



Prepared in cooperation with the University of California, Berkeley and the Washington State Department of Transportation

Geotechnical Soil Characterization of Intact Quaternary Deposits Forming the March 22, 2014 SR-530 (Oso) Landslide, Snohomish County, Washington



Open-File Report 2015-1089

U.S. Department of the Interior
U.S. Geological Survey

FRONT COVER: Image of the March 22, 2014, landslide near Oso, Washington showing the distribution of geologic units exposed in both the headscarp (background) and hummock deposits (foreground).

Geotechnical Soil Characterization of Intact Quaternary Deposits Forming the March 22, 2014 SR-530 (Oso) Landslide, Snohomish County, Washington

By Michael F. Riemer, Brian D. Collins, Thomas C. Badger, Csilla Toth, and Yat Chun Yu

Open-File Report 2015-1089

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

For product and ordering information:
World Wide Web: <http://www.usgs.gov/pubprod>
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth,
its natural and living resources, natural hazards, and the environment:
World Wide Web: <http://www.usgs.gov>
Telephone: 1-888-ASK-USGS

Any use of trade, product, or firm names is for descriptive purposes only and does not imply
endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual
copyright owners to reproduce any copyrighted material contained within this report.

Suggested citation:
Riemer, M.F., Collins, B.D., Badger, T.C., Toth, C., and Yat Chun, Y., 2015, Geotechnical soil characterization of
intact Quaternary deposits forming the March 22, 2014 SR-530 (Oso) landslide, Snohomish County, Washington:
U.S. Geological Survey Open-File Report 2015-1089, 17 p., <http://dx.doi.org/10.3133/ofr20151089>.

ISSN 2331-1258 (online)

Acknowledgments

The Washington State Department of Transportation managed the geotechnical drilling investigation with geologic field oversight and geotechnical input from Snohomish County Department of Public Works. In addition, the Washington State Department of Natural Resources aided in the stratigraphic interpretation of the samples recovered from the borings. The geotechnical testing was performed by the University of California, Berkeley through cooperation and coordination with the U.S. Geological Survey. Funding for the geotechnical drilling and sampling was collectively provided by the Snohomish County Public Works Department, the Washington State Department of Transportation, the Washington State Department of Natural Resources, the Tulalip Tribes, and the Stillaguamish Tribe of Washington. Funding for the geotechnical testing was provided by the U.S. Geological Survey, Landslide Hazards Program through a cooperative agreement with the University of California, Berkeley, Department of Civil and Environmental Engineering Geotechnical Laboratory. We thank Rex Baum (USGS) and Robert Holtz (University of Washington) for providing reviews that improved the quality of this report.

Contents

Acknowledgments.....	iii
Introduction.....	1
Methods.....	3
Geotechnical Drilling and Sampling	3
Geotechnical Index Testing.....	3
Water Content	5
Unit Weight.....	5
Specific Gravity	6
Grain-size Distribution	6
Atterberg Limits	6
Unified Soil Classification System (USCS) Designation	6
Results.....	7
Correlation With Previously Mapped Geologic Units.....	7
Index Testing and Soil Classification.....	7
Conclusions	8
References	17

Figures

Figure 1.	Site map of the March 22, 2014 SR-530 landslide near Oso, Washington.	2
Figure 2.	Generalized stratigraphic column of glacial and nonglacial deposits forming the area of the March 22, 2014 SR-530 (Oso) landslide.	4
Figure 3.	Grain-size curves for recessional outwash samples.	10
Figure 4.	Grain-size curves for till samples.	11
Figure 5.	Grain-size curves for advance outwash samples.....	12
Figure 6.	Grain-size curves for advance glaciolacustrine samples.	13
Figure 7.	Grain-size curves for Olympia-age nonglacial samples.	14
Figure 8.	Plasticity chart for till and advance outwash samples.	15
Figure 9.	Plasticity chart for advance glaciolacustrine samples.	16

Tables

Table 1.	Geotechnical index testing data for deposits forming the March 22, 2014 SR-530 landslide near Oso, Washington	9
----------	---	---

Datum Information

Horizontal coordinate information is referenced to the North American Datum of 1983-11 – High Accuracy Reference Network of 1991 (NAD 83-11/91 HARN) and projected to Washington State Plane North coordinates, expressed in feet.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 expressed in feet. Elevation, as used in this report, refers to distance above the vertical datum.

Conversion Factors

US to Metric

Multiply	By	To obtain
inch (in.)	2.54×10^1	millimeter (mm)
foot (ft)	3.048×10^{-1}	meter (m)
cubic foot (ft ³)	2.832×10^{-2}	cubic meter (m ³)
pound per cubic foot (lb/ft ³)	1.571×10^{-1}	kilonewton per cubic meter (kN/m ³)
ounce (oz)	2.835×10^1	gram (g)
fluid ounce (fl. oz)	2.957×10^1	milliliter (ml)
quart (qt)	9.464×10^{-1}	liter (L)

Geotechnical Soil Characterization of Intact Quaternary Deposits Forming the March 22, 2014 SR-530 (Oso) Landslide, Snohomish County, Washington

By Michael F. Riemer¹, Brian D. Collins², Thomas C. Badger³, Csilla Toth¹, and Yat Chun Yu¹

Introduction

During the late morning of March 22, 2014, a devastating landslide occurred near the town of Oso, Washington. The landslide (fig. 1), with an estimated volume of 10.9 million cubic yards ($8.3 \times 10^6 \text{ m}^3$) of both intact glacially deposited and previously disturbed landslide sediments, reached speeds averaging 40 miles per hour (64 kilometers per hour) and crossed the entire 2/3-mile (~1100 m) width of the adjacent North Fork Stillaguamish River floodplain in approximately 60 seconds, resulting in the complete destruction of an entire neighborhood (Iverson and others, 2015). More than 40 homes were destroyed as the debris overran the neighborhood, resulting in the deaths of 43 people.

Landslides in glacial deposits are common in the Pacific Northwest (for example, Baum and others, 2008), and in fact, the site of the March 22, 2014 SR-530 landslide had experienced significant reactivation several times in past decades, with the most recent event occurring in 2006 (for example, Miller and Sias, 1998). However, these previous landslides were of considerably less volume and mobility (Iverson and others, 2015), and debris had never reached the Steelhead Haven neighborhood. Further, no landslides with the type of mobility that the March 22, 2014 landslide underwent have been recorded in historic times within the North Fork Stillaguamish River valley. However, mapping performed immediately following the landslide indicates that several other slopes in the North Fork Stillaguamish River valley have experienced large-volume landslides exhibiting high mobility in prehistoric times (Haugerud, 2014). The presence of previous high-mobility landslides in the valley, and the now well-documented occurrence of one involving many fatalities, underscores both the hazard and risk for those that live and travel in this and other river valleys in the Pacific Northwest with similar steep exposures of glacial deposits.

To understand the hazards posed by highly mobile landslides in the Pacific Northwest, the U.S. Geological Survey (USGS), together with its project partners, the University of California, Berkeley Department of Civil and Environmental Engineering (UCB), and the Washington State Department of Transportation (WSDOT), is undertaking a critically needed study to identify the geologic, hydrogeologic, and geotechnical conditions in which these large landslides initiate, as well as the processes responsible for the exceptional mobility of this, and potentially other, landslides in the region. One of the first study activities involves characterizing the stratigraphy and materials from which the landslide deposits are derived, so that the fundamental geotechnical nature of the soils can be understood. This understanding is required to begin identifying possible conditions leading to slope

