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Hydraulic Laboratory Technical Memorandum, PAP-1125

Erosion Analysis for the Emergency Spillway at Willow Creek Dam

Sun River Project
Montana

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

March 2016

BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Hydraulic Investigations and Laboratory Services Group, 86-68560

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U.S. DEPARTMENT OF THE INTERIOR
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Denver, Colorado

March 2016

Introduction and Purpose

This report summarizes studies conducted to address Safety of Dams recommendation 2011-SOD-A for Willow Creek Dam on the Sun River Project:

> **2011-SOD-A** Complete a spillway erosion study utilizing an up-to-date and appropriate soil erosion modeling tool (such as the SITES Model or WinDAM) to evaluate the frequency of a spillway erosion failure. Determine incremental discharges utilizing the results of the spillway erosion study. Depending on the incremental discharges, develop incremental discharge inundation maps and evaluate the population-at-risk and the risk associated with a hydrologic spillway erosion failure.

This document addresses the modeling of spillway erosion, possible spillway breach, and the prediction of the breach outflow hydrograph that might be produced by a spillway failure. No work has been performed at this time to route the flood or predict the extent of flood inundation.

Background

Willow Creek Reservoir is a 32,230 ac-ft storage reservoir located about 70 miles north of Helena, MT on Willow Creek, a tributary to the Sun River. The reservoir is formed by an embankment dam and 3 small freeboard dikes. The dam was designed and constructed by the Bureau of Reclamation (Reclamation), and is presently operated by the Greenfields Irrigation District. The reservoir stores water from both Willow Creek and the Sun River and supplies water to irrigated land within the Greenfields and Fort Shaw Divisions.

The main dam is a homogeneous earthfill embankment with a structural height of 93 ft and a hydraulic height of 64 ft. The dam was constructed during 1907 to 1911, raised 2 ft in 1917, and raised another 12 ft (to the present crest elevation of 4154.0 ft) in 1941. Freeboard dikes were also constructed at this time, and an uncontrolled emergency spillway was provided through Dike No. 5. The spillway crest consists of a 700-ft long (6-ft deep) concrete cutoff wall with rockfill adjacent to both the upstream and downstream sides of the wall. The inlet and outlet channels are level upstream and downstream from the crest structure and vegetated with grass. The spillway crest is at elevation 4144.0 ft, and the spillway capacity is about 10,000 ft^3/s when the reservoir water surface is at elevation 4147.0 ft.

Geologic information for the spillway channel varies. The most recent Comprehensive Review (CR) report for Willow Creek Dam states that during original construction of the spillway, the excavated material was described as coarse gravel overlaid with about five inches of sod, and that based on the geology, the spillway area was thought to be blanketed by 3 to 7 feet of glacial till consisting of sandy, gravelly clay with a minor amount of large rocks. It is expected that for floods more frequent than 100 years, this material would begin eroding. The CR also states that underlying the glacial till is an unknown thickness of dense, tough clay till containing numerous large rocks. The CR states that the clay material should be more resistant to erosion but could erode for more remote, larger damaging floods. In contrast, the 1997 field investigation reports that "the glacial till in the spillway area is up to at least 95.0 ft thick (drill hole DH-79-101)." Operating experience for the spillway is very limited. In June 1964 the spillway operated with a flow that was estimated to be 30 ft^3/s for 1 to 2 days (approx. 100 ac-ft total volume), causing minor damage in the lower reach of the spillway discharge channel. Modifications were made to the dam in 2000 to address seismic liquefaction and provide additional protection against internal erosion. At the same time, rockfill excavated from the surface of the dam slopes was placed around the spillway crest, in steeper sections of the spillway exit channel, and on portions of the adjacent Dike No. 5 to provide erosion protection (see Figure 1).

Figure 1. — Aerial view of the emergency spillway at Willow Creek Dam. Note rockfill placed in steeply sloped areas of the spillway exit channel (center and upper right).

A study of potential spillway erosion was conducted by Simões and Klumpp (1997), utilizing the GSTARS sediment transport model. That study concluded that large amounts of fine-grained soil and steep slopes (exceeding 5%) in the spillway channel would lead to extensive erosion, and that a 100-yr flood event could produce enough erosion to cause the failure of the concrete cutoff wall leading to breach of the spillway. However, there is a lack of confidence in the previous erosion study due to the fact that GSTARS related erodibility only to the soil particle size, not cohesive soil properties.

Additionally, headcutting processes are expected to dominate the behavior of the spillway, and these processes were not specifically simulated by GSTARS.

In recent years, significant progress has been made towards understanding the physical mechanisms of headcut erosion and modeling headcut erosion mathematically. The present study utilizes computer models developed by the USDA to simulate headcut erosion processes affecting earthen spillways and embankment dams. Headcutting is the term used to describe concentrated erosion that leads to the development of a free overfall, or downward step in the channel profile. Once the overfall forms, flow plunging over the headcut causes concentrated erosion at the base of the headcut that leads to periodic mass failures and upstream migration of the overfall. Headcuts generally form in materials that can sustain a near-vertical face, such as cohesive soils or rock, or in soils that have sufficient sand-size material to develop apparent cohesion due to capillary tension. The SITES model contains an empirical energy dissipation-based model for predicting the headcut advance rate in earthen spillways. WinDAM B simulates spillway erosion almost identically to SITES, and also simulates erosion and breaching of embankments. WinDAM B's embankment erosion module contains the SITES energy-based headcut model as well as a deterministic model (Robinson and Hanson 1994) based on an idealized geometric and mathematical representation of the headcut process (Figure 2).

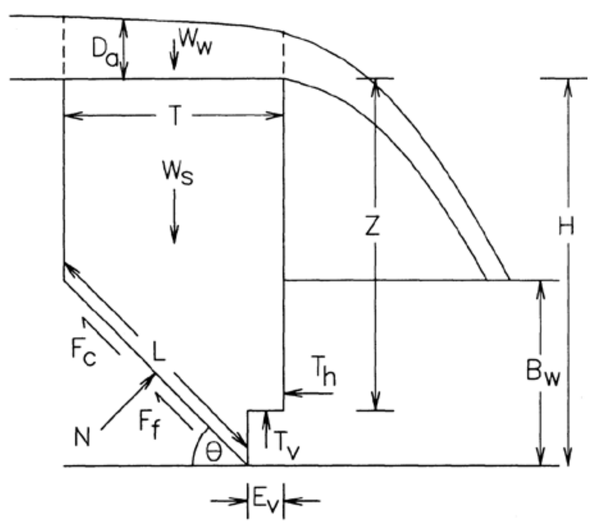

Figure 2. — Idealized representation of an advancing headcut (Robinson and Hanson 1994). Erosion takes place at the base of the headcut until E_v increases to a point that the soil mass becomes unstable and fails along diagonal line L.

Models

Two models were used in this study, SITES version 5.1.7, and WinDAM B version 1.1. These models were both developed by the USDA, based on laboratory and field studies conducted over several decades by the Agricultural Research Service and Natural

Resources Conservation Service (formerly Soil Conservation Service). The SITES model is a comprehensive watershed dam design and analysis tool that includes modules for rainfall-runoff modeling and auxiliary spillway performance evaluation. The auxiliary spillway component simulates flow and erosion occurring in earthen spillway channels, with the focus on the development and upstream advance of headcuts that can breach through a spillway, leading to uncontrolled release of the reservoir. SITES is limited to spillways with a uniform channel cross section along their length, but can accommodate varying channel slopes and multiple underlying soil layers that have differing erodibility properties. The spillway channel is assumed to be straight and the channel slope and underlying soil profile must be defined uniformly for the entire channel width, so variations of channel slope or soil type across the width of the spillway cannot be specifically modeled. A SITES simulation routes a flood through the spillway and predicts when headcuts will develop in the downstream channel and how fast they will advance toward the crest of the spillway. Multiple headcuts beginning at different stations along the channel can be tracked, and headcuts may overtake one another and combine as erosion progresses. The simulation stops when any headcut breaks through the crest of the spillway into the reservoir. Thus, SITES will indicate whether a spillway breaches, but does not simulate the breach development process or the release of reservoir storage through the breach (i.e., no breach outflow hydrograph).

WinDAM B contains a spillway erosion module that is nearly identical to that in SITES. In addition, WinDAM B includes the ability to model erosion and breach of embankment dams due to overtopping flow. The dam breach module of WinDAM B is able to model the breach development process and predict a breach outflow hydrograph.

The general modeling approach used for this study was to utilize SITES for initial modeling of the spillway headcut process. The user interface of SITES is more convenient for modeling multiple spillway erosion scenarios and testing parameter sensitivity. As a check, WinDAM B was also used to confirm the spillway erosion analysis results from SITES for a few specific cases. Following the SITES model runs, WinDAM B was utilized in a breach modeling phase in which the spillway crest was represented as an embankment dam so that the model could be used to estimate breach outflow hydrographs and test the sensitivity of hydrograph properties to soil material inputs.

Materials

The erodibility properties of soil materials in the emergency spillway are critically important to assessing the potential for headcut erosion and breach of the spillway. This study was carried out in two phases. The first phase utilized already available information to make estimates of soil erodibility needed for the SITES and WinDAM B modeling efforts. The second phase of the study used information from soil samples obtained in 2015 from four new drill holes in the spillway channel. These soil samples were used for a laboratory-based erosion testing and materials classification effort.

1997 Field Investigation

During the first phase of the present study, the primary source of information for evaluating soil erodibility was the 1997 field investigation in which eight test pits were excavated to depths of 3.3 to 8.5 ft. As part of this investigation, soil density was measured in the field, soils were visually classified, and soil samples were recovered and tested in the laboratory to determine gradation, soil classification, compaction, and plasticity properties. A map of the test pit locations is shown in Figure 3. The most relevant test pits were TP96-1, located just downstream from the spillway crest near the centerline of the excavated channel, and TP96-8, located just upstream from the spillway cutoff wall. The other test pits were located well downstream from the spillway crest, generally along the middle of the spillway exit channel. Figure 4 summarizes the laboratory test results and Figure 5 shows the soil gradation charts from each test pit.

