E	moderate–high
BELLINGHAM	Qls	Hls	D	low–moderate
BELLINGHAM	Qp	Hpt	F	peat
BELLINGHAM	Qc(w)	oPsdf	C-D	very low
BELLINGHAM	Qga	yPgao	C-D	very low–low
BELLINGHAM	Qgd	yPgd	C-D	very low–low
BELLINGHAM	Qgdm(e)	yPgmd	D	low–moderate
BELLINGHAM	Qgo(e)	yPgo	C-D	low
BELLINGHAM	Qgo(es)	yPgo	C-D	low
BELLINGHAM	Qgo(s)	yPgo	C-D	low
BELLINGHAM	Qgom(e)	yPgo	C-D	low
BELLINGHAM	Qgom(ee)	yPgo	C-D	low
BELLINGHAM	Qgom(s)	yPgo	C-D	low
BELLINGHAM	Qat(e)	yPgt	C	very low
BELLINGHAM	Qgt	yPgt	C	very low
BELLINGHAM	Qgt(s)	yPgt	C	very low
CAPE FLATTERY	Qa	Hal	D-E	moderate–high
CAPE FLATTERY	Qb	Hb	D	moderate–high
CAPE FLATTERY	Qls	Hls	D	low–moderate
CAPE FLATTERY	Qgd	yPgd	C-D	very low–low
CAPE FLATTERY	Qgl	yPgl	D	very low
CAPE FLATTERY	Qgo	yPgoc	C	very low
CAPE FLATTERY	Qgt	yPgt	C	very low
CENTRALIA	Qa	Hal	D-E	moderate–high
CENTRALIA	Qvl(e)	Hlh	D-E	moderate–high
CENTRALIA	Qls	Hls	D	low–moderate
CENTRALIA	Qp	Hpt	F	peat
CENTRALIA	Qap(wh)	oPgd	C-D	very low
CENTRALIA	Qgp	oPgd	C-D	very low
CENTRALIA	Qapo(h)	oPgo	C-D	very low
CENTRALIA	Qapo(lh)	oPgo	C-D	very low
CENTRALIA	Qap(h)	oPgoc	C	very low
CENTRALIA	Qapo(he)	oPgoc	C	very low
CENTRALIA	Qapo(wh)	oPgoc	C	very low
CENTRALIA	Qapt(h)	oPgt	C	very low
CENTRALIA	Qapt(wh)	oPgt	C	very low
CENTRALIA	Qvl(lc)	Plh	D-E	moderate–high
CENTRALIA	Qga	yPgao	C-D	very low–low

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
CENTRALIA	Qad(e)	yPgd	C-D	very low–low
CENTRALIA	Qgd	yPgd	C-D	very low–low
CENTRALIA	Qgm	yPgd	C-D	very low–low
CENTRALIA	Qgo	yPgo	C-D	low
CENTRALIA	Qao(e)	yPgoc	C	very low
CENTRALIA	Qgog	yPgoc	C	very low
CENTRALIA	Qgos	yPgos	D	low–moderate
CENTRALIA	Qat(e)	yPgt	C	very low
CENTRALIA	Qgt	yPgt	C	very low
CHEHALIS RIVER	Qb	Hbs	D	moderate–high
CHEHALIS RIVER	Qgp	oPgd	C-D	very low
CHEHALIS RIVER	Qapo(lh)	oPgoc	C	very low
CHEHALIS RIVER	Qapo(wc)	oPsdc	B-C	very low
CHEHALIS RIVER	QPLc	oPsdc	B-C	very low
CHEHALIS RIVER	Qoa	Pal	D-E	low–moderate
CHEHALIS RIVER	Qt	Ptr	C	very low–low
CHEHALIS RIVER	Qa	Qal	D-E	moderate–high
CHEHALIS RIVER	Qls	Qls	D	low–moderate
CHEHALIS RIVER	Qgo	yPgo	C-D	low
CHEHALIS RIVER	Qgog	yPgoc	C	very low
CHEHALIS RIVER	Qgos	yPgos	D	low–moderate
CHEHALIS RIVER	Qgm	yPgt	C	very low
CHEHALIS RIVER	Qgt	yPgt	C	very low
CHELAN	Qf	afl	E	high
CHELAN	Qd	Haef	D	low
CHELAN	Qp	Hpt	F	peat
CHELAN	Qad	Pgd	C-D	very low–low
CHELAN	QMs	Psdc	C	very low–low
CHELAN	Qt	Ptrc	C	very low–low
CHELAN	Ql	Qaef	D	low
CHELAN	Qa	Qal	D-E	moderate–high
CHELAN	Qls(m)	Qcv	D	moderate
CHELAN	Qls	Qls	D	low–moderate
CHELAN	Qfg	yPgfc	C	very low
CHELAN	Qta	Htl	B	bedrock
CHELAN	Qgl	yPgl	D	very low
CHEWELAH	Qa	Hal	D-E	moderate–high
CHEWELAH	Qla	Hlc	D	moderate–high
CHEWELAH	Qp	Hpt	F	peat
CHEWELAH	Qgp	oPgt	C	very low
CHEWELAH	Qgd	Pgd	C-D	very low–low
CHEWELAH	Qgo	Pgo	C-D	low
CHEWELAH	Ql	Qaef	D	low
CHEWELAH	Qls	Qls	D	low–moderate
CHEWELAH	Qs	Qsd	D	very low–low
CHEWELAH	Qfg	yPgfc	C	very low
CHEWELAH	Qfs	yPgfs	D	low–moderate
CHEWELAH	Qgl	yPgl	D	very low
CHEWELAH	Qglf	yPglf	D	low
CHEWELAH	Qgt	yPgt	C	very low
CLARKSTON	QMcg	oPsdc	B-C	very low
CLARKSTON	Ql	Qaef	D	low
CLARKSTON	Qaf	Qaf	D	low–moderate
CLARKSTON	Qa	Qal	D-E	moderate–high
CLARKSTON	Qls	Qls	D	low–moderate
CLARKSTON	QPLls	Qls	D	low–moderate
CLARKSTON	Qf(b)	yPgf	C-D	low
CLARKSTON	Qf(m)	yPgf	C-D	low
CLARKSTON	Qfs(t)	yPgfs	D	low–moderate
COLVILLE	Qa	Hal	D-E	moderate–high
COLVILLE	Qls	Qls	D	low–moderate
COLVILLE	Qgd	yPgd	C-D	very low–low
COLVILLE	Qgl	yPgl	D	very low
COLVILLE	Qgo	yPgo	C-D	low
COLVILLE	Qgt	yPgt	C	very low
CONNELL	Qf	afl	E	high
CONNELL	PLMc(r)	bdC	C	bedrock
CONNELL	Qd	Hae	D	low
CONNELL	Qla	Hlc	D	moderate–high
CONNELL	QMcg	oPsdc	B-C	very low
CONNELL	Ql	Qae	D	low
CONNELL	Qaf	Qaf	D	low–moderate

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
CONNELL	Qa	Qal	D-E	moderate–high
CONNELL	Qls	Qls	D	low–moderate
CONNELL	Qf(b)	yPgfc	C	very low
CONNELL	Qf(bg)	yPgfc	C	very low
CONNELL	Qfg	yPgfc	C	very low
CONNELL	Qfs(t)	yPgfs	D	low–moderate
COPALIS BEACH	Qa	Hal	D-E	moderate–high
COPALIS BEACH	Qb	Hbs	D	moderate–high
COPALIS BEACH	Qap	oPgd	C-D	very low
COPALIS BEACH	Qapw(1)	oPgd	C-D	very low
COPALIS BEACH	Qapw(2)	oPgd	C-D	very low
COPALIS BEACH	Qapo	oPgo	C-D	very low
COPALIS BEACH	Qapwo(1)	oPgo	C-D	very low
COPALIS BEACH	Qapwo(2)	oPgo	C-D	very low
COPALIS BEACH	Qapt	oPgt	C	very low
COPALIS BEACH	Qapwt(2)	oPgt	C	very low
COPALIS BEACH	Qc(d)	oPsdf	C-D	very low
COPALIS BEACH	Qao	yPgo	C-D	low
COULEE DAM	Mc(l)	bdC	C	bedrock
COULEE DAM	Qd	Haef	D	low
COULEE DAM	Qa	Hal	D-E	moderate–high
COULEE DAM	Qp	Hpt	F	peat
COULEE DAM	Qgpo	oPgo	C-D	very low
COULEE DAM	Qgpt	oPgt	C	very low
COULEE DAM	Ql	Qae	D	low
COULEE DAM	Qls	Qls	D	low–moderate
COULEE DAM	Qgd	yPgd	C-D	very low–low
COULEE DAM	Qfg	yPgfc	C	very low
COULEE DAM	Qfs	yPgfs	D	low–moderate
COULEE DAM	Qgl	yPgl	D	very low
COULEE DAM	Qglf	yPglf	D	low
COULEE DAM	Qgo	yPgo	C-D	low
COULEE DAM	Qgt	yPgt	C	very low
FORKS	Qapw(1)	oPgd	C-D	very low
FORKS	Qapw(2)	oPgd	C-D	very low
FORKS	Qapo	oPgoc	C	very low
FORKS	Qapwo(1)	oPgoc	C	very low
FORKS	Qapwo(2)	oPgoc	C	very low
FORKS	Qapt	oPgt	C	very low
FORKS	Qapt(m)	oPgt	C	very low
FORKS	Qapwt(1)	oPgt	C	very low
FORKS	Qapwt(1m)	oPgt	C	very low
FORKS	Qapwt(2)	oPgt	C	very low
FORKS	Qapwt(2m)	oPgt	C	very low
FORKS	Qad	Pgd	C-D	very low–low
FORKS	Qgdc	Psdc	C	very low–low
FORKS	Qa	Qal	D-E	moderate–high
FORKS	Qls	Qls	D	low–moderate
FORKS	Qap	yPgd	C-D	very low–low
FORKS	Qgd	yPgd	C-D	very low–low
FORKS	Qao	yPgoc	C	very low
FORKS	Qgo	yPgoc	C	very low
FORKS	Qat	yPgt	C	very low
FORKS	Qat(m)	yPgt	C	very low
FORKS	Qgt	yPgt	C	very low
GOLDENDALE	Qd	Haef	D	low
GOLDENDALE	Qa	Hal	D-E	moderate–high
GOLDENDALE	QMc	oPsd	C-D	very low
GOLDENDALE	Qt	Ptr	C	very low–low
GOLDENDALE	Ql	Qaef	D	low
GOLDENDALE	Qaf	Qaf	D	low–moderate
GOLDENDALE	Qls	Qls	D	low–moderate
GOLDENDALE	Qta	Qtr	C	very low–low
GOLDENDALE	Qfg	yPgfc	C	very low
GOLDENDALE	Qfs(t)	yPgfs	D	low–moderate
HERMISTON	Qf	afl	E	high
HERMISTON	Qd	Haef	D	low
HERMISTON	Qa	Hal	D-E	moderate–high
HERMISTON	Qt	Ptr	C	very low–low
HERMISTON	Ql	Qae	D	low
HERMISTON	Qaf	Qaf	D	low–moderate
HERMISTON	Qls	Qls	D	low–moderate

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
HERMISTON	Qfg	yPgfc	C	very low
HERMISTON	Qfs(t)	yPgfs	D	low–moderate
HOOD RIVER	Qf	afl	E	high
HOOD RIVER	Qd	Hae	D	low
HOOD RIVER	Qvl(t)	Hlhc	D-E	moderate–high
HOOD RIVER	Qapt(h)	oPgt	C	very low
HOOD RIVER	QPLc(s)	oPsd	C-D	very low
HOOD RIVER	Qa	Qal	D-E	moderate–high
HOOD RIVER	Qoa	Qal	D-E	moderate–high
HOOD RIVER	Qls	Qls	D	low–moderate
HOOD RIVER	Qt	Qtr	C	very low–low
HOOD RIVER	Qfg	yPgfc	C	very low
HOOD RIVER	Qfs	yPgfs	D	low–moderate
HOOD RIVER	Qao(e)	yPgo	C-D	low
HOOD RIVER	Qat(e)	yPgt	C	very low
ILWACO	Qa	Hal	D-E	moderate–high
ILWACO	Qb	Hbs	D	moderate–high
ILWACO	Qt	Qtr	C	very low–low
MOSES LAKE	PLMc(r)	bdC	C	bedrock
MOSES LAKE	Qoa	Palc	B-C	very low–low
MOSES LAKE	Ql	Qaef	D	low
MOSES LAKE	Qd	Qaes	D	low
MOSES LAKE	Qa	Qal	D-E	moderate–high
MOSES LAKE	Qls	Qls	D	low–moderate
MOSES LAKE	Qfg	yPgfc	C	very low
MOSES LAKE	Qfs	yPgfs	D	low–moderate
MOUNT ADAMS	Qvl(t)	Hlhc	D-E	moderate–high
MOUNT ADAMS	Qvc(a)	Hvc	D	low–moderate
MOUNT ADAMS	Qvc(sh)	Hvc	D	low–moderate
MOUNT ADAMS	Qap(h)	oPgd	C-D	very low
MOUNT ADAMS	Qap(ws)	oPgd	C-D	very low
MOUNT ADAMS	Qapt(h)	oPgt	C	very low
MOUNT ADAMS	Qa	Qal	D-E	moderate–high
MOUNT ADAMS	Qls	Qls	D	low–moderate
MOUNT ADAMS	Qad	yPgd	C-D	very low–low
MOUNT ADAMS	Qad(e)	yPgd	C-D	very low–low
MOUNT ADAMS	Qad(md)	yPgd	C-D	very low–low
MOUNT ADAMS	Qat(e)	yPgt	C	very low
MOUNT BAKER	Qaf	Hafc	D	very low–low
MOUNT BAKER	Qa	Hal	D-E	moderate–high
MOUNT BAKER	Qat	Hgt	C	very low
MOUNT BAKER	Qp	Hpt	F	peat
MOUNT BAKER	Qgpc	oPsds	C	very low
MOUNT BAKER	Qoa	Palc	B-C	very low–low
MOUNT BAKER	Qad	Qgd	C-D	very low–low
MOUNT BAKER	Qls	Qls	D	low–moderate
MOUNT BAKER	Qga	yPgao	C-D	very low–low
MOUNT BAKER	Qgd	yPgd	C-D	very low–low
MOUNT BAKER	Qgo	yPgro	C-D	low
MOUNT BAKER	Qta	Htl	B	bedrock
MOUNT BAKER	Qgt	yPgt	C	very low
MOUNT OLYMPUS	Qaf	Hafc	D	very low–low
MOUNT OLYMPUS	Qap	oPgd	C-D	very low
MOUNT OLYMPUS	Qapo	oPgoc	C	very low
MOUNT OLYMPUS	Qapt	oPgt	C	very low
MOUNT OLYMPUS	Qapt(m)	oPgt	C	very low
MOUNT OLYMPUS	Qc	oPsd	C-D	very low
MOUNT OLYMPUS	Qgl	Pgl	D	very low
MOUNT OLYMPUS	Qa	Qal	D-E	moderate–high
MOUNT OLYMPUS	Qls	Qls	D	low–moderate
MOUNT OLYMPUS	Qls(s)	Qls	D	low–moderate
MOUNT OLYMPUS	Qls(r)	Qlsc	D	low–moderate
MOUNT OLYMPUS	Qga	yPgaoc	B-C	very low
MOUNT OLYMPUS	Qad	yPgd	C-D	very low–low
MOUNT OLYMPUS	Qgd	yPgd	C-D	very low–low
MOUNT OLYMPUS	Qao	yPgoc	C	very low
MOUNT OLYMPUS	Qgo	yPgoc	C	very low
MOUNT OLYMPUS	Qat	yPgt	C	very low
MOUNT OLYMPUS	Qat(m)	yPgt	C	very low
MOUNT OLYMPUS	Qgt	yPgt	C	very low
MOUNT RAINIER	Qf	aflc	C	very low
MOUNT RAINIER	Qaf	Hafc	D	very low–low