¹University of California, Berkeley

²U.S. Geological Survey

³Washington State Department of Transportation

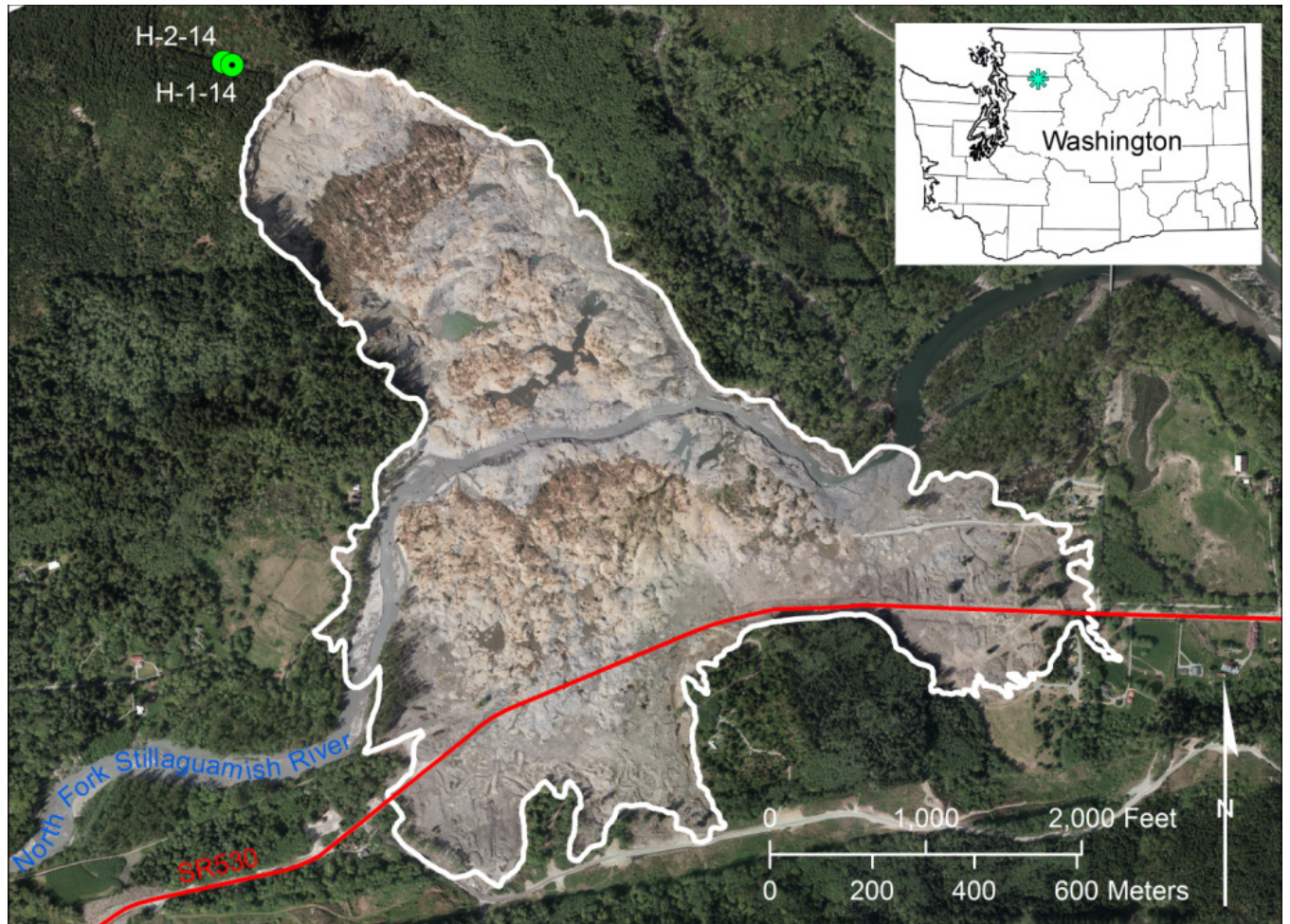


Figure 1. Site map of the March 22, 2014 SR-530 landslide near Oso, Washington. The locations of two boreholes where samples were obtained for geotechnical testing presented in this report are shown (H-1-14 and H-2-14), along with major geographic features of the area. Base photo source and date: Washington State Dept. of Transportation, May 1, 2014

failure and their relation to the landslide’s high mobility. In addition, detailed characterization of each stratigraphic unit encountered in initial geotechnical borings is needed to relate stratigraphy between borings for this study and as a part of ongoing investigations by WSDOT and other project partners.

This report provides a description of the methods used to obtain and test the intact soil stratigraphy behind the headscarp of the March 22 landslide. Detailed geotechnical index testing results are presented for 25 soil samples representing the stratigraphy at 20 different depths along a 650 ft (198 m) soil profile. The results include (1) the soil’s in situ water content and unit weight (where applicable); (2) specific gravity of soil solids; (3) each sample’s grain-size distribution; (4) critical limits for fine-grain water content states (that is, the Atterberg limits); and (5) official Unified Soil Classification System (USCS) designation. In addition, preliminary stratigraphy and geotechnical relations within and between soil units are presented.

Methods

Geotechnical Drilling and Sampling

WSDOT performed geotechnical drilling in the fall of 2014 at three locations near the landslide. Two borings (H-1-14 and H-2-14) located approximately 300 ft and 360 ft (91 and 110 m) behind the 2014 headscarp (fig. 1), were drilled to depths of 650 ft and 635 ft (198 m and 194 m), respectively, in order to sample the major stratigraphic units present in the landslide deposit (fig. 2). A third, 300-ft-deep (91 m) boring (H-3-14) was drilled through a prehistoric landslide deposit on the opposite side of the valley from the 2014 landslide to investigate stratigraphic relations across the valley, to ascertain the existing shear plane depth of the prehistoric landslide, and to characterize the groundwater conditions within and beneath the landslide mass. In this report, only samples from the two boreholes nearest the landslide (H-1-14 and H-2-14) are presented.

WSDOT used a Central Mine Equipment Company CME-850X track-mounted drill rig (<http://cmeco.com/drills/track-carrier-mounted-drills/cme-850x-track-carrier-auger-drill/>) to advance both HWT-type casing (4.6-in. [116.8 mm] outside diameter) with a tricone casing advancer, and HQ3-type coring equipment (3.782-in. [96.1 mm] outside diameter, 2.375-in. [60.3 mm] core diameter) using reverse circulation, mud rotary drilling. A high-yield bentonite (CETCO Super Gel X; <http://www.cetco.com>) and a liquid polymer (CETCO Insta-Vis Plus) were used in the drilling mud for advancing casing and coring. Brass liner tubes (with 2.5-in. [63.5 mm] outside diameter and 2.4-in. [61.0 mm] inside diameter) were used for sample collection in the uppermost approximately 120 feet of the borings. Below this depth, HQ3 core samples were typically retained in steel split sleeves (with inside diameter of 2.50 in. [63.5 mm]). However, during some of the coring, transparent polycarbonate (Lexan) core tubes, also with inside diameter of 2.50 in. (63.5 mm), were substituted for the steel sleeves to obtain intact samples at their in situ moisture content for geotechnical laboratory testing. The annular space between the core and the inside surface of the polycarbonate tubes allowed for some swelling and moisture intrusion into the soil samples, but in general, the tubes were successful in retaining the soil core in a more intact and protected state. Where cores were not contained in sleeves, they were placed in a core box and wrapped in plastic to slow drying.

All samples were transported by truck to WSDOT's State Materials Laboratory in Tumwater, Washington. Samples contained in polycarbonate tubes were maintained in an upright position during transport and storage in laboratory wet rooms. Samples selected for geotechnical index testing were transported to the University of California, Berkeley Department of Civil and Environmental Engineering Geotechnical Laboratory by commercial aircraft, shipping company, or truck. All geotechnical testing reported herein was performed at the University of California, Berkeley Geotechnical Laboratory.

Geotechnical Index Testing

We performed a variety of geotechnical index testing on selected samples depending on their sampling method (for example, unit weight was only measured for those samples taken and stored in protective tubes) and soil type (for example, Atterberg limits were only performed for samples exhibiting plasticity). It was observed in the laboratory that many of the core samples were coated with a thin layer of soft, gray material with high moisture content that was suspected to be the drilling mud mixed with the soil cuttings. The cores were trimmed of this outer layer prior to index testing to ensure that tests were not contaminated by this material. Testing protocols outlined by ASTM International (<http://www.astm.org/>) were followed in nearly all cases. We detail any exceptions that were necessary to the ASTM testing methods in the subsequent test-specific sections.