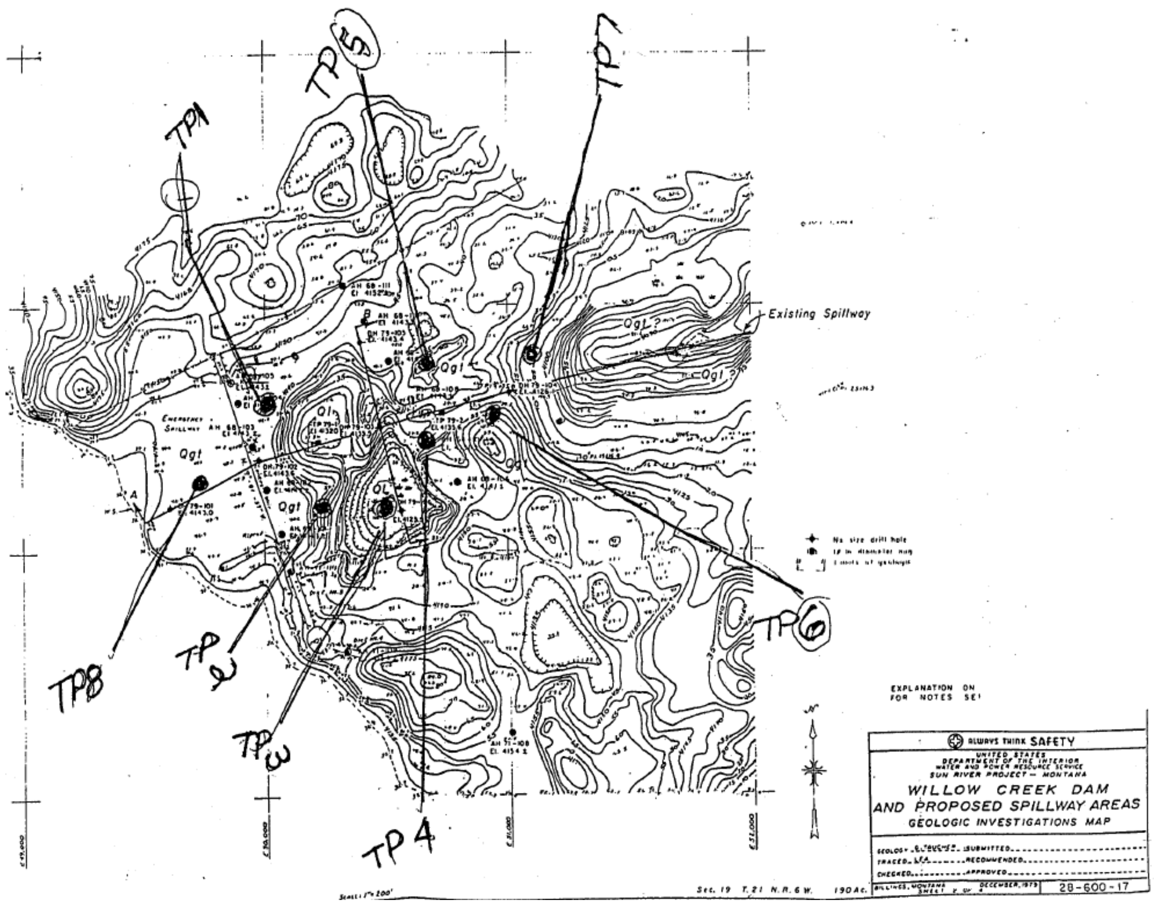

Figure 3. — Map of the emergency spillway area at Willow Creek Dam showing test pit locations from 1997 field investigation.

The test pit results were generally consistent with the earlier observation that the spillway is excavated through glacial till consisting of sandy, gravelly clay with a minor amount of large rocks. Clay particle fractions for 7 of the 8 test pits (not including TP96-3) were in the range of 9 to 25% and plasticity index values varied in a narrow range from 10 to 14, except TP96-2 which was non-plastic. Test pit TP96-3 was excavated in limited lacustrine deposits of fat clay (0- to 6.5-ft depth) and lean clay (6.5- to 9.0-ft depth) with clay contents of 70% and 35% and PI values of 41 and 14, respectively. None of the test pits were deep enough to access the tougher clay till that was said by the CR report to lie below the glacial till. Only test pit TP96-3 showed indication of significantly greater clay content, exclusively in the upper soil layer. The predominant material in the spillway channel based on the test pits is the glacial till soil which was judged in previous erosion studies to have some capability to form an armor layer that would slow the rate of erosion. However, it seems unlikely that such an armor layer could significantly affect a headcut-type erosion process, since the crucial erosion zone in headcutting is the near-vertical face of the advancing headcut, not the channel bed upon which an armor layer might form (Hanson et al. 2001).

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SUMMARY OF PHYSICAL PROPERTIES TEST RESULTS (Proctor Compaction)

Table: 1
Sheet 2 0f 2

Project: Sun River Project, Montana   Feature: Willow Creek Dam

IDENTIFICATION				PARTICLE-SIZE FRACTIONS						CONSISTENCY LIMITS			SPECIFIC GRAVITY				COMPACTION TEST		
SAMPLE NUMBER	HOLE NUMBER	DEPTH - Feet (m)	CLASSIFICATION SYMBOL	SMALLER THAN 0.005 mm	0.005 TO 0.074 mm	SAND NO. 200(0.074 mm TO NO. 4(4.76 mm)	GRAVEL NO. 4(4.76 mm) TO 3 IN.(76.2 mm)	COBBLES 3 IN.(76.2 mm) TO 5 IN.(127 mm)	OVERSIZE LARGER THAN 5 IN.(127 mm)	LIQUID LIMIT - %	PLASTICITY INDEX - %	SHRINKAGE LIMIT - %	MINUS NO. 4	BULK - PLUS NO. 4	APPARENT - PLUS NO. 4	ABSORPTION-PLUS NO. 4 %	MAXIMUM DRY DENSITY - pcf (gm/cm3)	OPTIMUM WATER CONTENT - %	PENETRATION RESISTANCE - PSI
11408	TP96-1	2.8 - 3.6	SC	17.2	24.0	31.5	21.1	6.2	0.0	24	11			2.62	2.71	2.0	118.3	12.6	
11409	TP96-2	3.1 - 4.0	SM	9.3	14.0	76.6	0.1	0.0		Gran.	NP						111.9	13.6	
11410	TP96-3	2.5 - 3.3	CH	70.0	16.4	13.5	0.1	0.0		61	41						96.0	25.0	
11411	TP96-3	7.0 - 7.8	CL	35.2	34.5	30.3	0.0			38	14						96.7	23.9	
11412	TP96-4	0.0 - 8.0	SC	17.7	21.4	30.8	30.1	0.0		27	14								
11413	TP96-5	0.0 - 7.0	SC	16.3	21.6	31.7	30.4	0.0		26	14								
11414	TP96-6	0.0 - 8.2	SC	20.9	23.1	31.8	24.2	0.0		28	13								
11415	TP96-7	0.0 - 8.0	CL	25.3	32.2	39.1	3.4	0.0		25	10								
11416	TP96-8	0.0 - 8.5	GC	12.5		31.9	53.1	2.5	0.0	N/T	N/T								

NOTE: Numbers in parentheses are metric equivalents of numbers directly above.

Figure 4. — Data summary from test pits (Reclamation 1997).

2015 Field Investigation

Following the first phase of the study and the completion of SITES and WinDAM B simulations that predicted a high likelihood of spillway breach and potentially large peak breach outflows, a new field investigation program was undertaken. This effort included the drilling of four new holes in the spillway channel area, subsequent testing to describe and classify the recovered materials, and lab-based erosion tests to estimate the parameters needed for refined model runs. The goal of this effort was to reduce the uncertainty of key material input parameters and thus improve confidence in modeling results.

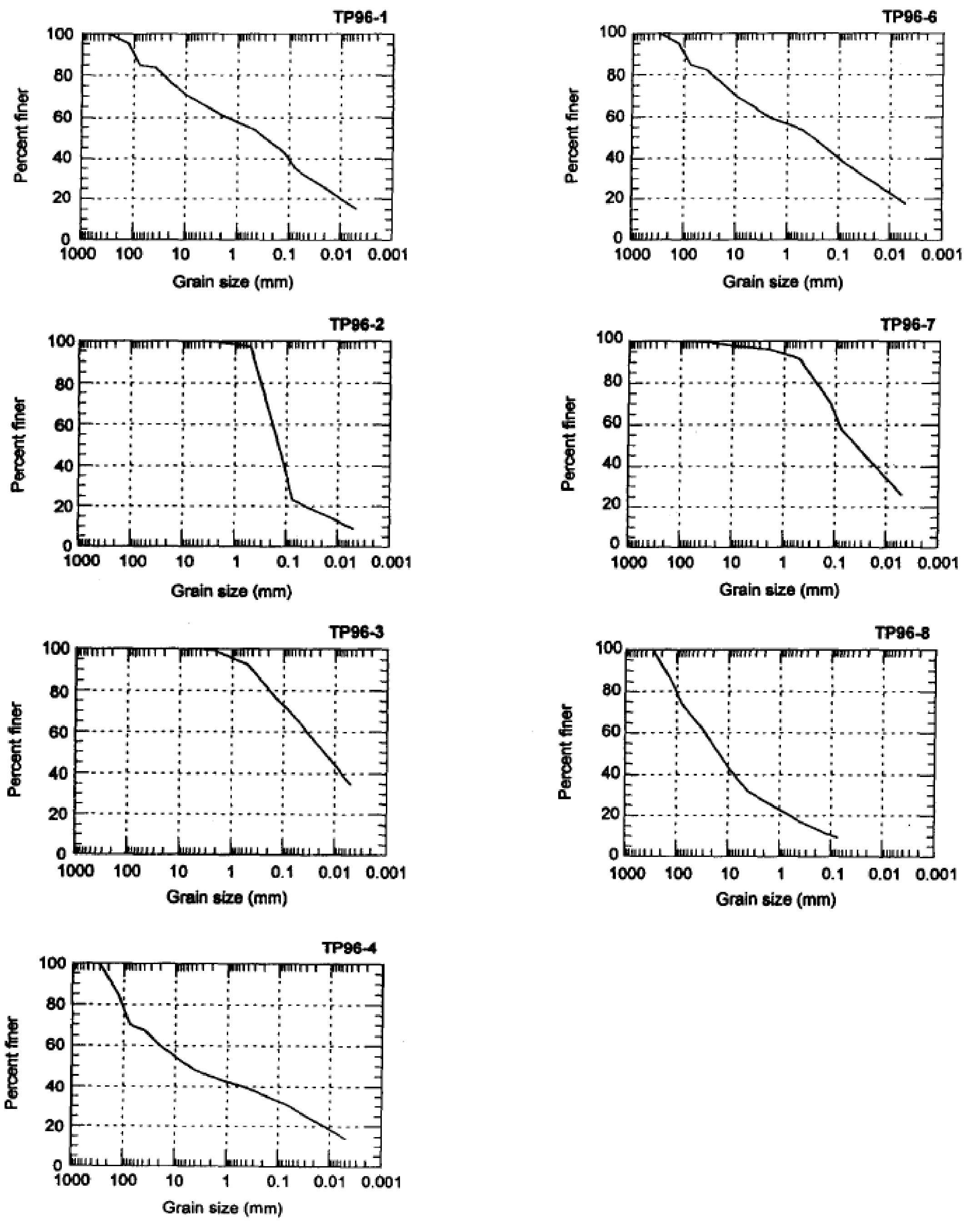

Figure 5. — Soil gradation charts from test pit samples (Simões 1997). Test pit TP96-5 is not plotted, but was nearly identical to TP96-4.

Figure 6 shows the emergency spillway and the four drill hole locations and outlines the area included in an accompanying topographic survey. Drill logs for the four holes are provided in Appendix A. Holes DH-15-201 and DH-15-202 were drilled in the excavated spillway control section area, upstream from the concrete cutoff wall, at approximate elevation 4144 ft. These holes encountered bedrock at elevations of 4081.4 and 4083.4 ft, respectively. Holes DH-15-203 and DH-15-204 were drilled downstream from the spillway crest section at elevation 4136 and 4131, respectively. Drilling in both of these holes was rough and slow and both were terminated before reaching bedrock.

