PHYSICAL CHARACTERISTICS AND ESTIMATED HYDRAULIC CONDUCTIVITY FROM GRAIN-SIZE DISTRIBUTION FOR VASHON TILL, SOUTH-CENTRAL PUGET LOWLAND, WA

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Abstract

Population growth, urban development, and increased commercial and industrial activity in the south-central Puget Lowlands of Washington State has led to an increased demand for groundwater. The Vashon till is a glacially consolidated, low-permeability unit comprising unstratified clay, silt, cobbles and boulders with ubiquitous coarse-grained lenses and is an extensive surficial unit throughout the south-central Puget Lowland. Thus, understanding the physical and hydrological characteristics – specifically, the hydraulic conductivity – of this unit is a necessary component of a groundwater model. This study provides (1) a record of the physical characteristics of Vashon till deposits within the study area; and (2) an estimate of the highest, lowest, and average value of saturated hydraulic conductivity based on the grain-size distribution of Vashon till samples collected from six field sites in the Puyallup River Watershed. Analysis shows that the average moisture content ranges between about 1 and 6%, average dry bulk density is about 2.20 g/cm^3, and average porosity is about 17%. Grain-size distributions show that half of the samples analyzed are well graded, while the other half is poorly graded. Grain-size distributions also show an average d_{10} value of about 0.20 mm, and average f_f values $\leq$ 16%, which are key values in estimating the saturated hydraulic conductivity of over-consolidated glacial deposits. Based on these observed values, the estimates of hydraulic conductivity range from a minimum of 0.02 m/d to a maximum of 1.38 m/d in within the general Vashon till.

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1 Introduction

Population growth, urban development, and increased commercial and industrial activity in the south-central Puget Lowlands of Washington State has led to an increased demand for groundwater, which helps maintain late-summer and early-fall streamflow (Jones et al., 1999 and M. Savoca, USGS Washington Water Science Center (WSC), personal communication, 2013). The quantity of useable groundwater and the recharge patterns in this region are not well understood (M. Savoca, WSC, personal communication, 2013). In 2011, the WSC, operating within the Water Resources Mission Area of the U.S. Geological Survey, began a study of the Puyallup River Watershed (PRW) aimed at creating a hydrogeologic framework to characterize the groundwater flow patterns and interactions with surface water features within the watershed. The PRW study will combine monthly groundwater-level and synoptic stream baseflow measurements with information from driller's logs, including subsurface geology and specific capacity, to create a numerical groundwater flow model to improve the understanding of water resources within the PRW (U.S. Geological Survey, 2013 and M. Savoca, WSC, personal communication, 2013). As a contribution to the PRW study, this work provides an estimate of the saturated hydraulic conductivity for the Vashon till, an extensive surficial unit in the PRW. These estimates can be used to set the upper and lower bounds for the till unit during model calibration.

1.1 Study area

Figure 1 shows the location of the PRW, which covers about 1000 mi^2 in northeastern Pierce and southern King Counties. The study area comprises approximately the western one-third of the PRW extending from southwest of the Puyallup River northeast to the White River. The foothills of the Cascade Range mark the eastern border, while the mouth of the Puyallup River, at Commencement Bay, marks the western border of the study area.

The Vashon till (Qvt) is a glacially over-consolidated surficial deposit associated with the Vashon Stade of the Fraser glaciation (Armstrong et al., 1965) and is spatially extensive throughout the study area (see Figure 1). Hydrologic studies of the Chambers-Clover

Creek Watershed (Savoca et al., 2010), Skagit River Basin (Savoca et al., 2009) and Tacoma-Puyallup area (Jones et al., 1999) describe Qvt as a low-permeability unit comprising unstratified clay, silt, cobbles and boulders with sand and gravel lenses found throughout the unit. In the Tacoma-Puyallup area, the unit ranges in thickness from a thin veneer to about 260 ft. with an average thickness of about 70 ft. (Jones et al., 1999). Because Qvt deposits are at the surface and spatially extensive, understanding the physical and hydrological characteristics – specifically, the hydraulic conductivity – of this unit is a necessary component of the PRW groundwater model.

1.2 Hydraulic conductivity

Hydraulic conductivity (K), one of the principal components of a numerical groundwater flow model, is a measure of the ability of geologic media to transmit water; it is dependent on both the physical characteristics of the media and the fluid flowing through the media. Because we are concerned with groundwater, the physical characteristics of the fluid are essentially constant. Therefore, to describe K, only the physical characteristics of the geologic media are of concern. Values of K for geologic media are dependent on the size, shape, and distribution of the constituent grains as well as the degree of compaction of the material. Typically, the physical characteristics of glacially derived sedimentary deposits, such as Qvt, are highly variable, which lead to highly variable values of K.

For more than a century, researchers have studied the relationship between the physical characteristics and the hydraulic properties of sedimentary deposits. Hazen (1911) estimated the K of sandy sediments by considering the square of the effective grain size diameter (d_{10}), or the grain size, in mm, where 10% of the grains are finer. Since the work of Hazen, many attempts have been made to relate K to key grain-size parameters. For example, Shepherd (1989) relates K to the i-th power (where $1.65 \geq i \leq 1.85$) of the mean grain size diameter (d_{50}), or the grain size, in mm, where 50% of the grains are finer. Alyamani and Sen (1993) relate K to the initial slope and intercept of the grain-size distribution curve while Rogiers et al. (2012) estimate K by combining artificial neural networks with a generalized likelihood uncertainty estimation, or GLUE approach.

Massman (2003) and Nguyen (2013) both use a linear regression technique to estimate K values for surficial deposits in the Puget Lowland. These linear regression techniques are described in more detail below. Estimated K values reported here will be calculated using the approach of Nguyen (2013) because this approach is calibrated for over-consolidated sedimentary deposits in the Puget Lowland.

A distinction must be made between saturated hydraulic conductivity (K_{sat}) and unsaturated hydraulic conductivity. K_{sat} is the hydraulic conductivity within the saturated zone (i.e., below the water table). The unsaturated hydraulic conductivity (K_u) is a measure of the ability of a geologic media to transmit water within the unsaturated zone, between the ground surface and the water table. Flow processes within the unsaturated zone affect the rate and pattern of infiltration (Bear, 1979). As with K_{sat}, unsaturated hydraulic conductivity is also dependent on the physical characteristics of the geologic material. However, this parameter is also dependent on the volumetric water content (θ_v), which is defined as the volume of water divided by the volume of soil. θ_v influences both the gravity potential, and the moisture potential of the soil (Bear, 1979; Fetter, 1994). Fetter (1994) defines the gravity potential as the potential energy due to the position of soil moisture above a datum. The moisture potential is defined as a tensional (negative) pressure exerted on the pore water due to the attraction of the soil-water interface (Fetter, 1994). These factors can vary through time; thus the unsaturated hydraulic conductivity is expressed as a function of θ_v, denoted as $K(\theta_v)$. The relationship between $K(\theta_v)$ and θ_v is such that as θ_v increases, so does $K(\theta_v)$ (see Fetter, 1994). Equations governing flow within the unsaturated zone are nonlinear and require a substantial effort to solve (Fetter, 1994). The difficulties presented by the nonlinearity of unsaturated flow can be avoided by using the Green-Ampt infiltration model to approximate a saturated condition.

1.3 The Green-Ampt approximation

The Green-Ampt infiltration model is one of the most widely used models to estimate the infiltration rate through homogeneous soils under ponded conditions (Kale and Sahoo, 2011, and Van den Putte et al., 2013). Kale and Sahoo (2011) provide an extensive review of the Green-Ampt equation and analyzes the usefulness of several variants of the Green-Ampt infiltration model. This model assumes that a sharp wetting front is driven deeper into a soil column by (1) ponded water at the ground surface and (2) capillary suction below the wetting front. The soil is assumed to be fully saturated above the wetting front and unsaturated below the wetting front, as illustrated in Figure 2. The infiltration rate is approximated by:

$$f(t) = K_{sat}\left(1 + \frac{h_0 + h_s}{L}\right) = K_{sat} i_v, \qquad (1.1)$$

where $f(t)$ is the vertical infiltration rate as a function of time (dimenstions [L]/[t]), h_0 is the depth of ponded water at the ground surface [L], h_s is the capillary pressure (or suction) head at the wetting front [L] and L is the depth of the wetting front below the bottom of the ponded water [L] (Kale and Sahoo, 2011). Massman (2003) notes that h_s is approximately equal to the air entry pressure. The term $(1 + h_0 + h_s/L)$ in equation 1.1 represents the hydraulic gradient for vertical infiltration (i_v).

Figure 3 illustrates the general shape of the infiltration curve resulting from equation 1.1. For early time, the vertical infiltration rate is higher than K_{sat} because L is small compared to $h_0 + h_s$ (i.e., $i_v > 1$). As more water infiltrates, L becomes large compared to $h_0 + h_s$, thus i_v approaches 1 and a steady-state condition is reached where $f(t) = K_{sat}$. While different soil types will result in different infiltration rates at steady state and different time periods to reach these steady-state rates, the general shape illustrated in Figure 3 will be maintained.

1.4 Scope of work

The objectives of this study are to (1) provide a record of the physical characteristics of Qvt deposits within the study area; and (2) estimate the highest, lowest, and average value of saturated hydraulic conductivity within the general Qvt based on the grain-size distribution of the material. Samples collected from six field sites within the study area, shown in Figure 1, are analyzed to determine moisture content, grain-size distribution, bulk density, and porosity of the Qvt deposits and coarse-grained lenses. The latitude, longitude, and altitude for these field sites are given in Table 1. The general character of till is represented by 15 bulk samples (3 weathered and 12 unweathered) while 5 bulk samples represent sand and gravel lenses (see Table 1A in Appendix A). Six intact samples, collected from 3 sample sites, provide an estimate of the bulk density of Qvt deposits in the study area.

2 Regional geologic setting

The PRW study area is located in the south-central Puget Lowland physiographic province. The Puget Lowland is an elongate, slightly arcuate basin, within the forearc of the Cascadia Subduction Zone, situated between the Olympic Mountains to the west and the Cascade Range to the east. Since late Cenozoic time, north-south shortening, which results from the complex interplay between the eastward subduction of the Juan de Fuca plate beneath the North American plate, the northward migration of the Pacific plate relative to the North American plate and extension in the Basin and Range province, has been accommodated by a series of east-west to southeast-northwest-trending folds and faults (Wells et al., 1998; Sherrod et al., 2004; Blakely et al., 2002).

The tectonic signature within the Puget Lowland is overprinted by repeated Quaternary glaciations. Evidence of at least seven advances of the Puget Lobe, a portion of the Cordilleran ice sheet, is preserved in a discontinuous sequence of glacial and interglacial deposits, which can be as much as 2000 feet thick within the study area (Troost and Booth, 2008; Borden and Troost, 2001). Ice advanced south to beyond Olympia, WA during the Vashon stade of the Fraser Glaciation, the most recent glacial period. Spatially expansive areas of glacially consolidated till deposits, made up of glacially eroded and entrained material, are left behind as the continental glaciers melt and recede. Although portions of these deposits are eroded and re-worked, large areas of the surface remain covered with these till deposits. Within about 500 years, the Puget Lobe had quickly retreated, leaving the Puget Lowland ice-free (Porter and Swanson, 1998).

3 Methods

This section describes the field methods used to collect samples of Qvt deposits within the study area, and summarizes the laboratory methods used to determine the physical characteristics of these samples.

3.1 Field methods

Activities at each field site included (1) mapping sand and/or gravel lenses, and (2) material sample collection. Despite its significant spatial extent, exposures of Qvt within the study area are not easy to locate. As a result, many of the field sites described in the sections below are located in quarries and road-cuts where human intervention created exposures. It is difficult to distinguish Qvt deposits from disturbed material (e.g., fill) in the field. Interviews with workers supervising construction and/or excavation, as described below, were combined with an examination of each exposure to ensure that the below-described samples were collected in the Qvt deposits. This examination was focused on qualitatively estimating the density of the exposure and searching for foreign objects (i.e., soda cans, candy wrappers, landscape fabric, etc.).

Sand and/or gravel lense mapping involved extending a surveyor's tape perpendicular to the exposure to establish horizontal reference stations, vertical reference was established using either a stadia rod or folding ruler, depending on access and scale.

Material sampling occurred during August and involved collecting: (1) loose or bulk material for moisture content and grain-size distribution analysis; and (2) intact material, or clods, for density analysis. Bulk material sampling involved scraping 1/2" to 1" from the exposure surface to ensure that only native material was collected. Then, material was collected from the exposure by scraping the surface with a folding shovel or a rock pick. A minimum of one bulk sample was collected at each sampling site to represent the overall material (termed general Qvt), and one bulk sample was collected to represent coarse-grained lenses present and accessible in the exposure. These bulk samples ranged from about 1 kg to 4 kg. The minimum mass required to determine the grain-size distribution, based on the maximum particle size, can be as much as 75 kg (ASTM

D6913, 2009). Collection and transport of samples this large was not practical for this study; therefore, bulk samples were collected according to the minimum mass requirements for determining the moisture content (see Table 2), which are substantially smaller. Deviation from the minimum mass requirement necessary for determining the grain-size distribution is justified because the smallest diameter grain-size component of the samples control the hydraulic conductivity estimates reported in this study.

Intact samples were carefully pried from the exposure using either a folding shovel or a rock pick. The nature of the till did not lend itself to intact sampling; therefore, intact samples were taken at only sampling sites 1, 2, and 6. A portion of sample 010 was intact and used for density analysis; therefore, sample 010, collected at site 2, functioned as both a bulk and intact sample.

3.1.1 Sampling site descriptions

The locations of these sampling sites are represented by red dots in Figure 1 and tabulated in Table 1. Latitude, longitude, and altitude are recorded in the North American Datum of 1983 (NAD83) coordinate system using a Garmin Etrex 30 handheld Global Positioning System receiver.

3.1.1.1 Site 1

Site 1 is located at the southwest corner of Columbia Vista Phase II, a residential housing community developed by Newland Communities. This development is 2.5 miles northeast of Orting, WA. Two sets of samples, from two locations about 60 ft. apart, were collected at site 1. The first set of samples, including two bulk samples and one intact sample, is from an approximately 3.5-ft. deep, 5.0-ft. wide and 150-ft. long trench on the west side of, and parallel to Overlook Dr. E (see Figure 4). This trench was cut into native material (K. Ghormley, Rickabaugh Pentecost Development, personal communication, 2013) and is used for the placement of buried utilities. The overall material is very dense with sub-rounded to rounded, medium to coarse gravel and cobble supported by a gray matrix that is slightly platy. There were no obvious coarse-grained lenses in the trench. The second set of samples, including two bulk samples and three intact samples, is from a road-cut on the east side of Overlook Dr. E (see Figure 5), which is cut into a hill that provides local fill material for the housing development (K. Ghormley, Rickabaugh Pentecost Development, personal communication, 2013). The exposure is about 40 ft. long and a maximum of about 7.5 ft. high. The overall character of the material in the exposure is identical to the material in the trench.

3.1.1.2 Site 2

Site 2 is located near an active gravel quarry owned and operated by Corliss Resources, 1.8 miles east of Sumner, WA. The site and surrounding area are hummocky suggesting that this material was deposited beneath stagnant ice (K. Troost, University of Washington, personal communication). The samples were collected from a road-cut along a primitive road. The exposure ranges from about 4.0-ft. to 6.0-ft. tall and approximately 50-ft. long. The upper 1.5-ft. to 2.5-ft. is composed of rounded to sub-rounded gravel and cobble set in a light tan, fine matrix with abundant roots and plant material; this horizon is interpreted as a weathered horizon. Below the weathered horizon, the material is gray to light tan, competent, and slightly platy (see Figure 6). This lower horizon is consistent with the general character of Qvt deposits observed at other sites. Three gravel lenses, ranging from less than 1 ft. to about 5.0 ft. long and less than 1.0 ft. wide, were observed in the exposure; Figure 7 is a close-up view of one of these gravel lenses. These lenses are oriented approximately horizontal. Also, four tight fractures, with generally horizontal orientations, were observed in the exposure. These are low persistence (< 5.0 ft.) fractures with both termination points visible. Two bulk samples collected from the weathered horizon, three bulk samples collected from the general Qvt horizon, and one bulk sample collected from a gravel lens are included in this study.

3.1.1.3 Site 3

Site 3 is located along a primitive road 1.5 miles northeast of Electron, WA near the King Creek Pit, a sand and gravel quarry owned and operated by Washington Rock Quarries, Inc. One sample of weathered Qvt was collected from a road-cut, which is located in a heavily wooded area. The road-cut was mantled with loose material and vegetation (see Figure 8). No discontinuities were observed at this location.