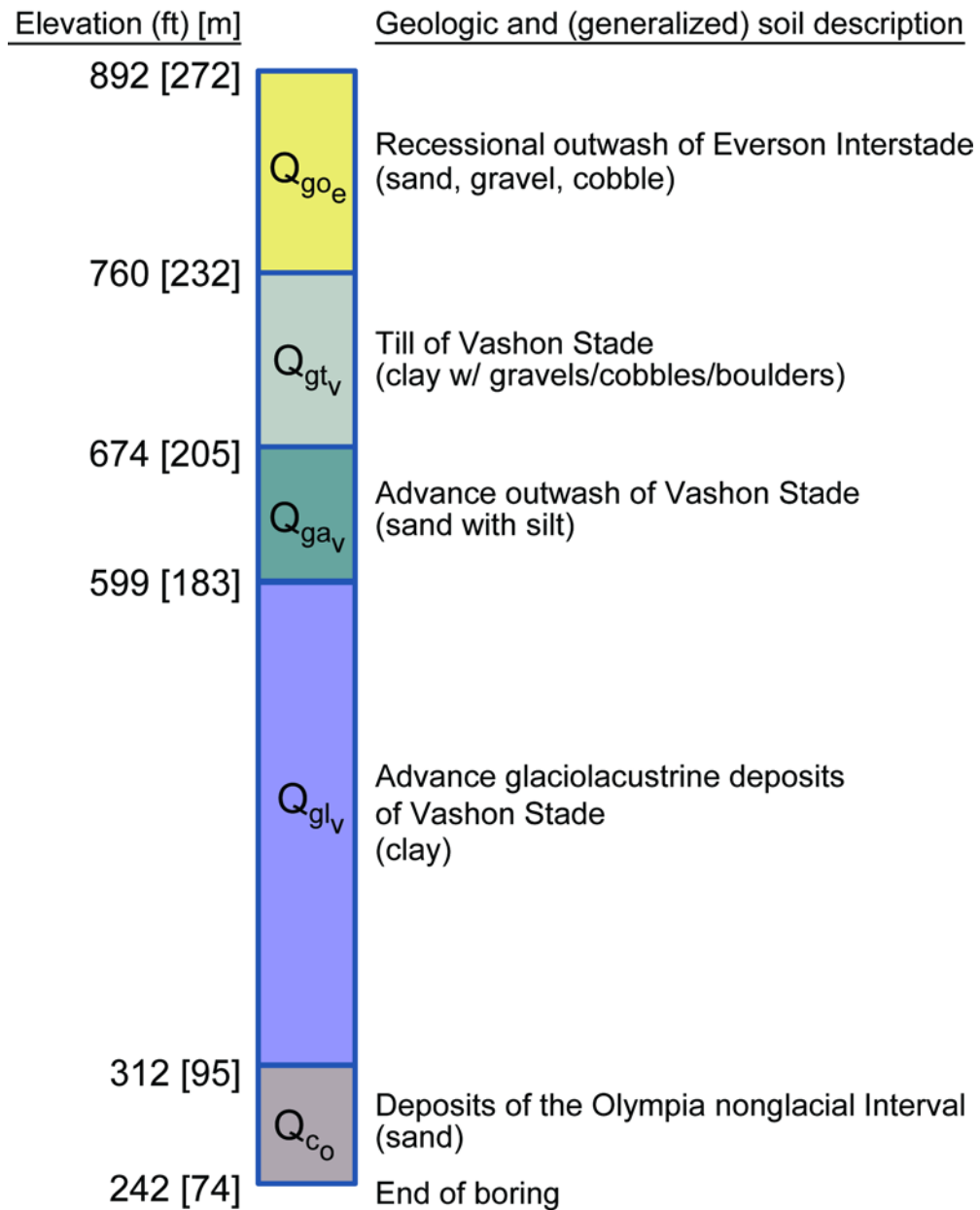


Figure 2. Generalized stratigraphic column of glacial and nonglacial deposits forming the area of the March 22, 2014 SR-530 (Oso) landslide, following the naming convention of Dragovich and others (2003). Unit contacts are assumed horizontal for purposes of presentation.

Water Content

Determination of the water content (w), defined as the ratio of the mass of water relative to the mass of solids in a given volume of soil, is guided by ASTM D2216-10 - Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (<http://www.astm.org/>). Water content was measured and recorded for those materials that were transported and stored in a sealed condition, providing confidence that the materials had not dried out between the time of sampling and testing in the laboratory. In general, these were samples either in polycarbonate (Lexan) or brass tubes, as shown by Sample Type in table 1.

It is important to recognize, however, that soils with significant plasticity swell when exposed to water if the confining stress is reduced, and that this will result in a higher water content than was present prior to sampling in the field. Because the polycarbonate tubes had a slightly larger inside diameter than the diameter of the core itself, it is very likely that the samples of the glaciolacustrine formation, for example, experienced significant swelling prior to measurement of the water content, and therefore the measured values reported in table 1 are upper bounds on the likely values in situ.

Unit Weight

Determination of the soil mass density, or unit weight, is guided by ASTM D7263-09 - Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens (<http://www.astm.org/>). Densities were only measured and recorded for samples which had not been substantially remolded prior to testing. In general, these are samples either in the polycarbonate (Lexan) or brass tubes, as shown by Sample Type in table 1.

Moist densities (γ) were determined by carefully cutting a section of the desired sample tube of approximately 4 in. (102 mm) in length and extruding the soil. The inner diameter of the polycarbonate tube, the length of the extruded core, and the specimen's moist mass were recorded and used to calculate the density. The soil sample was then typically cut along its cylindrical axis and divided into subsamples for subsequent determination of moisture content and other index properties.

As noted earlier, all samples retained in polycarbonate tubes likely underwent swelling due to the available moisture in the tubes and annular space between the tubes and the original core diameter. This suggests that the measured moist unit weights shown in table 1 are probably lower bounds on the values of these soils prior to sampling, particularly in materials that were saturated in the field.

The samples of till available for index testing had not been maintained at original moisture levels, and because of the wide range of particle sizes within this material, it was not possible to trim a uniform, right-circular cylindrical sample from the available core. Instead, the dry density (γ_d) of the till from one depth was estimated by a simple exercise in water displacement when submerged. A relatively large (5-in.-long [127 mm]), roughly cylindrical sample was oven dried to obtain its dry mass, and then was submerged in a 2.1 qt (2 L) graduated cylinder that was partly full of distilled water. Measurements of the water level in the graduated cylinder before and immediately after submersion of the till sample provided an approximate bulk volume of the sample, before water could significantly penetrate the sample voids. Over the following hours, as the till sample slaked and became a pile of sediment on the bottom of the cylinder, the overall volume was observed to decline as air within the original sample voids was released, thereby verifying that the water-volume-displacement measurement was reasonable since the water had not immediately filled the air-filled voids upon submersion.

Specific Gravity

The specific gravity of soil solids (G_s) was measured following the procedures of ASTM D854-14 - Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (<http://www.astm.org/>). A 4.23 fluid ounce (125-ml) pycnometer and approximately 1.06 oz (30 g) of oven-dried soil were used, and a combination of both vacuum and heating was applied to ensure removal of air bubbles. Measured values are shown in table 1.

Grain-size Distribution

Gradation curves for the samples were determined using both hydrometer and sieve methods, as described in ASTM D422-63 (2007): Standard Test Method for Particle-Size Analysis of Soils (<http://www.astm.org/>). In most cases, the soil samples were oven-dried to determine the mass of solids, soaked in the prescribed dispersing solution, and then tested with the hydrometer. Following completion of hydrometer testing, the entire samples were wet-sieved over a No. 200 sieve, and the coarse fraction was retained, oven-dried, and used for sieve analysis. In a few cases, two different samples from approximately the same depth were used for the sieving and hydrometer portions of the test. In several other cases, the material clearly had very few fines, and so no hydrometer test was performed. For the samples of the till, it should be noted that the geometry of the core samples necessarily limited the maximum particle sizes that could be observed, whereas the deposit contains much larger coarse particles (that is, up to and including boulders). As a check for consistency, two samples from the same depth within the borehole and stratigraphic column (fig. 2, table 1) were run on both the till (sample H-1-14-@176) and the glaciolacustrine unit (sample H-1-14-C72). In these cases, both grain-size curves are presented, but only mean values are reported. Gradation curves are shown in figures 3-7, and the values for percent fines (percentage by mass less than the No. 200 sieve which has openings of 0.0030 in., or 0.075 mm), and the clay-size fraction (percentage by mass less than 0.000079 in., or 0.002 mm) are shown in table 1.