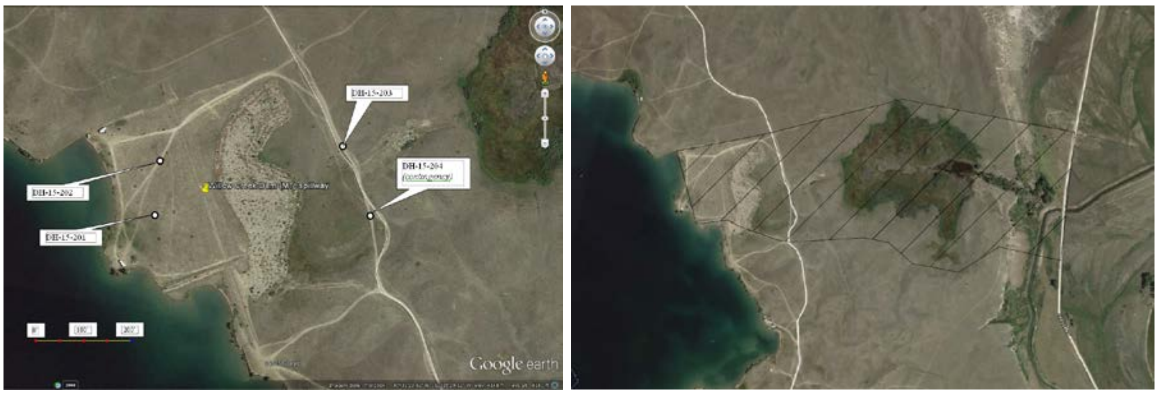

Figure 6. — Location of drill holes (left) and area of topographic survey from 2015 Field Exploration Request.

Samples were recovered from the drill holes in lexan acrylic-lined tubes or as boxed split-barrel samples, alternated at approximately 5 ft intervals. Tube samples were analyzed in the field to obtain in-place unit weight and water content information. All samples were then shipped to the Technical Service Center (TSC) soils lab in Denver. Selected tube samples were used for submerged jet erosion tests; the objectives for choosing erosion test samples were to represent a variety of depths and to test samples without excessive quantities of gravel or larger pieces. Boxed samples and remaining tube samples were sent to the Great Plains (GP) Region soils laboratory (Glendo, WY) for physical properties testing. Remnants of jet erosion test samples were analyzed in the Denver soils laboratory to obtain detailed gradation curves and cohesive soil properties. Summary tables from soils lab testing are provided in Appendix A. Erosion test data are provided in Appendix B.

The tabular data in Appendix A shows that soil types found in the four drill holes were typically clayey gravel and silty gravel, with a few instances of clayey sand, silty sand, and lean clay. Although most of the gravels were relatively broadly graded, none met the requirements for classification as well graded. The variability of the soils was high in comparison to the test pit investigations from 1997, with materials varying from non-plastic up to liquid limits as high as 35 and plasticity indices as high as 20. In situ water content varied from 5 to 18 percent and dry unit weights varied considerably, from about 80 to 143 lb/ft^3.

Erosion Rate Coefficient

The most important parameter in the SITES and WinDAM B models is the soil detachment rate coefficient, k_d, which is used to estimate rates of downward erosion and breach widening. This coefficient indicates the rate of erosion per unit of excess hydraulic shear stress, i.e., the stress that exceeds a critical value, τ_c. In mathematical form, the erosion rate is given by the excess stress equation:

$$\dot{\varepsilon} = k_d \left(\tau - \tau_c \right)$$

where $\dot{\varepsilon}$ is the volume of material removed per unit surface area per unit time (ft/hr), τ is the applied shear stress (psf), τ_c is the critical shear stress needed to initiate sediment detachment (psf), and k_d is a detachment rate coefficient (ft/hr/psf). Typical S.I. units for k_d are $cm^3/(N \cdot s)$, with a conversion factor of 1 $cm^3/(N \cdot s)$ = 0.5655 ft/hr/psf.

When possible, it is desirable to estimate k_d and τ_c by direct testing, either in the laboratory or in the field, using a submerged jet erosion test device. When direct testing is not performed, values can be estimated based on the percentage of clay-size particles and the degree of compaction. For materials that were placed and mechanically compacted, a knowledge of the water content during compaction and the applied compaction energy is useful. Table 1 and Table 2 (Hanson et al. 2010) can be used to estimate values of k_d and τ_c. Because τ_c is often very small compared to the stresses that will be applied during an erosion event, its value is often assumed to be zero. Note when applying the tables that clay-size particles are considered to be those smaller than 0.002 mm (USDA definition). Also note in the tables that k_d is a parameter that varies dramatically with changes in soil composition and compaction conditions. Even when submerged jet erosion tests can be performed, variability is often up to one order of magnitude.

Table 1. — Approximate values of k_d in $cm^3/(N\text{-}s)$ as a function of compaction conditions and percent clay (Hanson et al. 2010). [1 $cm^3/(N\text{-}s)$ = 0.5655 ft/hr/psf]

% Clay (<0.002 mm)	Modified Compaction (56,250 ft-lb/ft^3)		Standard Compaction (12,375 ft-lb/ft^3)		Low Compaction (2,475 ft-lb/ft^3)	
	≥Opt WC%	<Opt WC%	≥Opt WC%	<Opt WC%	≥Opt WC%	<Opt WC%
	Erodibility, k_d, $cm^3/(N \cdot s)$					
>25	0.05	0.5	0.1	1	0.2	2
14-25	0.5	5	1	10	2	20
8-13	5	50	10	100	20	200
0-7	50	200	100	400	200	800

For the first phase of this study, detachment rate coefficients were estimated using these tables and the information available from the 1997 field investigation. Percentages of clay-size particles smaller than 0.002 mm were visually estimated from the gradation charts (lab tests provided the gradations down to only 0.005 mm). Test pit TP96-1 was considered most relevant, since erosion in the zone just downstream from the cutoff wall will determine whether the cutoff wall fails. Since the soil in the spillway is a naturally occurring glacial till, compaction effort was assumed to be low, but compaction was assumed to occur at or above optimum water content. Assuming 8-13% clay-size particles and rounding the conversion factor from $cm^3/(N\text{-}s)$ to ft/hr/psf to a value of 0.5, the estimated k_d value from the tables was 10 ft/hr/psf.

Table 2. — Approximate values of τ_c in Pa as a function of compaction conditions and percent clay (Hanson et al. 2010). [1 Pa = 0.0209 psf]

% Clay (<0.002 mm)	Modified Compaction (56,250 ft-lb/ft^3)		Standard Compaction (12,375 ft-lb/ft^3)		Low Compaction (2,475 ft-lb/ft^3)	
	≥Opt WC%	<Opt WC%	≥Opt WC%	<Opt WC%	≥Opt WC%	<Opt WC%
	Critical shear stress, τ_c, Pa					
>25	16	0.16	4	0	1	0
14-25	0.16	0	0	0	0	0
8-13	0	0	0	0	0	0
0-7	0	0	0	0	0	0

One other means of estimating k_d was considered during the first phase of the study. Chapter 51 of USDA's National Engineering Handbook Part 628 provides a formula for estimating k_d as a function of clay content and dry density. An in-place density test in TP96-1 yielded a value of 117.2 pcf, which is 90% of Proctor maximum density for the minus No. 4 fraction of the soil. Taking the clay content to be 10%, the computed value of k_d is 1.2 ft/lb/psf.

Based on these considerations, for use in the SITES model during the first phase of the study, a k_d value of 1 ft/hr/psf was considered a best estimate, and values of 10 ft/hr/psf and 0.1 ft/hr/psf were used to represent high and low estimates.

For the second phase of the study the detachment rate coefficient values were based on submerged jet erosion tests (JET) performed on specimens cut from tube samples recovered during the 2015 field exploration program. The JET was developed by the Agricultural Research Service (ARS) at their Hydraulic Engineering Research Unit (HERU) in Stillwater, Oklahoma (Hanson and Cook 2004). The test is described in ASTM standard D5852, Standard Test Method for Erodibility Determination of Soil in the Field or in the Laboratory by the Jet Index Method. The Bureau of Reclamation hydraulics laboratory in Denver, Colorado has used a device of this type for several years (Wahl et al. 2008).

The submerged jet test simulates scour of a soil surface due to a perpendicular impinging jet. The jet is positioned a few inches above the soil surface of interest, and the depth of scour produced by the jet is recorded over time. The jet is typically produced from a ¼-inch diameter nozzle operating under a pressure of about 1 to 8 ft of head, depending on the expected erosion resistance of the soil. The data analysis process adjusts the results based on the actual jet pressure used, but it is desirable to run the test in a stress range that is similar to the actual stresses expected to be applied in the prototype flow situation.

Figure 7 shows a schematic diagram of the test and an accompanying photo of the laboratory apparatus constructed by Reclamation from plans provided by Greg Hanson, USDA-ARS (retired).

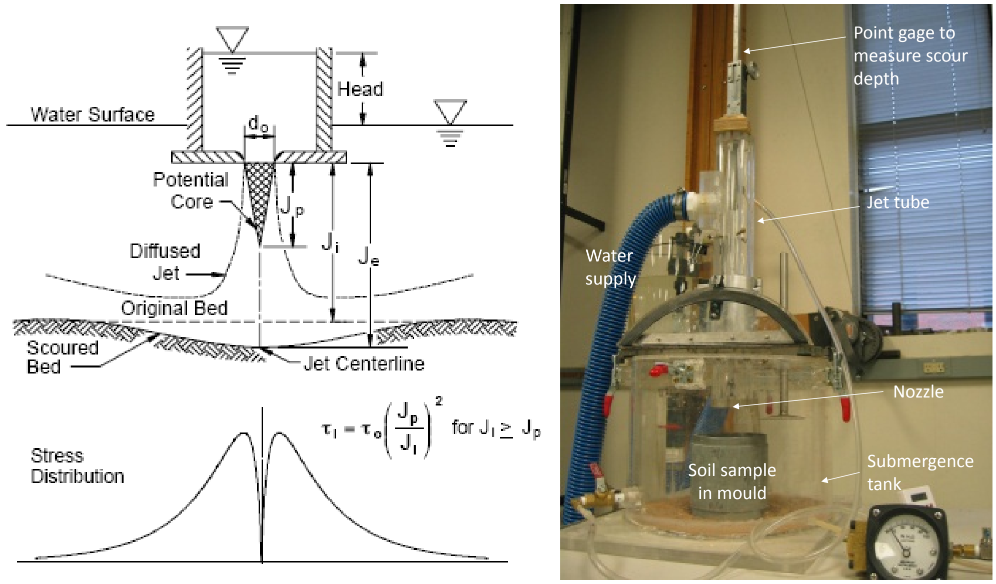

Figure 7. — Jet test schematic diagram and photo of laboratory test apparatus.