3.1.1.4 Site 4

Site 4 is located 3.4 miles southeast of Tacoma, WA on the right bank of Swan Creek. The exposure, shown in Figure 9, is about 15 ft. long and a maximum of about 6.5 ft. high and located in a heavily vegetated area. Overall, the exposure is moist and dark brown with grain sizes ranging from sandy silt to small boulders. An approximately 2-ft. thick sand lens that extends across the exposure is bound on top and bottom by matrix-supported gravel and cobble horizons indicative of Qvt. One bulk sample from each of these horizons and the sand lens are included in this study.

3.1.1.5 Site 5

Site 5 is located in a sand and gravel quarry, owned and operated by Lloyd Enterprises, Inc., 2.1 miles northeast of Fife, WA. The exposure at this site, shown in Figure 10, is about 75 ft. long and an estimated 35 ft. high. Much of the exposure is inaccessible because of a steep (~40°) embankment at the foot of the exposed wall. Overall, the material is very very dense, with sub-rounded to rounded gravel and cobble supported by a light gray matrix. Multiple coarse-grained lenses can be observed extending tens of feet across the exposure. These lenses range from <1 ft. to 3 ft. thick and are generally oriented horizontally. Vertically, these lenses are randomly distributed, separated by as little as 1.0 ft. in some places and as much as 10 ft. in others. A set of two approximately parallel vertical fractures can be observed near the center of the exposure. The fractures are separated by about 1.0 to 1.5 ft. and are about 15 ft. long with both termination points visible. Other physical characteristics of these fractures cannot be determined because they are inaccessible. One bulk sample representing the general Qvt, and one bulk sample representing an accessible coarse-grained lens are included in this study.

3.1.1.6 Site 6

Site 6 is located 2.0 miles north of Orting, WA and 1.8 miles west of Site 1. This site is used as a source of backfill material for the Tehaleh housing community currently under development by Newland Communities. The exposure at Site 6, shown in Figure 11, is about 75 ft. long and between 6.0 and 8.0 ft. tall. Two coarse-grained lenses, oriented horizontally, extend about 45 ft. from the western edge of the exposure. These lenses range from about 1.0 to 2.0 ft. thick and are vertically separated by about 2.0 ft. Three bulk samples of the general Qvt, one bulk sample of the lower coarse-grained lens, and one intact sample of the general Qvt are included in this study.

3.2 Laboratory methods

Field-collected samples were analyzed in the Applied Geosciences laboratory, located in the Atmospheric Sciences and Geophysics building at the University of Washington, Seattle campus. The ASTM Standards listed below guided laboratory procedures. Deviations from the standard test methods are described where appropriate in the following sections. Unless otherwise noted, an Acculab V-4800 scale with 4800 g capacity and 0.1 g readability was used to weight samples as needed. The accuracy of this scale, determined using calibration weights ranging from 100 g to 1000 g, was determined to be within 0.1% of the known weight. A Central Scientific, model L-5 oven was used to dry the samples as described below. A Humboldt Economy sieve shaker with a 30-minute timer was used to determine the grain-size distribution as described in section 3.2.4 of this report. The samples were analyzed to:

1. Determine moisture content as outlined in ASTM D2216-10;
2. Describe soil within the Unified Soil Classification System (USCS) using the procedure outlined in ASTM D2487-00;
3. Wash samples to separate material finer than No. 200 sieve as outlined in ASTM C117-13;
4. Re-dry samples as outlined in ASTM D6913-13;
5. Determine gradation using sieve analysis as outlined in ASTM D6913-13, Method A, and ASTM C136-06; and
6. Determine the bulk density of intact specimens per ASTM D7263-09.

3.2.1 Moisture content

Two test methods, Method A and Method B, are described in ASTM D2216-10 and can be used to determine the moisture content (w) of a soil sample. These two methods differ in the amount of significant digits reported and the size of the specimen required to perform the test. Moisture content is recorded to the nearest 1% in Method A, and 0.1% in Method B. Method A is the standard test method and will be used for this analysis.
To determine the moisture content of a material, a test specimen is dried in an oven at 110 ± 5°C to a constant dry mass. The constant dry mass of a material is attained when further heating will cause less than 1% (Method A) additional loss in mass (ASTM D2216, 2010).

The minimum test specimen mass considered representative of the field-collected sample is based on a visual estimation of the maximum particle size for each sample. Table 2 shows the minimum requirements for test specimen mass and balance readability.
The procedure for determining the moisture content of a material is outlined in section 10 of ASTM D2216-10 and is summarized below.

1. Record the mass of the clean and dry specimen container and the associated identification number.
2. Select the representative test specimen as outlined in section 9 of ASTM D2216-10.
3. Place the test specimen in the container. Determine and record the mass of the container and moist test specimen to the accuracy listed in Table 2.
4. Place the container and moist test specimen in the drying oven. Maintain the drying oven temperature at 110 ± 5°C until the test specimen has reached a constant mass. A quick test, outlined in section 10.4.1 of ASTM D2216-10, to determine if a specimen > 100 g is dry involves placing a small piece of torn paper on top of the sample while it is in the oven. If the paper curls, the specimen is not dry.
5. After reaching a constant mass, remove the test specimen and container from the drying oven and allow it to cool to room temperature. Determine and record the

mass of the container and dried test specimen using the same type and capacity balance used in step 3 above.

The moisture content of a material sample is defined as the ratio of the mass of water contained in the pore spaces of the material to the mass of the solid portion of the material, expressed as a percentage (ASTM D2216, 2010). This definition is mathematically expressed as:

$$w = \left(\frac{M_W}{M_S}\right) 100, \qquad (3.1)$$

where w is the moisture content expressed as a percentage, M_w is the mass of water contained in the pore spaces of the material (g) and M_s is the mass of solid material (g).

The mass of pore water in the test specimen is determined using:

$$M_w = M_{cms} - M_{cds}, \qquad (3.2)$$

where M_{cms} is the mass of the container and moist test specimen and M_{cds} is the mass of the container and the dry test specimen. The mass of the oven-dried specimen is determined using:

$$M_s = M_{cds} - M_c, \qquad (3.3)$$

where M_c is the mass of the container. Result from equations 3.2 and 3.3 are then input into equation 3.1 to determine w. There are no assumptions related to the calculation of w. The accuracy of this calculation is based on the accuracy of the scale and the degree to which a constant dry mass was achieved. Each sample was dried overnight and weighed to be sure that a constant dry mass, as defined above, was achieved. Also, the standard notes that variation in the data is just as likely to be the result of specimen variation as operator or laboratory testing variation (ASTM D2216, 2010). Therefore, values for w are considered accurate to within ± 1.0% as prescribed in ASTM D2216-10.

3.2.2 Soil description

Field-collected samples were described within the USCS as outlined in ASTM D2487-00. Grain-size parameters, descriptive information, and simple manual tests were used to assign a group symbol(s) and name according to flow charts detailed in the abovementioned standard. Descriptive information should include: angularity, shape, color, odor, moisture condition, HCL reaction, consistency, cementation, structure, the range of particle sizes, the maximum particle size (e.g., sand, gravel, etc.), and hardness. One should also note the presence of recognizable roots and/or micas, and the local commercial or geologic name. Descriptions of consistency, cementation and structure are only applicable to intact soil samples. The designations assigned to each soil contains a two or four letter symbol indicating the dominant grain size; the degree of sorting, for samples with < 50% fines, or the plasticity, for samples with ≥ 50% fines; and a secondary grain size if a sand (S) or gravel (G) has between 5% and 12% fines. There are no assumptions associated with this method. The uncertainty associated with this method is dependent on the precision of the grain-size parameters as determined by the grain-size distribution analysis described in section 3.2.4 of this report.

3.2.3 Soil wash

ASTM C117-13 outlines two procedures for determining the amount of fines, defined as material finer than a No. 200 (75 μm) sieve, by washing. Procedure A uses only water, while Procedure B calls for using a wetting agent to assist the loosening of fines from the more coarse material. Procedure A was used for this study.

The field-collected samples were dried to a constant mass, as described in section 3.2.1 of this report. Then, each sample was placed in a container large enough to contain the sample covered with water. In most cases, the sample was too large to fit in the container with water. In such cases, the below-described procedure was carried out on a portion of the sample, and then repeated for the remainder of the sample. The container with the sample, or sample portion, and water was vigorously agitated in order to result in the suspension of fines in the water. Then, the wash water with the suspended fines was poured over a set of two nested sieves, with the No. 100 (150 μm) sieve on top, and No. 200 (75 μm) sieve on bottom. Any material retained on the sieves was returned to the sample container. This procedure was repeated until the wash water contained no (or very little) suspended material after agitation. The sample was then re-combined, if portioned, and oven-dried to a constant dry mass.

The mass of fines passing the No. 200 (75 μm) sieve be washing is determined using:

$$A = \left(\frac{(M_d - C)}{M_d}\right) 100, \qquad (3.4)$$

where A is the percentage of fines, M_d is the original dry mass of the sample in grams, and C is the post-wash dry mass of the sample in grams. The uncertainty for this procedure is calculated by dividing the mass of material passing the No. 200 (75 μm) sieve using sieve analysis, described in the following section, by the mass of material (M_d - C) washed. The average uncertainty is ± 0.14% with a high value of 0.46% (sample numbers 010 and 014) and a low value of < 0.01% (sample number 021). The average uncertainty is consistent with the single-operator precision of ± 0.1% reported in ASTM C117-13, which is based on the analyses of more than 100 paired test results from 40 to 100 laboratories.

3.2.4 Grain-size distribution

ASTM D6913-04 and ASTM C136-06 guided the grain-size distribution analysis for this study. Field-collected samples were placed on the coarsest sieve at the top of a set of nested sieves with progressively smaller openings, then mechanically shaken for at least 10 minutes. The mass of particles retained on each sieve is determined and used to calculate the percent of the material passing through each sieve. Two methods for determining the grain-size distribution are outlined in ASTM D6913-04. Method A requires determining the percentage (by mass) passing each sieve size to the nearest 1%, whereas Method B requires determining the percentage to the nearest 0.1%. Method A is used for this report.

Brass sieves used in this analysis are 8-inches (200-mm) in diameter and are 2-inches (50-mm) deep. The sieve set used in this analysis, listed in Table 3, deviated slightly from the standard sieve set listed in section 6.1.1 of ASTM D6913-04. The oven-dried samples from the soil wash analysis, described above, were used for this grain-size distribution analysis. Each sample was divided into several portions, which were sieved separately to reduce the occurrence of sieve overloading. Sieve overloading occurs when all particles do not have an opportunity to reach a sieve opening several times during the sieve shaking process. The overloading limit for each sieve is listed in Table 3. If any sieve was overloaded by at least two times the limit (e.g., ≥ 40 g of material on the No. 200 sieve), the sample was divided and re-sieved in accordance with section 11.3 of ASTM D6913-04. If any sieve was overloaded by less than two times the limit, the sample was re-sieved, without being divided, until no more than 1% by mass of the material passed the overloaded sieve during 1 minute of continuous hand sieving as directed by section 8.4 of ASTM C136-06.

The mass (g) retained for each N^{th} sieve (MR_N) was used to calculate the cumulative mass (g) retained for each N^{th} sieve (CMR_N) by:

$$CMR_N = MR_{N-1} + MR_N. \qquad (3.5)$$

Results from equation 3.5 were used to calculate the percent passing (or percent finer by weight) each N^{th} sieve (PP_N) by:

$$PP_N = 100\left(1 - \frac{CMR_N}{M_d}\right), \qquad (3.6)$$

where M_d is the original dry mass as defined in section 3.2.3 of this report. There are no assumptions associated with the grain-size distribution analysis. Uncertainty is calculated by using:

$$100\left(\frac{CMR_t}{M_d}\right), \qquad (3.7)$$

where CMR_t is the total cumulative mass retained for all sieves. Results from equation 3.7 indicate that the grain-size distributions are accurate to ± 0.1%. A detailed record of the above grain-size parameters for each sample is listed in Appendix B.

Grain-size distribution curves were made for each bulk material sample by plotting PP_n against the grain-size diameter where the PP_n axis is linear and the grain-size diameter axis is logarithmic (see Figures 12 through 15). A linear interpolation method was used for grain-size values between 75 mm (3” sieve) and 75 µm (No. 200) and a spline interpolation method was used for grain-size values between 75 µm (No. 200) sieve and an assumed value of 1 µm, which represents the fine material fraction.

3.2.5 Bulk density

Two methods to determine the moist and dry densities of soil specimens are described in ASTM D7263-09. These methods may be used on intact samples collected from thin-walled sampling tubes, block samples or clods. For Method A, the quantity of water displaced is used to determine the volume of a wax-coated sample. Method B requires the direct measurement of the dimensions and mass of a specimen. For this study, intact samples in the form of clods are analyzed using Method A.

An Ohaus 700 series triple beam balance with a 610 g capacity and 0.1 g readability was used to measure the mass of specimens used in the bulk density analysis. This scale can operate as a hanging scale, which is necessary to determine the submerged mass as described below. The accuracy of this scale, determined using calibration weights ranging from 100 g to 1000 g, was determined to be within 1% of the known weight. The mass (g) of each field-collected intact sample (M_t) was determined and recorded; then the sample was coated in melted beeswax and allowed to cool. The mass (g) of each wax-coated sample in air (M_C) was determined and recorded. The mass (g) of each wax-coated sample submerged in water (M_{sub}) was determined and recorded along with the temperature of the water (to the nearest 1°C). The moist density for each sample is determined by:

$$\rho_m = M_t/[((M_C - M_{sub})/\rho_w) - ((M_C - M_t)/\rho_{wax})], \qquad (3.7)$$

where ρ_m is the moist density of the sample (g/cm^3), ρ_w is the density of water (g/cm^3) at the measured temperature, and ρ_{wax} is the density of the beeswax (g/cm^3). The dry density of the sample is determined by:

$$\rho_d = \rho_m/\left(1 + \frac{w}{100}\right), \qquad (3.8)$$

where ρ_d is the dry density of the sample (g/cm^3), and w is the moisture content of the sample. For this analysis, values of w, determined from bulk samples (as described in section 3.2.1 of this report) collected at the same sample site, were used in equation 3.8.

There are no assumptions associated with the bulk density analysis. A ρ_{wax} of 0.91 ± 0.05 g/cm^3 was used in equation 3.7. This value was calculated by making three 'pucks' of known volume using the wax, recording the mass of these pucks, then dividing the mass by the volume to get the density of the pucks. The uncertainty in the ρ_{wax} value represents half of the largest difference in the densities of the three pucks – i.e., the maximum value was 0.96 g/cm^3 and the minimum value was 0.86 g/cm^3. The temperature of the water during the testing procedure ranged from 24°C to 21°C. These correspond to a ρ_w of 0.998 g/cm^3 (from Appendix 14 in Fetter (1994)). A change in ρ_{wax} of ± 0.05 g/cm^3 results in a small (< 5%) change in ρ_m and ρ_d. The relationship between ρ_{wax}, ρ_m, and ρ_d is such that an increase in ρ_{wax} leads to a decrease in ρ_m and ρ_d.

3.2.6 Porosity

The porosity (n), or void spaces between particles expressed as a percentage, can be calculated by:

$$n = 100\left[1 - \left(\frac{\rho_d}{\rho_p}\right)\right], \qquad (3.9)$$

where ρ_p is the particle density. The porosity of sedimentary deposits is largely a function of the shape, packing, and size range of the constituent grains (see Fetter, 1994). Grain shape influences the packing arrangement of the grains, thereby influencing the porosity. Sphere-shaped grains pack more tightly and have less porosity than other grain shapes (Fetter, 1994). The range of grain-sizes is likely to have greater influence on porosity compared to grain shape and packing. A large range in grain-sizes – i.e., well graded – leads to a decrease in porosity because smaller particles will fill the void spaces created by the larger grains. For this report, ρ_p is assumed to be 2.65 g/cm^3 because that is the particle density for most soil and rock (Fetter, 1994). A change in ρ_{wax} of ± 0.05 g/cm^3 results in a change in porosity of about 9%. The relationship between ρ_{wax} and n is such that an increase in ρ_{wax} leads to an increase in n.

4 Analytical Approach

This section describes how the grain-size distributions of field-collected samples are used to estimate the hydraulic conductivity of Qvt deposits within the study area.