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
MOUNT RAINIER	Qa	Hal	D-E	moderate–high
MOUNT RAINIER	Qad(b)	Hgd	C-D	very low–low
MOUNT RAINIER	Qad(g)	Hgd	C-D	very low–low
MOUNT RAINIER	Qad(mn)	Hgd	C-D	very low–low
MOUNT RAINIER	Qvl	Hlh	D-E	moderate–high
MOUNT RAINIER	Qvl(e)	Hlh	D-E	moderate–high
MOUNT RAINIER	Qvl(g)	Hlh	D-E	moderate–high
MOUNT RAINIER	Qvl(o)	Hlh	D-E	moderate–high
MOUNT RAINIER	Qvl(p)	Hlh	D-E	moderate–high
MOUNT RAINIER	Qvl(r)	Hlh	D-E	moderate–high
MOUNT RAINIER	Qls	Hlsc	D	low–moderate
MOUNT RAINIER	Qap(h)	oPgd	C-D	very low
MOUNT RAINIER	Qapt(h)	oPgt	C	very low
MOUNT RAINIER	Qap	Pgd	C-D	very low–low
MOUNT RAINIER	Qt	Ptrc	C	very low–low
MOUNT RAINIER	Qad(e)	yPgd	C-D	very low–low
MOUNT RAINIER	Qta	Htl	B	bedrock
MOUNT RAINIER	Qat(e)	yPgt	C	very low
MOUNT SAINT HELENS	Qf	aflc	C	very low
MOUNT SAINT HELENS	Qvl(3sh)	Hlhc	D-E	moderate–high
MOUNT SAINT HELENS	Qvp(3sh)	Htf	D	low
MOUNT SAINT HELENS	Qvc(1sh)	Hvc	D	low–moderate
MOUNT SAINT HELENS	Qvc(2sh)	Hvc	D	low–moderate
MOUNT SAINT HELENS	Qvc(3sh)	Hvc	D	low–moderate
MOUNT SAINT HELENS	Qap(lh)	oPgd	C-D	very low
MOUNT SAINT HELENS	Qapo(h)	oPgoc	C	very low
MOUNT SAINT HELENS	Qapo(wh)	oPgoc	C	very low
MOUNT SAINT HELENS	Qapt(h)	oPgt	C	very low
MOUNT SAINT HELENS	PLMc(t)	oPsd	C-D	very low
MOUNT SAINT HELENS	Qgu	Pgd	C-D	very low–low
MOUNT SAINT HELENS	Qa	Qal	D-E	moderate–high
MOUNT SAINT HELENS	Qls	Qlsc	D	low–moderate
MOUNT SAINT HELENS	Qvc(sh)	Qvc	D	low–moderate
MOUNT SAINT HELENS	Qad(e)	yPgd	C-D	very low–low
MOUNT SAINT HELENS	Qao	yPgoc	C	very low
MOUNT SAINT HELENS	Qao(e)	yPgoc	C	very low
MOUNT SAINT HELENS	Qapo(e)	yPgoc	C	very low
MOUNT SAINT HELENS	Qat(e)	yPgt	C	very low
MOUNT SAINT HELENS	Qt	yPtrf	C	very low–low
NESPELEM	Qgpt	oPgt	C	very low
NESPELEM	Qgd	Pgd	C-D	very low–low
NESPELEM	Ql	Qaef	D	low
NESPELEM	Qa	Qal	D-E	moderate–high
NESPELEM	Qls	Qls	D	low–moderate
NESPELEM	Qs	Qsd	D	very low–low
NESPELEM	Qgl(n)	yPgl	D	very low
NESPELEM	Qglf(n)	yPglf	D	low
NESPELEM	Qgo	yPgoc	C	very low
NESPELEM	Qgt	yPgt	C	very low
OMAK	Qd	Haef	D	low
OMAK	Qa	Hal	D-E	moderate–high
OMAK	Qls	Hls	D	low–moderate
OMAK	Qfg	yPgfc	C	very low
OMAK	Qfs	yPgfs	D	low–moderate
OMAK	Qgl(n)	yPgl	D	very low
OMAK	Qgo	yPgo	C-D	low
OMAK	Qgd	yPgt	C	very low
OMAK	Qgt	yPgt	C	very low
OROFINO	QMcg	oPsdc	B-C	very low
OROFINO	Qa	Qal	D-E	moderate–high
OROFINO	QPLls	Qls	D	low–moderate
OROFINO	Qf(b)	yPgf	C-D	low
OROFINO	Qf(m)	yPgf	C-D	low
OROVILLE	Qd	Haef	D	low
OROVILLE	Qa	Hal	D-E	moderate–high
OROVILLE	Qls	Hls	D	low–moderate
OROVILLE	Qp	Hpt	F	peat
OROVILLE	Qoa	Pal	D-E	low–moderate
OROVILLE	Qgd	yPgd	C-D	very low–low
OROVILLE	Qgl	yPgl	D	very low
OROVILLE	Qgo	yPgo	C-D	low
OROVILLE	Qgt	yPgt	C	very low

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
PORT ANGELES	Qf	afl	E	high
PORT ANGELES	Qa	Hal	D-E	moderate–high
PORT ANGELES	Qb	Hb	D	moderate–high
PORT ANGELES	Qp	Hpt	F	peat
PORT ANGELES	Qc	oPsdc	B-C	very low
PORT ANGELES	Qguc	Psd	D	very low–low
PORT ANGELES	Qaf	Qafs	D	low–moderate
PORT ANGELES	Qoa	Qal	D-E	moderate–high
PORT ANGELES	Qls	Qls	D	low–moderate
PORT ANGELES	Qga	yPgao	C-D	very low–low
PORT ANGELES	Qad	yPgd	C-D	very low–low
PORT ANGELES	Qgd	yPgd	C-D	very low–low
PORT ANGELES	Qgl	yPgl	D	very low
PORT ANGELES	Qgdm(es)	yPgmd	D	low–moderate
PORT ANGELES	Qgdm	yPgmdf	D	very low
PORT ANGELES	Qgdm(e)	yPgmds	D	low–moderate
PORT ANGELES	Qao	yPgo	C-D	low
PORT ANGELES	Qgo(i)	yPgro	C-D	low
PORT ANGELES	Qgo	yPgroc	C-D	very low
PORT ANGELES	Qgos	yPgros	D-E	low–moderate
PORT ANGELES	Qat	yPgt	C	very low
PORT ANGELES	Qgt	yPgt	C	very low
PORT TOWNSEND	Qf	afl	E	high
PORT TOWNSEND	Qd	Haes	D	moderate
PORT TOWNSEND	Qaf	Hafc	D	very low–low
PORT TOWNSEND	Qa	Hal	D-E	moderate–high
PORT TOWNSEND	Qoa	Hal	D-E	moderate–high
PORT TOWNSEND	Qa(c)	Half	D-E	moderate–high
PORT TOWNSEND	Qoa(c)	Half	D-E	moderate–high
PORT TOWNSEND	Qa(s)	Hals	D-E	high
PORT TOWNSEND	Qoa(s)	Hals	D-E	high
PORT TOWNSEND	Qb	Hb	D	moderate–high
PORT TOWNSEND	Qgp	oPgd	C-D	very low
PORT TOWNSEND	Qgpm	oPgmd	D	very low
PORT TOWNSEND	Qc	oPsd	C-D	very low
PORT TOWNSEND	Qguc	oPsd	C-D	very low
PORT TOWNSEND	Qc(o)	oPsdf	C-D	very low
PORT TOWNSEND	Qc(w)	oPsdf	C-D	very low
PORT TOWNSEND	Qgpc	oPsdf	C-D	very low
PORT TOWNSEND	Qvl(k)	Qlh	D-E	moderate–high
PORT TOWNSEND	Qls	Qls	D	low–moderate
PORT TOWNSEND	Qp	Qpt	F	peat
PORT TOWNSEND	Qga	yPgao	C-D	very low–low
PORT TOWNSEND	Qga(t)	yPgao	C-D	very low–low
PORT TOWNSEND	Qgac	yPgaof	D	very low
PORT TOWNSEND	Qgas	yPgaos	C-D	low
PORT TOWNSEND	Qgd	yPgd	C-D	very low–low
PORT TOWNSEND	Qgdc	yPgd	C-D	very low–low
PORT TOWNSEND	Qgl	yPglf	D	low
PORT TOWNSEND	Qgdm	yPgmd	D	low–moderate
PORT TOWNSEND	Qgdm(e)	yPgmd	D	low–moderate
PORT TOWNSEND	Qgo	yPgro	C-D	low
PORT TOWNSEND	Qgom	yPgro	C-D	low
PORT TOWNSEND	Qgom(e)	yPgro	C-D	low
PORT TOWNSEND	Qgog	yPgroc	C-D	very low
PORT TOWNSEND	Qgogm(p)	yPgroc	C-D	very low
PORT TOWNSEND	Qgoc	yPgrof	D	very low
PORT TOWNSEND	Qgocm	yPgrof	D	very low
PORT TOWNSEND	Qgos	yPgros	D-E	low–moderate
PORT TOWNSEND	Qgosm	yPgros	D-E	low–moderate
PORT TOWNSEND	Qta	Qtl	B	bedrock
PORT TOWNSEND	Qgt	yPgt	C	very low
PRIEST RAPIDS	PLMc(r)	bdC	C	bedrock
PRIEST RAPIDS	Qd	Haef	D	low
PRIEST RAPIDS	Qda	Haef	D	low
PRIEST RAPIDS	Qds	Haef	D	low
PRIEST RAPIDS	QPLcg	oPsdc	B-C	very low
PRIEST RAPIDS	Ql	Qaef	D	low
PRIEST RAPIDS	Qaf	Qaf	D	low–moderate
PRIEST RAPIDS	Qafo	Qaf	D	low–moderate
PRIEST RAPIDS	Qa	Qal	D-E	moderate–high
PRIEST RAPIDS	Qls	Qls	D	low–moderate

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
PRIEST RAPIDS	Qfg	yPgfc	C	very low
PRIEST RAPIDS	Qfg(1)	yPgfc	C	very low
PRIEST RAPIDS	Qfg(2)	yPgfc	C	very low
PRIEST RAPIDS	Qfg(3)	yPgfc	C	very low
PRIEST RAPIDS	Qfg(3-4u)	yPgfc	C	very low
PRIEST RAPIDS	Qfg(4)	yPgfc	C	very low
PRIEST RAPIDS	Qfs(1)	yPgfs	D	low–moderate
PRIEST RAPIDS	Qfs(3)	yPgfs	D	low–moderate
PRIEST RAPIDS	Qfs(4)	yPgfs	D	low–moderate
PRIEST RAPIDS	Qta	Qtl	B	bedrock
PRIEST RAPIDS	Qfs(t)	yPgfs	D	low–moderate
PULLMAN	Qf	afl	E	high
PULLMAN	Qd	Haef	D	low
PULLMAN	Qla	Hlc	D	moderate–high
PULLMAN	QMcg	oPsdc	B-C	very low
PULLMAN	Ql	Qaef	D	low
PULLMAN	Qaf	Qaf	D	low–moderate
PULLMAN	Qa	Qal	D-E	moderate–high
PULLMAN	Qls	Qls	D	low–moderate
PULLMAN	Qt	Qtr	C	very low–low
PULLMAN	Qf(b)	yPgfc	C	very low
PULLMAN	Qfs(t)	yPgfc	C	very low
PULLMAN	Qfg	yPgfs	D	low–moderate
REPUBLIC	Qd	Haef	D	low
REPUBLIC	Qa	Hal	D-E	moderate–high
REPUBLIC	Qls	Hls	D	low–moderate
REPUBLIC	Qoa	Pal	D-E	low–moderate
REPUBLIC	Qgd	yPgd	C-D	very low–low
REPUBLIC	Qgl	yPgl	D	very low
REPUBLIC	Qgo	yPgoc	C	very low
REPUBLIC	Qgt	yPgt	C	very low
RICHLAND	PLMc(r)	bdC	C	bedrock
RICHLAND	Qd	Haef	D	low
RICHLAND	Qda	Haef	D	low
RICHLAND	Qds	Haef	D	low
RICHLAND	QPLcg	oPsdc	B-C	very low
RICHLAND	Ql	Qaef	D	low
RICHLAND	Qaf	Qafc	D	very low–low
RICHLAND	Qa	Qal	D-E	moderate–high
RICHLAND	Qls	Qls	D	low–moderate
RICHLAND	Qfg	yPgfc	C	very low
RICHLAND	Qfg(1)	yPgfc	C	very low
RICHLAND	Qfg(2)	yPgfc	C	very low
RICHLAND	Qfg(3)	yPgfc	C	very low
RICHLAND	Qfg(4)	yPgfc	C	very low
RICHLAND	Qfs(1)	yPgfs	D	low–moderate
RICHLAND	Qfs(2)	yPgfs	D	low–moderate
RICHLAND	Qfs(3)	yPgfs	D	low–moderate
RICHLAND	Qfs(t)	yPgfs	D	low–moderate
RITZVILLE	PLMc(r)	bdC	C	bedrock
RITZVILLE	Ql	Qaef	D	low
RITZVILLE	Qa	Qal	D-E	moderate–high
RITZVILLE	Qls	Qls	D	low–moderate
RITZVILLE	Qfg	yPgfc	C	very low
RITZVILLE	Qfs	yPgfs	D	low–moderate
ROBINSON MOUNTAIN	Qa	Hal	D-E	moderate–high
ROBINSON MOUNTAIN	Qls	Hls	D	low–moderate
ROBINSON MOUNTAIN	Qoa	Pal	D-E	low–moderate
ROBINSON MOUNTAIN	Qs	Qsd	D	very low–low
ROBINSON MOUNTAIN	Qgd	yPgd	C-D	very low–low
ROBINSON MOUNTAIN	Qao	yPgo	C-D	low
ROCHE HARBOR	Qa	Hal	D-E	moderate–high
ROCHE HARBOR	Qb	Hb	D	moderate–high
ROCHE HARBOR	Qls	Hls	D	low–moderate
ROCHE HARBOR	Qp	Hpt	F	peat
ROCHE HARBOR	Qguc	Pgd	C-D	very low–low
ROCHE HARBOR	Qgd	yPgd	C-D	very low–low
ROCHE HARBOR	Qgd(s)	yPgd	C-D	very low–low
ROCHE HARBOR	Qgdm(es)	yPgmdf	D	very low
ROCHE HARBOR	Qgdm(e)	yPgmds	D	low–moderate
ROCHE HARBOR	Qgog	yPgroc	C-D	very low
ROCHE HARBOR	Qgt	yPgt	C	very low

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
ROSALIA	Qa	Hal	D-E	moderate–high
ROSALIA	Ql	Qaef	D	low
ROSALIA	Qfg	yPgfc	C	very low
ROSALIA	Qglf	yPglf	D	low
SAUK RIVER	Qa	Hal	D-E	moderate–high
SAUK RIVER	Qvl(s)	Hlh	D-E	moderate–high
SAUK RIVER	Qls	Hls	D	low–moderate
SAUK RIVER	Qp	Hpt	F	peat
SAUK RIVER	Qvp(gp)	Htf	D	low
SAUK RIVER	Qgpc	oPsdc	B-C	very low
SAUK RIVER	Qad	Pgd	C-D	very low–low
SAUK RIVER	Qaf	Qafc	D	very low–low
SAUK RIVER	Qa(m)	Qal	D-E	moderate–high
SAUK RIVER	Qoa	Qal	D-E	moderate–high
SAUK RIVER	Qvl(gp)	Qlh	D-E	moderate–high
SAUK RIVER	Qvl(w)	Qlh	D-E	moderate–high
SAUK RIVER	Qls(m)	Qls	D	low–moderate
SAUK RIVER	Qga	yPgao	C-D	very low–low
SAUK RIVER	Qga(tb)	yPgaof	D	very low
SAUK RIVER	Qgo	yPgroc	C-D	very low
SAUK RIVER	Qgo(i)	yPgroc	C-D	very low
SAUK RIVER	Qgos(s)	yPgros	D-E	low–moderate
SAUK RIVER	Qta	Htl	B	bedrock
SAUK RIVER	Qgt	yPgt	C	very low
SEATTLE	Qf	afl	E	high
SEATTLE	Qa	Hal	D-E	moderate–high
SEATTLE	Qb	Hb	D	moderate–high
SEATTLE	Qls	Hls	D	low–moderate
SEATTLE	Qt	Htr	C	very low–low
SEATTLE	Qgp	oPgd	C-D	very low
SEATTLE	Qgp(d)	oPgd	C-D	very low
SEATTLE	Qgp(p)	oPgd	C-D	very low
SEATTLE	Qc(w)	oPsdc	B-C	very low
SEATTLE	Qcg	oPsdc	B-C	very low
SEATTLE	Qgpc	oPsdc	B-C	very low
SEATTLE	Qgu	Pgd	C-D	very low–low
SEATTLE	Qp	Qpt	F	peat
SEATTLE	Qga	yPgao	C-D	very low–low
SEATTLE	Qga(t)	yPgaof	D	very low
SEATTLE	Qad	yPgd	C-D	very low–low
SEATTLE	Qgd	yPgd	C-D	very low–low
SEATTLE	Qgdm	yPgmd	D	low–moderate
SEATTLE	Qgo	yPgro	C-D	low
SEATTLE	Qgt	yPgt	C	very low
SEATTLE	Qc	yPsdf	D	very low–low
SEATTLE	Qc(o)	yPsdf	D	very low–low
SHELTON	Qa	Hal	D-E	moderate–high
SHELTON	Qls	Hls	D	low–moderate
SHELTON	Qp	Hpt	F	peat
SHELTON	Qap	oPgd	C-D	very low
SHELTON	Qapw(1)	oPgd	C-D	very low
SHELTON	Qapw(2)	oPgd	C-D	very low
SHELTON	Qgp	oPgd	C-D	very low
SHELTON	Qapo(wx)	oPgl	D	very low
SHELTON	Qapo	oPgoc	C	very low
SHELTON	Qapwo(1)	oPgoc	C	very low
SHELTON	Qapwo(2)	oPgoc	C	very low
SHELTON	Qapt	oPgt	C	very low
SHELTON	Qapwt(1)	oPgt	C	very low
SHELTON	Qapwt(2)	oPgt	C	very low
SHELTON	Qc(k)	oPsdf	C-D	very low
SHELTON	Qga	yPgao	C-D	very low–low
SHELTON	Qgas	yPgaos	C-D	low
SHELTON	Qad	yPgd	C-D	very low–low
SHELTON	Qgd	yPgd	C-D	very low–low
SHELTON	Qao	yPgroc	C-D	very low
SHELTON	Qgo	yPgroc	C-D	very low
SHELTON	Qat	yPgt	C	very low
SHELTON	Qgt	yPgt	C	very low
SKYKOMISH RIVER	Qf	aflc	C	very low
SKYKOMISH RIVER	Qgpc	oPsdc	B-C	very low
SKYKOMISH RIVER	Qa	Qal	D-E	moderate–high