The recorded data (scour depth, elapsed time, and jet pressure) are used to estimate the critical shear stress needed to initiate erosion and the detachment rate coefficient relating the rate of erosion to the applied stress in excess of the critical value. The analysis is based on a volumetric form of the excess stress erosion model (the same erosion model that forms the basis for most components of SITES and WinDAM B).

A significant challenge for these tests was the presence of large amounts of gravel in the soil samples. Wahl (2013) demonstrated the potential for removing gravel particles so that erosion tests could be performed using only the finer fraction of the soil (particles passing the No. 4 sieve), since it is the resistance of the fine-grained material that tends to control the erosion rate of mixed soils. Unfortunately, in this case the quantity of gravel was expected to be so large that it would violate assumptions underlying that approach, so it was decided that the best chance for obtaining useful results would be to perform the tests with the samples tilted on their sides so that detached gravel particles could be readily flushed out of the scour hole by a combination of flow action and gravitational forces.

A total of 9 JETs were attempted, with 7 providing enough data that a value of k_d could be estimated from the test. All of the tested samples contained significant amounts of gravel, despite the efforts to select tube samples with less gravel visible through the lexan liners. All of the tests were run with the jet test apparatus inclined at a 45 degree angle. The inclination-aided cleansing of the hole simulates the expected behavior during prototype spillway flows, when it is expected that detached soil particles and gravel pieces will be easily transported away by the flow, leaving the actively eroding surface unarmored.

Figure 8 shows the erosion test results graphically, and Table 3 provides a statistical comparison to the values assumed for the first phase of modeling. The k_d values obtained from the erosion tests exhibited a somewhat larger range and average value than the first phase assumed values. There was not a strong correlation of k_d values with depth or elevation. One sample from near the surface in hole DH-15-204 exhibited a very large k_d, but 5 of the 7 tests yielded values within about ±½ order of magnitude of a central value around 5-7 ft/hr/psf. Curiously, the erosion tests run on the two samples with the highest clay contents yielded both the highest and lowest k_d values; clay content is often considered one good indicator of potential for erosion resistance, but it is clear that other factors, such as in place density or compaction history are also important. Based on the JET results, for the second phase of modeling, values of 0.5 ft/hr/psf, 5 ft/hr/psf, and 10 ft/hr/psf were adopted initially as low, best-estimate, and high values. (A larger high value would have been chosen, but the SITES model would not permit entry of a value greater than 10 ft/hr/psf.) Ultimately, a value of 7 ft/hr/psf (the approximate median of the jet test results) was used for final Phase II runs of the WinDAM B model.

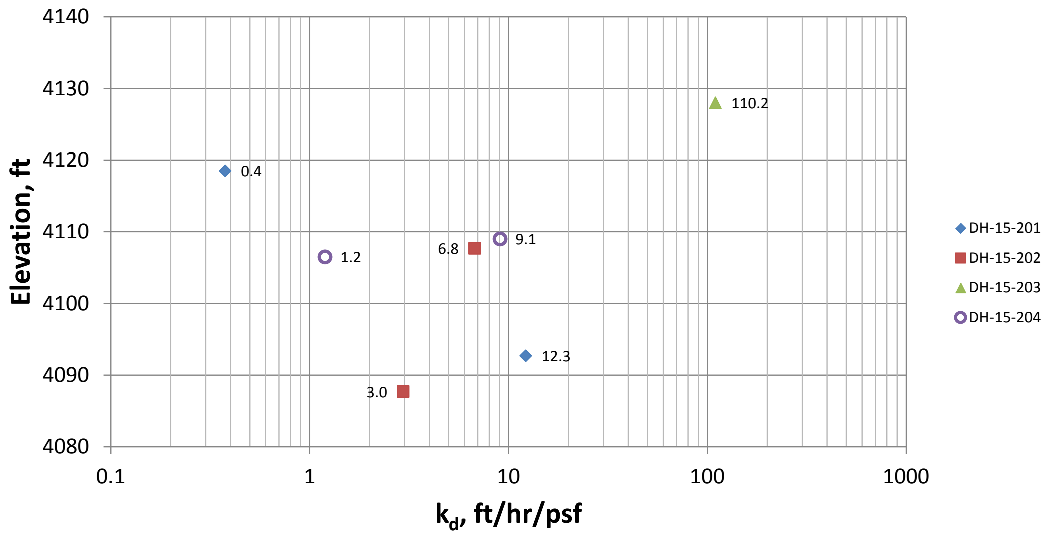

Figure 8. — Detachment rate coefficient values obtained from submerged jet erosion tests of tube samples recovered during the 2015 field exploration program.

Table 3. — Statistical summary of k_d values (ft/hr/psf).

	Values assumed for first phase of modeling	Submerged jet erosion test results
Range, orders of magnitude	2 (0.1 to 10)	2.5 (0.4 to 110)
Low, best-estimate, high values	0.1, 1, 10	0.5, 5, 10
Median	—	6.8
Geometric mean	—	5.25

Although the k_d value has proven in previous modeling efforts to be the most important input parameter to the SITES and WinDAM B models, three other soil parameters are also needed: the headcut erodibility index, a representative particle diameter, and the undrained shear strength.

Headcut Erodibility Index

The SITES model requires an estimate of the headcut erodibility index, K_h. This index can be assigned to rock or soil materials in the field by combining estimates of four different numerical parameters related to mass strength, block size, joint strength and joint orientation. Alternately, the SITES user documentation provides a library of images of a range of different soil and rock materials with corresponding K_h values. Examining this resource, values of K_h=0.02 to 0.16 were deemed to be realistic for the glacial till material. (Values of K_h can vary from 0.01 for loose sand up to 50,000 or more for competent, massive rock). A best estimate value of 0.05 was adopted, with 0.02 and 0.16 representing lower and upper bounds. The same values were used for the first and second phase modeling efforts.

Representative Diameter

The SITES model utilizes a representative diameter parameter when determining the initiation of surface erosion that eventually leads to headcut development. The model suggests setting this equal to the diameter for which 75 percent of the soil gradation is finer. For test pit TP96-1 this is approximately 20 mm (0.8 inches). Lower and upper bounds of 0.04 inches (D_{50}) and 2 inches were also used. A review of the gradation curves obtained from the remnants of the submerged jet erosion test samples confirmed that these were reasonable values, so no adjustments to these inputs were made in the second phase model runs.

Undrained Shear Strength

The WinDAM B model utilizes the undrained shear strength, c_u, in its mechanistic model for headcut advancement. This parameter can be estimated by assessing the material consistency on a 5-tier descriptive scale (very soft; soft; firm; stiff; very stiff). The glacial till was assumed to be firm, and values ranging from 835 to 1565 psf were used (Hanson et al. 2011). The same values were used for both the first and second phase model runs.

Simulation Results

The study by Simões and Klumpp (1997) was based on a spillway flow hydrograph corresponding to a 100-yr flood inflow. The peak spillway flow was 2560 ft^3/s and the total duration was 33 days. For this study, a routed spillway hydrograph based on an updated 100-yr flood from the 2005 CFR report was used (Figure 9). This spillway flow hydrograph peaks at 1632 ft^3/s and the total duration of spillway flows is about 120 hrs (5 days), although the routing was not extended far enough to return to zero spillway flow. This routing assumes that the outlet works operates at 350 ft^3/s until the time that spillway flows begin, and then the outlet is closed for the duration of the routing.

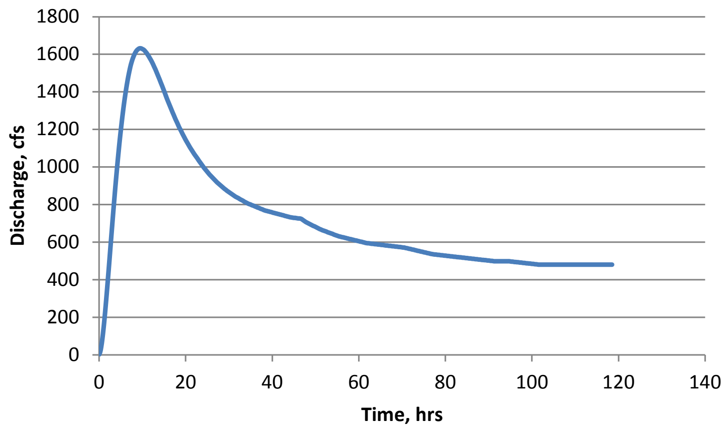

Figure 9. — 100-yr spillway outflow.

Maximum reservoir elevation during this event is 4145.32 ft, about 16 inches above the spillway crest. This flood has a peak discharge that is about 55 times greater than the spillway flows that occurred in 1964.

Phase I Model Runs

SITES Modeling to Predict Breach or No-Breach

SITES allows multiple soil layers with different properties to be defined in the spillway channel. In the first phase of modeling, the spillway channel was represented as just one uniform soil. However, initial runs were made in which the concrete cutoff wall was included as a distinct soil "layer" with soil properties that made it essentially non-erodible. If a shallow headcut were to reach the downstream side of this structure, the SITES model would stop advancement of the headcut until it deepened below the base of the non-erodible cutoff wall. At this point it would become possible for SITES to erode the soil layers below the footing of the cutoff wall and eventually advance the headcut through the cutoff wall. It should be emphasized that the SITES model does not perform any structural analysis of the cutoff wall.

Initial runs showed that headcuts in the spillway channel tended to deepen more quickly than they advanced upstream, with the result being that the headcuts were always at least tens of feet below the cutoff wall when they reached it. It was judged that in such a situation the cutoff wall would have no effect on the breaching process, since it would be perched high above the base of the headcut. However, the SITES model computes the erosion resistance of the entire exposed vertical face of each headcut as a weighted average of the erodibility properties for the exposed layers, giving mathematical credit for erosion resistance due to the cutoff wall. In the weighted average calculation, layers near the base of the overfall are most heavily weighted, but the layers near the top of the overfall still have some influence, especially if they have high erosion resistance. This effect was noticed in the early model runs, with the headcut advance pausing significantly when the cutoff wall was reached. To obtain more realistic results, the decision was made to eliminate the cutoff wall from the model.

The geologic profile through the spillway is shown in Figure 10. SITES requires a uniform profile along the spillway channel (no variation across the width of the spillway channel), and this profile represents the approximate ground surface elevation profile along the center of the spillway channel. Note that the valley floor is shown at elevation 4085. This is not the actual valley floor at the Sun River, but instead represents the approximate elevation of a bench above the Sun River. A steep slope leading from this bench down to the river is described by Simões and Klumpp (1997) as being exposed bedrock, setting a lower limit on the depth of erosion that might take place in the spillway channel. This elevation is consistent with the level at which drill holes DH-15-201 and DH-15-202 were terminated due to encountering bedrock during the 2015 drilling program.