4.1 Estimates of hydraulic conductivity from grain-size distribution

Massman (2003) derived estimated values of K_{sat} from laboratory measured air conductivity through natural and synthetic material ranging from poorly graded coarse sand to well-graded silty sand. These K_{sat} estimates were linearly regressed to derive the following equation describing the relationship between K_{sat} and grain-size distribution:

$$\log_{10}(K_{sat}) = -1.57 + 1.90d_{10} + 0.015d_{60} - 0.013d_{90} - 2.08f_f, \qquad (4.1)$$

where d_{10}, d_{60}, and d_{90} are the grain-sizes (mm) at which 10, 60 and 90% respectively, of the material by weight are smaller, and f_f is the weight fraction of material that passes the 75 μm (No. 200) sieve.

Glacially over-consolidated deposits, such as Qvt, are common throughout the Puget Lowland. Over consolidation results from being over-ridden by an advancing continental glacier as the weight of the ice compresses the underlying sediment. This compression results in decreased permeability due to a decrease in pore size. Recent work by Nguyen (2013) shows that these over-consolidated deposits should be analyzed separately from normally consolidated and unconsolidated deposits. Using a similar linear regression technique as Massman (2003), Nguyen derived the following equation to better estimate K_{sat} for over-consolidated deposits in the Puget Lowland from the grain-size distribution:

$$\log_{10}(K_{sat}) = 0.88 + 1.01d_{10} - 7.59f_f. \qquad (4.2)$$

Unlike Massman (2003), Nguyen (2013) compared estimated K_{sat} values based on grain-size distributions with field-determined K_{sat} values from infiltration tests. This method leads to a robust estimate because estimated K_{sat} values are compared with in-situ K_{sat} values. Equation 4.2 indicates that K_{sat} is wholly controlled by the smallest grain-size components – i.e., d_{10} and f_f. No assumptions are associated with using equation 4.2 and Nguyen (2013) argues that equation 4.2 results in estimated K_{sat} values that are accurate to within ± one order of magnitude.

5 Results

Results of the laboratory and analytical procedures, described in sections 3 and 4 of this report are presented below. Laboratory procedures were focused on determining the physical characteristics of Qvt deposits within the study area. Estimates of the hydraulic conductivity from the analytical procedures described in section 4 are presented in section 5.2.

5.1 Physical characteristics of Qvt deposits

Physical characteristics of Qvt deposits within the study area include (1) the moisture content; (2) the grain-size distribution and USCS soil classification; (3) the moist and dry bulk density; and (4) the porosity. A detailed accounting of these characteristics arranged by sample number can be found in Table 1A. The following sections describe the physical characteristics with respect to the type of feature represented. These features include the general Vashon till (Qvt), weathered Vashon till (Qvt-w), sand lenses (S.L.), and gravel lenses (G.L.).

5.1.1 Moisture content

Moisture content of the Qvt samples is summarized in Table 4(a). The average moisture content is low, about 3% for Qvt and Qvt-w and about 6% for S.L. features. Average moisture content is particularly low (< 1%) in G.L. features. These low ratios are likely due, at least in part, to the sampling season. The samples were collected during August, during the height of the dry season in western Washington; therefore, low values of w can be expected.

5.1.2 Grain-size distribution and USCS soil classification

The uniformity coefficient (C_u) and coefficient of curvature (C_c) are dimensionless numbers that indicate if a material is well or poorly graded. C_u is the ratio of d_{60} to d_{10} (i.e., $C_u = d_{60}/d_{10}$), while C_c is the ratio of the square of the d_{30} to the product of d_{60} and d_{10} (i.e., $C_c = (d_{30})^2/[d_{60}]\,[d_{10}]$). Sand is classified as well-graded if $C_u \geq 6.0$ and $1.0 \leq C_c \leq 3.0$. Gravel is classified as well-graded if $C_u \geq 4.0$ and $1.0 \leq C_c \leq 3.0$. If these conditions are not met, the material is classified as poorly graded (ASTM D2487, 2000). Values of C_u and C_c for each sample are given in Table 1A.

Figure 12 shows the grain-size distribution curves for the 12 Qvt samples. Of these samples, 5 are well graded and 7 are poorly graded. The maximum C_u value is about

1500 and the minimum C_u value is about 20. The C_c value for Qvt samples ranges between about 0 and 21. The shape of the grain-size distribution curve for sample 020 is indicative of a gap-graded material. A gap-graded material is one that is missing one or more grain-size(s) and is well graded with respect to the remaining grain-sizes. Gap grading is not reflected in the C_u value and is indicated only by the shape of the grain-size distribution curve. The d_{10} values range between 0.03 mm and 0.58 mm with an average value of 0.22 mm. The f_f value ranges from 1.0% to 19% with an average value of 9.0%.

Figure 13 shows the grain-size distribution curves for the three Qvt-w samples. One Qvt-w sample is well graded and two are poorly graded, with a maximum C_u value of about 410 and minimum C_u value of about 55. The C_c value ranges between about 0 and 3 for the Qvt-w samples. The d_{10} value ranges between 0.04 mm and 0.50 mm with an average value of 0.20 mm. The f_f value ranges from 4.0% to 23% with an average value of 16%.

Figure 14 shows the grain-size distribution curves for the three samples collected from S.L. features. All three S.L. samples are poorly graded. The C_u value for these samples ranges between about 2 and 39, and the C_c value ranges between about 0 and 1. The shape of the grain-size distribution curve for sample 022 indicates that it is gap-graded. The d_{10} value ranges between 0.17 mm and 0.33 mm with an average value of 0.26 mm. The f_f value ranges from 2.0% to 4.0% with an average value of 3.0%.

Figure 15 shows the grain-size distribution curves for two samples collected from G.L. features. Both G.L. samples are well graded. Samples 009 and 016 have C_u values of 7.0 and 4.9; and C_c values of 1.8 and 1.6 respectively. The d_{10} value ranges between 5.97 mm and 7.12 mm with an average value of 6.54 mm. The f_f value ranges from 2.0% to 4.0% with an average value of 3.0%.

5.1.3 Bulk density

The average, minimum and maximum moist and dry bulk densities determined from intact Qvt samples are presented in Table 4(b). The values for moist and bulk densities are essentially identical due to the low moisture content for bulk samples, as presented in section 5.1.1 of this report. An inspection of equation 3.8 shows that as w increases, ρ_d decreases and widens the gap between ρ_m and ρ_d. The average ρ_d is within about 17% of the assumed density of rock and soil particles of 2.65 g/cm^3 indicating that the general Qvt is highly compacted.

5.1.4 Porosity

Values for the porosity are provided in Table 4(a). Typical porosity values for glacial till range from 10 – 20% (see Fetter, 1994). This typical range of porosity is low relative to other typical sediments such as well-sorted sand or gravel (n = 25–50%), silt (n = 35–50%), and clay (n = 35–60%) (see Fetter, 1994). The average and minimum porosity, determined herein, of about 17% and about 12%, respectively are within the typical porosity range for till. The maximum value of about 21% is just outside the typical porosity range for till.

5.2 Hydraulic conductivity of Qvt deposits

This section includes a summary of the hydraulic conductivity values for Qvt deposits in the study area.

The minimum, maximum, and average values of K_{sat} for Qvt, Qvt-w, S.L., and G.L. features are presented in Table 5. The average K_{sat} value for Qvt is 0.39 m/d with a minimum value of 0.02 m/d and a maximum value of 1.38 m/d. K_{sat} values range from 0.01 to 0.74 m/d for Qvt-w samples, with an average of 0.25 m/d. K_{sat} values range from 0.34 to 0.69 m/d, with an average of 0.54 m/d for S.L. features. The average K_{sat} value for G.L. features is 2.80 x 10^6 m/d, which is likely incorrect, indicating that there is some upper limit on the d_{10} and f_f grain size for which equation 4.2 is applicable.

Average K_{sat} values for the Qvt and Qvt-w features generally agree with values typical of till (see Fetter, 1994). Both of these values are one order of magnitude lower than the median value reported in Savoca et al. (2010). The maximum and minimum K_{sat} values for Qvt and Qvt-w are one to three orders of magnitude lower than those reported in

Jones et al. (1999) and Savoca et al. (2010). However, these previous studies use estimates of hydraulic conductivity from specific capacity data gathered from driller's logs for municipal, industrial and private water supply wells. Also, there are only a handful of these wells completed in the Vashon till that are used to calculate these estimates. Thus, it is likely that the previously reported values are over-estimates because the wells are likely completed in coarse-grained lenses that are not representative of the Qvt deposits.

Minimum, maximum and average K_{sat} values for S.L. features are relatively consistent, considering the typical range of K_{sat} values for poorly graded sands range from about 0.8 to 80 m/d (Fetter, 1994). This consistency is likely a reflection of the low sample count. However, this consistency also reflects the similarity in grain-size portions.

6 Limitations

The following limitations should be considered when judging the appropriateness of this analysis.

- Grain-size distributions are considered representative of the feature sampled (e.g., Qvt-w, G.L., etc.). Just as there is variation between the grain-size characteristics of the general till, there is likely variation in the grain-size characteristics of the weathered till and coarse-grained lenses.
- The physical characteristics, and related hydraulic conductivity values are based on a modest number of samples.

7 Summary and Conclusions

Increased groundwater demand in the south central Puget Lowlands has prompted the WSC to begin a study of the PRW that will culminate in a groundwater flow model. The Vashon till, or Qvt, is an extensive surficial deposit in the western third of the PRW composed of clay, silt, cobbles and boulders with sand and gravel lenses. The physical characteristics of this unit can be used to estimate the hydraulic conductivity and inform the PRW groundwater model. The objectives of this study were to (1) provide a record of the physical characteristics of Qvt deposits within the study area; and (2) estimate the highest, lowest, and average value of saturated hydraulic conductivity within the general Qvt. Samples collected from six field sites were analyzed for moisture content, grain-size distribution, bulk density, and porosity of the general Qvt and coarse-grained lenses. Hydraulic conductivity is estimated using key parameters from the grain-size distribution following the approach described by Nguyen (2013).

Moisture content, density, and porosity are summarized by feature type in Table 4, while grain-size distributions are shown in Figures 12 to 15. Average moisture contents were between about 1 and 6%, which is likely low because the samples were collected toward the end of the dry season. Moist and bulk densities are essentially identical because of the low moisture content. The average ρ_d is within about 17% of the assumed density of rock and soil particles indicating that the general Qvt is highly compacted. Average porosity of about 17% for general Qvt is within the range of typical glacial till porosity. Grain-size distributions show that half of the samples analyzed are well graded and the other half is poorly graded. Grain-size distributions also show (1) an average d_{10} value of about 0.20 mm in Qvt, Qvt-w, and S.L.; and (2) an average f_f value of 9.0%, 16%, and 3.0% in Qvt, Qvt-w and S.L. respectively. These values result in similar values for hydraulic conductivity, which ranges from a minimum of 0.02 m/d to a maximum of 1.38 m/d in within the general Vashon till.

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Tables

Table 1 - FIELD SITE LOCATIONS. The locations of these sampling sites are represented by red dots in Figure 1 and tabulated in Table 1. Latitude and longitude are recorded in the North American Datum of 1983 (NAD83) coordinate system using a Garmin Etrex 30 handheld Global Positioning System receiver.

Field Locations				
ID	Name	Latitude (°N)	Longitude (°E)	Altitude (ft.)
1	Newland Communities - Columbia Vista Phase II	47.12754	122.17052	856
2	Corliss Resources Sand and Gravel Pit	47.20636	122.20312	596
3	Washington Rock Quarries - King Creek Plant	47.01086	122.17728	853
4	Swan Creek	47.21761	122.39454	288
5	Lloyd's Sand and Gravel Pit	47.26001	122.32458	91
6	Newland Communities - Backfill Pit #1	47.12779	122.20771	563

Table 2 - MINIMUM REQUIREMENTS FOR MOISTURE CONTENT. Minimum requirements for test specimen mass and balance readability for determination of water content by Method A described in ASTM D2216-10. Modified from ASTM D2216 (2010).

Maximum Particle Size (100% passing)		Method A Water Content Measured to ± 1%	
SI Unit Sieve Size (mm)	Alternative Sieve Size	Min. Specimen Mass	Balance Readability (g)
75.0	3 in.	5 kg	10
37.5	1-½ in.	1 kg	10
19.0	¾ in.	250 g	1
9.50	⅜ in.	50g	0.1
4.75	No. 4	20 g	0.1
2.00	No. 10	20 g	0.1

Table 3 - SIEVE OVERLOADING LIMITS. Modified from ASTM D6913-04. A '-' indicates that there is no information available because the sieve is not listed as a standard sieve in ASTM 6913-04. ^{A} Reported value is for sieve opening of 12.5 mm from Table 1 in ASTM C136-06. ^{B} Reported value is for the No. 60 (250 μm) sieve. The values for ^{A} and ^{B} are used because they are smaller than the openings for the sieves used in this analysis and are, therefore, the more limiting mass.

Overloading limits for sieve set				
Grain size, inches	Grain size, mm	Sieve No.	Maximum Mass retained on sieve, g	Number of grain layers on sieve
3.00	75	3 in.	2700	0.8
2.00	50	2 in.	2000	0.9
0.63	16	5/8 in.	890^{A}	-
0.19	4.75	No. 4	325	1.5
0.08	2.0	No. 10	180	2
0.03	0.83	No. 20	115	3
0.02	0.43	No. 40	75	4
0.01	0.25	No. 60	60	5
0.01	0.18	No. 80	60^{B}	-
0.01	0.15	No. 100	40	6
0.003	0.075	No. 200	20	6

Table 4 - SUMMARY OF PHYSICAL CHARACTERISTICS. Physical characteristics of the general Vashon till (Qvt), weathered Vashon till (Qvt-w), sand lenses (S.L.), and gravel lenses (G.L.).

Table 4 (a) - Moisture content obtained from bulk samples collected from Qvt, Qvt-w, S.L., and G.L. Porosity is calculated using equation 3.9, the particle density (ρp) is assumed to be 2.65 g/cm3 (see Fetter, 1994) and the dry bulk density (ρd) are determined from intact samples of Qvt collected at sample sites 1, 2, and 6; intact samples could not be collected for Qvt-w, S.L., or G.L.

Moisture Content and Porosity								
Sampled feature	Number of samples	Moisture content (w), %			Number of samples	Porosity (n), %		
		Min.	Max.	Avg.		Min.	Max.	Avg.
Qvt	12	0.8	6.8	3.0	6	11.7	21.1	16.5
Qvt - w	3	2.7	2.7	3.0	0	-	-	-
S.L.	3	1.0	16.3	6.3	0	-	-	-
G.L.	2	0.6	1.2	0.9	0	-	-	-

Table 4 (b) - Values for moist and dry bulk densities were obtained from intact samples of Qvt collected at sample sites 1,2, and 6; intact samples were not collected for Qvt-w, S.L., or G.L.

Densities							
Sampled feature	Number of samples	Moist bulk density (ρ_m), g/cm^3			Dry bulk density (ρ_d), g/cm^3		
		Min.	Max.	Avg.	Min.	Max.	Avg.
Qvt	6	2.09	2.34	2.20	2.09	2.34	2.20
Qvt - w	0	-	-	-	-	-	-
S.L.	0	-	-	-	-	-	-
G.L.	0	-	-	-	-	-	-

Table 5 – ESTIMATED HYDRAULIC CONDUCTIVITY. Hydraulic conductivity estimates for the general Vashon till (Qvt), weathered Vashon till (Qvt-w), sand lenses (S.L.), and gravel lenses (G.L.) based on equation 4.2.