Atterberg Limits

The plasticity characteristics of samples with appreciable fines were determined following ASTM D4318-10e1 - Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (<http://www.astm.org/>). Using a Casagrande cup, multiple points using the Casagrande cup were run to identify the liquid limit (LL). The plastic limit (PL) values were determined by manual rolling of threads on glass plates, rather than using a tray. All samples were initially tested by the “wet method” of preparation, without oven drying and pulverizing, although some of the bulk samples of material had apparently lost considerable moisture from their field state prior to testing. Several additional tests were performed on samples that had already been tested for plasticity, following oven drying, to investigate the effect on the liquid limit and thereby identify whether the soils had appreciable organic content. Values of liquid limit, plastic limit, and plasticity index (PI) are shown in table 1.

Unified Soil Classification System (USCS) Designation

The results of the index testing of the samples were used to assign Unified Soil Classification System (USCS) soil classifications following ASTM D2487-11 - Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) (<http://www.astm.org/>). These designations are listed in the far right column of table 1. It should be noted that the although the

samples of till, as tested, resulted in a low plasticity clay (CL) classification, larger samples that better captured the gradation of the coarsest particles might classify as a coarse-grained soil instead.

Results

Correlation With Previously Mapped Geologic Units

We characterized 25 samples from the two borings that penetrated the intact stratigraphy immediately upslope of the March 22 landslide headscarp (fig. 1). These samples represent 20 generalized depths (table 1) along a 650-ft-deep (198 m) profile of the original (pre-failure) stratigraphic configuration of the northernmost section of the landslide. The number of samples reported in table 1 (20) is less than the number of samples actually tested (25) because, in some cases, additional samples from the same depth were tested but are reported as single mean values. By comparing soil texture observations and index test results with previously mapped Quaternary geologic unit descriptions (Dragovich and others, 2003), we assigned each sample to one of five mapped units (fig. 2). Further, by inspecting the entire core box, along with field notes taken during drilling, we assigned approximate stratigraphic boundaries to each unit. In general, we were able to distinguish boundaries of adjacent units to within a depth of 10 ft (3 m). Due to the inherent variability of nonhorizontally deposited sediments (especially the till), these boundaries should be viewed as approximate with potentially considerable variability throughout the area forming, and adjacent to, the landslide deposit.

The generalized section consists of 132 ft (40 m) of recessional outwash (primarily sand and gravels) of the Everson Interstade (Q_{go_e}) overlying 86 ft (~26 m) of glacial till (well graded mix of clay to boulder sizes) of the Vashon Stade (Q_{gt_v}). These units overlie a downward fining sequence (that is, the mean grain size becomes smaller with depth) composed of 75 ft (~23 m) of advance outwash deposits (sand and silt) of Vashon Stade (Q_{ga_v}) followed by 287 ft (~87 m) of advance glaciolacustrine deposits, also of Vashon Stade (Q_{gl_v}). Underlying the entire Vashon Stade glacial deposits are sand and silt deposits of the Olympia nonglacial interval (Q_{c_o}). Both borings were terminated in this unit, and the Q_{c_o} deposit thickness was not determined.

Index Testing and Soil Classification

The recessional outwash forms the shallowest unit in the stratigraphic sequence (fig. 2). The material is predominantly a broadly graded sand with significant gravel and nonplastic fines content, as shown by the gradation curves in figure 3. Based on the samples selected and tested from these borings, the fines content increases with depth, and the USCS classification ranges from well-graded sand and silty sand (SW-SM) to just silty sand (SM). Because the material is free-draining, measured water contents and moist densities were dependent on a specimen's position within the core, and are likely to vary in the field depending on hydrologic conditions.

The Vashon till forms a sharp contact with the recessional outwash, and is very dense and extremely broadly graded (fig. 4). Due to the condition of the tested core sample, the estimated unit weight of 140 lb/ft^3 (22 kN/m^3) is a dry unit weight. The fines content, as determined from the core sample, is over 50 percent, leading to a USCS classification of this material as a low-plasticity clay (CL) with large sand and gravel fractions. The plasticity values are plotted on the Casagrande chart for classification in figure 8. It is quite possible that larger bulk samples that better captured the coarser gravels and cobbles observed in the field would classify as a coarse-grained soil. Nevertheless, test results characterize the matrix portion of the till, which is probably more relevant to landslide behavior than a bulk classification conducted with larger samples.

Samples of the advance outwash unit have fines content close to 50 percent (fig. 5, table 1) and therefore classify as either a relatively uniform silty fine sand (SM) or a fine sandy low plasticity silt (ML). Clay-size fractions are low, less than 5 percent, as are the *PI* values, when measurable at all.

The advance glaciolacustrine unit is the thickest of the sequence and was the most thoroughly investigated. An apparent gradational contact exists with the advance outwash unit above it. All samples from this unit classify as clays with the clay-size fraction ranging from 26 percent to 66 percent, and only a few contain any measurable sand content (fig. 6). Specific gravity values are typically between 2.78 and 2.83, consistently higher than those in other units. The plasticity of these samples varies considerably, with *PI* values ranging from 20 to 45, and roughly in correspondence with the clay-size fraction as one might expect in a single geologic unit. The plasticity values are plotted on the Casagrande chart for classification in figure 9, in which distribution of low plasticity (CL) and high plasticity (CH) can be seen. Although there are some exceptions, the general trend is that the lower half of the unit has higher plasticity and is finer grained than the upper half. However, this unit shows some variation even with small changes in depth (that is, within 1 ft [30.5 cm], as shown by the somewhat different grain-size curves obtained for sample H-1-14-C72 (fig. 6). These clays showed only a moderate reduction in plasticity when oven dried and rehydrated, as measured by the change in liquid limit. For the two samples tested in this manner, the post-drying liquid limit was approximately 90 percent of its original value, indicating the material does not classify as an organic fine-grained soil.

The measured moist unit weights of the glaciolacustrine samples of between 116 to 124 lb/ft³ (18.2 and 19.5 kN/m³) are probably somewhat lower than field values due to swelling following unloading. For the same reason, the measured moisture contents of between 26 percent and 36 percent are probably upper bounds on the field values at the relevant depths.

The deepest unit investigated was the Olympia-age nonglacial deposits, which underlie the advance glaciolacustrine. Based on the limited testing of samples and examination of the core retrieved, this unit ranges from a relatively clean uniform sand (SP) to a silty sand (SM). Gradation curves for two samples from this unit are shown in figure 7.

Conclusions

The deep coring and sampling of the intact materials behind the headscarp of the March 22, 2014 SR-530 landslide have provided valuable insight into the intact sequence of geologic materials involved in the failure. The subsequent geotechnical index testing and resulting characterization of selected samples during this phase of laboratory testing generally confirms the stratigraphic sequence shown in figure 2. In addition, the data provide index-test property values of sufficient precision and spatial distribution through the stratigraphic section to begin to assist in development of geotechnical models of the landslide, and may be useful in estimating behavioral properties based on comparison with similar glacial sediments from other landslide-prone nearby areas of northwestern Washington (Savage and others, 2000).

Table 1. Geotechnical index testing data for deposits forming the March 22, 2014 SR-530 landslide near Oso, Washington

[USCS desig. = United Soil Classification System designation. No data indicates that tests either were not, or could not be, run on these samples.]