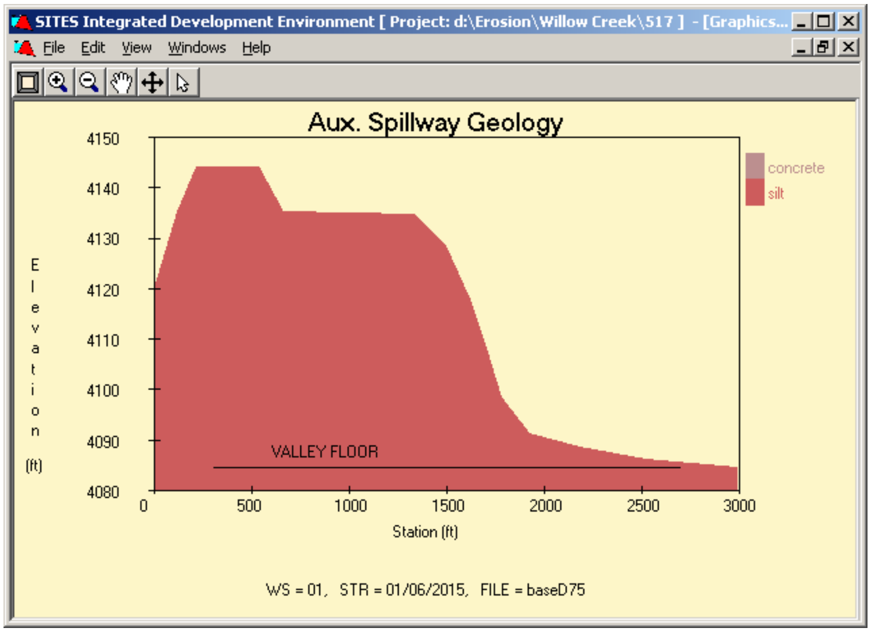

Figure 10. — Spillway geology as defined in the SITES model.

Table 4 shows results of several SITES model runs with different soil material inputs for three key parameters, the detachment rate coefficient (k_d), the representative diameter, and the headcut erosion index (K_h) . Program runs made using best-estimate values and combinations of best-estimate and more erodible values all indicated that the spillway would breach. In each case, the model predicted a deep headcut penetrating down to the assumed bedrock (valley floor elevation) and advancing upstream through the crest section until it reached the reservoir. All of the breaches occurred after the passage of the peak of the spillway flow hydrograph. Setting one parameter at a time to upper bound values of erosion resistance delayed the breach, with the k_d parameter having the greatest influence (partly due to its having the greatest uncertainty and widest range of values used). Setting all three key erodibility parameters to the most erosion resistant values prevented a breach from occurring, but this is a low-probability scenario.

Table 4. — SITES model spillway erosion results. Shaded cells indicate erodibility parameters that represent less erosion resistance than the best estimate values, while values inside heavy borders represent more erosion resistance than the best estimate values.

Detachment rate coefficient, k_d (ft/hr/psf)	Representative diameter, D (inches)	Headcut index, K_h	Time of breach after start of spillway flow* (hr)	Discharge at time of breach (ft^3/s)
1	0.8	0.05	41	752
10	0.8	0.05	24	1003
1	0.04	0.05	36.5	785
1	0.8	0.02	30.5	858
10	0.04	0.02	15.75	1359
0.1	0.8	0.05	262.5**	480
1	2	0.05	66	583
1	0.8	0.16	100	484
0.1	2	0.16	No breach	

*Time of peak inflow is 9.5 hr after the beginning of spillway flow.

**This run assumes that a spillway flow of 480 ft^3/s continues indefinitely.

Flow velocities in the spillway exit channel may be of interest during future studies. Since SITES does not provide a detailed velocity profile in its output, velocities in the steepest reach of the spillway exit channel (slope=12.2%) were manually calculated for a range of discharges using the Manning equation (Figure 11). A roughness value of n=0.040 was assumed for the vegetated channel. These velocities assume normal-depth flow conditions and only apply before erosion initiates in the channel. Once erosion occurs and headcuts form, the assumption of uniform, normal-depth flow no longer applies.

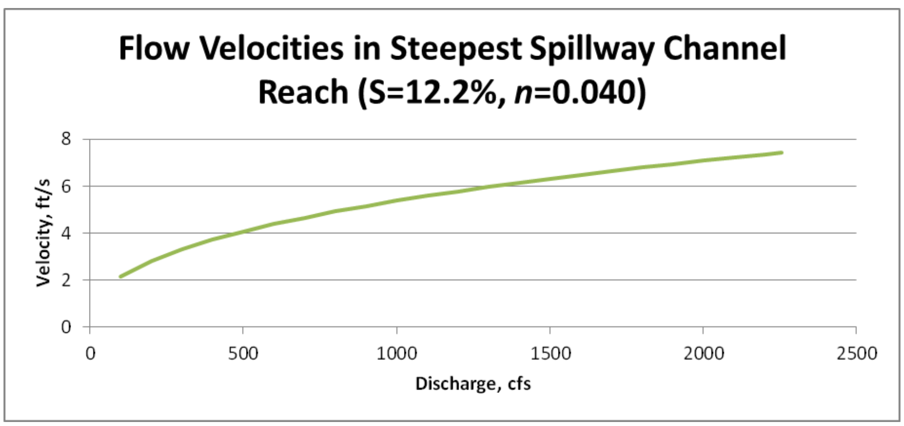

Figure 11. — Flow velocity in steepest reach of exit channel as a function of spillway discharge.

To provide an illustration of the progression of headcut erosion in the spillway, the first case in Table 4 (all parameters set to best-estimate values) in which breach is predicted at t=41 hr was re-run multiple times with the inflow hydrograph truncated at 5 and 10 hr intervals. This allows plots of the incremental spillway erosion to be produced. Figure 12 shows the progression of headcut development and advance through the spillway.

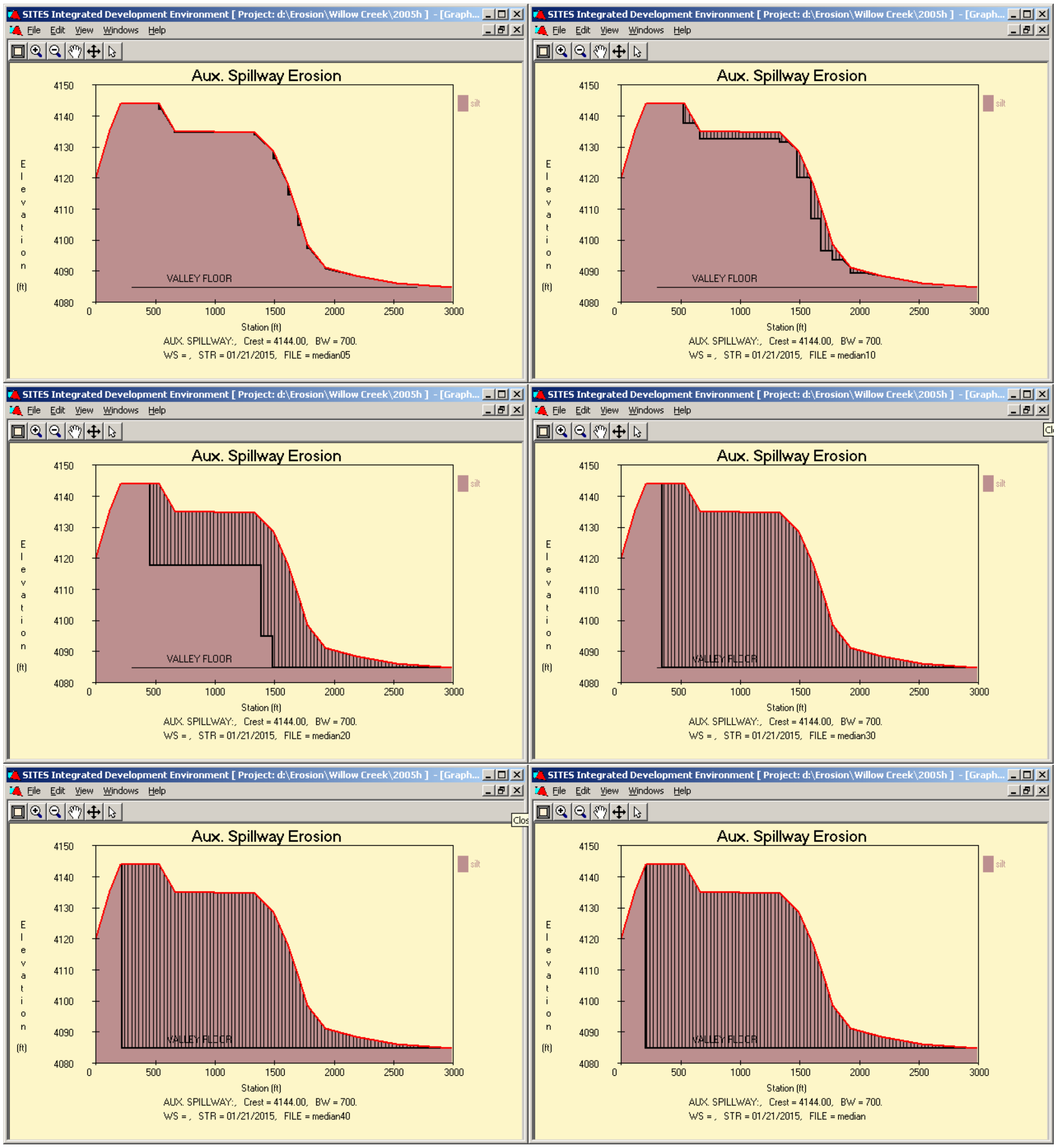

Figure 12. — Progression of erosion in the emergency spillway channel, ultimately leading to spillway breach. Images are shown at *t*=5, 10, 20, 30, 40, and 41 hr.

While the depth of erosion depicted in Figure 12 may seem tremendous, it is not unrealistic given the expected erodibility of the soil. For comparison, Figure 13 and Figure 14 show photos of spillway erosion that occurred at Lake LaMoure, North Dakota in April 2009. This spillway was not breached only because the flood inflow stopped before the headcut advanced into the reservoir. For the Willow Creek spillway, even if the depth of erosion is not as great as simulated in these model runs (approx. 60 ft), it is still likely that the depth of erosion would be enough to destabilize the 6-ft deep cutoff wall and could cause a deep breach of the spillway channel.

Figure 13. — Spillway erosion in progress and the aftermath of flooding at Lake LaMoure, North Dakota, April 2009.

Figure 14. — Deep headcut erosion in progress in the spillway at Lake LaMoure, North Dakota, April 2009.

WinDAM B Modeling

As explained previously, the SITES model only gives an indication of whether a spillway breach will occur. It does not predict an outflow hydrograph. To obtain an estimate of potential breach outflow hydrographs, the WinDAM B model was used to model the spillway crest as though it were a thick embankment dam. The spillway section above elevation 4085 was represented in WinDAM B as an embankment with a crest length of 700 ft, a crest thickness of 375 ft (upstream to downstream dimension), and upstream and downstream slopes of 25:1 (H:V) and 26.5:1, respectively. The slopes were estimated by approximating the topography of the site with straight lines. The upstream slope was somewhat uncertain because topographic maps of the bed of the reservoir were not readily available. However, the area-capacity curve for the reservoir was used to estimate the slope of the reservoir bowl and this was assumed to represent the slope of the approach to the spillway crest.