Hydraulic conductivity estimates				
Sampled feature	Number of samples	Hydraulic conductivity (K_{sat}), m/d		
		Min.	Max.	Avg.
Qvt	12	0.02	1.38	0.39
Qvt - w	3	0.01	0.74	0.25
S.L.	3	0.34	0.69	0.54
G.L.	2	2.52 x 10^5	5.34 x 10^6	2.80 x 10^6

Figures

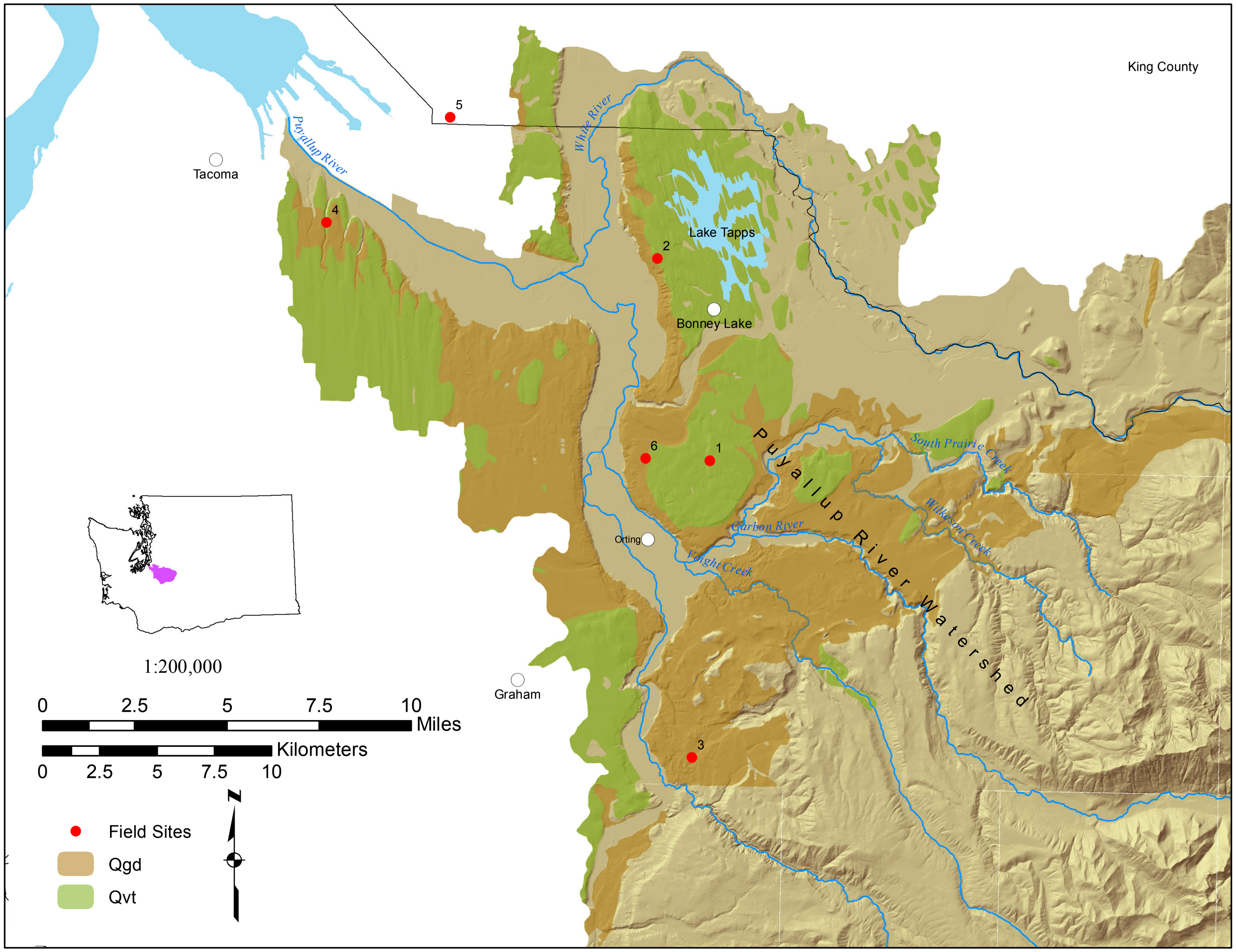


Figure 1 – FIELD SITE LOCATIONS. Map showing approximately the western third of the Puyallup River Watershed and the study area. Red dots indicate field site locations with numbers corresponding to those listed in Table 1. Fraser-age continental drift (Qgd) comprises undifferentiated, glacially derived drift units including Vashon till (Qvt).

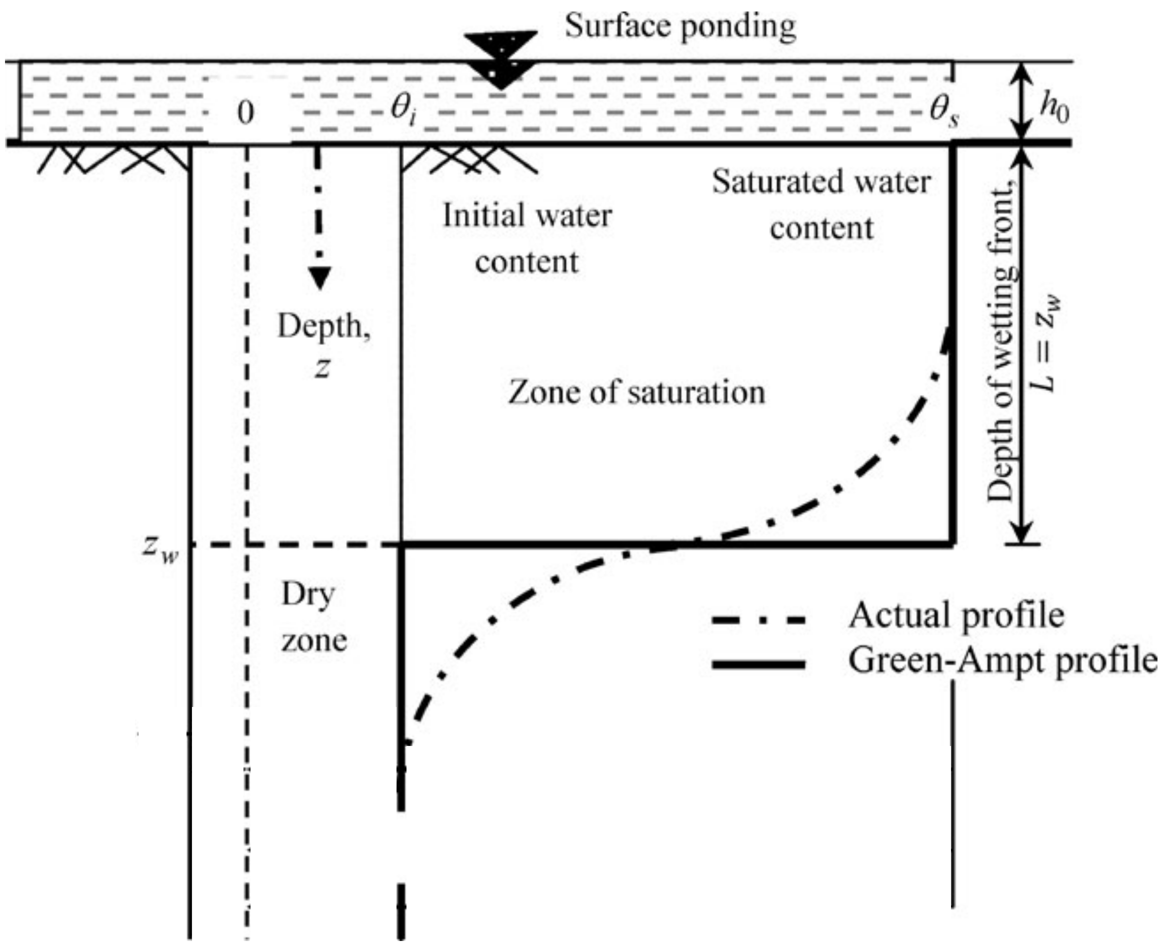


Figure 2 – GREEN-AMPT INFILTRATION MODEL. Illustration representing the geometry, parameters and infiltration profile for the Green-Ampt Infiltration model, from Kale and Sahoo (2011).

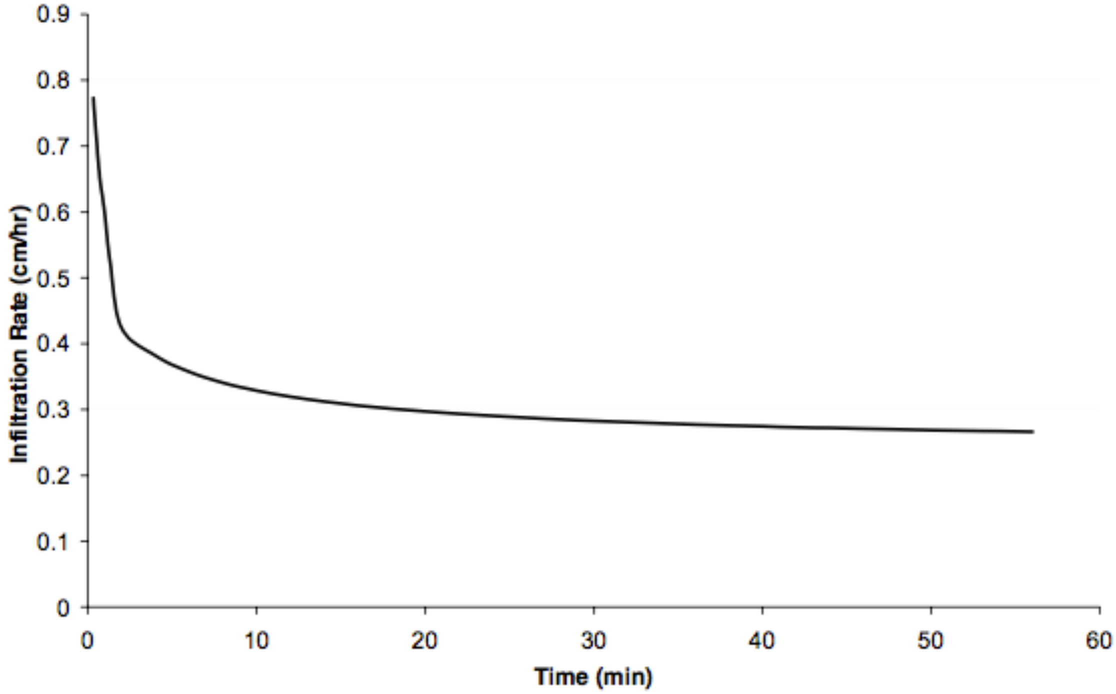


Figure 3 – GREEN-AMPT INFILTRATION CURVE. Estimated infiltration rate for loamy sand using the Green-Ampt approximation, from Massman (2003). Different soil types will result in different infiltration rates at steady state and will require different time periods to reach this steady-state rate; however, the general shape of the infiltration curve is maintained.

Figure 4 – COLUMBIA VISTA PHASE II TRENCH. Southeast-facing view of the trench along the west side of Overlook Dr. E in the Columbia Vista Phase II housing development (site 1). The trench is excavated in Vashon till (Qvt) with sand fill covering the bottom.

Figure 5 – COLUMBIA VISTA PHASE II ROAD-CUT. East-facing view of the road cut exposing Vashon till (Qvt) east of Overlook Dr. E in the Columbia Vista Phase II housing development (site 1). A Rite in the Rain ® No. 540F field book is included for scale.

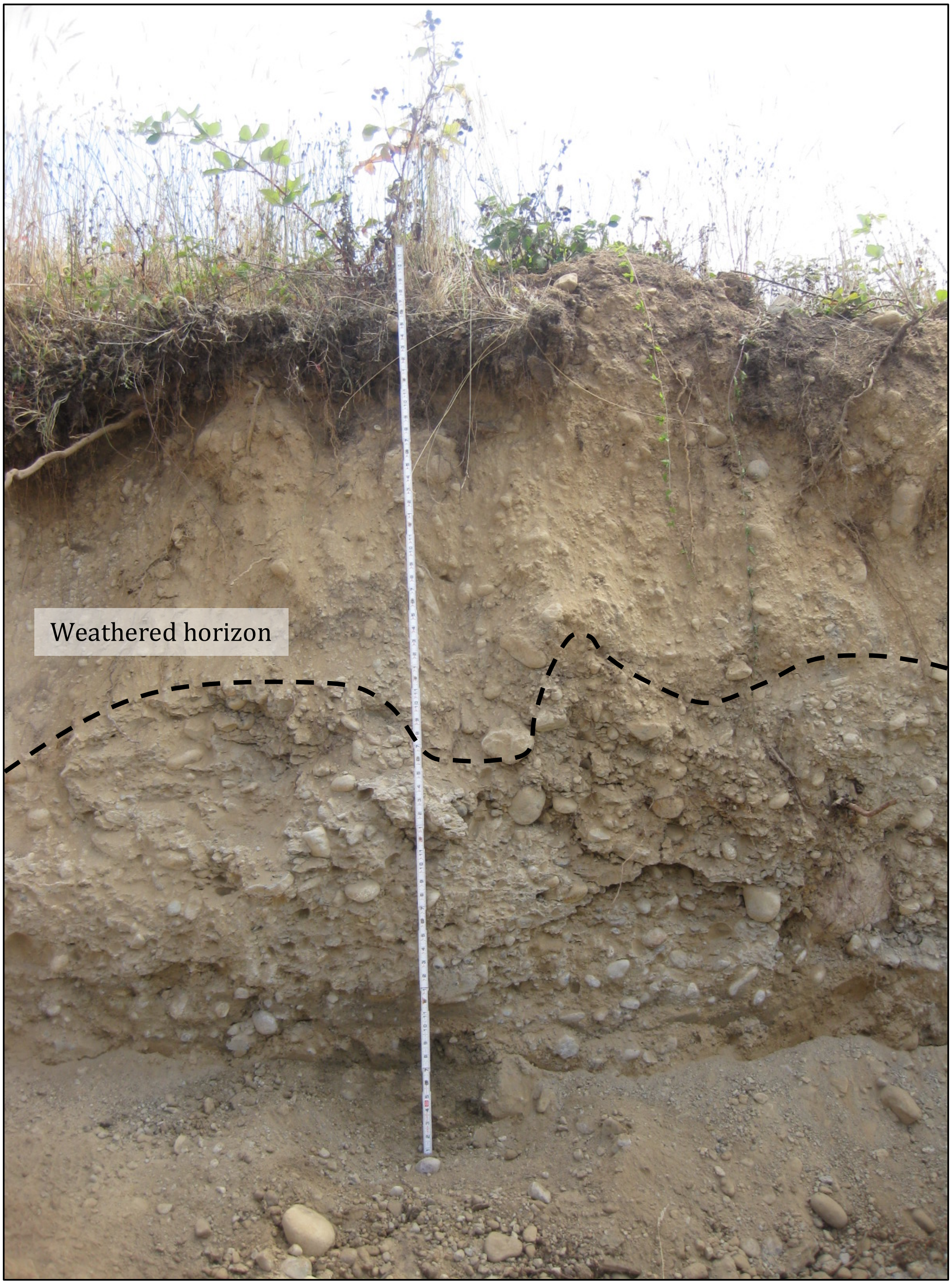


Figure 6 – CORLISS GRAVEL QUARRY EXPOSURE. Southeast-facing view of a portion of the exposure at the Corliss Gravel Quarry (site 2). The dashed, black line represents the approximate contact between the weathered and unweathered Qvt horizon. The vertical scale is a Lufkin 6-ft. SAE folding ruler, which is fully extended.

Figure 7 – GRAVEL LENS AT CORLISS GRAVEL QUARRY. Close-up view of a gravel lens in Vashon till (Qvt) at the Corliss Gravel Quarry (site 2). The dashed, black line represents the approximate boundary of the lens. The vertical scale is a stadia rod; numbered gradations represent decimeters.

Figure 8 – WASHINGTON ROCK QUARRIES ROAD CUT. East-facing view of the road cut near the King Creek Pit operated by Washington Rock Quarries, Inc (site 3). The dugout portion is where the sample was collected, from weathered Vashon till (Qvt-w). A Rite in the Rain ® No. 540F field book is included for scale.

Figure 9 – SWAN CREEK EXPOSURE. East-facing view of the exposure along the right bank of Swan Creek (site 4) where a sand lens is enclosed by Vashon till (Qvt). The vertical scale is a Lufkin 6-ft. SAE folding ruler, which is fully extended.

Figure 10 – EXPOSURE AT LLOYD'S SAND AND GRAVEL PIT. Northwest-facing view of the exposure at Lloyd's Sand and Gravel Pit (site 5). The sub horizontal features are sand lenses. The vertical reference is a telescopic stadia rod extended to 5.0 m (16.4 ft.).

Figure 11 – EXPOSURE AT TEHALEH BACKFILL PIT #1. North-facing view of the exposure at the Tehaleh Backfill Pit #1 (site 6). Vashon till (Qvt) is present below the root layer with a sand lens about 80 cm below the root layer. The vertical reference is a telescopic stadia rod extended to 4.0 m (13.1 ft.).