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
SKYKOMISH RIVER	Qad(p)	Qgt	C	very low
SKYKOMISH RIVER	Qls(m)	Qls	D	low–moderate
SKYKOMISH RIVER	Qls	Qlsc	D	low–moderate
SKYKOMISH RIVER	Qls(a)	Qlsc	D	low–moderate
SKYKOMISH RIVER	Qp	Qpt	F	peat
SKYKOMISH RIVER	Qga	yPgaos	C-D	low
SKYKOMISH RIVER	Qad	yPgd	C-D	very low–low
SKYKOMISH RIVER	Qgl	yPglf	D	low
SKYKOMISH RIVER	Qgo	yPgro	C-D	low
SKYKOMISH RIVER	Qta	Qtl	B	bedrock
SKYKOMISH RIVER	Qgt	yPgt	C	very low
SNOQUALMIE PASS	Qf	aflc	C	very low
SNOQUALMIE PASS	Qvl(o)	Hlh	D-E	moderate–high
SNOQUALMIE PASS	Qap	oPgd	C-D	very low
SNOQUALMIE PASS	Qgpc	oPsd	C-D	very low
SNOQUALMIE PASS	Qvt	Pvc	D	low
SNOQUALMIE PASS	Qa	Qal	D-E	moderate–high
SNOQUALMIE PASS	Qls(m)	Qls	D	low–moderate
SNOQUALMIE PASS	Qls	Qlsc	D	low–moderate
SNOQUALMIE PASS	Qp	Qpt	F	peat
SNOQUALMIE PASS	Qs	Qsd	D	very low–low
SNOQUALMIE PASS	Qga	yPgao	C-D	very low–low
SNOQUALMIE PASS	Qad(e)	yPgd	C-D	very low–low
SNOQUALMIE PASS	Qgd	yPgd	C-D	very low–low
SNOQUALMIE PASS	Qgo	yPgro	C-D	low
SNOQUALMIE PASS	Qgo(i)	yPgro	C-D	low
SNOQUALMIE PASS	Qta	Qtl	B	bedrock
SNOQUALMIE PASS	Qgt	yPgt	C	very low
SPOKANE	Mc(l)	bdC	C	bedrock
SPOKANE	Qa	Hal	D-E	moderate–high
SPOKANE	Qp	Hpt	F	peat
SPOKANE	Ql	Qaef	D	low
SPOKANE	Qd	Qaes	D	low
SPOKANE	Qls	Qls	D	low–moderate
SPOKANE	Qgd	yPgd	C-D	very low–low
SPOKANE	Qfg	yPgfc	C	very low

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
SPOKANE	Qgl	yPgl	D	very low
SPOKANE	Qglf	yPglf	D	low
TACOMA	Qf	afl	E	high
TACOMA	Qa	Hal	D-E	moderate–high
TACOMA	Qb	Hb	D	moderate–high
TACOMA	Qvl(e)	Hlh	D-E	moderate–high
TACOMA	Qvl(o)	Hlh	D-E	moderate–high
TACOMA	Qls	Hls	D	low–moderate
TACOMA	Qp	Hpt	F	peat
TACOMA	Qap(h)	oPgd	C-D	very low
TACOMA	Qap(wh)	oPgd	C-D	very low
TACOMA	Qgp	oPgd	C-D	very low
TACOMA	Qgp(o)	oPgd	C-D	very low
TACOMA	Qgp(s)	oPgd	C-D	very low
TACOMA	Qgp(st)	oPgd	C-D	very low
TACOMA	Qgpc	oPgd	C-D	very low
TACOMA	Qapo	oPgo	C-D	very low
TACOMA	Qc	oPsd	C-D	very low
TACOMA	Qc(a)	oPsd	C-D	very low
TACOMA	Qc(k)	oPsd	C-D	very low
TACOMA	Qc(p)	oPsd	C-D	very low
TACOMA	Qoa(sk)	Palc	B-C	very low–low
TACOMA	Qoa	Qal	D-E	moderate–high
TACOMA	Qvl(lc)	Qlh	D-E	moderate–high
TACOMA	Qga	yPgao	C-D	very low–low
TACOMA	Qgac	yPgaof	D	very low
TACOMA	Qgas	yPgaos	C-D	low
TACOMA	Qgd	yPgd	C-D	very low–low
TACOMA	Qgl	yPgl	D	very low
TACOMA	Qgo	yPgro	C-D	low
TACOMA	Qgos	yPgros	D-E	low–moderate
TACOMA	Qgm	yPgt	C	very low
TACOMA	Qgt	yPgt	C	very low
TOPPENISH	QPLcg	oPsdc	B-C	very low
TOPPENISH	Qt	Ptr	C	very low–low
TOPPENISH	Ql	Qaef	D	low

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
TOPPENISH	Qaf	Qafc	D	very low–low
TOPPENISH	Qafo	Qafc	D	very low–low
TOPPENISH	Qa	Qal	D-E	moderate–high
TOPPENISH	Qls	Qls	D	low–moderate
TOPPENISH	Qfs(t)	yPgfs	D	low–moderate
TWISP	Qoa	Palc	B-C	very low–low
TWISP	Qaf	Qafc	D	very low–low
TWISP	Qa	Qal	D-E	moderate–high
TWISP	Qls	Qls	D	low–moderate
TWISP	Qls(m)	Qls	D	low–moderate
TWISP	Qls(a)	Qlsc	D	low–moderate
TWISP	Qs	Qsd	D	very low–low
TWISP	Qad	yPgd	C-D	very low–low
TWISP	Qgd	yPgd	C-D	very low–low
TWISP	Qgl	yPgl	D	very low
TWISP	Qgo	yPgo	C-D	low
TWISP	Qta	Htl	B	bedrock
TWISP	Qgt	yPgt	C	very low
VANCOUVER	Qvc(sh)	Hvc	D	low–moderate
VANCOUVER	Qap(a)	oPgd	C-D	very low
VANCOUVER	Qap(h)	oPgd	C-D	very low
VANCOUVER	Qapo(a)	oPgd	C-D	very low
VANCOUVER	Qgu	oPgd	C-D	very low
VANCOUVER	PLMc(t)	oPsd	C-D	very low
VANCOUVER	Qaf	Paf	D	low
VANCOUVER	Qa	Qal	D-E	moderate–high
VANCOUVER	Qls	Qls	D	low–moderate
VANCOUVER	Qp	Qpt	F	peat
VANCOUVER	Qt	Qtr	C	very low–low
VANCOUVER	Qad(e)	yPgd	C-D	very low–low
VANCOUVER	Qfs	yPgfc	C	very low
VANCOUVER	Qfg	yPgfs	D	low–moderate
WALLA WALLA	PLMc(r)	bdC	C	bedrock
WALLA WALLA	Qd	Haef	D	low
WALLA WALLA	QMcg	oPsdc	B-C	very low
WALLA WALLA	Ql	Qaef	D	low
WALLA WALLA	Qaf	Qafc	D	very low–low
WALLA WALLA	Qa	Qal	D-E	moderate–high
WALLA WALLA	Qls	Qls	D	low–moderate
WALLA WALLA	Qfg	yPgfc	C	very low
WALLA WALLA	Qfs(t)	yPgfs	D	low–moderate
WENATCHEE	Qf	afl	E	high
WENATCHEE	Mc(ev)	bdC	C	bedrock
WENATCHEE	Qd	Haef	D	low
WENATCHEE	Qap(l)	oPgd	C-D	very low
WENATCHEE	Qla(ki)	oPgl	D	very low
WENATCHEE	Qla(kso)	oPgl	D	very low
WENATCHEE	Qla(ksy)	oPgl	D	very low
WENATCHEE	Qapo(k)	oPgoc	C	very low
WENATCHEE	Qapo(ki)	oPgoc	C	very low
WENATCHEE	Qapo(ks)	oPgoc	C	very low
WENATCHEE	Qapt(k)	oPgt	C	very low
WENATCHEE	Qapt(ki)	oPgt	C	very low
WENATCHEE	Qapt(ks)	oPgt	C	very low
WENATCHEE	Qoa	Palc	B-C	very low–low
WENATCHEE	Ql	Qaef	D	low
WENATCHEE	Qaf	Qafc	D	very low–low
WENATCHEE	Qa	Qal	D-E	moderate–high
WENATCHEE	Qls	Qls	D	low–moderate
WENATCHEE	Qp	Qpt	F	peat
WENATCHEE	Qt	Qtrc	C	very low–low
WENATCHEE	Qfs	yPgfc	C	very low
WENATCHEE	Qfg	yPgfs	D	low–moderate
WENATCHEE	Qao(lb)	yPgoc	C	very low
WENATCHEE	Qao(ld)	yPgoc	C	very low
WENATCHEE	Qao(lr)	yPgoc	C	very low
WENATCHEE	Qat(lb)	yPgt	C	very low
WENATCHEE	Qta	Htl	B	bedrock
WENATCHEE	Qta(r)	Htl	B	bedrock
WENATCHEE	Qat(lh)	yPgt	C	very low
WESTPORT	Qa	Hal	D-E	moderate–high
WESTPORT	Qb	Hbs	D	moderate–high

1:100,000-scale quadrangle	1:100,000-scale geologic map unit	Customized geologic unit	Assigned site class	Assigned liquefaction susceptibility
WESTPORT	Qoa	Pal	D-E	low–moderate
WESTPORT	Qt	Ptr	C	very low–low
YAKIMA	Mc(ev)	bdC	C	bedrock
YAKIMA	PLMc(r)	bdC	C	bedrock
YAKIMA	QPLcg	oPsdc	B-C	very low
YAKIMA	Qt	Ptrc	C	very low–low
YAKIMA	Ql	Qaef	D	low
YAKIMA	Qaf	Qafc	D	very low–low
YAKIMA	Qafo	Qafc	D	very low–low
YAKIMA	Qa	Qal	D-E	moderate–high
YAKIMA	Qls	Qls	D	low–moderate
YAKIMA	Qfg	yPgfc	C	very low
YAKIMA	Qfs	yPgfs	D	low–moderate
YAKIMA	Qfs(t)	yPgfs	D	low–moderate

Appendix B. Liquefaction susceptibility for each geologic unit.

Our assessments of liquefaction susceptibility for each of the customized geologic units, including a detailed explanation of our reasoning in making these determinations.

Customized geologic unit(s)	Liquefaction susceptibility	Liquefaction susceptibility justification
Hae Haef Qae Qaef Qaes	low	Youd and Perkins (1978) rank Quaternary dunes and loess as having a low to high susceptibility. The groundwater table is typically deep in most areas where these deposits occur in eastern WA (consequently decreasing overall susceptibility), so a low susceptibility is assigned to these units.
Haes	moderate	Marine dune deposits mapped in the Port Townsend 100,000-scale geologic quadrangle are designated as Haes. For these dune deposits the groundwater could be shallow because of their proximity to the shoreline, and so a moderate susceptibility is assigned.
Haf	low–moderate	Youd and Perkins (1978) rank Holocene alluvial fans as low to moderate susceptibility.
Hafc	low–very low	Youd and Perkins (1978) rank Holocene alluvial fans as low to moderate susceptibility. The coarse (gravelly) texture is judged to decrease the overall susceptibility of these deposits, and they are assigned a low to very low susceptibility.
Paf	low	Youd and Perkins (1978) rank Pleistocene alluvial fans as low susceptibility.
Qaf Qafs	low–moderate	Youd and Perkins (1978) rank Quaternary alluvial fans as low to moderate susceptibility.
Qafc	low–very low	Youd and Perkins (1978) rank Quaternary alluvial fans as low to moderate susceptibility. The coarse (gravelly) texture is judged to decrease the overall susceptibility of these deposits, and they are assigned a low to very low susceptibility.
Hal	moderate–high	Youd and Perkins (1978) rank Holocene channel and flood plain deposits as moderate to high susceptibility, consistent with quantitative evaluations documented in western Washington liquefaction hazard investigations.
Hals	high	This textural facies of Holocene channel and flood plain deposits typically have a high susceptibility based on quantitative evaluations documented in western Washington liquefaction hazard investigations.
Half	moderate–high	This textural facies of Holocene channel and flood plain deposits typically have a moderate to high susceptibility based on quantitative evaluations documented in western Washington liquefaction hazard investigations.
Pal	low–moderate	This generalized unit was assigned to older alluvium mapped on a number of 100,000-scale geologic quadrangles, which could range from early to late Pleistocene. Youd and Perkins (1978) assigns a low susceptibility to Pleistocene alluvium, but a conservative low to moderate susceptibility is assigned to these deposits because of the possibility them having a late Pleistocene or possibly early Holocene age.
Palc	low–very low	Youd and Perkins (1978) rank Pleistocene alluvium as having a low susceptibility. We assign a low to very low susceptibility to this unit because the coarse (gravelly) texture can inhibit liquefaction.
Qal	moderate–high	Qal often includes, and may be entirely comprised of, Holocene alluvium where the geologic map author didn't distinguish age or dominant texture of the deposit.
Hb	moderate–high	This deposit includes both low and high energy Holocene beach deposits (sand or gravel, respectively), which Youd and Perkins (1978) rank as having low to high susceptibility. We assign a susceptibility assuming a low energy (sandy) depositional environment.
Hbs	moderate–high	This is a low energy (sandy) Holocene beach deposit, which Youd and Perkins (1978) rank as a moderate to high susceptibility. This susceptibility ranking is consistent with quantitative evaluations documented in western Washington liquefaction hazard investigations
Qcv	moderate	Youd and Perkins (1978) rank Holocene coluvium as having a moderate susceptibility, which is a conservative assignment for this deposit type.
afl	high	Youd and Perkins (1978) rank artificial (uncompacted) fill as a very high susceptibility. We assign a high susceptibility to artificial fill, and this assignment is consistent quantitative evaluations documented in western Washington liquefaction hazard investigations.
aflc	very low	We use aflc to designate the engineered fill used in major earth-filled dams, and assume that this is engineered fill and consequently has a very low susceptibility.
yPgao	low–very low	Quantitative evaluations of all textures of Fraser advance outwash documented in western Washington liquefaction hazard investigations yields a range of low to very low susceptibility