Table 5 shows the results of performing several simulations (scenarios A through H) with a range of soil erodibility characteristics and upstream slope configurations. A very wide range of peak breach outflows is produced, from 10,600 up to 441,000 ft^3/s. Most of the breaches occur well after the peak spillway flow has occurred, although for scenario H (the most erodible case) the breach takes place just after the peak. As expected, results are very sensitive to the detachment rate coefficient, k_d. The upstream slope of the simulated embankment dam also has a large impact on peak outflow, as a steep slope allows the headcut to penetrate rapidly into the reservoir and develop full head on the breach opening before the reservoir drains significantly. The simulation with the best combination of erosion resistant material inputs (Scenario C) does not cause a breach. The input data for that run are similar to those used in the SITES run that predicted a very late breach at t=262.5 hrs. The value of k_d=0.1 ft/hr/psf in this run is not believed to be realistic based on the known soil properties, but was used to demonstrate the importance of this parameter in the model. The value of k_d=10 ft/hr/psf was thought during the first phase of modeling to be at the upper end of the plausible range (typical of soils with low or no plasticity) and was also included to demonstrate the importance of the k_d parameter. With such highly erodible soils, a breach would fully form in just a few minutes, producing an extraordinary peak outflow.

Table 5. — WinDAM B predictions of breach outflow. Shaded cells indicate erodibility parameters that are believed to be unrealistic, indicating greater erosion resistance than is possible for the materials in the spillway channel.

Scenario	k_d ft/hr/psf	Undrained shear strength, c_u psf	Upstream slope Z_u	Downstream slope Z_d	Breach initiation hr	Q_{peak} ft^3/s	t_{peak} hr
A	1	835	25	26.5	82.3	34,740	94.5
B	1	1565	25	26.5	90.9	34,350	103.0
C	0.1	835	25	26.5	no breach	1,590	9.6
D	0.5	1565	25	26.5	205.1	10,603	228.3
E	0.5	1565	10	26.5	204.4	56,947	215.8
F	0.5	1565	20	26.5	205.0	16,081	225.4
G	1	835	10	26.5	82.0	165,042	88.0
H	10	835	25	26.5	10.3	440,906	11.6

For comparison purposes, two regression-based methods for predicting peak breach outflow from embankment dams were applied to this case. Both equations utilize the stored water volume and dam height, which were assumed to be 32,230 ac-ft and 64 ft, respectively. The Froehlich (1995) equation predicts a peak outflow of 149,000 ft^3/s. The Xu and Zhang (2009) method, which includes a factor to account for soil erodibility (high/medium/low), predicts a peak outflow of 342,000 ft^3/s when high erodibility is assumed. The Froehlich method's lower value is consistent with the fact that it was developed from analysis of dam failure case studies in which embankment soils were typically much more erosion resistant than the glacial till found in the Willow Creek emergency spillway channel. The Xu and Zhang method predicts a peak outflow with a similar order of magnitude as the WinDAM B results for case H, which used the most erodible soil assumptions. The fact that the Xu and Zhang peak outflow is still lower than the value obtained with WinDAM B is not surprising, since even the "high erodibility" dams studied by Xu and Zhang were engineered structures rather than naturally occurring, non-compacted glacial till soils.

Although dramatic differences in peak outflow occur in these simulations, the result at a short distance downstream from the dam may be less sensitive to these details, since the outflow hydrograph would probably attenuate significantly when it reaches the Sun River. Figure 15 shows the outflow hydrographs and the cumulative volume of water released for the different scenarios. A logarithmic scale is used because of the wide variation in peak outflows, and the passage of the inflow hydrograph is visible as the base of the hydrographs.

It is very significant to note in both the SITES spillway erosion simulations and the WinDAM B breach simulations that for most of the cases simulated, breach occurs many hours after the passage of the peak of the spillway outflow hydrograph, and the peak spillway outflow occurs 9.5 hr after the first flow through the spillway. In the SITES simulations, the most erodible combination of input parameters produced a breach at t=15.75 hr, while other runs produced breaches at 24 or more hours after the first spillway flow. In the WinDAM B simulations, breach occurred about 11.6 hr after the first spillway flow for the most erodible case, and 88 hr or later for other cases. The variability of the breach times indicates that specific timing predictions are highly uncertain, but it appears that for the 100-yr flood event inflow, a significant duration of spillway flows is needed to produce a breach. The current Emergency Action Plan calls for downstream response agencies to be notified of a potential flooding event when the reservoir reaches elevation 4143 ft, so there could be significant time available for downstream warning and evacuation, although with larger, lower frequency flood events, the time needed for breach to occur would be shortened.

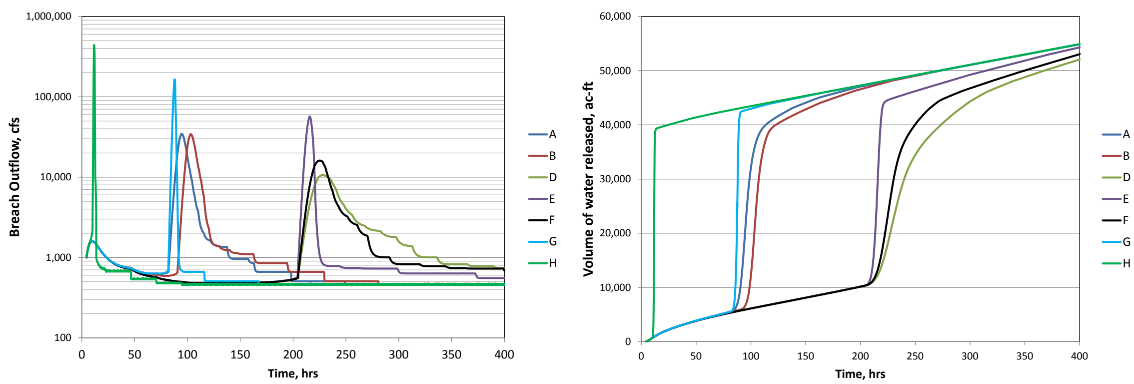

Figure 15. — Breach outflow hydrographs and cumulative volumes of water released versus time.

Phase II Modeling

SITES – Layered Soil Zones and Spillway Channel Modifications

Changes to the input data for the SITES model were relatively minor as a result of the 2015 field exploration program. The low-estimate value of k_d was increased from 0.1 to

0.5 ft/hr/psf and the best-estimate value was increased from 1 to 5 ft/hr/psf; both changes indicate greater erodibility as a result of the submerged jet erosion test results. The high-estimate value was kept at 10 ft/hr/psf. It was apparent that re-running the SITES models with these new values of k_d would predict spillway breach at earlier times in the flood hydrograph. Since this was a predictable result and not of dramatic consequence to the conclusions of this study, those specific model runs were not repeated.

One aspect of the soil properties that was evident from the submerged jet testing was the large variability of the k_d parameter. Although the field exploration program did not suggest much consistency of this variation versus depth or elevation, SITES provides the ability to define soil layers with different erodibility properties, so the Phase II modeling effort was used to test the significance of some hypothetical soil layering scenarios. Additional runs were also made to evaluate some possible spillway exit channel modifications.

Table 6 shows results of the Phase II runs. These runs all modeled the 100 yr flood hydrograph condition. Cases A, B, and C illustrate the effect of soil layers. Case A is an unlayered case that uses the best-estimate values of k_d and K_h. Breach is predicted after 18 hours of spillway operation. Case B and C are layered configurations, with the weakest soil layer deep in the ground and at the ground surface, respectively. Figure 16 shows the assumed layer configuration. The valley floor elevation was adjusted up slightly to 4090 ft based on preliminary information from the field about the levels at which rock was being encountered during the 2015 drilling program. (Later review of the drill logs shows that the bedrock levels probably were not much different from the originally assumed elev. 4085, but the effect of this change on the modeling results appears to have been negligible.) Both layered options developed a breach, but at later times in the hydrograph, due to the addition of stronger soils into the spillway channel profile. Breach occurs more quickly when the weaker soils are at the ground surface.

Cases D and E in Table 6 show the possible effect of two potential spillway channel modifications. Case D adds a continuous layer of 6-inch diameter riprap to the surface of the spillway exit channel. The k_d value for the riprap layer was estimated to be 0.12 ft/hr/psf (similar to the low value used for the glacial till soil in the Phase I modeling), based on research on erosion rates of noncohesive soils by Criswell et al. (2013). The headcut index, K_h, for the riprap layer was estimated to be 1.5, but this value could be too large; when actual spillway erosion events have been analyzed to estimate effective K_h values, sand-size non-cohesive (granular) soils have typically been assigned very low values in the range of 0.01, but there is no guidance for determining K_h values for larger-size granular materials (e.g., riprap). The effect of adding the riprap layer in the SITES model is a delay of the breach by about 10 hours.

Case E modifies the spillway exit channel (non-layered configuration) to have a uniform slope. Since concentrated erosion and headcutting are known to begin on steeper sections and at points of slope change, it was thought that a more uniform channel could be beneficial. The model run shows that the effect is quite small, with only a 1 hr increase in the time needed to breach the spillway.

Table 6. — SITES model runs to test effects of soil layering and possible spillway exit channel modifications.

Case	Detachment rate coefficients, k_d (ft/hr/psf)			Headcut index, K_h			Time of breach after start of spillway flow* (hr)	Description
	Top	Mid	Bottom	Top	Mid	Bottom		
A	5			0.02			18	No layers – best estimate
B	0.5	5	10	0.15	0.10	0.02	45	Weak bottom layer
C	10	5	0.5	0.02	0.10	0.15	32	Weak top layer
D	5			0.02			28.8	No layers – 6" riprap over entire spillway channel
E	5			0.02			19	Uniform 3.8% slope exit channel

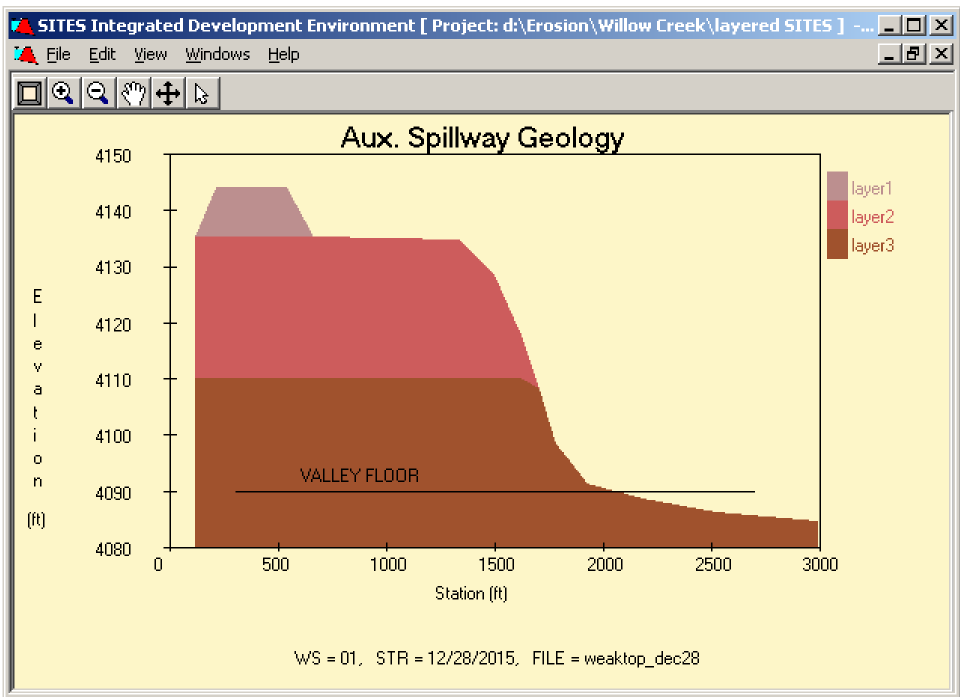

Figure 16. — Layered soil profiles used for Phase II SITES model runs.