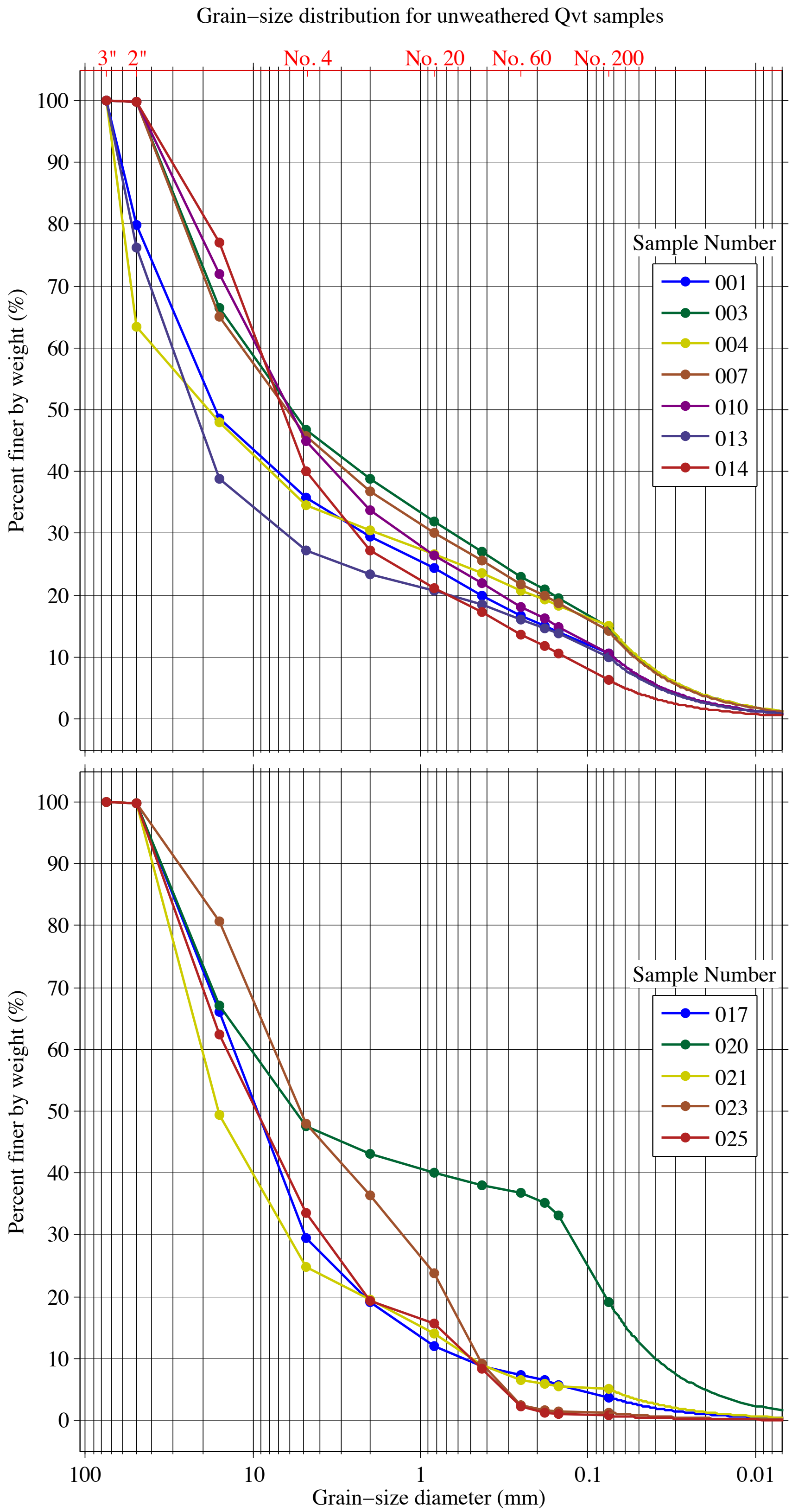


Figure 12 – GRAIN-SIZE DISTRIBUTION FOR GENERAL VASHON TILL. Grain-size distribution curves for general Vashon till (Qvt) samples. The red x-axis labels represent the U.S. Standard sieve sizes.

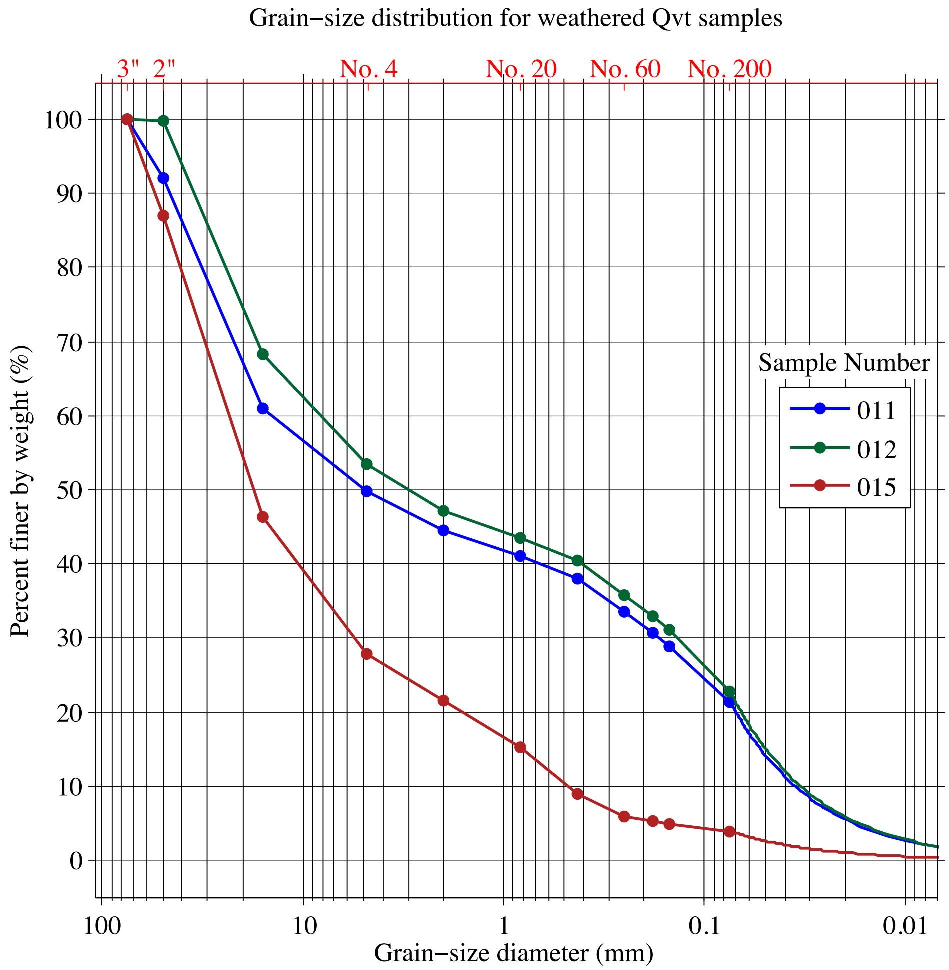


Figure 13 – GRAIN-SIZE DISTRIBUTION FOR WEATHERED VASHON TILL. Grain-size distribution curves for weathered Vashon till (Qvt-w) samples. The red x-axis labels represent the U.S. Standard sieve sizes.

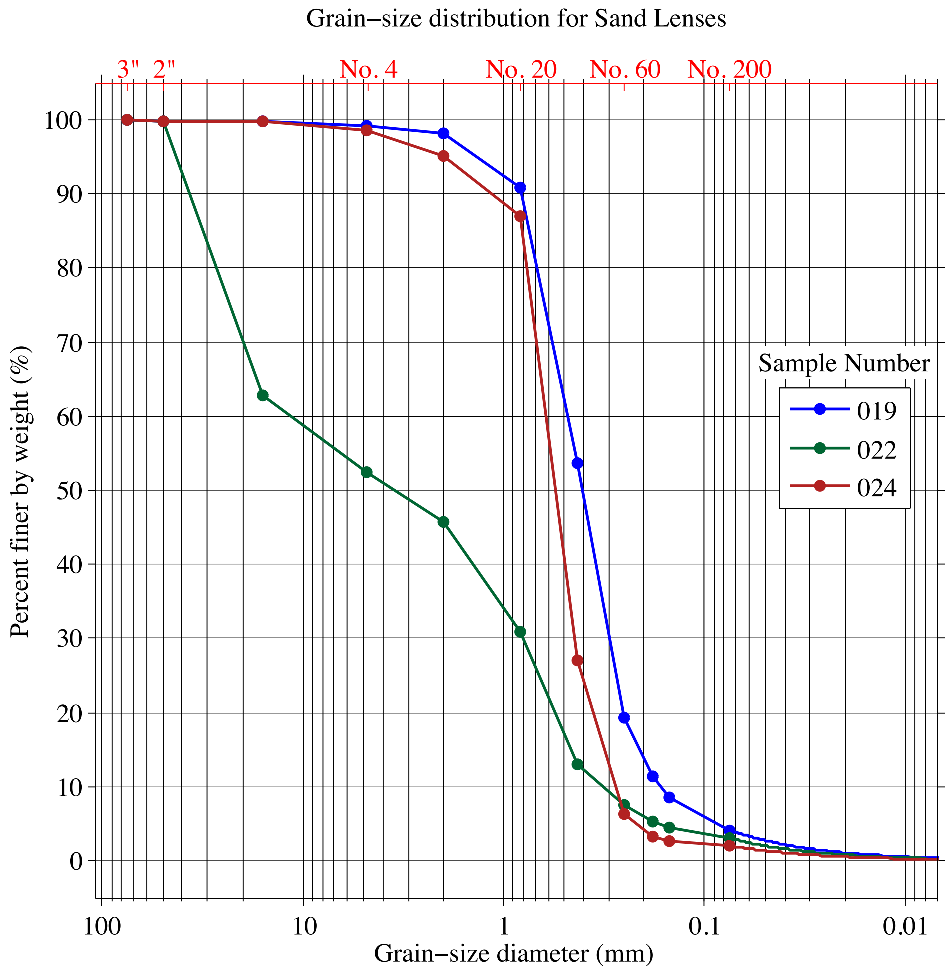


Figure 14 – GRAIN-SIZE DISTRIBUTION FOR SAND LENSES. Grain-size distribution curves for samples collected from sand lenses (S.L.). The red x-axis labels represent the U.S. Standard sieve sizes.

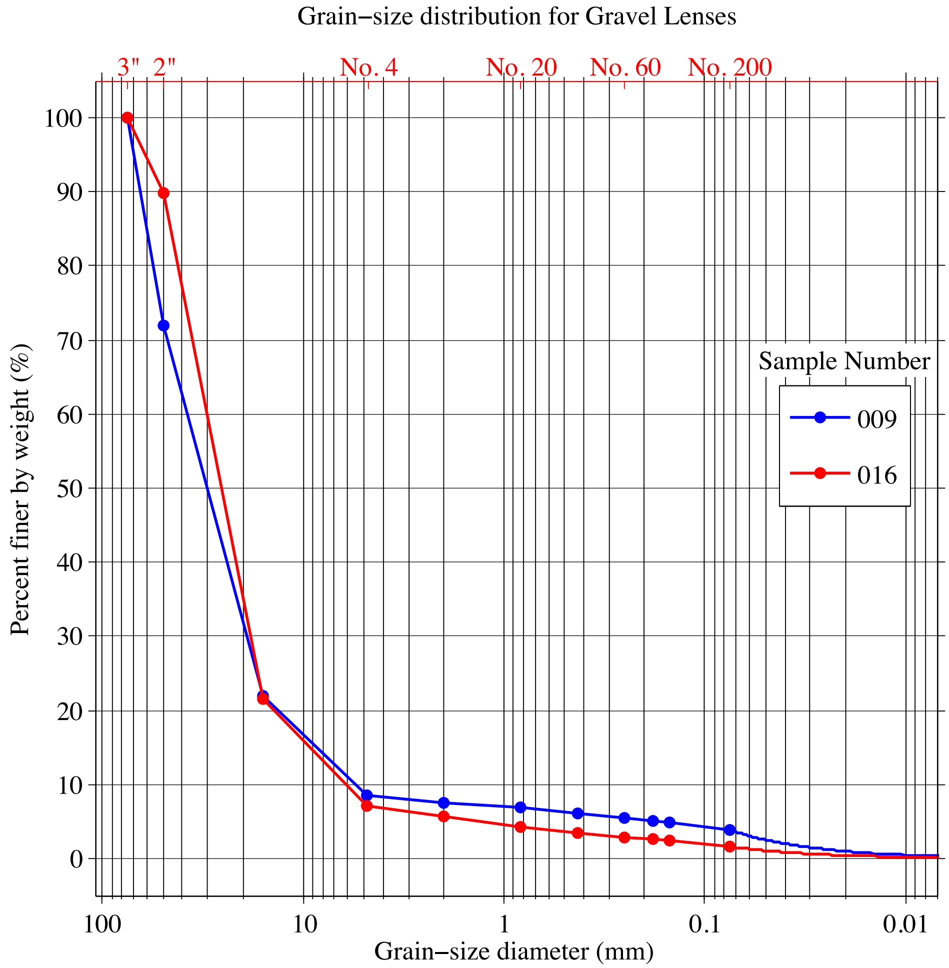


Figure 15 – GRAIN-SIZE DISTRIBUTION FOR GRAVEL LENSES. Grain-size distribution curves for samples collected from gravel lenses (G.L.). The red x-axis labels represent the U.S. Standard sieve sizes.

APPENDIX A – PHYSICAL CHARACTERISTICS AND HYDRAULIC CONDUCTIVITY BY SAMPLE NUMBER

Table 1A - PHYSICAL CHARACTERISTICS AND HYDRAULIC CONDUCTIVITY BY SAMPLE NUMBER. The sample location numbers correspond to the field locations listed in Table 1. Values for hydraulic conductivity (K) are estimated using equation 4.5. Porosity is calculated using equation 3.9 and assuming a particle density (ρ_p) of 2.65 g/cm^3 (see Fetter, 1994). Qvt indicates that the sample is representative of the general Vashon till, G.L. indicates a gravel lense, S.L. indicates a sand lense, and 'w' indicates weathered material.

Physical characteristics and hydrolic conductivity by sample number															
Sample Number	Site Location	Sampled Feature	Moisture Content (w), %	USCS Group Symbol	d_{10}, mm	d_{30}, mm	d_{60}, mm	d_{90}, mm	f_f, %	C_u	C_c	Moist bulk density (ρ_m), g/cm^3	Dry bulk density (ρ_d), g/cm^3	Porosity (n), %	Hydraulic Conductivity (K_{sat}), m/d
001	1	Qvt	3.1	GW-GM	0.07	2.22	28.42	62.62	11	423.0	2.6	–	–	–	0.08
002	1	Intact Qvt	–	–	–	–	–	–	–	–	–	2.24	2.24	15.40	–
003	1	Qvt	3.4	GM	0.03	0.67	12.36	39.95	14.70	372.3	1.1	–	–	–	0.04
004	1	Qvt	3.3	GM	0.03	1.87	42.49	68.17	14.90	1528.5	3.0	–	–	–	0.04
005	1	Intact Qvt	–	–	–	–	–	–	–	–	–	2.09	2.09	21.07	–
006	1	Intact Qvt	–	–	–	–	–	–	–	–	–	2.13	2.13	19.54	–
007	1	Qvt	1.7	GM	0.03	0.82	13.06	40.33	14.26	393.2	1.6	–	–	–	0.04
008	1	Intact Qvt	–	–	–	–	–	–	–	–	–	2.34	2.34	11.71	–
009	2	G.L.	1.2	GW	5.97	21.45	41.89	66.10	3.87	7.0	1.8	–	–	–	2.52×10^5
010	2	Qvt	1.6	GW-GM	0.07	1.41	11.04	37.94	10.48	164.3	2.7	2.21	2.21	16.52	0.09
011	2	Qvt - w	2.7	SM	0.04	0.17	15.10	47.71	21.40	407.0	0.1	–	–	–	0.01
012	2	Qvt - w	3.1	SM	0.06	0.14	9.72	39.35	22.77	166.4	0.0	–	–	–	0.01
013	2	Qvt	2.2	GP-GM	0.08	7.48	35.23	64.50	9.72	462.4	20.8	–	–	–	0.10
014	2	Qvt	5.8	GP-GM	0.14	2.59	10.84	35.30	6.00	76.7	4.4	–	–	–	0.23
015	6	Qvt - w	3.0	GW	0.50	6.08	27.42	55.62	3.95	55.0	2.7	–	–	–	0.74