Customized geologic unit(s)	Liquefaction susceptibility	Liquefaction susceptibility justification
yPgaof	very low	A high silt and clay content coupled with consolidation resulting from glacial loading results in a very low susceptibility, consistent with quantitative evaluations documented in western Washington liquefaction hazard investigations.
yPgaos	low	Quantitative evaluations of sandy Fraser advance outwash documented in western Washington liquefaction hazard investigations typically yields a low susceptibility.
yPgaoc	very low	Quantitative evaluations of coarse (gravelly) Fraser advance outwash documented in western Washington liquefaction hazard investigations yields a range of low to very low susceptibility.
Hgd yPgd Pgd Qgd	low–very low	Glacial drift can represent a broad spectrum of textures and glacial depositional environments. Glacial drift is often used in geologic mapping to describe a gravel-rich diamicton or well sorted outwash deposits where outcrop exposure is poor and stratigraphic or sedimentological indicators are inconclusive. Quantitative analyses of gravel-dominated glacial deposits documented in a number of western Washington liquefaction hazard investigations support an assignment of low to very low susceptibility.
oPgd	very low	A very low susceptibility for pre-Fraser glacial drift is based on quantitative analyses documented in a number of western Washington liquefaction hazard investigations and behavior of these older Pleistocene glacial deposits during historical earthquakes in the Puget Sound region.
yPgf	low	The assigned susceptibility is common to coarse (gravelly) and sandy glacial outburst flood deposits.
yPgfs	low–moderate	A low to moderate susceptibility assigned to this deposit because of textural, age, and depositional similarity to Fraser sandy recessional outwash.
yPgfc	very low	Coarse glacial outburst flood deposits are presumed similar to gravelly Fraser glacial deposits, and are consequently assigned a very low susceptibility.
yPgl Pgl oPgl	very low	Quantitative analyses documented in a number of western Washington liquefaction hazard investigations and behavior of these glacial deposits during historical earthquakes in the Puget Sound region indicates a very low susceptibility.
yPglf	low	The assigned susceptibility is common to coarse (gravelly) and sandy glacial outburst flood and glaciolacustrine deposits.
yPgmd	low–moderate	The susceptibility assignment is based on the assumption that Fraser undifferentiated glaciomarine drift is analogous to Fraser sandy recessional outwash.
yPgmdf	very low	The susceptibility assignment based on the assumption that fine texture, Fraser glaciomarine drift is analogous to younger Pleistocene glaciolacustrine deposits.
yPgmds	low–moderate	The susceptibility assignment is based on the assumption that Fraser sandy glaciomarine drift is analogous to Fraser sandy recessional outwash.
oPgmd	very low	A very low susceptibility assignment is based on assumption that pre-Fraser glaciomarine drift has been compacted by ice loading from subsequent glaciations.
yPgo	low	The assigned susceptibility is common to the wide textural range of Fraser glacial outwash deposits.
yPgos	low–moderate	The assigned susceptibility covers the range of Fraser sandy advance and recessional glacial outwash deposits based on quantitative analyses and behavior of these glacial deposits during historical earthquakes in the Puget Sound region.
yPgoc	very low	A very low susceptibility for coarse (gravelly) glacial outwash is based on quantitative analyses and behavior of these glacial deposits during historical earthquakes in the Puget Sound region.
Pgo	low	The assigned susceptibility is based on the susceptibility assigned to texturally undifferentiated Fraser (younger Pleistocene) glacial outwash deposits.
oPgo oPgpc	very low	A very low susceptibility for pre-Fraser glacial outwash is based on quantitative analyses and behavior of these glacial deposits during historical earthquakes in the Puget Sound region.
yPgro	low	The assigned susceptibility is common to the wide textural range of Fraser recessional glacial outwash
yPgrof	very low	A very low susceptibility is assigned as these deposits are likely analogous to younger Pleistocene glaciolacustrine deposits.
yPgros	low–moderate	A low to moderate susceptibility for sandy recessional glacial outwash is based on quantitative analyses and behavior of these glacial deposits during historical earthquakes in the Puget Sound region.

Customized geologic unit(s)	Liquefaction susceptibility	Liquefaction susceptibility justification
yPgroc	very low	A very low susceptibility for coarse (gravelly) recessional glacial outwash is based on quantitative analyses and behavior of these glacial deposits during historical earthquakes in the Puget Sound region.
yPgt	very low	A very low susceptibility for Fraser-age glacial till is based on quantitative analyses and behavior of these glacial deposits during historical earthquakes in the Puget Sound region.
Hgt oPgt Qgt	very low	The susceptibility ranking is based on the determination for Fraser-age glacial till.
Hlc	moderate–high	Youd and Perkins (1978) rank Holocene lacustrine deposits as having a moderate to high susceptibility.
Hlh	moderate–high	The moderate to high susceptibility assignment is based on quantitative evaluation of Holocene lahar deposits in the Puget Sound region and recent Mount St. Helens lahars.
Hlhc Plh Qlh	moderate–high	The susceptibility assignment is based on the determination for texturally undifferentiated Holocene lahars.
Hls	low–moderate	The susceptibility assignment is based on quantitative evaluation of Holocene landslide deposits in the Puget Sound region
Hlsc Qls Qlsc	low–moderate	The susceptibility assignment is based on the determination for texturally undifferentiated Holocene landslides.
Hpt Qpt	peat	Peat deposits are not susceptible to liquefaction, but may undergo large permanent ground displacements as a result of earthquake shaking
yPsdf Psd Psdc Qsd	low–very low	Youd and Perkins (1978) rank all Pleistocene deposit types as having a low to very low susceptibility
oPsd oPsdf oPsds oPsdc	very low	Susceptibility assignment is based on quantitative evaluation of older Pleistocene glacial and non-glacial deposits and behavior of these deposits during historical earthquakes in the Puget Sound region.
Htf	low	Youd and Perkins (1978) rank Holocene tuff as having a low susceptibility.
Htl Qtl	bedrock	Talus deposits are typically a thin cover of unweathered rock lying on top of parent bedrock
Htr yPtrf Ptr Ptrc Qtr Qtrc	low–very low	Youd and Perkins (1978) rank Holocene and Pleistocene marine terraces as having a low to very low susceptibility, respectively. We assume that alluvial terraces are analogous to marine terraces in terms of liquefaction behavior.
Hvc	low–moderate	Youd and Perkins (1978) rank Holocene alluvial fans as low to moderate. We assume that volcaniclastic deposits are analogous to alluvial fan deposits.
Pvc	low	Youd and Perkins (1978) rank Pleistocene alluvial fans as low. We assume that volcaniclastic deposits are analogous to alluvial fan deposits.
Qvc	low–moderate	Quaternary volcaniclastic deposits can be either Holocene or Pleistocene, so that their assigned susceptibility ranges from low to moderate.

Appendix C. Summary of shear-wave velocity values and site class assignments for each geologic unit.

A tabulation of our groupings of geologic units, the queried VS data sets, the mean, median, and lower bound V_S values for each grouping, and the number of VS measurements used in the calculation of these quantities. Also summarized is the site class determined for the mean and lower bound velocities based on Table 1, and our final assignment of site class for all non-bedrock geologic units in the digital map coverage.

Customized geologic unit	Data sets queried in evaluation	Median Vs (m/sec)	Mean Vs (m/sec)	Lower bound Vs (m/sec)	Number of measurements	Mean/median site class	Lower bound site class	Assigned site class	Site class justification
Haef Qaef Qaes	HMGP 2003, Mabey and others (1993), and Mabey 2003, except Vs data from Mabey 2003 having an exact value of 250 m/sec	238	294	176	13	D	E	D	This site class assignment is based on all Vs values measured in aeolian deposits.
Hae Haes Qae	None	None	None	None	None			D	This assignment is based on the site class determination for aeolian deposits with measured Vs values.
Haf Paf Qaf Hafc Qafs Qafc	None	None	None	None	None			D	This assignments is based on the site class default value when no geologic or Vs information is available.
Hal Hals Qal	HMGP 2003, HMGP 2004, Mabey and others (1993), Mabey 2003, Miscellaneous, and Wong and others (2003), except Vs data from Mabey 2003 having exact values of either 0 or 250 m/sec	189	190	131	131	D	E	D-E	This site class assignment is based on all Vs values measured in alluvial deposits.
Half Pal Palc	None	None	None	None	None			D-E	This assignment is based on the site class determination for alluvial deposits with measured Vs values (units Hal, Hals, and Qal).
Hb	Wong and others (2003)	305	284	221	3	D	D	D	This site class assignment is based on all Vs values measured in beach deposits.
Hbs	None	None	None	None	None			D	This assignment is based on the site class determination for beach deposits with measured Vs values (unit Hb). It is also is the site class default value when no geologic or Vs information is available.

Customized geologic unit	Data sets queried in evaluation	Median Vs (m/sec)	Mean Vs (m/sec)	Lower bound Vs (m/sec)	Number of measurements	Mean/median site class	Lower bound site class	Assigned site class	Site class justification
Qcv	None	None	None	None	None			D	This assignments is based on the site class default value when no geologic or Vs information is available.
afl	HMGP 2003, HMGP 2004, and Wong and others (2003)	152	165	48	45	E	E	E	This site class assignment is based on all Vs values measured in artificial fill.
aflc	None	None	None	None	None			C	This unit (aflc) is assigned only to major earth-filled dams delineated on 1:100,000 geologic mapping, and the assigned site class is based on the analogy of this engineered fill to compacted, well-graded natural deposits such as glacial till.
yPgao	HMGP 2003	502	543	311	63	C	D	C-D	This site class assignment is based on all Vs values measured in texturally undifferentiated Fraser advance outwash and undifferentiated Fraser outwash of indeterminate glacial phase.
yPgaof	None	None	None	None	None			D	This site class assignment is based on the lower bound Vs of Fraser sandy advance outwash (unit yPgos). It is also the site class default value when no geologic or Vs information is available.
yPgaos	HMGP 2003, HMGP 2004, Miscellaneous, and Wong and others (2003)	493	482	335	45	C	D	C-D	This site class assignment is based on all Vs values measured in sandy Fraser advance outwash and sandy Fraser outwash of indeterminate glacial phase.
yPgaoc	HMGP 2003, Miscellaneous, and Wong and others (2003)	769	829	528	12	B	C	B-C	This site class assignment is based on all Vs values measured in coarse (gravelly) Fraser advance outwash and coarse Fraser outwash of indeterminate glacial phase.
yPgd oPgd Qgd	HMGP 2003, Miscellaneous, and Wong and others (2003)	513	547	333	104	C	D	C-D	This site class assignment is based on all Vs values measured in Pleistocene and undivided Quaternary glacial drift.
Hgd Pgd	None	None	None	None	None			C-D	This assignment is based on the site class determination for Pleistocene and undivided Quaternary glacial drift with measured Vs values (units yPgd, oPgd, and Qgd).
yPgf	HMGP 2003 and Mabey 2003	450	494	245	36	C	D	C-D	This site class assignment is based on all Vs values measured in Wisconsin glacial outburst flood deposits having a coarse (gravelly), sandy, or undifferentiated texture.

Customized geologic unit	Data sets queried in evaluation	Median Vs (m/sec)	Mean Vs (m/sec)	Lower bound Vs (m/sec)	Number of measurements	Mean/median site class	Lower bound site class	Assigned site class	Site class justification
yPgfs	HMGP 2003 and Mabey 2003	327	349	199	19	D	D	D	This site class assignment is based on all Vs values measured in sandy Wisconsin glacial outburst flood deposits.
yPgfc	HMGP 2003 and Mabey 2003	593	672	422	15	C	C	C	This site class assignment is based on all Vs values measured in coarse (gravelly) Wisconsin glacial outburst flood deposits.
yPgl	HMGP 2003 and Wong and others (2003)	320	328	278	16	D	D	D	This site class assignment is based on all Vs values measured in younger Pleistocene glaciolacustrine deposits.
Pgl oPgl	None	None	None	None	None			D	This assignment is based on the site class determination for younger Pleistocene glaciolacustrine deposits with measured Vs values (unit yPgl). It is also is the site class default value when no geologic or Vs information is available.
yPglf	None	None	None	None	None			D	This is a conservative assignment based on the site class determination for younger Pleistocene glaciolacustrine (unit yPgl) and sandy outburst flood (unit yPgfs) deposits. It is also the site class default value when no geologic or Vs information is available.
yPgmd	HMGP 2003	239	266	185	6	D	D	D	This site class assignment is based on all Vs values measured in texturally undifferentiated Fraser glaciomarine drift.
yPgmdf yPgmds oPgmd	None	None	None	None	None			D	This assignment is based on the site class determination for undifferentiated younger Pleistocene glaciomarine drift (unit yPgmd). It is also the site class default value when no geologic or Vs information is available.
yPgo	HMGP 2003 and HMGP 2004	410	403	263	9	C	D	C-D	This site class assignment is based on all measured Vs values of texturally undifferentiated, Fraser advance, recessional, and indeterminate phase outwash.
yPgos	HMGP 2003, HMGP 2004, Miscellaneous, and Wong and others (2003)	352	390	217	79	D	D	D	This site class assignment is based on all Vs values measured in sandy, Fraser advance, recessional, and indeterminate phase outwash.
yPgoc	HMGP 2003, HMGP 2004, Miscellaneous, and Wong and others (2003)	653	655	307	20	C	D	C	This site class assignment is based on all Vs values measured in coarse (gravelly) Fraser, recessional, and indeterminant phase outwash.

Customized geologic unit	Data sets queried in evaluation	Median Vs (m/sec)	Mean Vs (m/sec)	Lower bound Vs (m/sec)	Number of measurements	Mean/median site class	Lower bound site class	Assigned site class	Site class justification
Pgo oPgo	None	None	None	None	None			C-D	This assignment is based on the site class determined for texturally undifferentiated Fraser outwash (unit yPgo).
oPgoc	None	None	None	None	None			C	This assignment is based on the site class determined for coarse (gravelly) Fraser outwash (unit yPgoc).
yPgro	HMGP 2003 and HMGP 2004	410	383	295	7	C	D	C-D	This site class assignment is based on all Vs values measured in all texturally undifferentiated Fraser recessional and indeterminant phase outwash.
yPgros	HMGP 2003, HMGP 2004, Miscellaneous, and Wong and others (2003)	260	261	158	34	D	E	D-E	This site class assignment is based on all Vs values measured in all sandy Fraser recessional and indeterminant phase outwash.
yPgroc	HMGP 2003, HMGP 2004, Miscellaneous, and Wong and others (2003)	418	448	210	10	C	D	C-D	This site class assignment is based on all Vs values measured in all coarse (gravelly) Fraser recessional and indeterminant phase outwash.
yPgrof	None	None	None	None	None			D	This assignment is based on the site class determination for younger Pleistocene glaciolacustrine deposits with measured Vs values (unit yPgl). It is also is the site class default value when no geologic or Vs information is available.
yPgt	HMGP 2003, HMGP 2004, and Miscellaneous	611	618	458	23	C	C	C	This site class assignment is based on all Vs values measured in Fraser glacial till
Hgt oPgt Qgt	None	None	None	None	None			C	This assignment is based on the site class determined for Fraser glacial till (unit yPgt).
Hlc	None	None	None	None	None			D	This assignment is based on the site class determination for younger Pleistocene glaciolacustrine deposits with measured Vs values (unit yPgl). It is also is the site class default value when no geologic or Vs information is available.
Hlh Hlhc Qlh	HMGP 2003 and Miscellaneous	187	210	141	6	D	E	D-E	This site class assignment is based on all Vs values measured in all Holocene and Quaternary lahars, regardless of texture
Plh	None	None	None	None	None			D-E	This assignment is based on the site class determination for all Holocene and Quaternary lahars with measured Vs values (units Hlh, Hlhc, Qlh).