Sample no.	Depth below ground surface ¹ (ft)	Mean elev. ² (ft)	Sample type	Water content, W _c (%)	Moist unit weight, γ (lb/ft ³)	Specific gravity, G _s	Liquid limit, LL (%)	Plastic limit, PL (%)	Plasticity Index, PI (%)	Fines content (%)	Clay content (%)	USCS desig.
Recessional outwash of Everson Interstade (Qgoe)												
H-1-14-D2	39.0-40.5	850	Bulk							11	3	SW-SM
H-2-14-D1B	50.0-52.0	839	Brass liner	4.5	119.7							
H-1-14-D3	59.0-60.5	830	Bulk			2.73				14	3	SM
H-2-14-D2A	98.5-100.5	790	Brass liner	23.2	117.8							
H-1-14-D7	119.0-120.5	770	Bulk			2.73				44	5	SM
Till of Vashon Stade (Qgt_v)												
H-1-14-@176	176.0-178.0	713	Loose core		140.3 ³	2.76	40	18	22	56	22	CL
Advance outwash of Vashon Stade (Qga_v)												
H-1-14-C34A	242.5	648	Lexan tube	24.7		2.76				49	3	SM
H-1-14-C34B	245.5	645	Lexan tube	26.4		2.79	27	24	3	63	2	ML
H-2-14-C5L	271.0	619	Lexan tube			2.73	26	25	1	47	4	SM
Advance glaciolacustrine deposits of Vashon Stade (Qgl_v)												
H-1-14-C51	319.5-320.5	570	Loose core			2.81	53	21	32	98	40	CH
H-1-14-@354	353.0-355.0	536	Loose core			2.80	39	19	20	96	26	CL
H-1-14-C64	379.5-380.5	510	Loose core	26.0		2.81	58	24	34	100	45	CH
H-1-14-C72	418.0	472	Lexan tube	35.0	123.5	2.77	48	25	23	100	42	CL
H-1-14-C78	449.5-450.5	440	Lexan tube	28.6	122.2	2.78	57	24	33	100	38	CH
H-1-14-C86	487.5-490.5	401	Lexan tube	35.8	116.5	2.77	69	26	43	100	66	CH
H-1-14-C94	529.5-530.5	360	Lexan tube			2.81	70	25	45	100	57	CH
H-2-14-C9L	562.0	328	Lexan tube	26.4		2.79	54	25	29	99	35	CH
H-1-14-C103	572.0	318	Loose core			2.83	62	27	35	100	64	CH
Deposits of the Olympia nonglacial Interval (Qco)												
H-2-14-C11L	582.5	308	Lexan tube		140.0	2.76				18	3	SM
H-1-14-C114	627.5	263	Lexan tube	4.9		2.75				3	0	SP

¹Single values of depth represent those samples where the exact location of the sample is known within the core (as opposed to a range).

²Sample elevation is based upon an estimated ground surface elevation of 890±5 feet relative to NAVD88 and rounded to the nearest foot.

³For the till sample, only a dry density (γ_d) was measured (see Methods).

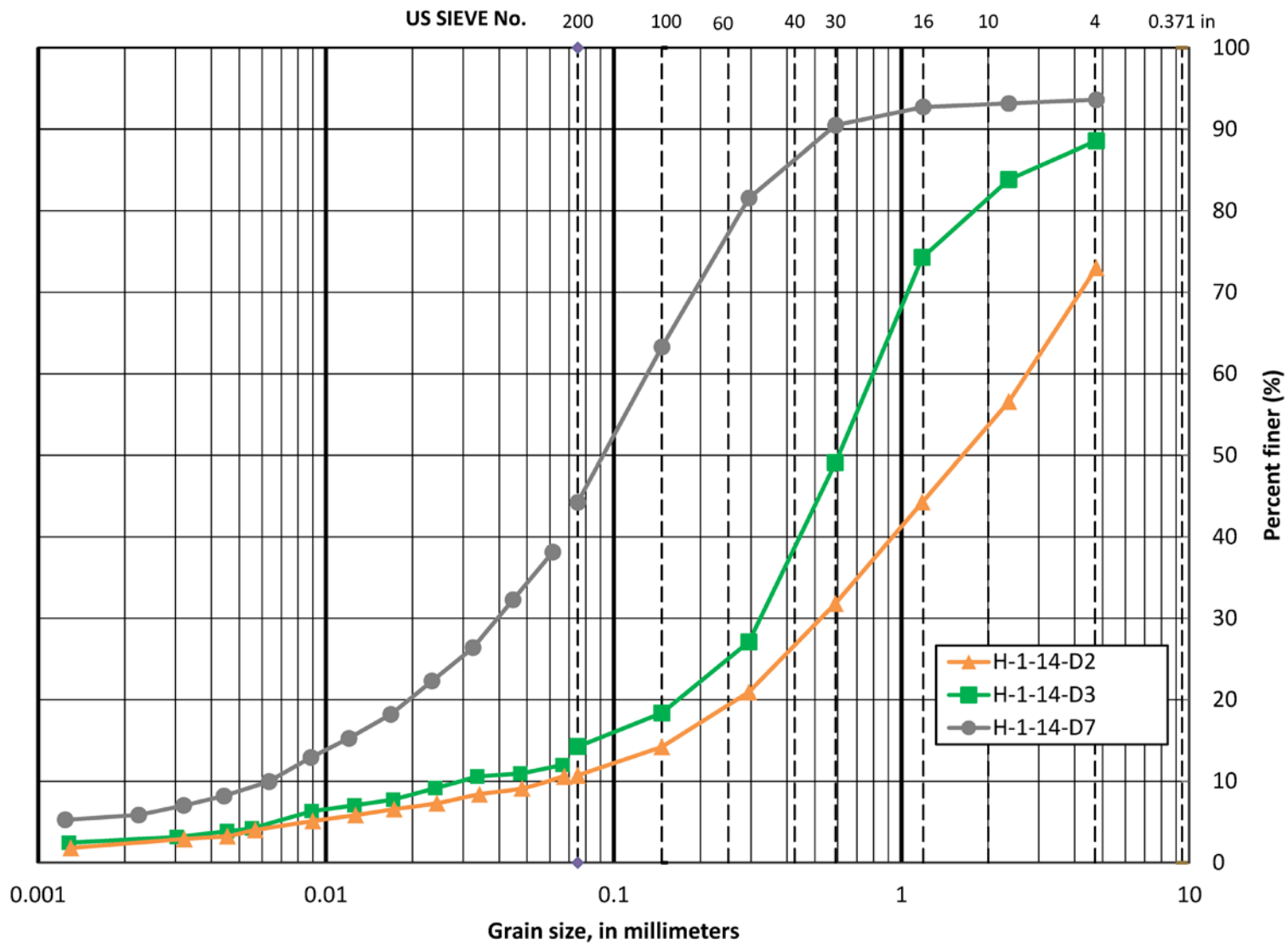


Figure 3. Grain-size curves for recessional outwash samples. Data less than the No. 200 sieve are from hydrometer testing. Data greater than the No. 200 sieve are from sieve testing.