Table A-1 - continued

Physical characteristics and hydrolic conductivity by sample number															
Sample Number	Site Location	Sampled Feature	Moisture Content (w), %	USCS Group Symbol	d_{10}, mm	d_{30}, mm	d_{60}, mm	d_{90}, mm	f_f, %	C_u	C_c	Moist bulk density (ρ_m), g/cm^3	Dry bulk density (ρ_d), g/cm^3	Porosity (n), %	Hydraulic Conductivity (K_{sat}), m/d
016	6	G.L.	0.6	GW	7.12	20.23	35.14	50.25	1.66	4.9	1.6	–	–	–	5.34 x 10^6
017	6	Qvt	0.9	GW	0.58	4.95	14.13	40.04	3.67	24.2	3.0	–	–	–	0.95
018	6	Intact Qvt	–	–	–	–	–	–	–	–	–	2.17	2.17	18.17	–
019	6	S.L.	1.5	SP	0.17	0.31	0.50	0.82	3.93	3.0	1.1	–	–	–	0.34
020	6	Qvt	1.4	SP-SM	0.08	0.13	11.92	39.74	19.12	156.0	0.0	–	–	–	0.02
021	5	Qvt	0.8	GP	0.52	7.20	23.14	43.33	5.03	44.8	4.3	–	–	–	0.64
022	5	S.L.	1.0	SP	0.33	0.81	12.88	40.90	2.91	38.6	0.2	–	–	–	0.60
023	4	Qvt	6.8	SP	0.45	1.41	8.93	32.47	1.05	19.6	0.5	–	–	–	1.11
024	4	S.L.	16.3	SP	0.28	0.45	0.65	1.26	1.51	2.3	1.1	–	–	–	0.69
025	4	Qvt	4.8	SW	0.52	4.11	15.07	41.02	0.64	29.0	2.2	–	–	–	1.38

APPENDIX B – RECORD OF GRAIN-SIZE CHARACTERISTICS FOR EACH SAMPLE

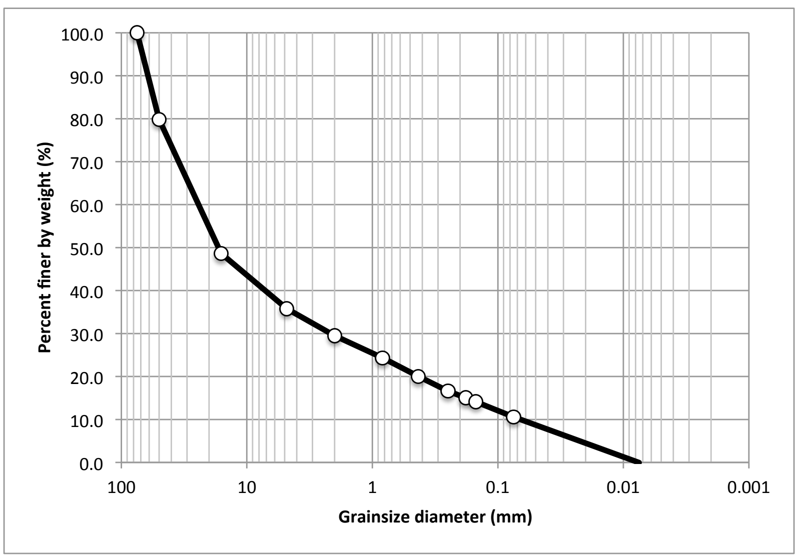
Calculations for Percent Passing

Sample Number: 001

Post-wash Dry Mass, g	2062.7	+	Mass < 75 µm, g	219.8	=	Ttl Dry Mass, g	2282.5

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	460.5	460.5	79.8
0.625	16	5/8"	712.3	1172.8	48.6
0.19	4.8	No. 4	293.3	1466.1	35.8
0.08	2.0	No. 10	143.4	1609.5	29.5
0.03	0.83	No. 20	117.1	1726.6	24.4
0.02	0.43	No. 40	98.9	1825.5	20.0
0.01	0.25	No. 60	77.8	1903.3	16.6
0.01	0.18	No. 80	35.7	1939.0	15.0
0.01	0.15	No. 100	20.9	1959.9	14.1
0.0030	0.075	No. 200	80.4	2040.3	10.6
0.00030	0.0075	< No. 200	243.1	2283.4	-0.04

Pan	23.3	From sieve analysis
Total	2283.4	
% Loss	-0.04	



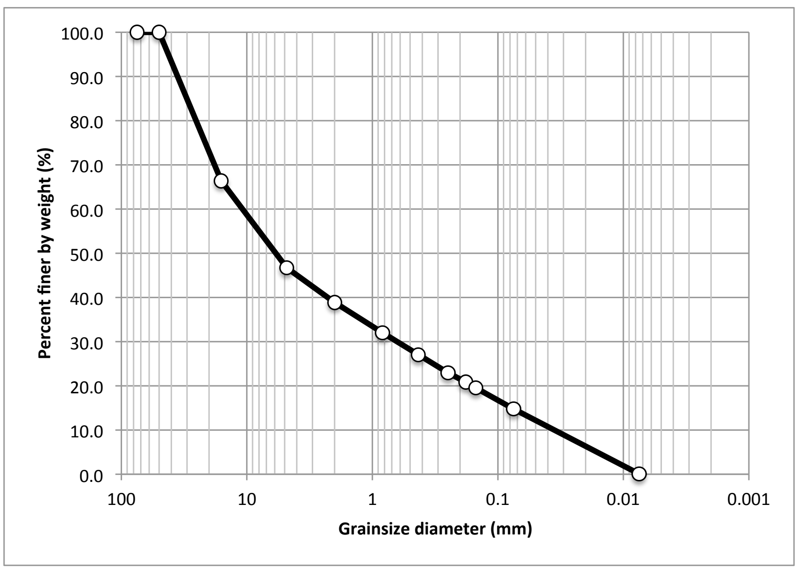
Calculations for Percent Passing

Sample Number: 003

Post-wash Dry Mass, g	1496	+	Mass < 75 µm, g	224.2	=	Ttl Dry Mass, g	1720.2

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0	0	100.0
2"	50	2"	0	0	100.0
0.625	16	5/8"	578.4	578.4	66.4
0.19	4.8	No. 4	338.5	916.9	46.7
0.08	2.0	No. 10	134.5	1051.4	38.9
0.03	0.83	No. 20	117.8	1169.2	32.0
0.02	0.43	No. 40	85.7	1254.9	27.0
0.01	0.25	No. 60	70.2	1325.1	23.0
0.01	0.18	No. 80	36.4	1361.5	20.9
0.01	0.15	No. 100	22.7	1384.2	19.5
0.0030	0.075	No. 200	81.7	1465.9	14.8
0.00030	0.0075	< No. 200	252.7	1718.6	0.09

Pan	28.5	From sieve analysis
Total	1718.6	
% Loss	0.09	



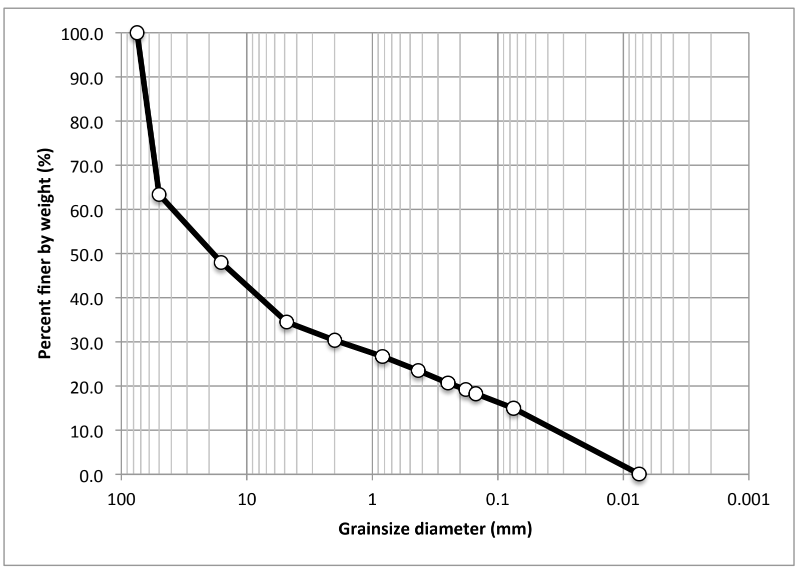
Calculations for Percent Passing

Sample Number: 004

Post-wash Dry Mass, g	2258.3	+	Mass < 75 µm, g	364.9	=	Ttl Dry Mass, g	2623.2

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0	0	100.0
2"	50	2"	960.6	960.6	63.4
0.625	16	5/8"	403.6	1364.2	48.0
0.19	4.8	No. 4	354.3	1718.5	34.5
0.08	2.0	No. 10	108.5	1827.0	30.4
0.03	0.83	No. 20	95.6	1922.6	26.7
0.02	0.43	No. 40	84.0	2006.6	23.5
0.01	0.25	No. 60	74.7	2081.3	20.7
0.01	0.18	No. 80	37.8	2119.1	19.2
0.01	0.15	No. 100	24.9	2144.0	18.3
0.0030	0.075	No. 200	86.7	2230.7	15.0
0.00030	0.0075	< No. 200	390.6	2621.3	0.07

Pan	25.7	From sieve analysis
Total	2621.3	
% Loss	0.07	



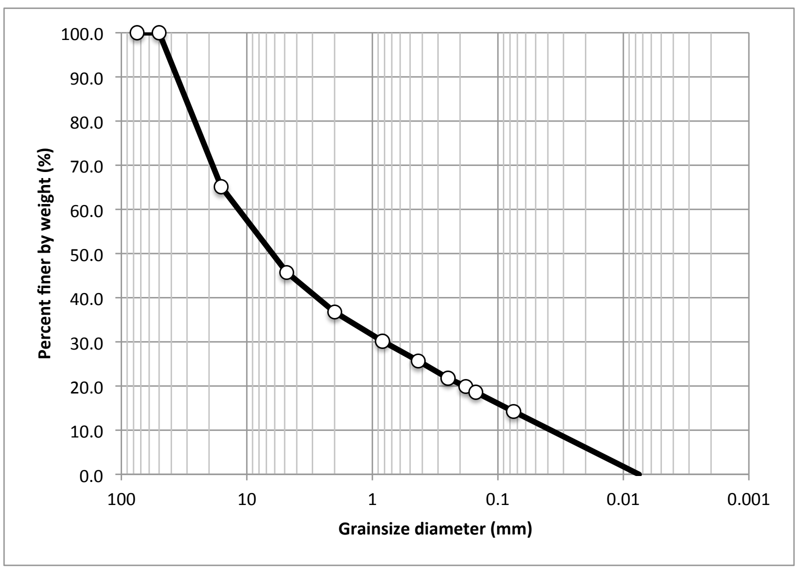
Calculations for Percent Passing

Sample Number: 007

Post-wash Dry Mass, g	1941.7	+	Mass < 75 µm, g	270.4	=	Ttl Dry Mass, g	2212.1

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0	0	100.0
2"	50	2"	0	0	100.0
0.625	16	5/8"	771.5	771.5	65.1
0.19	4.8	No. 4	428.8	1200.3	45.7
0.08	2.0	No. 10	198.6	1398.9	36.8
0.03	0.83	No. 20	146.4	1545.3	30.1
0.02	0.43	No. 40	98.8	1644.1	25.7
0.01	0.25	No. 60	86.5	1730.6	21.8
0.01	0.18	No. 80	41.8	1772.4	19.9
0.01	0.15	No. 100	28.5	1800.9	18.6
0.0030	0.075	No. 200	96.1	1897	14.2
0.00030	0.0075	< No. 200	315.6	2212.6	-0.02

Pan	45.2	From sieve analysis
Total	2212.6	
% Loss	-0.02	



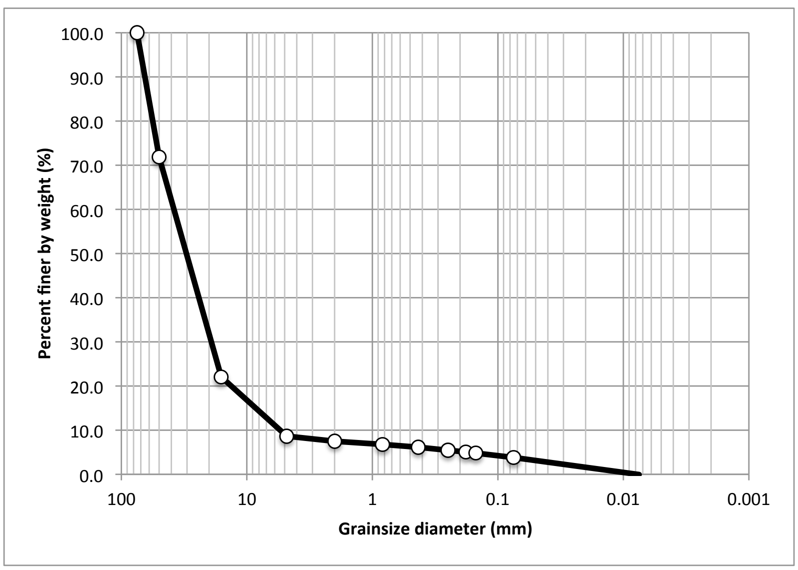
Calculations for Percent Passing

Sample Number: 009

Post-wash Dry Mass, g	2751.4	+	Mass < 75 µm, g	96.3	=	Ttl Dry Mass, g	2847.7

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0	0	100.0
2"	50	2"	800.9	800.9	71.9
0.625	16	5/8"	1419.0	2219.9	22.0
0.19	4.8	No. 4	381.7	2601.6	8.6
0.08	2.0	No. 10	32.7	2634.3	7.5
0.03	0.83	No. 20	20.1	2654.4	6.8
0.02	0.43	No. 40	18.6	2673	6.1
0.01	0.25	No. 60	19.6	2692.6	5.4
0.01	0.18	No. 80	10.9	2703.5	5.1
0.01	0.15	No. 100	7.3	2710.8	4.8
0.0030	0.075	No. 200	28.0	2738.8	3.8
0.00030	0.0075	< No. 200	110.2	2849	-0.05

Pan	13.9	From sieve analysis
Total	2849	
% Loss	-0.05	



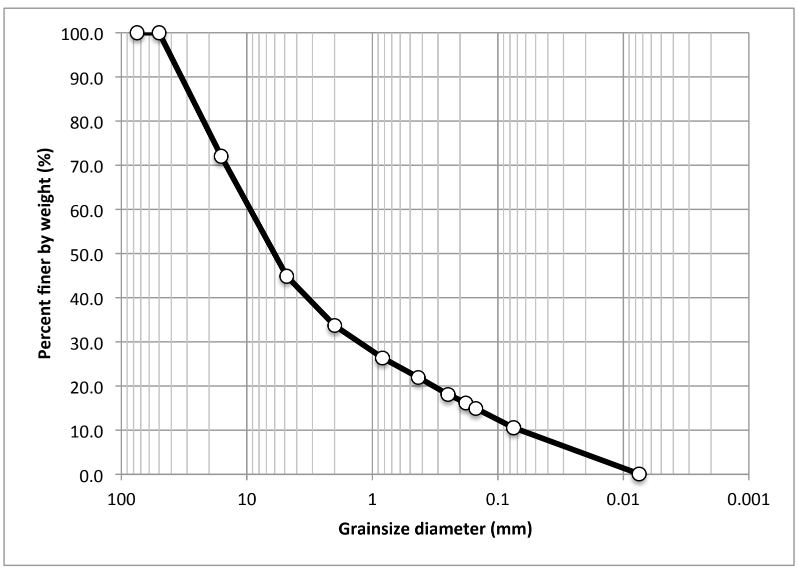
Calculations for Percent Passing

Sample Number: 010

Post-wash Dry Mass, g	3215.4	+	Mass < 75 µm, g	248.2	=	Ttl Dry Mass, g	3463.6

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	0.0	0.0	100.0
0.625	16	5/8"	969.6	969.6	72.0
0.19	4.8	No. 4	940.4	1910.0	44.9
0.08	2.0	No. 10	387.3	2297.3	33.7
0.03	0.83	No. 20	253.0	2550.3	26.4
0.02	0.43	No. 40	153.5	2703.8	21.9
0.01	0.25	No. 60	132.4	2836.2	18.1
0.01	0.18	No. 80	66.7	2902.9	16.2
0.01	0.15	No. 100	43.5	2946.4	14.9
0.0030	0.075	No. 200	151.2	3097.6	10.6
0.00030	0.0075	< No. 200	362.7	3460.3	0.10