WinDAM B Modeling – Phase II

The submerged jet erosion tests performed in 2015 confirmed that k_d values used in the first phase of WinDAM B modeling were reasonable, and in fact that somewhat larger k_d values (greater erodibility) would be realistic. Repeating the same simulations with the larger k_d values was not expected to provide much more useful information. Instead, a series of runs was undertaken to examine how the existing riprap zone in the spillway channel might affect a breaching scenario.

The WinDAM B model is only able to simulate a homogeneous embankment of simple geometry, i.e., a single upstream and downstream slope. However, the model is also able to consider the protection that might be provided by riprap on the downstream slope of a dam. In the case of the spillway for Willow Creek Dam, the spillway channel that we are simulating as a dam in WinDAM B actually has two distinct sloped sections downstream from the “dam crest”, with a nearly horizontal bench near elevation 4135 ft. (See, for example, Figure 16.) The first of these sloped sections is a 9-ft drop from the crest (El. 4144) that is protected by riprap that was removed from other locations on the project and placed into the spillway during modification activities in 2000. This riprap layer was ignored in the first phase of modeling with WinDAM B, since it is not continuous over the entire spillway channel and its properties were not well documented. WinDAM B accordingly assumed immediate initiation of erosion on this slope and started headcut development at the top of this slope, i.e., at the downstream end of the level spillway crest at elev. 4144. Headcutting then needed to advance about 375 ft upstream to reach the upstream edge of the crest and breach the spillway (“dam”), undermining the 6-ft deep concrete sill structure along the way.

If the riprap zone were to effectively stop or delay erosion, this erosion sequence might not be realistic. With the first slope protected by riprap, initiation of erosion would occur instead at the head of the second slope. This would greatly increase the distance that headcutting would need to advance to breach the spillway. This concept formed the basis for additional WinDAM B simulations.

To test whether the riprap layer might protect the first slope, a WinDAM B simulation was run with a downstream slope of 15H:1V, protected by a 2-ft thick layer of riprap with median diameter D_{50}=6 inches. The model indicated that the downstream slope would be protected against the flows occurring in the 100-yr flood event. While this is encouraging, WinDAM B is a dam breach simulation tool, not a riprap design tool, and this simple analysis should not be taken as proof that the riprap present at the site today would actually be adequate to protect the slope against these flows. Furthermore, although riprap might prevent erosion from initiating on the first slope, it would not be able to stop headcut erosion that begins at the second sloped section and advances back through the first slope.

Next, a model was created in which the crest width of the simulated “dam” was set to 1000 ft (compared to 375 ft in the first phase model runs), which was the estimated distance from the brink (upstream end) of the second sloped section of the spillway channel back to the upstream edge of the flat crest section (elev. 4144). The k_d value for the embankment soil was set to 7 ft/hr/psf, similar to the median and geometric means of the submerged jet erosion test results (higher than most of the k_d values used during the first phase of WinDAM B modeling, but similar to the worst-case value of 10 ft/hr/psf used for scenario H). The downstream slope was set at 13.55:1 (estimated slope of the two steep sections, ignoring the flat bench), compared with the average slope of 26.5:1 used in the first phase model runs. The other soil parameters were kept at the same values used in the first phase of modeling. The valley floor elevation was adjusted slightly, based on results from the 2015 drill holes.

When this model was run with the 100-yr flood event inflow, the headcut advanced upstream at an average rate of about 40 ft/hr and breach initiation took place in 25.5 hr (compared to 11.6 hr for scenario H, which was the similar run made during the first phase of modeling—see Table 5). The peak breach outflow was 451,000 ft^3/s, similar to the 441,000 ft^3/s result from scenario H. So, although the increased distance needed for headcut advance changed the time required to breach the spillway, the resulting outflow hydrograph was similar. This is consistent with the fact that the reservoir head would be similar in both scenarios at the moment that the headcut breaks through the crest and into the reservoir.

A rough calculation was made following this run to estimate the relative amount of sediment transported during the breach initiation phase. WinDAM B assumes that the sediment transport capacity of the flow will be greater than the rate at which soil particles can be detached, but the actual sediment transport capacity of the flow is never determined. Thus, this is a check on the reasonability of this assumption. The calculation showed that the volume of sediment eroded during breach initiation would be about 35% of the volume of water discharged. This seems realistic for a debris flow produced by high energy flow down a steep slope (7.5%) composed of very erodible glacial till soil.

Although the peak outflow obtained from the WinDAM B simulations is extremely large, it should be emphasized again that the duration of this peak flow is very short. The hydrograph rises from less than 10% of the peak outflow to the peak and back again to less than 10% of the peak in a total of 1.75 hr. Routing this flood through the downstream valley could attenuate the peak discharge considerably.

Final Hydrographs for Inundation Analysis

Following consultations with the project team members and interested parties, the decision was made to generate a set of three hydrographs that could be used to estimate inundation that would result from breach floods of different magnitudes. The high estimate case was assumed to use the erodibility parameters from the other Phase II runs (k_d = 7 ft/hr/psf; c_u = 835 lb/ft^2), but a review of typical operating procedures and project history related to the 1964 flood event suggested that the outlet works would probably be kept operating during any large flood event, so a constant outflow of 350 ft^3/s was assumed from the reservoir. This reduced the peak breach outflow to about 394,000 ft^3/s. For middle and low estimates of peak breach outflow, scenarios A and G from Phase I (Table 5) were used. The three chosen scenarios are summarized below in Table 7 and the hydrographs are shown graphically in Figure 17.

Table 7. — Final dam breach simulation scenarios used to generate outflow hydrographs for inundation modeling. Characteristics common to all scenarios are starting reservoir elevation 4144.0 ft, c_u=835 lb/ft^2, crest thickness=375 ft.

Case	Description	Outlet Works	k_d ft/hr/psf	Upstream slope, Z_u	$Q_{peak,}$ ft^3/s
Low	Scenario A – Phase I (see Table 5)	Closed	1	25	35,000
Middle	Scenario G – Phase I (see Table 5)	Closed	1	10	165,000
High	Median of jet-test erodibility results	Open – Q=350 ft^3/s	7	25	394,000

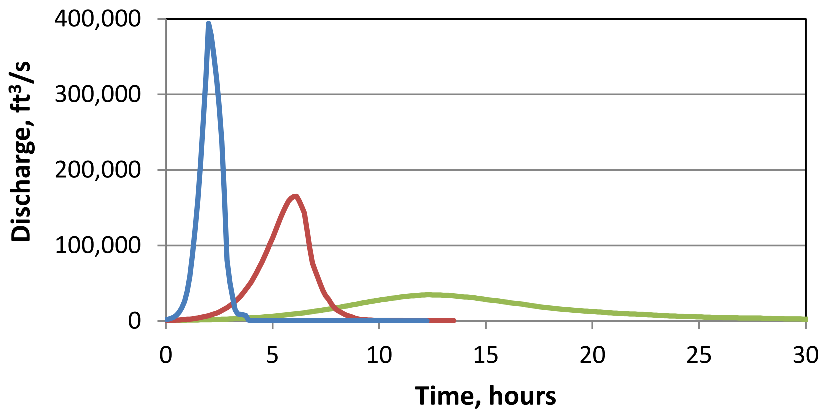

Figure 17. — High, middle, and low estimated breach outflow hydrographs. Times are referenced to the start of breach formation (when headcutting advances through the upstream crest).

Conclusions

SITES and WinDAM B modeling of the emergency spillway channel at Willow Creek Dam indicates that the spillway is likely to breach for floods at the 100-yr or lower frequency level. In the scenarios considered here, breach will occur only after at least several hours of spillway operation, although a faster breach should be expected for larger inflow floods.

In the first phase of modeling, a range of soil material properties was considered (erosion rates varying ±1 order of magnitude) and the only scenarios that did not lead to spillway breach were those in which all key erodibility parameters were set to the most erosion resistant values thought feasible based on material descriptions and previous lab and field investigations. Predictions of peak breach outflow from the WinDAM B model were sensitive to soil erodibility properties and the geometry of the reservoir in the vicinity of the spillway crest (i.e., the upstream slope of the simulated "dam").

In an attempt to reduce the uncertainty in the modeling results and test the reasonability of using input parameters indicating significant erosion resistance, a field exploration program was undertaken in 2015, and submerged jet erosion tests were performed on recovered soil samples. The uncertainty of the crucial soil erodibility parameter, (detachment rate coefficient, k_d) was reduced to about ±½ order of magnitude, but the erosion tests also indicated that average erodibility rates were somewhat higher than the best-estimate values used in the first phase of modeling.

A second phase of modeling was undertaken using soil properties based on the field exploration program and erosion test results. The second phase of SITES modeling tested the effect of possible layering of soils with different erodibility characteristics within the spillway, but the impact on predicted headcut advance times was relatively small. The second phase of model runs using WinDAM B tested the possible effects of the existing riprap zone that armors the first steep channel section downstream from the spillway crest area. These runs were used to estimate the extra time that would be needed for breach initiation to occur if, due to protection afforded by the riprap, headcut advance started not at the downstream end of the flat spillway crest section, but instead at the second steep section of the spillway channel. The breach initiation time did increase from 12 to about 25 hr, but the peak breach outflow remained about the same at 450,000 ft^3/s. A final model run was made using soil erodibility parameters matching the median of the jet test results and considering the effect of operating the dam's outlet works throughout the duration of the flood; this reduced the peak breach outflow to about 394,000 ft^3/s.

The final product of this work was a set of three breach outflow hydrographs that were provided to the project team to be routed downstream for estimating inundated areas and flooding consequences. Hydrographs for high, middle, and low peak outflow scenarios were provided with peak discharges of 394,000 ft^3/s, 165,000 ft^3/s, and 35,000 ft^3/s. The range of these estimates reflects uncertainty about soil erodibility parameters and other simplifying assumptions described in this report.