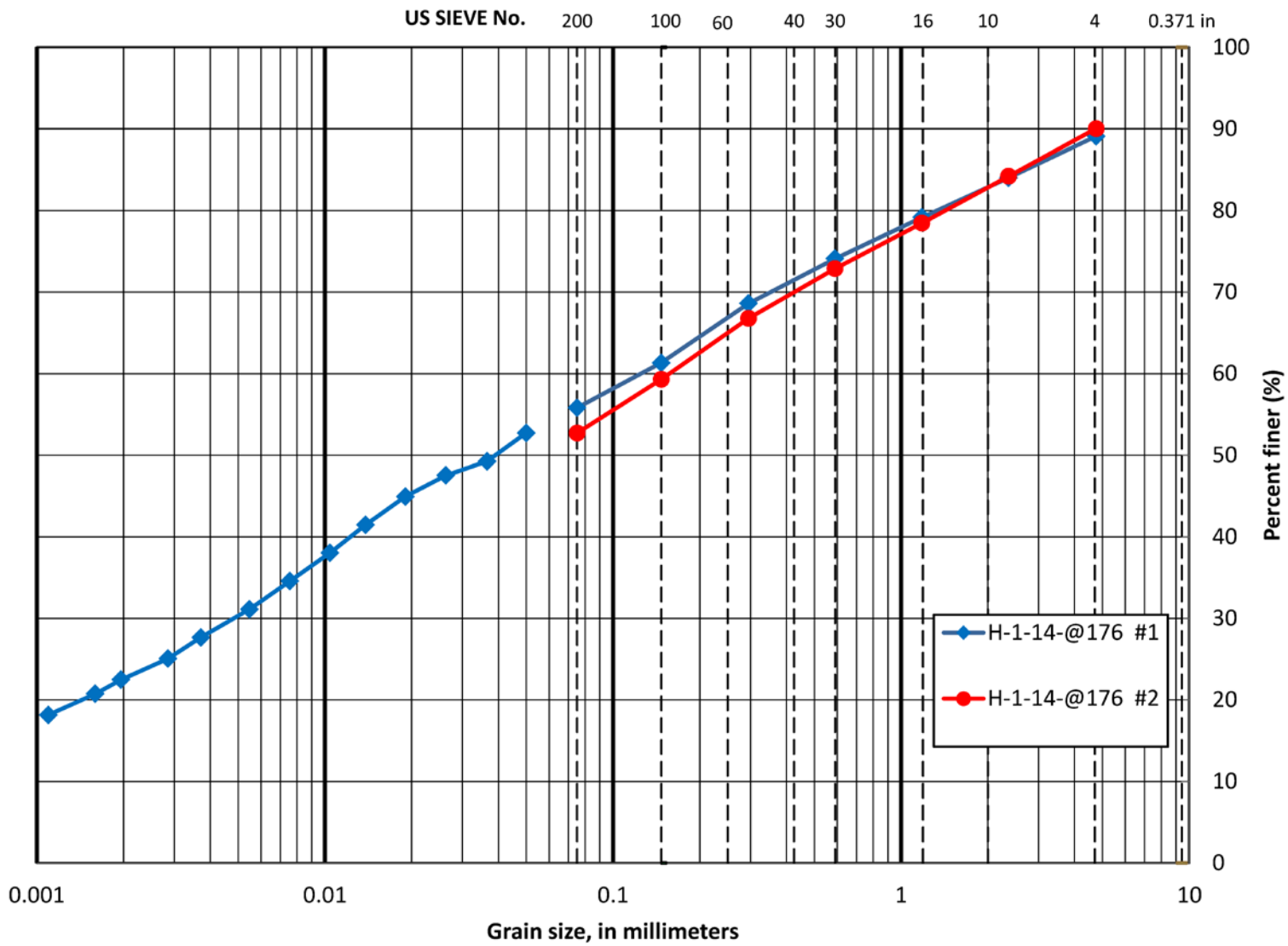


Figure 4. Grain-size curves for till samples. Data less than the No. 200 sieve are from hydrometer testing. Data greater than then No. 200 sieve are from sieve testing. Two samples were tested from the same depth as a check on consistency and mean values are reported in table 1.

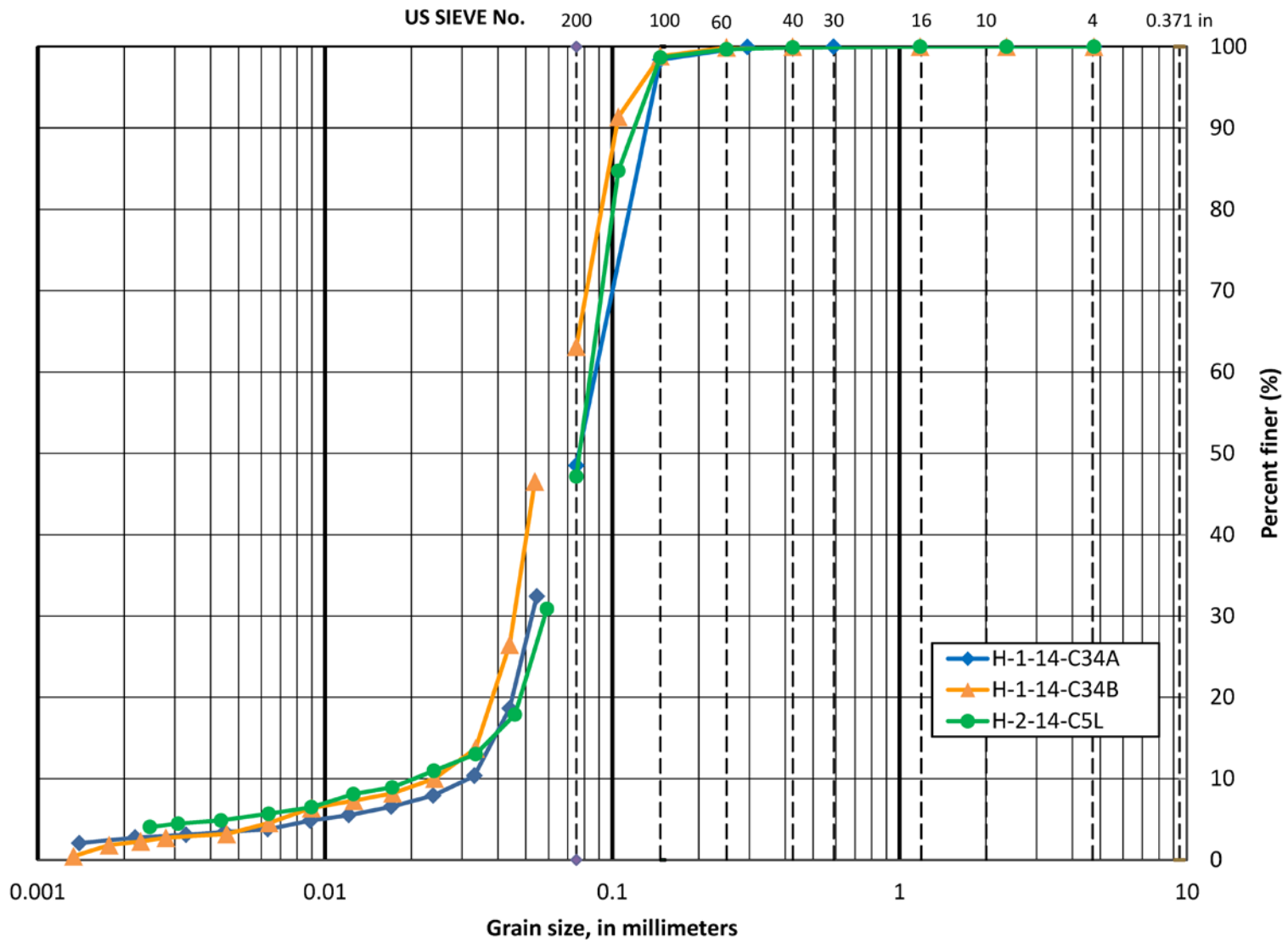


Figure 5. Grain-size curves for advance outwash samples. Data less than the No. 200 sieve are from hydrometer testing. Data greater than the No. 200 sieve are from sieve testing.