Pan	114.5	From sieve analysis
Total	3460.3	
% Loss	0.10	



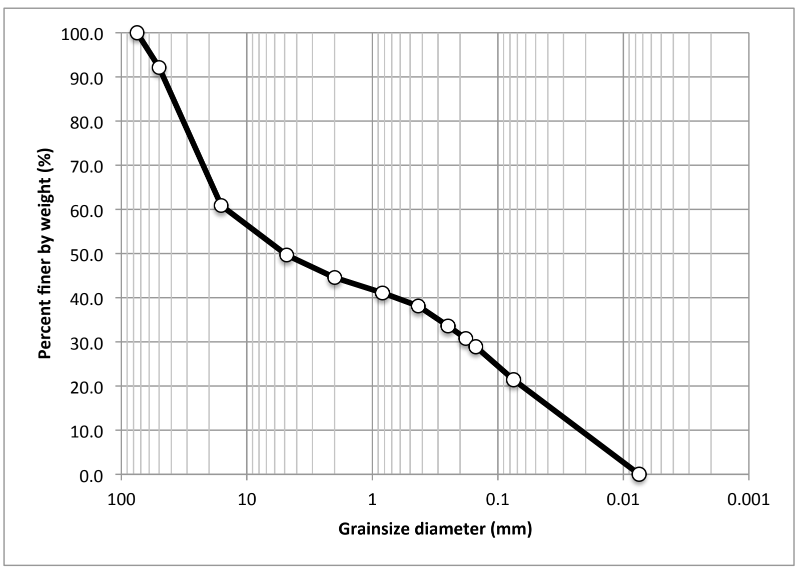
Calculations for Percent Passing

Sample Number: 011

Post-wash Dry Mass, g	3214.8	+	Mass < 75 µm, g	807.2	=	Ttl Dry Mass, g	4022.0

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0	0	100.0
2"	50	2"	316.4	316.4	92.1
0.625	16	5/8"	1257.2	1573.6	60.9
0.19	4.8	No. 4	451.4	2025	49.7
0.08	2.0	No. 10	205.5	2230.5	44.5
0.03	0.83	No. 20	138.8	2369.3	41.1
0.02	0.43	No. 40	120.5	2489.8	38.1
0.01	0.25	No. 60	180.9	2670.7	33.6
0.01	0.18	No. 80	114.8	2785.5	30.7
0.01	0.15	No. 100	73.8	2859.3	28.9
0.0030	0.075	No. 200	301.0	3160.3	21.4
0.00030	0.0075	< No. 200	860.2	4020.5	0.04

Pan	53.0	From sieve analysis
Total	4020.5	
% Loss	0.04	



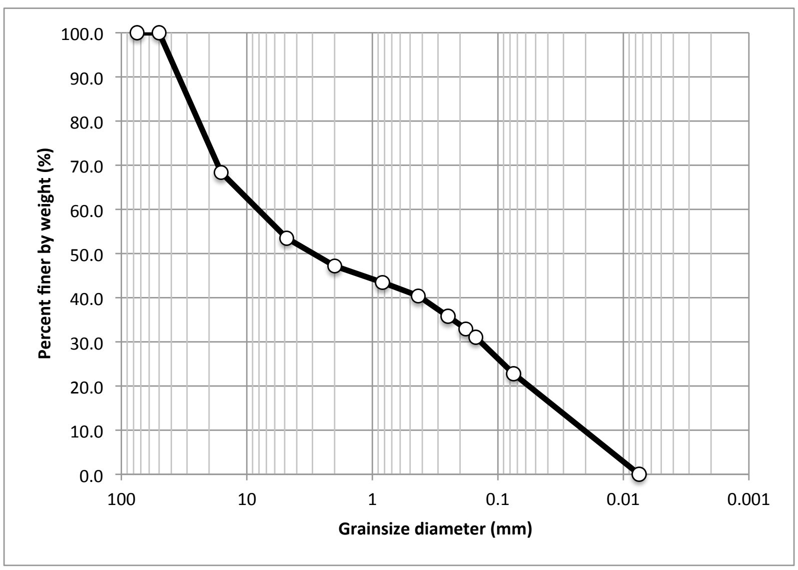
Calculations for Percent Passing

Sample Number: 012

Post-wash Dry Mass, g	2645.1	+	Mass < 75 µm, g	710.9	=	Ttl Dry Mass, g	3356.0

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0	0	100.0
2"	50	2"	0	0	100.0
0.625	16	5/8"	1062.5	1062.5	68.3
0.19	4.8	No. 4	498.9	1561.4	53.5
0.08	2.0	No. 10	211	1772.4	47.2
0.03	0.83	No. 20	125.6	1898	43.4
0.02	0.43	No. 40	102.2	2000.2	40.4
0.01	0.25	No. 60	155.4	2155.6	35.8
0.01	0.18	No. 80	95.1	2250.7	32.9
0.01	0.15	No. 100	63.3	2314	31.0
0.0030	0.075	No. 200	277.2	2591.2	22.8
0.00030	0.0075	< No. 200	764.1	3355.3	0.0

Pan	53.2	From sieve analysis	
Total	3355.3		
% Loss	0.02		



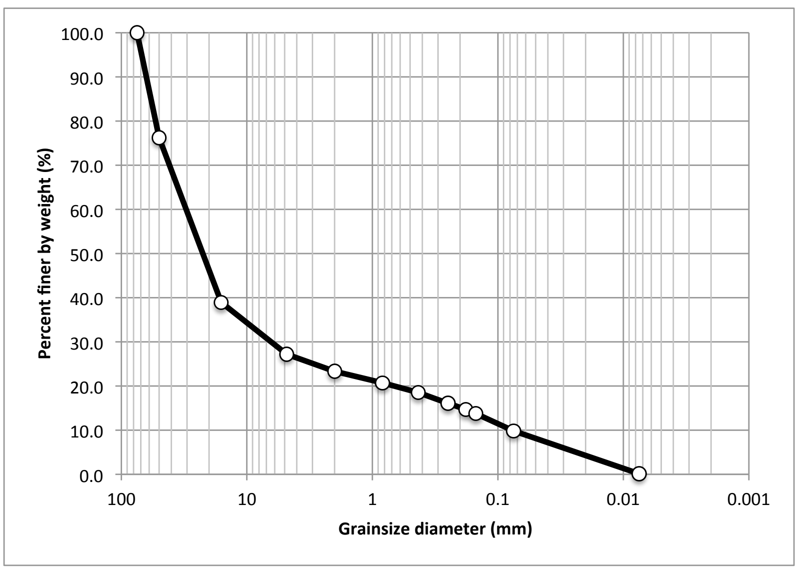
Calculations for Percent Passing

Sample Number: 013

Post-wash Dry Mass, g	3314.5	+	Mass < 75 µm, g	278.2	=	Ttl Dry Mass, g	3592.7

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	853.7	853.7	76.2
0.625	16	5/8"	1340.7	2194.4	38.9
0.19	4.8	No. 4	421.4	2615.8	27.2
0.08	2.0	No. 10	138.4	2754.2	23.3
0.03	0.83	No. 20	94.4	2848.6	20.7
0.02	0.43	No. 40	78.8	2927.4	18.5
0.01	0.25	No. 60	87.4	3014.8	16.1
0.01	0.18	No. 80	49.6	3064.4	14.7
0.01	0.15	No. 100	34.1	3098.5	13.8
0.0030	0.075	No. 200	140.3	3238.8	9.9
0.00030	0.0075	< No. 200	348.8	3587.6	0.14

Pan	70.6	From sieve analysis
Total	3587.6	
% Loss	0.14	



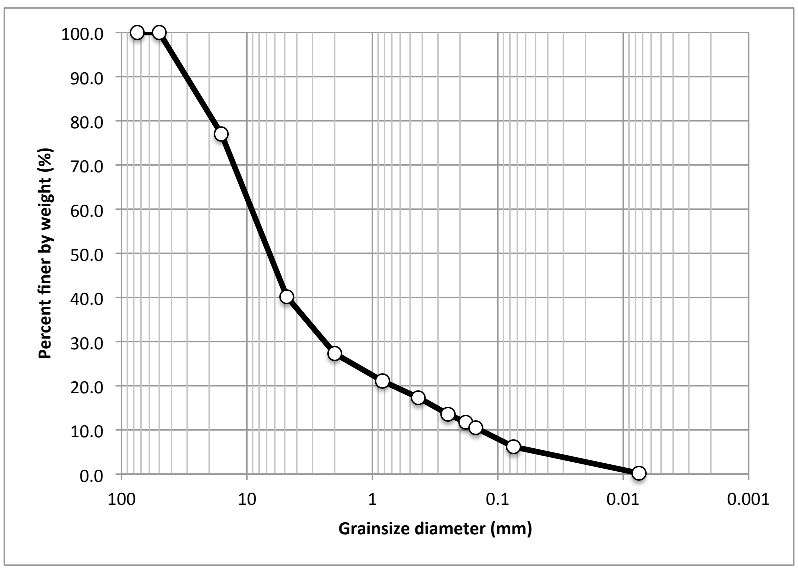
Calculations for Percent Passing

Sample Number: 014

Post-wash Dry Mass, g	2789.3	+	Mass < 75 µm, g	119.2	=	Ttl Dry Mass, g	2908.5

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	0.0	0.0	100.0
0.625	16	5/8"	668.4	668.4	77.0
0.19	4.8	No. 4	1072.6	1741.0	40.1
0.08	2.0	No. 10	372.9	2113.9	27.3
0.03	0.83	No. 20	181.5	2295.4	21.1
0.02	0.43	No. 40	109.7	2405.1	17.3
0.01	0.25	No. 60	108.0	2513.1	13.6
0.01	0.18	No. 80	54.8	2567.9	11.7
0.01	0.15	No. 100	35.4	2603.3	10.5
0.0030	0.075	No. 200	124.9	2728.2	6.2
0.00030	0.0075	< No. 200	174.2	2902.4	0.21

Pan	55.0	From sieve analysis
Total	2902.4	
% Loss	0.21	



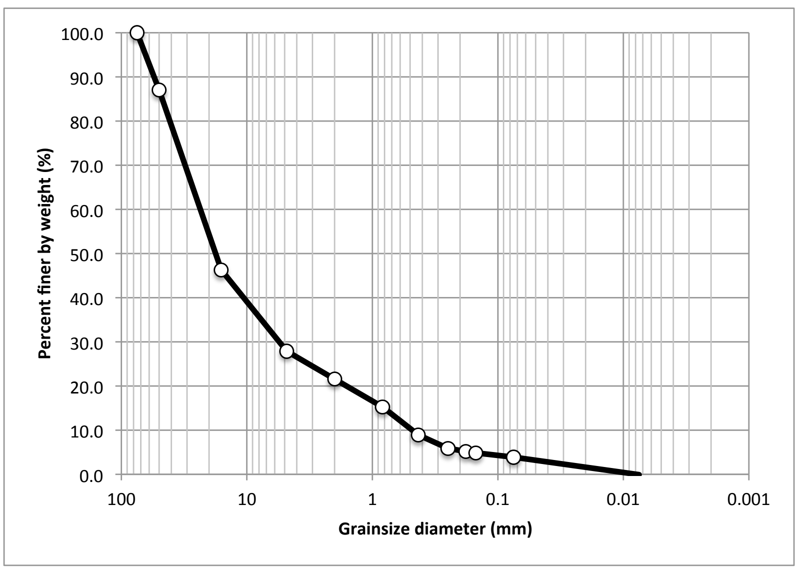
Calculations for Percent Passing

Sample Number: 015

Post-wash Dry Mass, g	2607.5	+	Mass < 75 µm, g	99.3	=	Ttl Dry Mass, g	2706.8

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	350.5	350.5	87.1
0.625	16	5/8"	1103.3	1453.8	46.3
0.19	4.8	No. 4	498.6	1952.4	27.9
0.08	2.0	No. 10	170.6	2123.0	21.6
0.03	0.83	No. 20	170.6	2293.6	15.3
0.02	0.43	No. 40	171.2	2464.8	8.9
0.01	0.25	No. 60	82.6	2547.4	5.9
0.01	0.18	No. 80	18.5	2565.9	5.2
0.01	0.15	No. 100	8.9	2574.8	4.9
0.0030	0.075	No. 200	26.9	2601.7	3.9
0.00030	0.0075	< No. 200	107.0	2708.7	-0.07

Pan	7.7	From sieve analysis
Total	2708.7	
% Loss	-0.07	



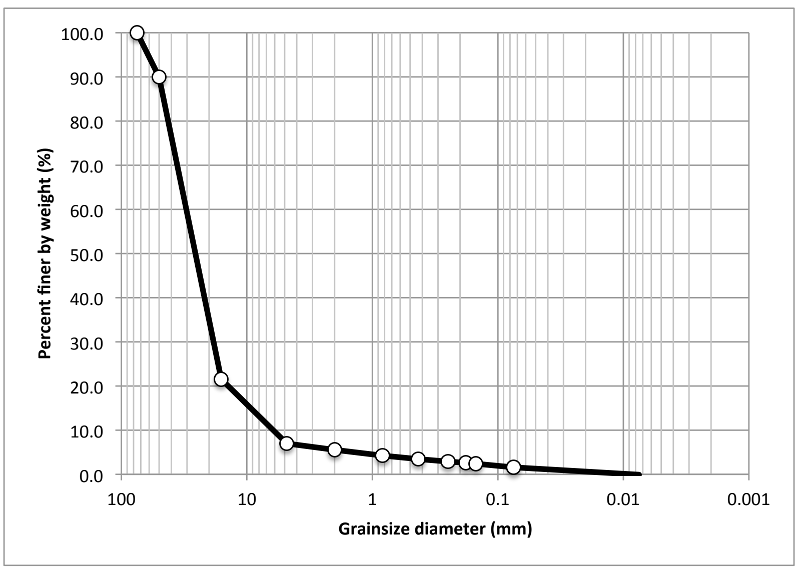
Calculations for Percent Passing

Sample Number: 016

Post-wash Dry Mass, g	3187.6	+	Mass < 75 µm, g	47.8	=	Ttl Dry Mass, g	3235.4

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	325.4	325.4	89.9
0.625	16	5/8"	2213.1	2538.5	21.5
0.19	4.8	No. 4	471.0	3009.5	7.0
0.08	2.0	No. 10	46.0	3055.5	5.6
0.03	0.83	No. 20	42.5	3098.0	4.2
0.02	0.43	No. 40	25.8	3123.8	3.4
0.01	0.25	No. 60	17.8	3141.6	2.9
0.01	0.18	No. 80	9.1	3150.7	2.6
0.01	0.15	No. 100	6.9	3157.6	2.4
0.0030	0.075	No. 200	26.7	3184.3	1.6
0.00030	0.0075	< No. 200	53.7	3238	-0.08

Pan	5.9	From sieve analysis
Total	3238	
% Loss	-0.08	



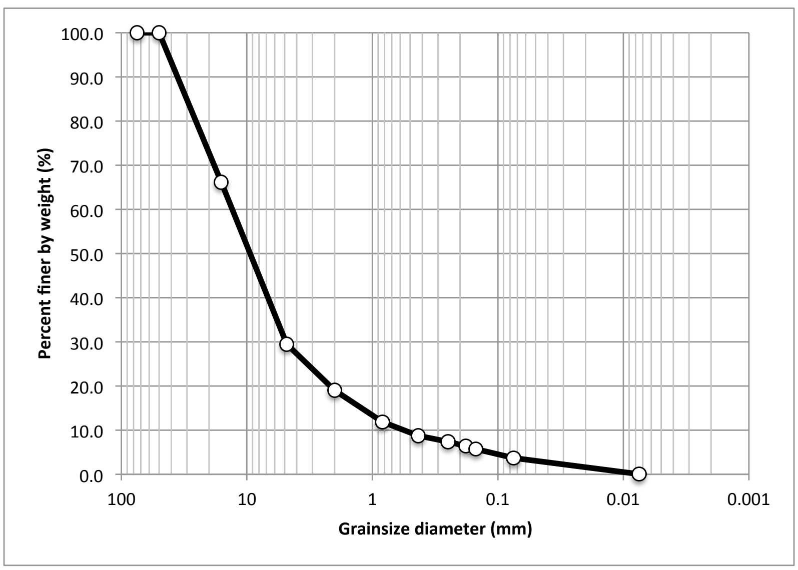
Calculations for Percent Passing

Sample Number: 017

Post-wash Dry Mass, g	1993.9	+	Mass < 75 µm, g	61.5	=	Ttl Dry Mass, g	2055.4

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	0.0	0.0	100.0
0.625	16	5/8"	695.8	695.8	66.1
0.19	4.8	No. 4	754.0	1449.8	29.5
0.08	2.0	No. 10	214.4	1664.2	19.0
0.03	0.83	No. 20	147.2	1811.4	11.9
0.02	0.43	No. 40	64.0	1875.4	8.8
0.01	0.25	No. 60	28.2	1903.6	7.4
0.01	0.18	No. 80	20.4	1924.0	6.4
0.01	0.15	No. 100	13.7	1937.7	5.7
0.0030	0.075	No. 200	41.2	1978.9	3.7
0.00030	0.0075	< No. 200	75.4	2054.3	0.05