Customized geologic unit	Data sets queried in evaluation	Median Vs (m/sec)	Mean Vs (m/sec)	Lower bound Vs (m/sec)	Number of measurements	Mean/median site class	Lower bound site class	Assigned site class	Site class justification
Hls Hlsc Qls Qlsc	None	None	None	None	None			D	This assignments is based on the site class default value when no geologic or Vs information is available.
Hpt	Wong and others (2003) and Miscellaneous	59	60	21	6	E	E	F	The assigned site class is consistent with the criteria for special study (type F) soils, assuming that the mapped peat is greater than 10 ft in thickness.
Qpt	None	None	None	None	None			F	The assigned site class is consistent with the criteria for special study (type F) soils, assuming that the mapped peat is greater than 10 ft in thickness.
oPsdf	HMGP 2003, Mabey and others (1993), and Miscellaneous	377	408	293	24	C	D	C-D	This site class assignment is based on all Vs values measured in older Pleistocene, fine (silty and clayey) sedimentary deposits.
oPsdc	HMGP 2003, and Mabey and others (1993)	805	795	640	13	B	C	B-C	This site class assignment is based on all Vs values measured in older Pleistocene, coarse (gravelly) sedimentary deposits.
oPsd	None	None	None	None	None			C-D	This is a conservative assignment based on the site class determined for older Pleistocene coarse (gravelly) and fine (silty or clayey) sedimentary deposits.
oPsds	None	None	None	None	None			C	This assignment is based on the site class common to coarse (gravelly) and fine (silty or clayey) older Pleistocene sedimentary deposits.
yPsdf Psd Qsd	None	None	None	None	None			D	This assignment is based on the lower bound site class determined for fine (silty and clayey) older Pleistocene sedimentary deposits. It is also the site class default value when no geologic or Vs information is available.
Psdc	None	None	None	None	None			C	This assignment is based on the lower bound site class determined for coarse (gravelly) older Pleistocene sedimentary deposits.
Htf	None	None	None	None	None			D	This assignments is based on the site class default value when no geologic or Vs information is available.
Htl Qtl	None	None	None	None	None			B	Talus deposits are typically a thin cover of unweathered rock lying on top of parent bedrock, and we assume that a soft rock site class is representative of these conditions.

Customized geologic unit	Data sets queried in evaluation	Median Vs (m/sec)	Mean Vs (m/sec)	Lower bound Vs (m/sec)	Number of measurements	Mean/median site class	Lower bound site class	Assigned site class	Site class justification
Ptr Qtr Qtrs	HMGP 2003 and HMGP 2004	730	859	412	3	C	C	C	This site class assignment is based on all Vs values measured in texturally undifferentiated Quaternary and Pleistocene terrace deposits. Note that Vs measurements were made in unit Qtrs, but that this unit did not appear on the 1:100,000-scale statewide geologic map.
Htr yPtrf Ptrc Qtrc	None	None	None	None	None			C	This assignment is based on the site class determination for texturally undifferentiated Quaternary and Pleistocene terrace deposits with measured Vs values (units Ptr, Qtr, and Qtrs).
Hvc Pvc Qvc	None	None	None	None	None			D	This assignments is based on the site class default value when no geologic or Vs information is available.

Appendix D. Construction of liquefaction susceptibility and site class maps of Clark County, Washington.

by Stephen P. Palmer, Sammantha L. Magsino, James L. Poelstra, and Rebecca A. Niggemann

This report describes the more detailed approach used in developing the liquefaction susceptibility and site class maps for Clark County.

INTRODUCTION

The Washington State Department of Natural Resources, Division of Geology and Earth Resources (DGER) received grant funding through the Hazard Mitigation Grant Program administered by the Federal Emergency Management Agency (FEMA) and the Washington State Military Department, Emergency Management Division (EMD) following the Nisqually earthquake of February 2001 (FEMA-1361-DRWA). This grant required DGER to develop statewide liquefaction susceptibility and National Earthquake Hazards Reduction Program (NEHRP) site class maps. The liquefaction susceptibility and NEHRP site class maps presented with this report benefited from work previously performed by DGER for the Clark Regional Emergency Services Agency. Regional earthquake hazard maps such as these support hazard mitigation, emergency planning and response, planning of local zoning ordinances, and building code enforcement.

The primary reason for producing this series of earthquake hazard maps is to support revisions to both state and local hazard mitigation plans required under final rules 44CFR201.4 and 44CFR201.6. These Federal code regulations require both state and local agencies to describe the location and extent of earthquake hazards that affect their jurisdictions. Additionally, these maps will serve a great variety of end-users that are crucial partners in earthquake hazard mitigation. In specific:

- EMD and local emergency management agencies will be able to implement more accurate HAZUS vulnerability assessments using real map inputs for ground-motion amplification and liquefaction-induced ground failure rather than the HAZUS default values (HAZUS is FEMA's earthquake loss estimation methodology).
- Generation of the NEHRP site class maps will benefit the response efforts of the Pacific Northwest Seismic Network in the near-real-time production of ShakeMap displays of ground shaking following significant earthquakes.
- Local jurisdictions will be able to use these maps to delineate earthquake hazardous areas and enforce critical areas ordinances as required by the State Growth Management Act.
- Local building officials will be able to use these maps in their enforcement of state and local building codes to define structural design requirements and to delineate areas where thorough geotechnical investigations should be conducted.

We performed detailed 1:24,000-scale earthquake hazard mapping in the area of Clark County underlain by unconsolidated Quaternary deposits, labeled Qs and QPLs in Figure D1. Past evaluations of earthquake hazards in the Portland–Vancouver urban area (Smith, 1975; Mabey and others, 1993, 1994) indicate that liquefaction and amplified ground shaking will most likely occur in areas underlain by units Qs and QPLs.

Water well and geotechnical boring log data were compiled in order to extend and refine the three-dimensional geologic model developed by Mabey and others (1994). The extended three-dimensional geologic model was used in conjunction with static groundwater elevation models developed by McFarland and Morgan (1996) and Rod Swanson (Clark County Dept. of Public Works, written commun., 2003) to construct the liquefaction susceptibility map. The susceptibility of the various geologic units to liquefaction during an earthquake was assessed using a standard engineering analysis (for example, Robertson and Wride, 1997; Youd, Idriss, and others, 1997) of the geotechnical boring data compiled as part of this project. Production of the NEHRP site class map utilized the extended three-dimensional geologic model and shear wave velocity data reported in Mabey and others (1993, 1994), supplemented by data we collected.

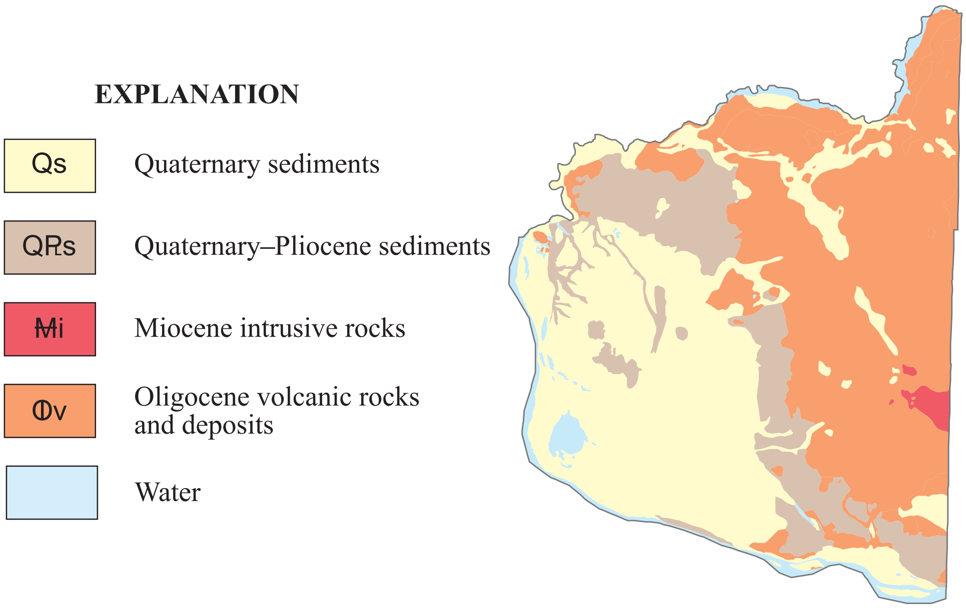

Figure D1. Generalized geologic map of Clark County showing major rock and soil units (modified from Walsh and others, 1987). Detailed earthquake hazard mapping at 1:24,000-scale was performed for the area underlain by units labeled Qs and QPLs (sediments deposited in the last one or two million years).

From this point forward we refer to NEHRP site class simply as 'site class', which is consistent with the terminology of the 2003 version of the International Building Code (International Code Council, 2003).

SURFICIAL GEOLOGY

A number of sources of surficial geologic mapping of varying scale and vintage were available for Clark County. We used the published maps listed in Table D1 as a basic framework for the geologic map used in this study, and modified unit contacts based on water well and geotechnical boring interpretation and field observation. The final map was based on our 1:24,000-scale geologic interpretation of the areas indicated as units Qs and QPLS in Figure D1, and on published 1:100,000-scale map data elsewhere. We understand that a significant portion of the 1:100,000-scale geologic map of McFarland and Morgan (1996) is based on unpublished 1:24,000-scale mapping performed as part of a Portland basin groundwater resource investigation (Rod Swanson, Clark County Dept. of Public Works, oral commun., 2004). The stratigraphic units used in our final geologic map are listed in Table D2.

We used McFarland and Morgan (1996) as a starting point for the surficial geologic mapping, as their outcrop pattern for the Troutdale Formation in Clark County was generally consistent with water well interpretations we performed during this study. However, we used the mapping of Tertiary bedrock presented by Phillips (1987a,b), as it appeared more consistent with our field observations of bedrock outcroppings. The Yacolt valley was mapped as glacial deposits following Mundorff (1964).

Additional modifications to our base geologic map were necessary to account for textural differences within individual geologic units. In the southern part of the county, it was necessary to differentiate alluvium, terrace deposits, Holocene peat, Missoula flood gravel, and Missoula flood sand and silt within the unconsolidated unit presented by McFarland and Morgan (1996).

We revised areas mapped as alluvium by Trimble (1963) and Mundorff (1964) along the Columbia and Lewis Rivers and Salmon and Burnt Bridge Creeks using 8 ft resolution black and white digital orthophotos from Washington State Department of Natural Resources and elevation contours generated using the U.S. Geological Survey (USGS) 10 m digital elevation model (DEM). Terrace deposits within the study area were mapped using Trimble (1963), Mundorff (1964), and Howard (2002) as the source data.

We used agricultural soil mapping presented by McGee (1972), and rendered into a digital format (Chas Scripter, U.S. Dept. of Agriculture, written commun., 2003), to define the outcrop pattern of Holocene peat and Missoula flood deposits. Holocene peat was mapped using the distribution of Semiahmoo muck soils (McGee, 1972; Chas Scripter, U.S. Dept. of Agriculture, written commun., 2003), in addition to other areas mapped as peat in the published geologic map references. We mapped the area of Missoula flood gravel outcrop based on the association with Lauren, Sifton, and Wind River gravelly loams that fell within the unconsolidated deposit of McFarland and Morgan (1996). The remainder of the unconsolidated deposits was mapped as Missoula flood sand and silt.

The outcrop pattern of Missoula flood deposits based on McGee's (1972) and Chas Scripter's (U.S. Dept. of Agriculture, written commun., 2003) soil boundaries compared favorably with those of Trimble (1963) and Howard (2002), with one major exception. An extensive area in northwestern Vancouver (south of Burnt Bridge Creek; secs. 15 and 22, T2N R1E) had previously been mapped as Missoula flood gravel by Trimble (1963) and Phillips (1987b). Geology inferred from McGee's soil mapping indicate the area is actually Missoula flood sand and silt. Field checking confirmed the latter interpretation. Additional field checking at spot locations supported our use of agricultural soil mapping to define the distribution of textural facies in the Missoula flood deposits.

Modifications to the mapped distribution of the Troutdale Formation north of the East Fork Lewis River were also necessary. Mapping by Swanson and others (1993) shows a definite stratigraphic sequence for the Troutdale Formation in Clark County where a coarse-grained unit (unit Qtrc, Table D2) overlies a fine-grained unit (unit Qtrf, Table D2). Our interpretation of water well data shows that this stratigraphic order is followed south of the East Fork Lewis River. North

Table D1. Summary of geologic maps used in developing the liquefaction susceptibility and site class maps for Clark County.

Citation	Map scale	Comments
Trimble (1963), *Geology of Portland, Oregon, and adjacent areas*	1:62,500	Field work done at 1:48,000-scale; recognizes Missoula flood deposits; only covers southern half of Clark County
Mundorff (1964), *Geology and ground-water conditions of Clark County, Washington, with a description of a major alluvial aquifer along the Columbia River*	1:48,000	Covers all of Clark County; doesn't recognize Missoula flood deposits; contact locations generally accurate
Phillips (1987b), *Geologic map of the Vancouver quadrangle, Washington*	1:100,000	Covers most of Clark County; Quaternary mapping compiled mainly from Trimble (1963) and Mundorff (1964)
Phillips (1987a), *Geologic map of the Mount St. Helens quadrangle, Washington and Oregon*	1:100,000	Covers the most northerly portion of Clark County near Lake Merwin; few Quaternary deposits in this area
McFarland and Morgan (1996), *Description of the ground-water flow system in the Portland basin, Oregon and Washington*	1:100,000	Geologic unit descriptions from Swanson and others (1993); covers all of Clark County; good mapping of Quaternary geologic contacts and units; maps alluvium and Missoula flood deposits as a single unit (unconsolidated deposits)
Howard (2002), *Geologic map of the Battle Ground 7.5-minute quadrangle, Clark County, Washington*	1:24,000	Covers only the Battle Ground 7.5-minute quadrangle; detailed mapping of Troutdale Formation and Lewis River terrace deposits

of the river (T5N R1E and T5N R2E), water well records and field observations all indicate a fine silt, similar to unit Qtrf, at the surface. This unit, designated unit Quf in our mapping, lies directly above the Qtrc–Qtrf sequence. Unit Quf is likely an upper fine-grained unit in the Troutdale Formation, and can be correlated to the Troutdale Formation sequence observed in Cowlitz County bordering on the Columbia and Cowlitz Rivers (Karl Wegmann, Washington Dept. of Natural Resources, oral commun., 2003).

The final geologic map used in developing the liquefaction susceptibility and site class maps is presented in Figure D2.

SUBSURFACE GEOLOGIC MODEL

Our interpretation of the subsurface geology in the study area is based primarily on the water well database used in a Portland basin groundwater investigation (McCarthy and Anderson, 1990). We acquired over 400 field-located water well records from this database and interpreted the subsurface geology using the geologic units shown in Table D2. These water well data were supplemented with additional water well records available on-line from the Washington State Department of Ecology (accessed Oct. 15, 2004 at http://apps.ecy.wa.gov/welllog/). Locations of the water wells from the on-line database are accurate only to the quarter-quarter section, but were useful in areas with few field-located water wells.

Thicknesses for most of the stratigraphic units, as indicated in Table D2, were determined based on our subsurface interpretations. Thicknesses of units Qlpf and Quf were assigned to be 100 ft, as existing field-located water well data were inadequate to allow generation of reliable thickness models. Peat (unit Qp) was assigned a 10 ft thickness, consistent with the NEHRP criteria for designating peat soils as a site class F (see Table D4). The single mapped area of artificial fill (unit af) was assigned a 15 ft maximum thickness and tapered to a thickness of 3.5 ft at its map boundary, consistent with a typical fill geometry encountered in geotechnical borings. Tertiary and Quaternary bedrock (units Tb and Qb) were assumed continuous with depth and to be at least 100 ft thick where exposed at the surface. They were also assumed to underlie all other geologic units where the total thickness of the other units did not equal or exceed 100 ft.

For those stratigraphic units not assigned a constant thickness (see Table D2), each unit thickness was contoured, digitized, and gridded on 50 ft cells using a natural neighbor interpolation method. The resulting thickness models could be arranged by

Table D2. Geologic units used in developing the liquefaction susceptibility and site class maps for Clark County.