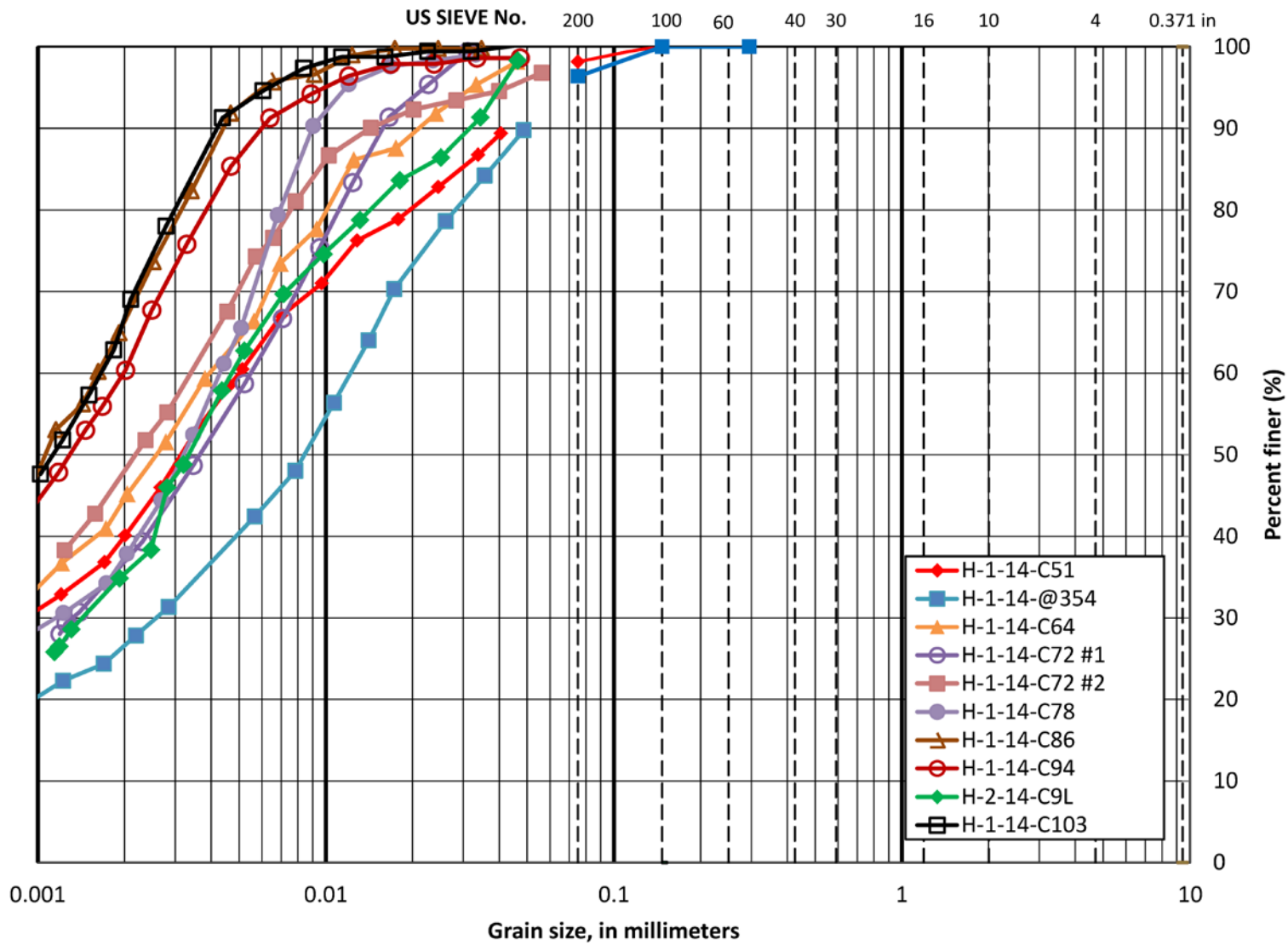


Figure 6. Grain-size curves for advance glaciolacustrine samples. Data less than the No. 200 sieve are from hydrometer testing. Data greater than the No. 200 sieve are from sieve testing. Two samples of H-1-14-C72 were tested from the same depth as a check on consistency and mean values are reported in table 1.

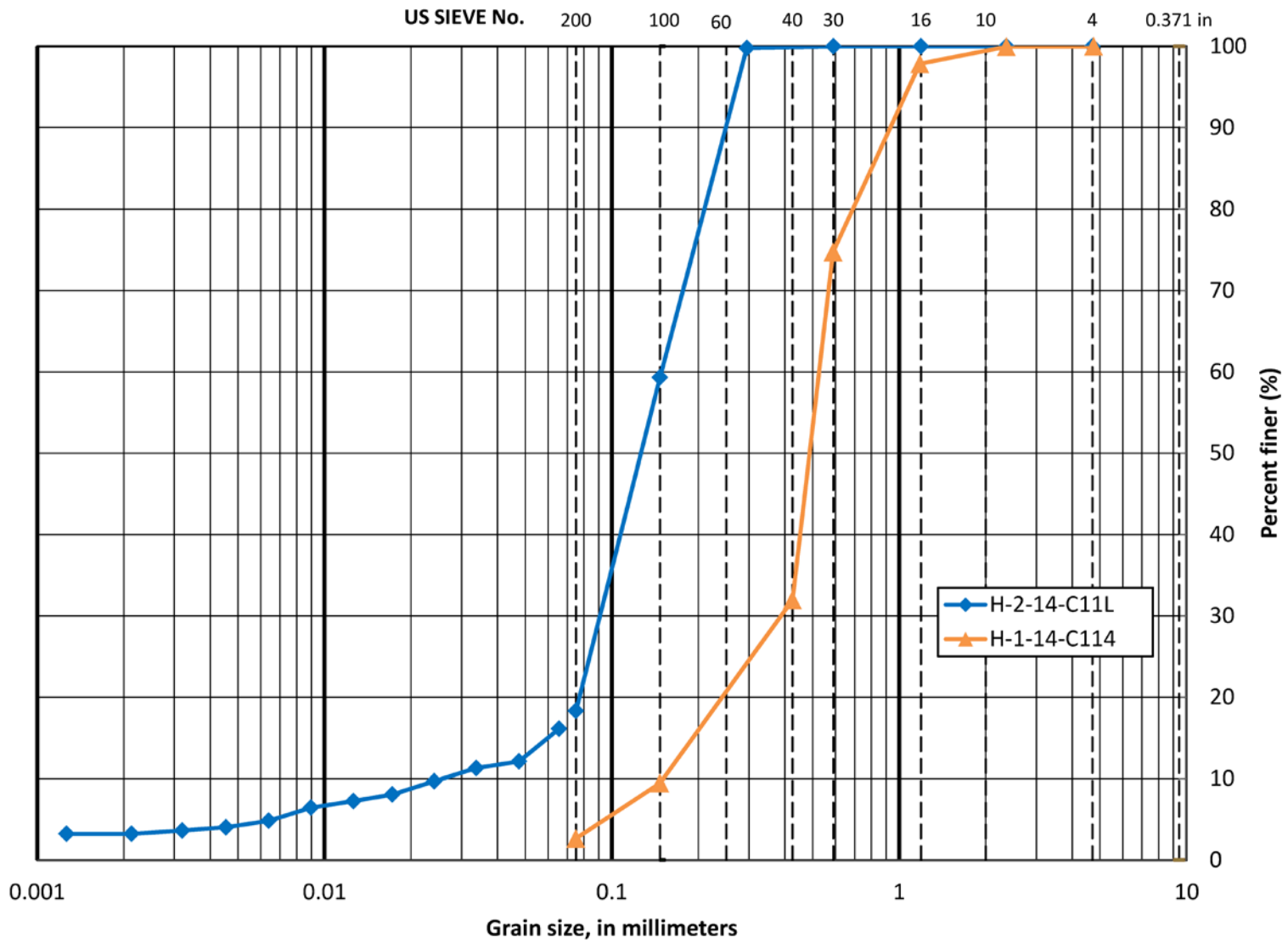


Figure 7. Grain-size curves for Olympia-age nonglacial samples. Data less than the No. 200 sieve are from hydrometer testing. Data greater than the No. 200 sieve are from sieve testing.