Pan	13.9	From sieve analysis
Total	2054.3	
% Loss	0.05	



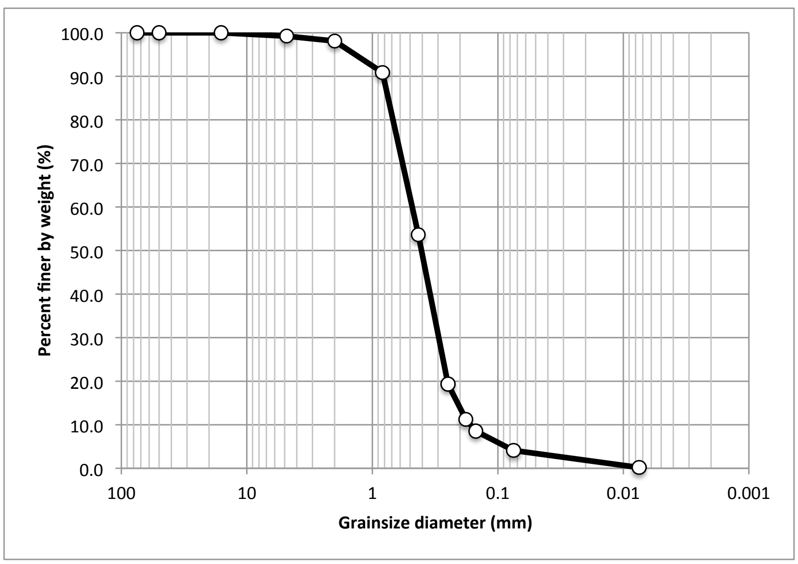
Calculations for Percent Passing

Sample Number: 019

Post-wash Dry Mass, g	1947.0	+	Mass < 75 µm, g	71.2	=	Ttl Dry Mass, g	2018.2

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	0.0	0.0	100.0
0.625	16	5/8"	0.0	0.0	100.0
0.19	4.8	No. 4	15.8	15.8	99.2
0.08	2.0	No. 10	22.5	38.3	98.1
0.03	0.83	No. 20	146.0	184.3	90.9
0.02	0.43	No. 40	751.3	935.6	53.6
0.01	0.25	No. 60	692.3	1627.9	19.3
0.01	0.18	No. 80	162.7	1790.6	11.3
0.01	0.15	No. 100	55.4	1846.0	8.5
0.0030	0.075	No. 200	89.2	1935.2	4.1
0.00030	0.0075	< No. 200	79.2	2014.4	0.19

Pan	8.0	From sieve analysis
Total	2014.4	
% Loss	0.19	



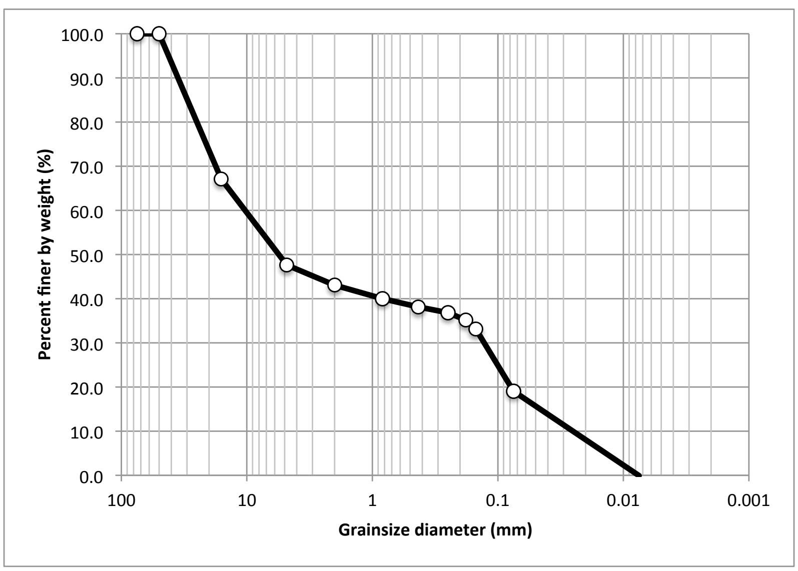
Calculations for Percent Passing

Sample Number: 020

Post-wash Dry Mass, g	1495.8	+	Mass < 75 µm, g	297.4	=	Ttl Dry Mass, g	1793.2

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	0.0	0.0	100.0
0.625	16	5/8"	590.5	590.5	67.1
0.19	4.8	No. 4	348.7	939.2	47.6
0.08	2.0	No. 10	81.8	1021.0	43.1
0.03	0.83	No. 20	54.7	1075.7	40.0
0.02	0.43	No. 40	33.8	1109.5	38.1
0.01	0.25	No. 60	23.3	1132.8	36.8
0.01	0.18	No. 80	29.6	1162.4	35.2
0.01	0.15	No. 100	36.3	1198.7	33.2
0.0030	0.075	No. 200	252.8	1451.5	19.1
0.00030	0.0075	< No. 200	343.1	1794.6	-0.08

Pan	45.7	From sieve analysis
Total	1794.6	
% Loss	-0.08	



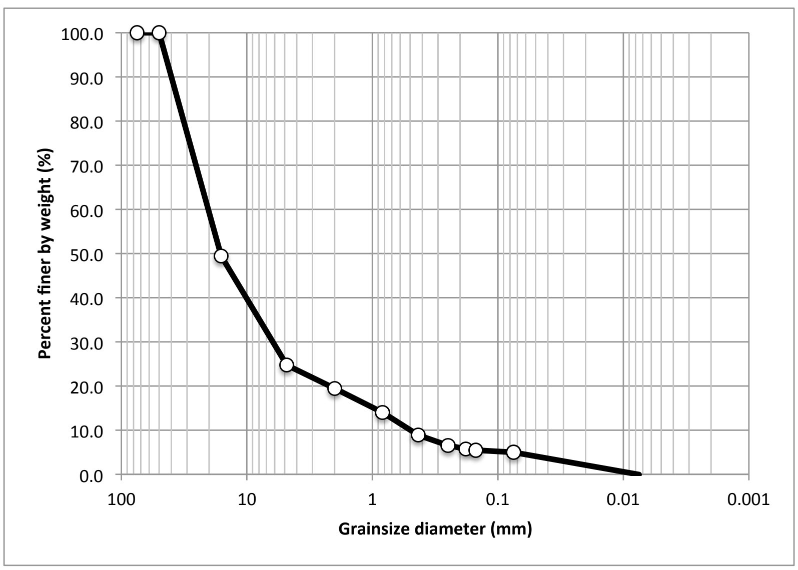
Calculations for Percent Passing

Sample Number: 021

Post-wash Dry Mass, g	1428.8	+	Mass < 75 µm, g	75.1	=	Ttl Dry Mass, g	1503.9

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	0.0	0.0	100.0
0.625	16	5/8"	760.9	760.9	49.4
0.19	4.8	No. 4	371.1	1132.0	24.7
0.08	2.0	No. 10	79.3	1211.3	19.5
0.03	0.83	No. 20	81.7	1293.0	14.0
0.02	0.43	No. 40	77.5	1370.5	8.9
0.01	0.25	No. 60	35.0	1405.5	6.5
0.01	0.18	No. 80	11.8	1417.3	5.8
0.01	0.15	No. 100	4.3	1421.6	5.5
0.0030	0.075	No. 200	7.3	1428.9	5.0
0.00030	0.0075	< No. 200	75.7	1504.6	-0.05

Pan	0.6	From sieve analysis
Total	1504.6	
% Loss	-0.05	



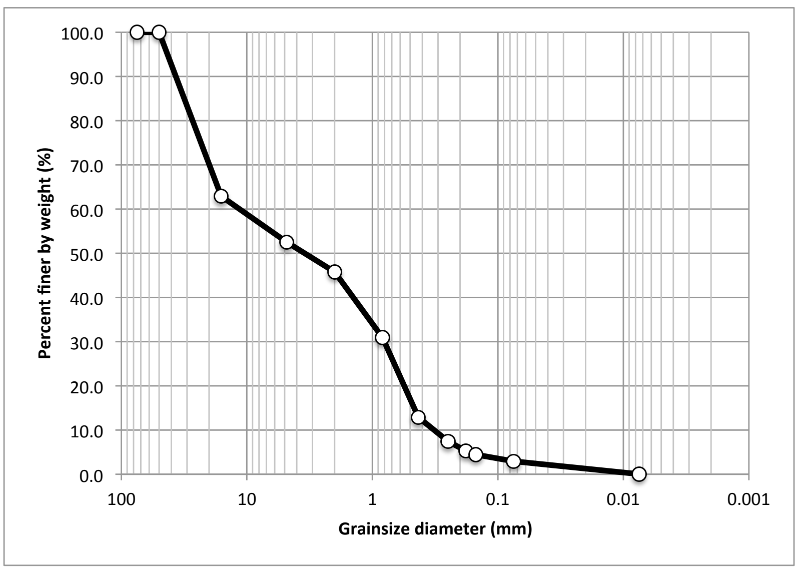
Calculations for Percent Passing

Sample Number: 022

Post-wash Dry Mass, g	942.6	+	Mass < 75 µm, g	25.5	=	Ttl Dry Mass, g	968.1

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	0.0	0.0	100.0
0.625	16	5/8"	359.3	359.3	62.9
0.19	4.8	No. 4	100.6	459.9	52.5
0.08	2.0	No. 10	65.0	524.9	45.8
0.03	0.83	No. 20	143.8	668.7	30.9
0.02	0.43	No. 40	174.5	843.2	12.9
0.01	0.25	No. 60	52.5	895.7	7.5
0.01	0.18	No. 80	21.0	916.7	5.3
0.01	0.15	No. 100	8.2	924.9	4.5
0.0030	0.075	No. 200	14.6	939.5	3.0
0.00030	0.0075	< No. 200	28.2	967.7	0.04

Pan	2.7	From sieve analysis
Total	967.7	
% Loss	0.04	



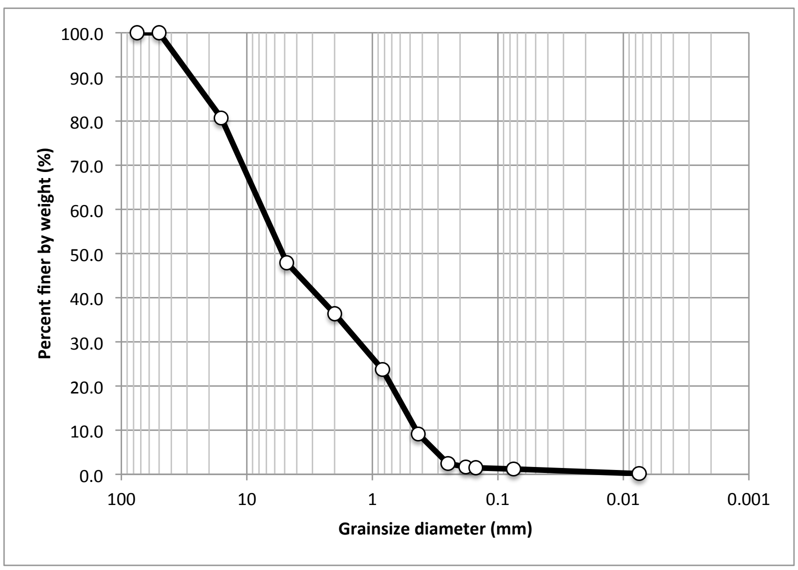
Calculations for Percent Passing

Sample Number: 023

Post-wash Dry Mass, g	1978.2	+	Mass < 75 µm, g	20.3	=	Ttl Dry Mass, g	1998.5

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	0.0	0.0	100.0
0.625	16	5/8"	385.6	385.6	80.7
0.19	4.8	No. 4	655.4	1041.0	47.9
0.08	2.0	No. 10	230.6	1271.6	36.4
0.03	0.83	No. 20	252.8	1524.4	23.7
0.02	0.43	No. 40	291.6	1816.0	9.1
0.01	0.25	No. 60	133.7	1949.7	2.4
0.01	0.18	No. 80	14.8	1964.5	1.7
0.01	0.15	No. 100	4.1	1968.6	1.5
0.0030	0.075	No. 200	5.9	1974.5	1.2
0.00030	0.0075	< No. 200	20.9	1995.4	0.16

Pan	0.6	From sieve analysis
Total	1995.4	
% Loss	0.16	



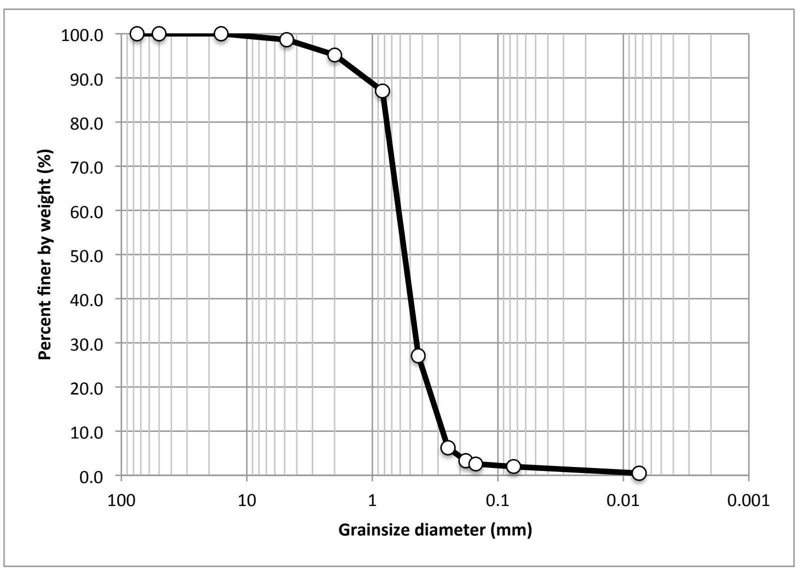
Calculations for Percent Passing

Sample Number: 024

Post-wash Dry Mass, g	1645.5	+	Mass < 75 µm, g	24.7	=	Ttl Dry Mass, g	1670.2

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	0.0	0.0	100.0
0.625	16	5/8"	0.0	0.0	100.0
0.19	4.8	No. 4	22.9	22.9	98.6
0.08	2.0	No. 10	57.2	80.1	95.2
0.03	0.83	No. 20	136.6	216.7	87.0
0.02	0.43	No. 40	1001.0	1217.7	27.1
0.01	0.25	No. 60	348.4	1566.1	6.2
0.01	0.18	No. 80	49.1	1615.2	3.3
0.01	0.15	No. 100	11.8	1627.0	2.6
0.0030	0.075	No. 200	10.1	1637.1	2.0
0.00030	0.0075	< No. 200	25.1	1662.2	0.48

Pan	0.4	From sieve analysis
Total	1662.2	
% Loss	0.48	



Calculations for Percent Passing

Sample Number: 025

Post-wash Dry Mass, g	1746.2	+	Mass < 75 µm, g	11.0	=	Ttl Dry Mass, g	1757.2

Grain size (in)	Grain size (mm)	Sieve No.	Mass Retained on Sieve, g (MR_n)	Cumulative Mass Retained, g (CMR_N)	Passing, % (PP_N)
3"	75	3"	0.0	0.0	100.0
2"	50	2"	0.0	0.0	100.0
0.625	16	5/8"	661.2	661.2	62.4
0.19	4.8	No. 4	506.5	1167.7	33.5
0.08	2.0	No. 10	251.4	1419.1	19.2
0.03	0.83	No. 20	63.5	1482.6	15.6
0.02	0.43	No. 40	127.0	1609.6	8.4
0.01	0.25	No. 60	109.7	1719.3	2.2
0.01	0.18	No. 80	16.8	1736.1	1.2
0.01	0.15	No. 100	4.3	1740.4	1.0
0.0030	0.075	No. 200	3.9	1744.3	0.7
0.00030	0.0075	< No. 200	11.3	1755.6	0.09

Pan	0.3	From sieve analysis
Total	1755.6	
% Loss	0.09