Geologic unit	Unit name	Description	Basis for thickness determination in subsurface model
		QUATERNARY	
af	artificial fill	area of filled land along Salmon Creek in the vicinity of the Interstate 5 crossing	assigned a 15 ft maximum thickness tapering to 3.5 ft at the map boundary
Qa	alluvium	mainly Holocene alluvium	contouring based on interpretation of water well and geotechnical boring data
Qp	peat	Holocene peat	assigned a constant thickness of 10 ft
Qfs	Missoula flood sand and silt	mapping based on McGee (1972)	contouring based on interpretation of water well and geotechnical boring data
Qfg	Missoula flood gravel	mapping based on McGee (1972)	contouring based on interpretation of water well and geotechnical boring data
Qtf	fine-grained terrace deposits	delineated using data from McGee (1972)	contouring based on interpretation of water well and geotechnical boring data
Qtc	coarse-grained terrace deposits	delineated using data from McGee (1972)	contouring based on interpretation of water well and geotechnical boring data
Qgd	glacial drift	glacial deposits mapped in the Cascade foothills	contouring based on interpretation of water well and geotechnical boring data
Quf	undifferentiated fine-grained deposits	Quaternary unit found north of the Lewis River overlying coarse-grained unit of the Troutdale formation (unit Qtrc); likely an upper unit of the Troutdale Formation	assigned a constant thickness of 100 ft
Qtrc	Troutdale Formation, coarse-grained	Pleistocene—Miocene coarse-grained deposits of the Troutdale Formation as defined by Swanson and others (1993)	contouring based on interpretation of water well and geotechnical boring data
Qtrf	Troutdale Formation, fine-grained	Pleistocene–Miocene fine-grained deposits of the Troutdale Formation as defined by Swanson and others (1993) to underlie unit Qtrc	contouring based on interpretation of water well and geotechnical boring data
Qlpf	Mount St. Helens volcanic deposits	single outcrop along the south side of Lake Merwin	assigned a constant thickness of 100 ft
Qb	bedrock	basalt flows of Battleground Lake and other Quaternary flows	contouring based on interpretation of water well and geotechnical boring data
		TERTIARY	
Tb	bedrock	Tertiary bedrock composed primarily of Skamania volcanics	assigned a constant thickness of 100 ft

stratigraphic position to yield a subsurface geologic column for each grid cell. The geologic columns were continued to a depth of 100 ft, the depth needed to generate the site class map. A sample thickness model, in this case for the Missoula flood sand and silt (unit Qfs), is presented in Figure D3.

LIQUEFACTION SUSCEPTIBILITY ANALYSIS AND MAP

The method used to evaluate liquefaction susceptibility in Clark County is documented by Palmer and others (2002). The evaluation was based on liquefaction factor-of-safety (ratio of resisting stresses to driving stresses) analyses using the methodology described in Robertson and Wride (1997) and Youd, Idriss, and others (1997). Countywide digital models of Quaternary geologic unit thicknesses and static groundwater depths were then used in mapping the spatial distribution of liquefaction susceptibility.

Factor-of-safety calculations were based on a variety of geotechnical data including Standard Penetration Test (SPT) blow counts (American Society for Testing and Materials, 2004d), depth-to-groundwater measurements, Atterberg limits (American Society for Testing and Materials, 2004c), and classification and grain size analysis of soil samples (American Society for Testing and Materials, 2004a,b) from geotechnical borings. Liquefaction factors of safety were calculated for two magnitude 7.3 earthquake scenarios, one having a 0.15 *g* peak ground acceleration, and the other a 0.30 *g* peak ground acceleration, where *g* is the acceleration due to gravity. The choice of earthquake scenarios is consistent with an intraplate earthquake similar to the 1949 Olympia and 2001 Nisqually events in the Puget Sound region. The standardization of the factor-of-safety methodology and earthquake scenarios allows comparison of this study's results to published Puget Sound region liquefaction susceptibility assessments (Grant and others,

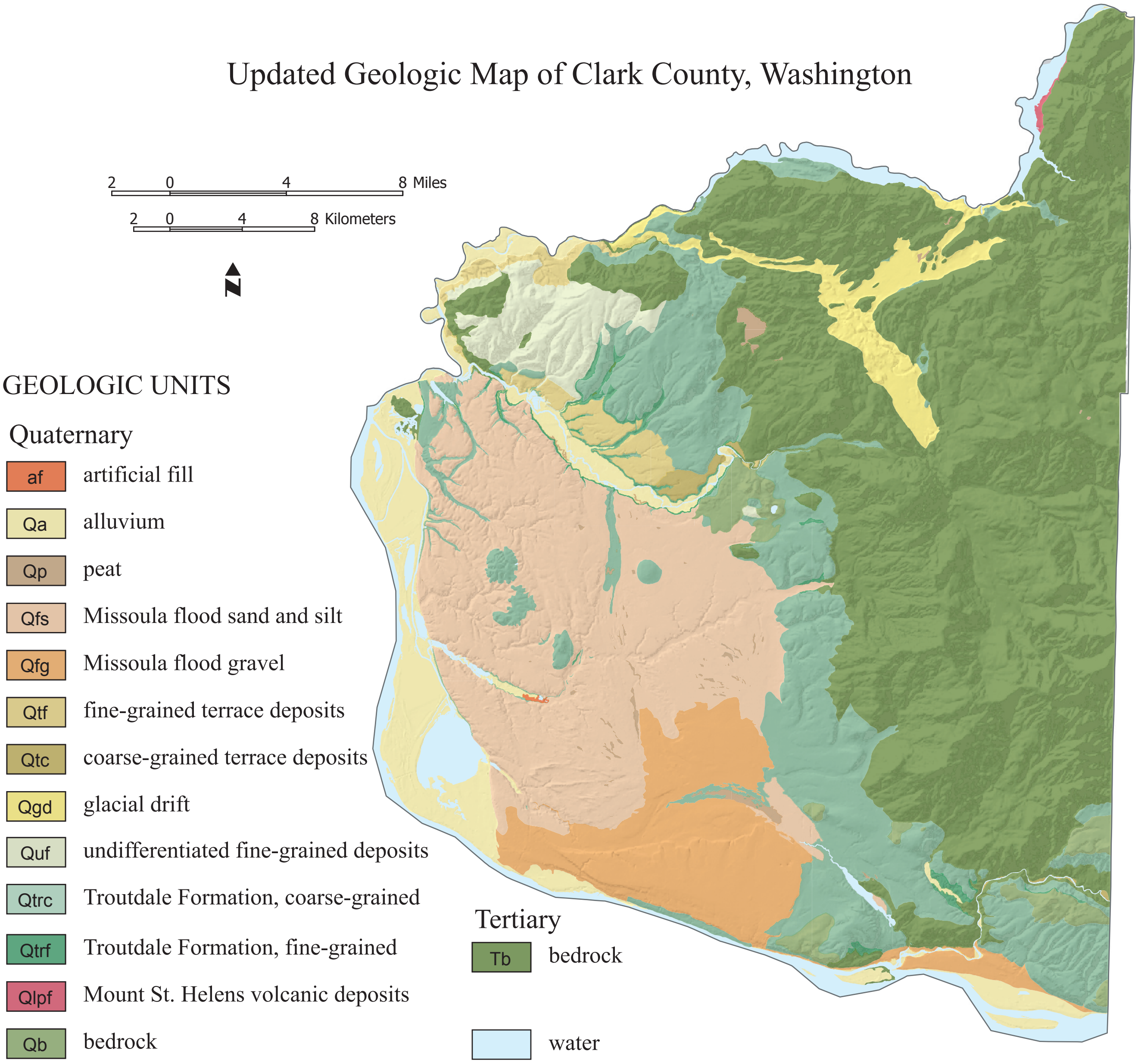

Figure D2. Final geologic map of Clark County used in developing the liquefaction susceptibility and site class maps.

1998; Palmer, 1995; Palmer and others, 1994, 1995, 1999, 2002, 2003).

During our initial geotechnical and geological assessment of Clark County, we evaluated the likelihood of soil liquefaction of each geologic unit based on SPT blow counts and textural characteristics obtained from geotechnical boring logs. Most of the non-bedrock units were determined to have a very low susceptibility to liquefaction, as described in the Final Liquefaction Susceptibility Map section of this report; the notable exceptions were Holocene alluvium (unit Qa) and Missoula flood sand and silt (unit Qfs). Quaternary and Tertiary bedrock were assigned a nil susceptibility, as rock is not capable of liquefying. We then conducted in-depth liquefaction susceptibility analyses on units Qa and Qfs using data from 171 geotechnical borings drilled by the Washington State Department of Transportation and various geotechnical consulting firms. For each boring, we determined the aggregated total thicknesses of liquefiable material within each geologic unit. We normalized the data by expressing these aggregated thicknesses as a percentage of the total penetrated thickness within each unit. By normalizing the data this way, we may then compare the aggregate thicknesses for borings having different drilled depths or penetrating varying geologic unit thicknesses.

Because the results of liquefaction factor-of-safety analyses are strongly dependent on the depth to groundwater, we performed factor-of-safety analyses separately for unit Qa and unit Qfs for a number of groundwater depths ranging from 0 ft (groundwater at ground surface) to 30 ft below ground surface, and also for the groundwater depth reported at the time of drilling. Groundwater at ground surface represents our most conservative (and most liquefiable) condition. We assumed in our final assessment that groundwater depths observed at time of drilling represent the lowest groundwater levels necessary to consider in assigning a liquefaction susceptibility rating.

Factor-of-safety Analysis and Susceptibility Rating—Holocene Alluvium

The results of the factor-of-safety analyses for the Holocene alluvium (unit Qa) are shown as a suite of histograms in Figure D4. A series of histograms, one for each earthquake scenario, presents the distribution of aggregate liquefiable thicknesses for Holocene alluvium for varying groundwater depths. These histograms are based on factor-of-safety analyses performed on 94 geotechnical borings penetrating Holocene alluvium. The series of histograms developed for each earthquake scenario demonstrates the sensitivity of the unit's capacity for liquefaction to groundwater depth.

We evaluated the suite of histograms shown in Figure D4 and determined liquefaction susceptibility ratings based on the percentage of borings in which Holocene alluvium exceeds certain normalized aggregate thicknesses (Table D3). These are the same criteria applied in previously published liquefaction susceptibility investigations in the Puget Sound region (for example, Palmer and others, 2002; Shannon and Wilson, 1993). For the 0.15 *g* scenario, the susceptibility

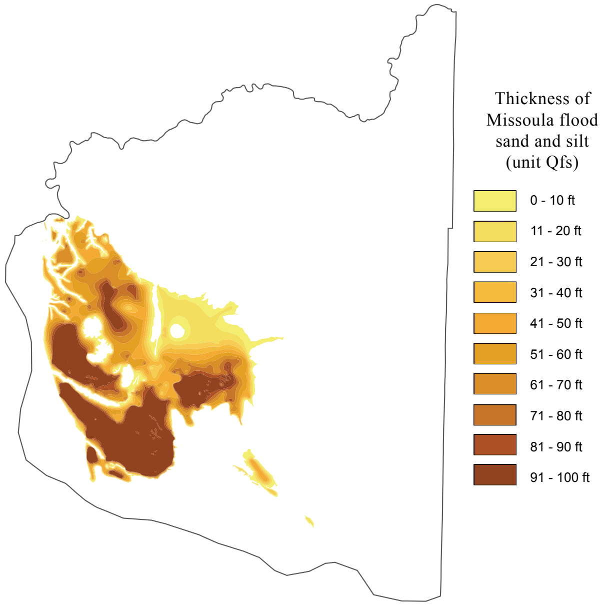

Figure D3. Thickness model for the Missoula flood sand and silt (unit Qfs) used in developing the liquefaction susceptibility and site class maps for Clark County.

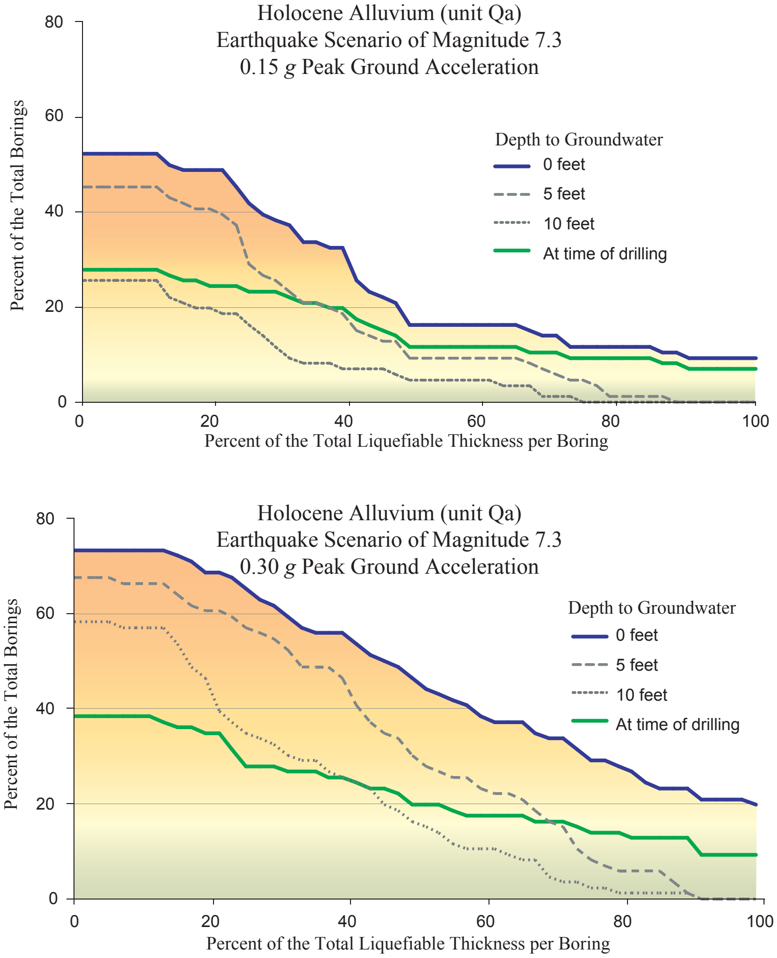

Figure D4. The suite of cumulative frequency histograms developed for Holocene alluvium (unit Qa) using data from 94 geotechnical borings drilled in this unit. Abscissa values are in increments of two percent of the total liquefiable thickness. The liquefaction susceptibility is indicated by the histogram frequency. For each ground motion scenario a series of histograms was developed for different groundwater depths. These histograms indicate that as the groundwater depth decreases, the liquefaction susceptibility increases.

rating is determined by the percentage of borings having any liquefiable soil in the geologic unit. This condition is defined as the percentage of borings in which the normalized aggregate thickness of liquefiable soil is greater than zero. The susceptibility rating for the 0.30 *g* scenario is determined by the percentage of borings in which the normalized aggregate thickness of liquefiable soil in the unit exceeds 25 percent. These criteria are a modification of similar criteria established by Shannon and Wilson (1993), in which they define the susceptibility rating using the absolute aggregate thickness (rather than the normalized aggregate thickness) of liquefiable material.

As shown in Figure D4, the 0.15 *g* scenario analysis of Holocene alluvium (unit Qa) indicates that more than 50 percent of the 94 geotechnical borings penetrating unit Qa had some liquefiable material for the case of groundwater at ground surface, and slightly over 25 percent of the borings had some liquefiable material for groundwater depths as measured at the time of drilling. Using the rating criteria presented in Table D3, Holocene alluvium has a moderate to high liquefaction susceptibility for the 0.15 *g* ground motion scenario and the range of groundwater depths considered. In the 0.30 *g* simulation, we find the susceptibility likewise ranges from moderate (for the groundwater depth measured at time of drilling) to high (groundwater at ground surface) using the criteria presented in Table D3.

We conclude that the Holocene alluvium has a moderate to high liquefaction susceptibility, especially given the near-surface groundwater levels observed in the static groundwater models discussed in the following section (McFarland and Morgan, 1996; Rod Swanson, Clark County Dept. of Public Works, written commun., 2003). The borings used in this evaluation were predominantly located along the Columbia River in the Port of Vancouver area and at interstate bridge crossings and overpasses. We have applied these results to all other areas of mapped alluvium (unit Qa).

Factor-of-safety Analysis and Susceptibility Rating—Missoula Flood Sand and Silt

We employed a factor-of-safety and groundwater sensitivity analysis similar to that used for Holocene alluvium in our evaluation of the liquefaction susceptibility of the Missoula flood sand and silt (unit Qfs). The suite of cumulative frequency histograms shown in Figure D5 was used as a basis to evaluate the susceptibility of unit Qfs. These histograms are based on factor-of-safety analyses performed on 69 geotechnical borings penetrating Missoula flood sand and silt.

Strict application of the criteria established in Table D3 was not practical for unit Qfs because different results were obtained when applying those criteria to the 0.15 *g* scenario and the 0.30 *g* scenario. We initially limited our evaluation of liquefaction susceptibility to the histograms developed for groundwater depths less than or equal to 15 ft. This is shallower that the 21.0 ft median depth of groundwater measured at the time of drilling of the 69 borings penetrating unit Qfs. For this restricted range of groundwater depths the 0.15 *g* scenario histograms indicate a low to moderate susceptibility rating, while the 0.30 *g* scenario histograms indicate a susceptibility rating ranging from low to high. When groundwater depth was greater than 15 ft the histograms developed for both earthquake scenarios indicated a

Table D3. The criteria used as the basis to derive the liquefaction susceptibility rating for a particular geologic unit. For the 0.15 g scenario, the susceptibility rating is determined by the percentage of borings in which any liquefiable soil was encountered in a geologic unit (normalized aggregate thickness exceeding zero percent). For the 0.30 g scenario, the susceptibility rating is determined by the percentage of borings in which the normalized aggregate thickness of liquefiable soil exceeds 25 percent.