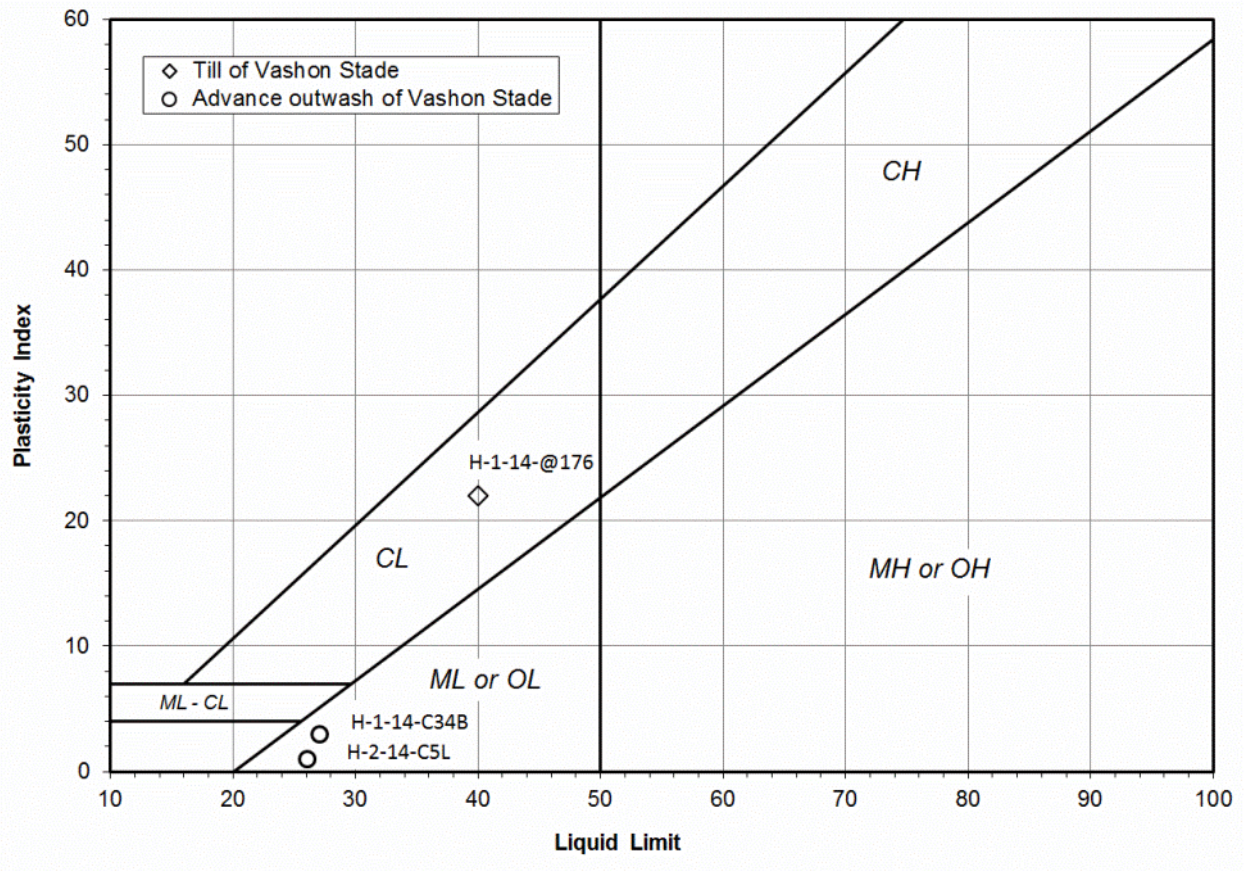


Figure 8. Plasticity chart for till and advance outwash samples. Cx = clay, Mx = silt, Ox = organic, xH = high plasticity, xL = low plasticity.

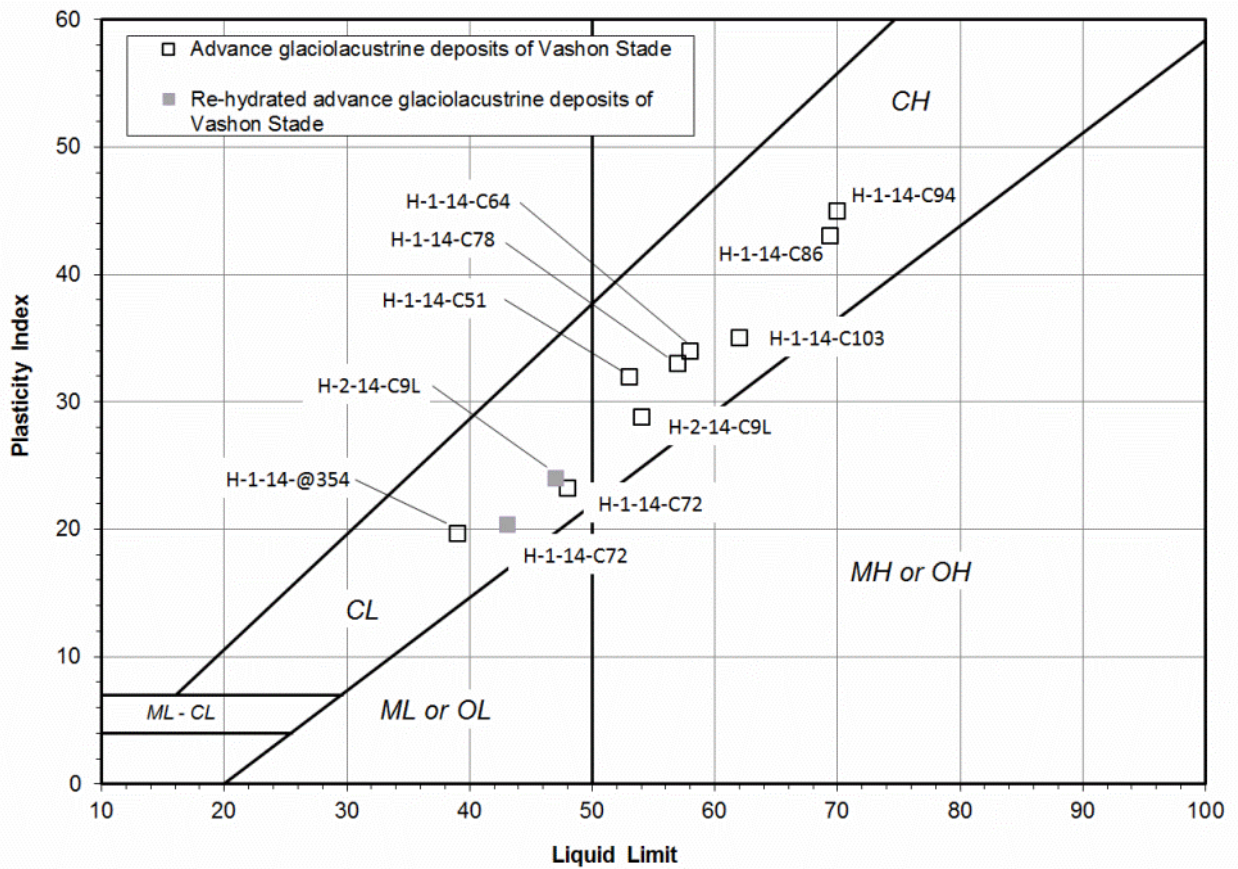


Figure 9. Plasticity chart for advance glaciolacustrine samples. Cx = clay, Mx = silt, Ox = organic, xH = high plasticity, xL = low plasticity.

References

- Baum, R.L., Godt, J.W., and Highland, L., eds., 2008, Landslides and engineering geology of the Seattle, Washington, area: Boulder, Colo., Geological Society of America, *Reviews in Engineering Geology*, v. 20, 181p.
- Dragovich, J.D., Stanton, B.W., Lingley, W.S., Griesel, G.A., and Polenz, M., 2003, Geologic map of the Mount Higgins 7.5 minute quadrangle, Skagit and Snohomish Counties, Washington: Washington State Division of Geology and Earth Research Open-File Report 2003-12, http://ngmdb.usgs.gov/Prodesc/proddesc_68677.htm
- Haugerud, R.A., 2014, Preliminary interpretation of pre-2014 landslide deposits in the vicinity of Oso, Washington: U.S. Geological Survey Open-File Report 2014-1065, 4 p., <http://dx.doi.org/10.3133/ofr20141065>.
- Iverson, R.M., George, D.L., Allstadt, K., Reid, M.E., Collins, B.D., Vallance, J.W., Schilling, S.P., Godt, J.W., Cannon, C.M., Magirl, C.S., Baum, R.L., Coe, J.A., Schulz, W.H., and Bower, J.B., 2015, Landslide mobility and hazards—Implications of the 2014 Oso disaster: *Earth and Planetary Science Letters*, v. 412, p. 197-208, <http://dx.doi.org/10.1016/j.epsl.2014.12.020>.
- Miller, D.J. and Sias, J., 1998, Deciphering large landslides—Linking hydrological, groundwater and slope stability models through GIS: *Hydrologic Processes*, v. 12. no. 6, p. 923–941, [dx.doi:%2010.1002/\(SICI\)1099-1085\(199805\)12:6%3c923::AID-HYP663%3e3.0.CO;2-3](https://doi.org/10.1002/(SICI)1099-1085(199805)12:6%3c923::AID-HYP663%3e3.0.CO;2-3)
- Savage, W.Z., Morrissey, M.M., and Baum, R.L., 2000, Geotechnical properties for landslide-prone Seattle area glacial deposits: U.S. Geological Survey Open-File Report 00-228, 6 p., <http://pubs.usgs.gov/of/2000/0228/report.pdf>.