Percentage of borings exceeding the specified normalized aggregate thickness	Susceptibility rating
greater than 50	high
25 to 50	moderate
5 to 25	low
less than 5	very low

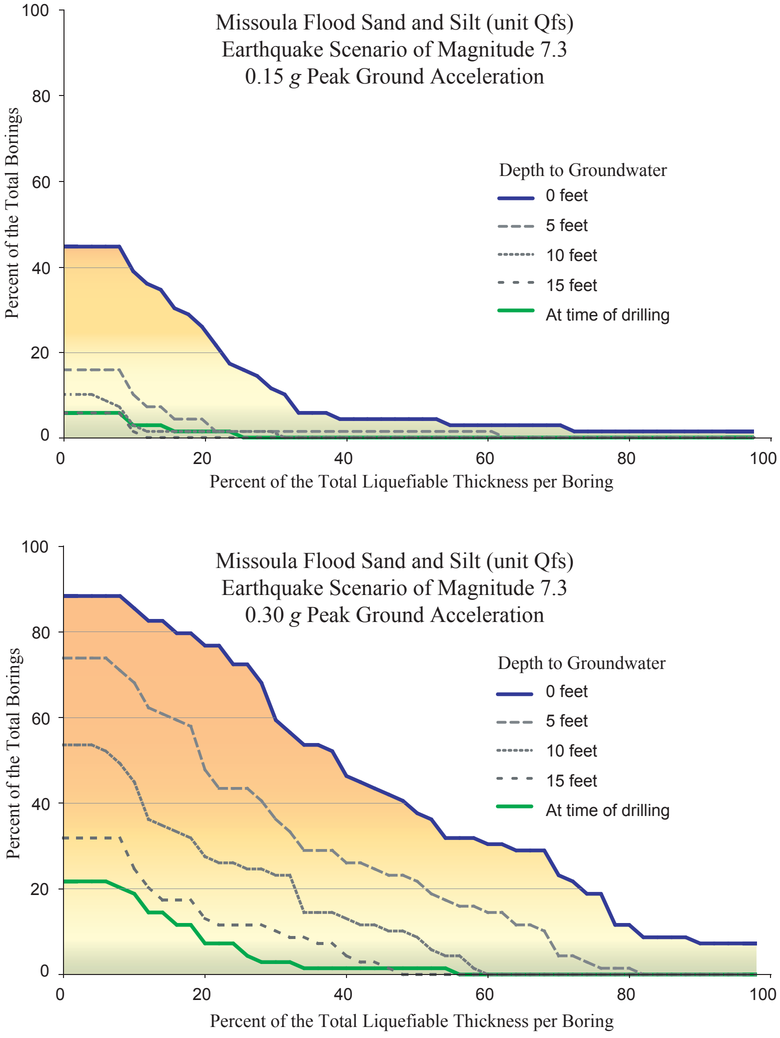

Figure D5. The suite of cumulative frequency histograms developed for the Missoula flood sand and silt (unit Qfs) using data from 69 geotechnical borings drilled in this unit. Abscissa values are in increments of two percent of the total liquefiable thickness. The liquefaction susceptibility is indicated by the histogram frequency. For each ground motion scenario a series of histograms was developed for different groundwater depths. These histograms indicate that as the groundwater depth decreases, the liquefaction susceptibility increases.

very low to low susceptibility rating when the criteria presented in Table D3 were applied. These results allowed us to separate those areas in unit Qfs having very low to low susceptibility from those having low to high susceptibility ratings by using the groundwater models of McFarland and Morgan (1996) and Rod Swanson (Clark County Dept. of Public Works, written commun., 2003).

McFarland and Morgan (1996) produced a series of maps of groundwater elevation for a number of geohydrological units as part of a cooperative investigation of the Portland basin groundwater system. One of these maps (plate 2 in McFarland and Morgan, 1996) shows the static groundwater elevation in the unconsolidated late Pleistocene and Holocene units of Clark County, which consist of the Missoula flood deposits and younger alluvium. Although this map is at 1:100,000 scale and groundwater elevation contours are at 50 ft intervals, it provides coverage for all of the Quaternary units in Clark County with any appreciable susceptibility to liquefaction. A depth-to-groundwater model within these unconsolidated Quaternary units was generated from McFarland and Morgan's map by interpolation of the groundwater elevations, and calculating the difference between this interpolation and the USGS 10 m DEM.

A more recent groundwater elevation map (Rod Swanson, Clark County Dept. of Public Works, written commun., 2003), based on more detailed data, was used to generate a similar depth-to-groundwater model in the southern part of the county. Both models, clipped to the extent of unit Qfs, are presented in Figure D6 for comparison. Swanson's model indicates that shallow groundwater (depths less than 15 ft, shown in dark blue in Fig. D6) covers a much larger area than the area of shallow groundwater portrayed in McFarland and Morgan's (1996) model. As shown in our sensitivity analyses of unit Qfs (Fig. D5), the presence of shallow groundwater significantly increases the liquefaction susceptibility, particularly where groundwater is less than 15 ft deep.

Closer scrutiny of the two groundwater models in areas covered by unit Qfs reveals an important difference relevant to the assignment of liquefaction susceptibility. Although Swanson's model indicates a larger area with groundwater depths less than 15 ft, his model also has no areas with groundwater shallower than 9 ft. In contrast, McFarland and Morgan's model often indicates groundwater reaching the surface (zero depth) in the areas mapped as unit Qfs. The areas where groundwater is at zero depth correlate strongly to drainages where stream incision causes an abrupt elevation change on the USGS 10 m DEM. Our interpretation is that the areas of very shallow groundwater indicated in McFarland and Morgan's model are mostly an artifact of differencing a very smooth groundwater elevation model that is based on interpolation of 50 ft groundwater elevation contours with the more spatially variable elevations derived from the USGS 10 m DEM. Consequently, we consider that Swanson's model provides a better estimate of both groundwater depth and the areal distribution of shallow groundwater, as the original groundwater elevation contour map was developed at a larger scale than McFarland and Morgan's 1:100,000-scale groundwater elevation map.

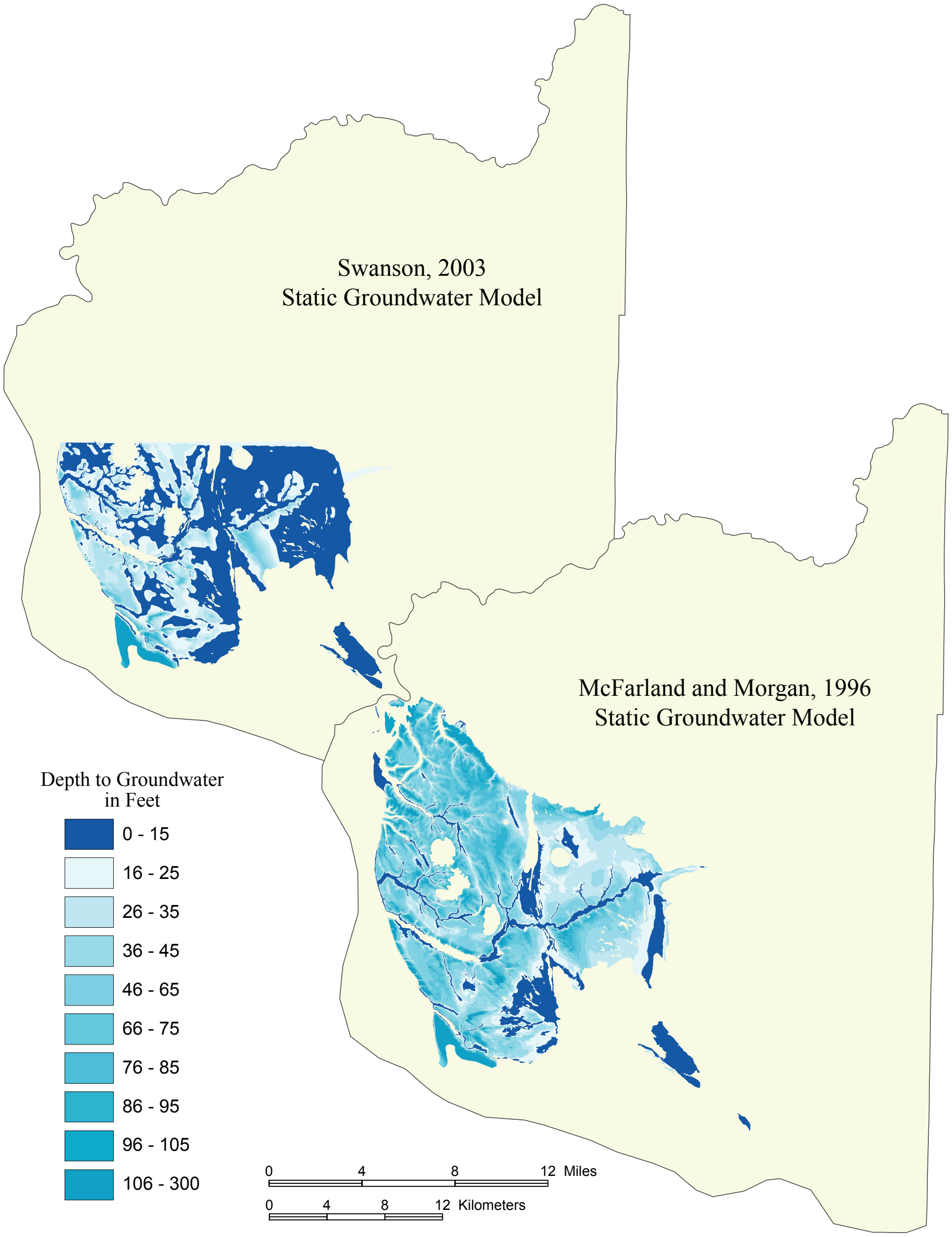

Figure D6. Comparison of static depth-to-groundwater models based on interpolation of contour map data from McFarland and Morgan (1996) and from Rod Swanson (Clark County Dept. of Public Works, written commun., 2003).

Inspection of the cumulative frequency histograms for the 0.30 *g* scenario (Fig. D5) for unit Qfs indicates that a high susceptibility only occurs in the case where the groundwater depth is shallower than 5 ft. We consider the high susceptibility ranking to be overly conservative, given that Swanson's groundwater model does not indicate any areas of unit Qfs where the groundwater depth is 5 ft or less. Consequently we separate unit Qfs into areas having a very low to low susceptibility (groundwater depth greater than 15 ft), and a low to moderate susceptibility (groundwater depth less than or equal to 15 ft).

In areas where the groundwater depth was 15 ft or less, we needed to ensure a sufficient thickness of unit Qfs beneath the groundwater table to support the assignment of a low to moderate (versus very low to low) liquefaction susceptibility. Therefore we established a thickness criterion where a low to moderate susceptibility would only be assigned if there was a minimum thickness (designated T_{crit}) of unit Qfs below the groundwater surface, using the relationship:

$$T_{crit} \geq 10 + (4/3) * D_{GW}$$

where D_{GW} is the depth to groundwater in feet.

This equation expresses that a minimum of 10 ft of unit Qfs must be present where groundwater is at the surface ($D_{GW} = 0$ ft), with the minimum required thickness of unit Qfs increasing with depth to groundwater. Where D_{GW} equals 15 ft, unit Qfs must be at least 30 ft thick to satisfy this minimum thickness criterion. A low to moderate susceptibility (rather than very low to low) was assigned to all areas of unit Qfs where the groundwater depth was 15 ft or less and the Qfs thickness model developed during this investigation (Fig. D3) indicated that the minimum

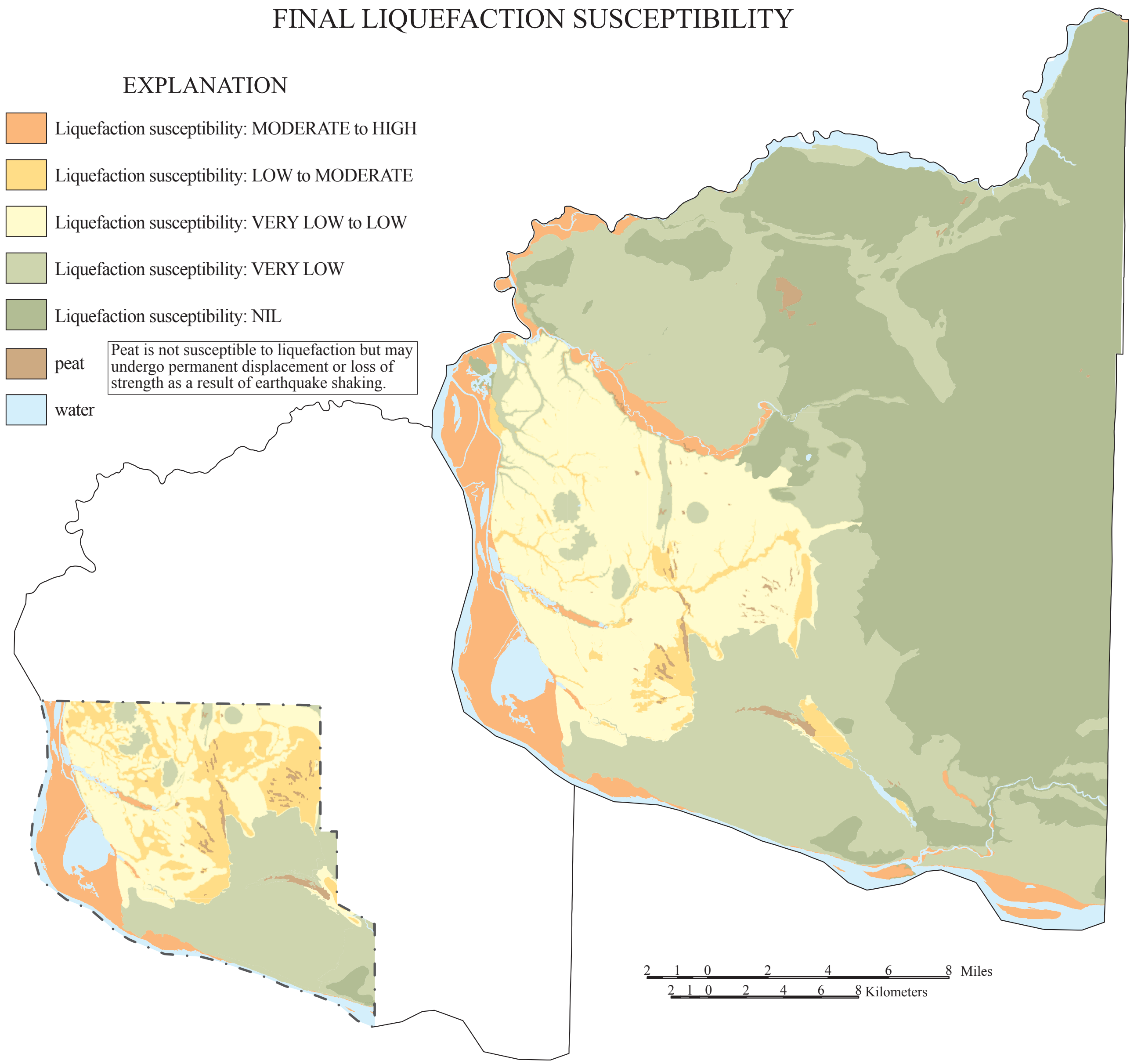

Figure D7. Final liquefaction susceptibility map developed from the geologic and geotechnical evaluations performed for this investigation. This is a reduced version of the final liquefaction susceptibility map presented in the plate entitled Liquefaction Susceptibility Map of Clark County, Washington. The map in the upper right is based on the groundwater model of McFarland and Morgan (1998); the map in the lower left is based on the groundwater model of Rod Swanson (Clark County Dept. of Public Works, written commun., 2003).

thickness criterion (T_{crit}) was satisfied. Otherwise a very low to low susceptibility was assigned.

Final Liquefaction Susceptibility Map

The final liquefaction susceptibility map is presented in the plate entitled *Liquefaction Susceptibility Map of Clark County, Washington*, and a reduced version is included in Figure D7 for the convenience of the reader. This map reflects the results of the groundwater depth analyses and thickness criteria applied to the Holocene alluvium and Missoula flood sand and silt. We assigned a moderate to high susceptibility to the one area mapped as artificial fill (unit af), as no geotechnical data were available to support a quantitative analysis. This assignment was made as the artificial fill is located within an area of mapped Holocene alluvium, and artificial fill can be very susceptible to liquefaction if not properly compacted. Geotechnical and geologic characterization of several other Quaternary units (coarse and fine facies of the Troutdale Formation, Missoula flood gravel, glacial drift, undifferentiated fine grained deposits, Mount St. Helens volcanic deposits, and terrace deposits) indicated these units have a very low liquefaction susceptibility. All areas mapped as bedrock (units Qb and Tb) were assigned a nil susceptibility as bedrock is incapable of liquefying. Peat deposits (unit Qp) are indicated on the map but are not assigned a susceptibility rating, as peat does not truly liquefy. However, peat soil is capable of undergoing large lateral deformation and vertical settlement resulting from earthquake shaking, and this potential for damaging ground failure should be recognized.

Table D4. Definitions of site class (Building Seismic Safety Council, 1997) based on average shear wave velocity in the upper 100 ft ($V_{S\ average}$).

Site class	$V_{S\ average}$	Rock or soil category
A	$V_S > 5000$ ft/s	hard rock
B	$2500 < V_S \leq 5000$ ft/s	rock
C	$1200 < V_S \leq 2500$ ft/s	very stiff soil or soft rock
D	$600 \leq V_S \leq 1200$ ft/s	stiff soil
E	$V_S < 600$ ft/s	soft soil
F	generally $V_S < 600$ ft/s	soils that are susceptible to potential failure under seismic loading such as liquefiable soils or sensitive clays, peats, or organic clays thicker than 10 feet, or thick sections of clays

Table D5. Summary of shear wave velocity measurements in Clark County, by geologic unit. Columns are blank where the shear wave survey at those locations did not obtain data for that particular geologic unit.

Measurement location	Shear wave velocity (ft/s)						
	af	Qa	Qfs	Qfg	Quf	Qtrc	Qtrf
From Mabey and others (1993)							
Airport (2)	459	827				3045	
Burnside	991		935			2684	
Carver				2257		2205	1578
Delta Park		633				2828	
East Arena			1047				
Fire Station	725	600				1795	
Fremont				1680		3051	
Grand And Division	666		1106			3783	
Hanna Car Wash				1476		2625	
Lombard				1946		2375	
Marquam	814	738				2208	
Old Town	942	522				2326	
Ross Island			932			2096	
Skidmore			1070	1473		2313	
Troutdale						3084	
Vaughn And Nicolai		781	1073				
Walker Road							1325
West Arena			1115			4003	
From Matthew Mabey (Oregon Dept. of Transportation, written commun., 2003)							
VND1			968	1690			
ORD1			896	1368			
MTD5				1467		1772	
From DGER measurements							
Annie's Berry Farm					1033	2917	
Rock Creek RD						2641	
Schultz RD					883		
Schultz RD					1598		
389th ST					1106	2890	
Mean	766	684	1016	1670	1155	2665	1452
Standard deviation	195	117	83	300	310	590	

SITE CLASS ANALYSIS AND MAPS

Site classes are defined by the average shear wave velocity in the uppermost 100 ft of soil, termed $V_{S\ average}$ (Table D4). A comprehensive database of shear wave velocity (V_S) measurements made in Quaternary units in the Portland basin was the basis for producing the final site class map. This dataset was based in part on V_S measurements originally reported by Mabey and others (1993), and included unpublished data from Clark County (Matthew Mabey, Oregon Dept. of Transportation, written commun., 2003). These data were supplemented by additional shear wave velocity measurements made as a part of this and other DGER investigations. Table D5 summarizes the V_S data used to produce the final site class map.

To assign average V_S values for geologic units in the area, we first calculated the mean V_S values and associated standard deviations for each unit, as shown in Table D5. For each unit we also calculated the value of the mean V_S minus one standard deviation, which we term the lower bound shear wave velocity. Using the lower bound velocity in site class determinations provides a conservative approach in accounting for the variability in V_S. We consider the mean and lower bound V_S values to represent the range of characteristic velocities of a geologic unit for the entire thickness of that unit. Table D6 summarizes the calculated mean and lower bound V_S values, and shows V_S values assigned to those geologic units for which we do not have measurements. We make these assignments based on geologic and geotechnical similarities with other geologic units in the area.

Table D6. Characteristic shear wave velocities (V_S) for the geologic units used in this study, based on mean value and standard deviation of V_S measurements shown in Table 5. The lower bound value is the difference of the mean V_S and its associated standard deviation. We assigned the lower bound value for unit Qtrf to the bounding velocity between site class C and D soils; we did not feel the standard deviation calculated using only two data values was statistically valid, and we chose this lower bound to be conservative. Geologic units lacking V_S measurements were assigned a mean and lower bound value based on their geologic and geotechnical similarities with other units having measured values. The V_S value assigned to Quaternary and Tertiary bedrock is a mid-range value for site class B rock.

Geologic unit	Mean V_S (ft/s)	Lower bound V_S (ft/s)	Comments
af	766	571	Measured values
Qa	684	567	Measured values
Qp	---	---	Mapped areas of peat are assigned to site class F; no V_S measurements available for this unit
Qlpf	984	984	Based on typical V_S values measured in debris flows deposited during the 1980 eruption of Mount St. Helens (Palmer, 1993)
Qfs	1016	933	Measured values
Qfg	1670	1370	Measured values
Qtf	1016	933	Assumed equal to V_S for unit Qfs
Qtc	1670	1370	Assumed equal to V_S for unit Qfg
Qgd	1670	1370	Assumed equal to V_S for unit Qfg
Quf	1155	845	Measured values
Qtrc	2665	2075	Measured values
Qtrf	1452	1200	Measured values; lower bound reflects boundary between site class C and D soils
Qb	3281	3281	Assumed bedrock V_S
Tb	3281	3281	Assumed bedrock V_S

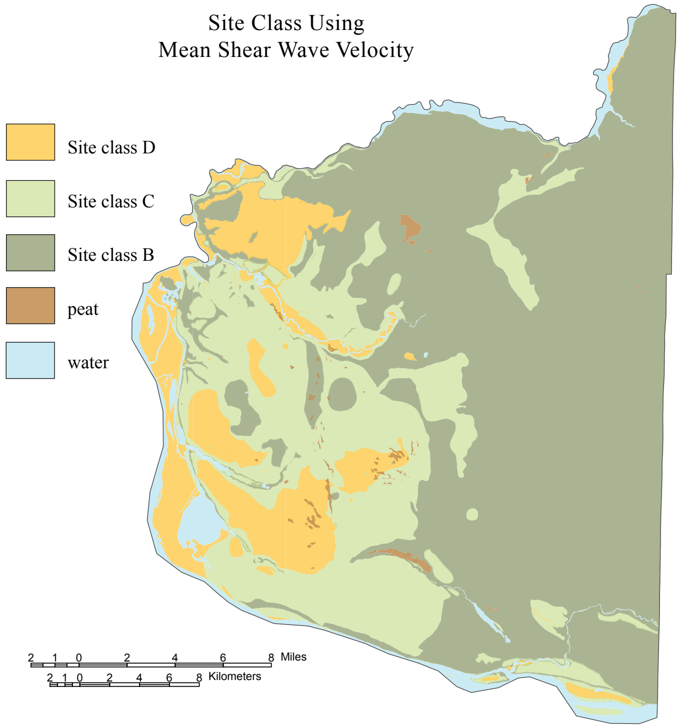

Figure D8. Site class map derived using the mean shear wave velocities presented in Table 6 and thickness models developed for this investigation.

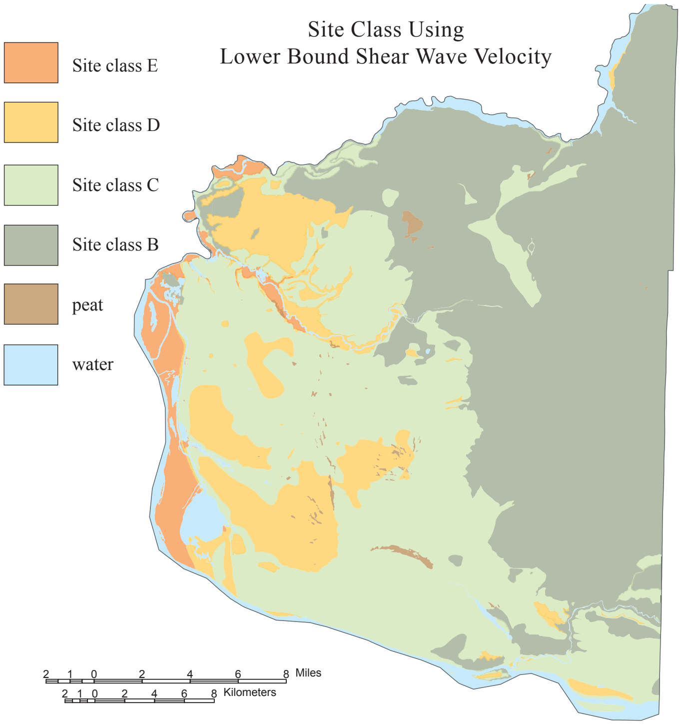

Figure D9. Site class map derived using the lower bound shear wave velocities presented in Table 6 and thickness models developed for this investigation.

Because more than one geologic unit may occur in the upper 100 ft, we applied the following weighting scheme to calculate the average shear wave velocity in the upper 100 ft ($V_{S\,average}$) for each 50 ft grid cell in our digital geologic model:

$$V_{S\,average} = \sum_{n=1}^{N} (D_n * V_{Sn}) / 100$$

where N is the number of geologic units occurring in the upper 100 ft at the grid cell location of the average velocity calculation, D_n is the thickness, in feet, of the nth geologic unit, and V_{Sn} is the characteristic shear wave velocity assigned to the nth geologic unit.

This calculation is slightly different from the one in the International Building Code, which reduces to:

$$V_{S\,average} = 100 / \sum_{n=1}^{N} (D_n * V_{Sn})$$

This equation is more sensitive to contrasts in velocity. Thus, the equation we used becomes unconservative at large velocity contrasts, which will generally occur where bedrock is less than 100 ft deep. This will be adjusted in a revised version of this map.

In calculating $V_{S\,average}$ we used the values summarized in Table D6 for the characteristic shear wave velocity V_{Sn}. We then used $V_{S\,average}$ to assign a site class to every grid cell in our digital geologic model using the site class definitions of Table D4. We developed two separate site class maps, one using the mean V_S (Fig. D8) and the other using the slower, and more conservative lower bound velocities (Fig. D9) as characteristic velocities. Differences in the distribution of site classes in Figures D8 and D9 reflects the conservatism resulting from using the lower bound values as the characteristic velocities. In particular, the floodplain along the Columbia River on the west side of the county is shown as site class D in Figure D8, and as site class E in Figure D9.

In order to reflect the uncertainty in the V_S measurements and their effect on the determination of site class, we combined the results of the two maps shown in Figures D8 and D9 to produce the final site class map presented as the plate entitled *Site Class Map of Clark County, Washington*; a reduced version of the final site class map is shown for the reader's convenience in Figure D10. For example, where the mean V_S map (Fig. D8) indicates site class D, and the map based on the lower bound velocities (Fig. D9) indicates site class E, Figure D10 shows a combined

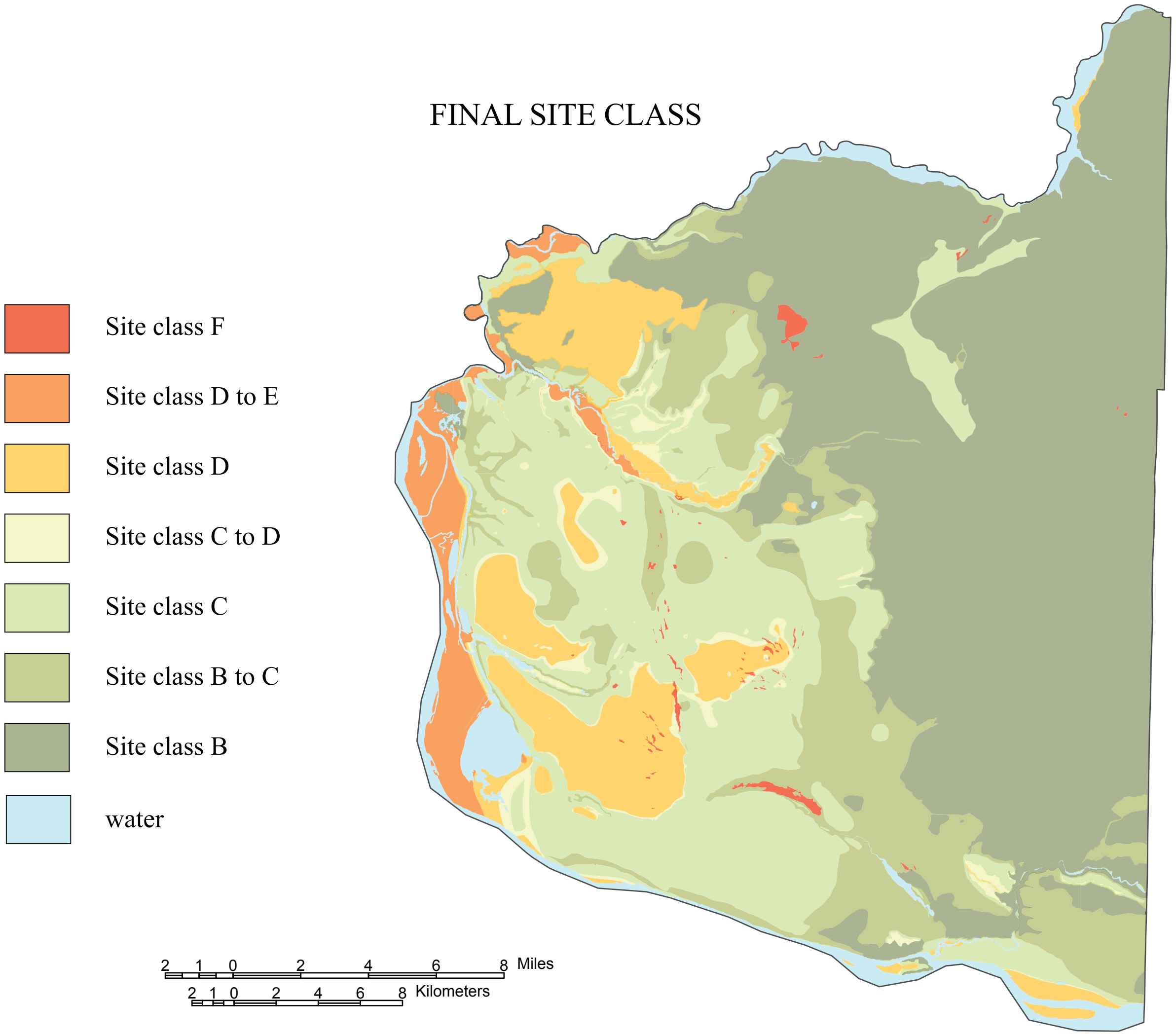

Figure D10. Final site class map based on combining the site class maps developed using the mean and lower bound shear wave velocities (Figs. 8 and 9). This is a reduced version of the final site class map presented in the plate entitled *Site Class Map of Clark County, Washington*.

site class D–E. Where both maps indicate the same site class at a particular location, then that coincident classification is shown.

According to the NEHRP site class methodology (Building Seismic Safety Council, 1997), peat deposits with a thickness greater than 10 ft are assigned to site class F. We assume that the peat deposits shown on our geologic map (Fig. D2) are a minimum of 10 ft thick, and display these as site class F on the final site class map. We do not distinguish any other areas in Clark County as a site class F. However, the NEHRP site class methodology also defines liquefiable soils susceptible to potential failure under seismic loading as site class F. We refer the reader to the liquefaction susceptibility map accompanying this report to determine other areas in Clark County that could be considered to be site class F based on their potential for liquefaction failure during an earthquake.

LIMITATIONS ON THE USE OF THESE MAPS

The maps presented in the two plates accompanying this report are meant only as a general guide to delineate areas based on their susceptibility to liquefaction or to determine site class. Because these maps are developed using regional geologic mapping, they cannot be used to make final determinations of liquefaction susceptibility or site class at any specific locality. They are not a substitute for a site-specific investigation to assess the actual geologic conditions and the potential for liquefaction or to assign the appropriate site class. These determinations require a site-specific evaluation performed by a qualified practitioner.

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