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SITES software download: **http://go.usa.gov/83z**

WinDAM B software download: **http://go.usa.gov/8Oq**

Appendix A – Soil Testing Results

- Drill logs
- Summary of tube density test results
- Summary of physical properties (box samples, combined box samples, tube samples, remnants of erosion-test tube samples
- Particle Size Distribution Reports (from erosion test sample remnants)

GEOLOGIC LOG OF DRILL HOLE: DH15-201WC

FEATURE: Willow Creek Dam	**PROJECT:** Sun River Project	**STATE:** Montana
LOCATION: Emergency spillway	**COORDINATES:** N 473,323 E 1,122,537	**GROUND ELEVATION:** 4143.9
BEGUN: 5/9/15 **FINISHED:** 5/12/15	**TOTAL DEPTH:** 69.0	**ANGLE FROM HORIZONTAL:** 90 **AZIMUTH:**
DEPTH AND ELEV. OF WATER LEVEL AND DATE MEASURED: 22.5 (4121.4) 5/10/15	**DEPTH TO BEDROCK:** 62.5	**HOLE LOGGED BY:** J. Lasater **REVIEWED BY:** K. Scannella

NOTES

LOCATION:
Emergency spillway, upstream of crest adjacent to DH79-101.

PURPOSE OF HOLE:
To collect undisturbed samples for laboratory testing and additional geologic data in order to better estimate potential erosion rates for materials within the spillway at Willow Creek Dam, MT.

DRILL EQUIPMENT:
Truck-mounted CME-85 rotary drill rig; 6-1/4 inch I.D. hollow stem auger (HSA); 5-foot-long, 5.38 inch I.D. split tube sample barrel; 2-1/2 foot long, 5.07 inch I.D. acrylic undisturbed sample tube; 1-3/8 inch I.D. SPT barrel.

DRILLER:
Sean Rafferty; USBR

DRILLING METHOD:
0.0 to 4.0 feet - Advanced hole with 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

4.0 to 5.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

5.0 to 9.0 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

9.0 to 37.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

37.0 to 39.0 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

39.0 to 44.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

44.0 to 61.5 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

61.5 to 62.5 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

62.5 to 64.0 feet - Single SPT with 6-1/4 inch HSA and 1-3/8 inch I.D. SPT barrel to break through rock layer.

DEPTH / FLD. CLASS/LITH. / % CORE RECOVERY / GEOL. UNIT SYM.

DEPTH	FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.
0.0–0.7	(GC)sc		ts
		82.5	
5		100	
		32.5	
10		0	
15		0	
20	(GC)sc	24	Qgt
25		77	
		100	
30		52	
35		0	
		55	
40		30	
45	(GP)sc	24	Qgf

CLASSIFICATION AND PHYSICAL CONDITION

0.0 to 0.7 feet - TOPSOIL:

0.0 to 0.7 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 60% sedimentary and igneous gravel; approximately 25% sand; approximately 15% high to medium plasticity fines; maximum particle size recovered 4-1/2 inches; subangular to subrounded; light brown; dry; strong reaction to HCl; consistency firm-hard; no cementation; slow to no dilatency; medium toughness; poorly sorted; high dry strength; organic odor.

Total sample (by volume): Approximately 5% metasedimentary and igneous cobbles, subangular to subrounded, 2-4-1/2 inches, hard.

0.7 to 37.0 feet - QUATERNARY GLACIAL TILL (Qgt):

0.7 to 9.0 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 50-60% metasedimentary and igneous gravel; approximately 25-30% sand; approximately 15-20% highly plastic fines; maximum particle size recovered 4 inches; subangular to subrounded; light brown; dry; strong reaction to HCl; consistency firm-hard; no cementation; hard; slow dilatency; medium toughness; poorly sorted; high dry strength.

Total sample (by volume): Approximately 5-50% metasedimentary and igneous cobbles, subangular to subrounded, 2-4 inches, hard.

<u>LAB TEST DATA:</u> 0.0 to 9.0 feet - 38% fines, 35% gravel, 27% sand; LL=24.9, PI=12.3; Laboratory classification is Clayey Gravel with Sand and Cobbles (GC)sc

9.0 to 19.0 feet - NO RECOVERY

19.0 to 34.0 feet -CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 50% metasedimentary and igneous gravel; approximately 20-30% sand; approximately 20-30% medium plasticity fines; maximum particle size recovered 4-1/2 inches; angular to subround; brown-light brown; wet; strong reaction to HCl; consistency firm-hard; no cementation; hard; slow dilatency; medium toughness; poorly sorted; high dry strength.

Total sample (by volume): Approximately 10% metasedimentary and igneous cobbles, subangular to subrounded, 2-4-1/2 inches, hard.

<u>LAB TEST DATA:</u> 23.0 to 33.6 feet - 40% gravel, 38% sand, 22% fines; LL=21.7, PI=7.9; Laboratory classification is Clayey Gravel with Sand and Cobbles (GC)sc

34.0 to 37.0 feet - NO RECOVERY

GEOLOGIC LOG OF DRILL HOLE: DH15-201WC

FEATURE: Willow Creek Dam	**PROJECT:** Sun River Project	**STATE:** Montana
LOCATION: Emergency spillway	**COORDINATES:** N 473,323 E 1,122,537	**GROUND ELEVATION:** 4143.9
BEGUN: 5/9/15 **FINISHED:** 5/12/15	**TOTAL DEPTH:** 69.0	**ANGLE FROM HORIZONTAL:** 90 **AZIMUTH:**
DEPTH AND ELEV. OF WATER LEVEL AND DATE MEASURED: 22.5 (4121.4) 5/10/15	**DEPTH TO BEDROCK:** 62.5	**HOLE LOGGED BY:** J. Lasater **REVIEWED BY:** K. Scannella

NOTES

64.0 to 69.0 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

DRILLING COMMENTS:
9.0 to 14.0 feet - No sample recovery due to the coarse nature of the material. Cobbles and boulders were likely pushed ahead of augers, preventing sample collection.

14.0 to 19.0 feet - No sample recovery due to the saturated conditions as well as the coarse nature of the material.

HOLE COMPLETION:
Drill holes backfilled from the bottom of the hole at 69.0 feet to ground surface with 42, 50 pound bags of 3/8 inch bentonite chips.

DEPTH	FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.
		34	
55	(GP)sc	20	Qgf
60		100	
		100	
		80	
65	ss, cs	98	Ktm

BOTTOM OF HOLE

CLASSIFICATION AND PHYSICAL CONDITION

37.0 to 62.5 feet - QUATERNARY GLACIAL FLUVIAL (Qgf):

37.0 to 39.0 feet - POORLY GRADED GRAVEL WITH SAND AND COBBLES (GP)sc:
Approximately 70% metasedimentary and igneous gravel; approximately 20% sand; approximately 10% medium plasticity fines; maximum particle size recovered 4-1/2 inches; subrounded to rounded; brown; wet; weak reaction to HCl; consistency soft-firm; no cementation; hard; slow dilatency; low toughness; well sorted; medium dry strength.

Approximately 5% metasedimentary and igneous cobbles, subrounded to rounded, 2-4-1/2 inches, hard.

39.0 to 44.0 feet - POORLY GRADED GRAVEL WITH COBBLES (GP)c:
All fine grain material was washed away. 100% metasedimentary and igneous gravel, 90% cobbles by volume, maximum particle size recovered 4 inches, subrounded, wet, weak reaction to HCl; hard; well sorted.

44.0 to 54.0 feet - POORLY GRADED GRAVEL WITH SAND AND COBBLES (GP)sc:
Approximately 75% metasedimentary and igneous gravel; approximately 15% non-plastic fines; approximately 10% sand; maximum particle size recovered 4-1/2 inches; subangular-subround; brown; wet; weak reaction to HCl; consistency firm; no cementation; hard; medium dilatency; low toughness; moderately sorted; weak to no dry strength.

Total sample (by volume): Approximately 10% metasedimentary and igneous cobbles, subrounded to rounded, 2-4-1/2 inches, hard.

54.0 to 59.0 feet - POORLY GRADED SAND WITH SILT AND GRAVEL (SP-SM):
Approximately 60% sand; approximately 30% metasedimentary and igneous gravel; approximately 10% non-plastic fines; maximum particle size recovered 2 inches; subangular to subrounded; brown; wet; weak reaction to HCl; consistency firm; no cementation; hard; rapid dilatency; low toughness; moderately sorted; weak to no dry strength.

59.0 to 62.5 feet - SANDY LEAN CLAY s(CL):
Approximately 65-75% plastic fines; approximately 15-20% sand; approximately 10-15% metasedimentary to igneous gravel; maximum particle size recovered 2 inches; subangular to subrounded; brown to gray; moist; weak reaction to HCl; consistency firm; no cementation; hard; slow to no dilatency; high toughness; moderate to well sorted; high dry strength.

LAB TEST DATA: 49.0 to 62.3 feet - 41% sand, 35% gravel, 24% fines; LL=18.8, PI=6.2; Laboratory classification is Silty, Clayey Sand with Gravel(SC-SM)g

GEOLOGIC LOG OF DRILL HOLE: DH15-201WC

FEATURE: Willow Creek Dam
LOCATION: Emergency spillway
BEGUN: 5/9/15 **FINISHED:** 5/12/15
DEPTH AND ELEV. OF WATER LEVEL AND DATE MEASURED: 22.5 (4121.4) 5/10/15

PROJECT: Sun River Project
COORDINATES: N 473,323 E 1,122,537
TOTAL DEPTH: 69.0
DEPTH TO BEDROCK: 62.5

STATE: Montana
GROUND ELEVATION: 4143.9
ANGLE FROM HORIZONTAL: 90 **AZIMUTH:**
HOLE LOGGED BY: J. Lasater
REVIEWED BY: K. Scannella

NOTES	DEPTH	FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.	CLASSIFICATION AND PHYSICAL CONDITION

62.5 to 69.0 feet - TWO MEDICINE FORMATION (Ktm):

62.5 to 62.9 feet - SANDSTONE:
Gray calcareous sandstone; strong reaction to HCl; moderately bedded; slight to fresh weathering (W1-W2); hard (H3).

62.9 to 67.2 feet - CLAYSTONE:
Green gray claystone; strong reaction to HCl; very thickly bedded; very intensely weathered to decomposed (W8-W9); soft (H6); well indurated; no fractures discernible (FD0-FD1); moist; moderate to rapid slaking.

67.2 to 67.4 feet - SANDSTONE:
Gray calcareous sandstone; strong reaction to HCl; thinly bedded; moderate weathering (W5); moderately hard (H4).

67.4 to 69.0 feet - CLAYSTONE:
Green gray claystone; strong reaction to HCl; thickly bedded; very intensely weathered to decomposed (W8-W9); soft (H6); well indurated; no fractures discernible; no fractures discernible (FD0-FD1); moist; moderate to rapid slaking.

GEOLOGIC LOG OF DRILL HOLE: DH15-202WC

FEATURE: Willow Creek Dam
LOCATION: Emergency spillway
BEGUN: 5/20/15 FINISHED: 5/26/15
DEPTH AND ELEV. OF WATER LEVEL AND DATE MEASURED: 10.1 (4134.1) 5/26/15

PROJECT: Sun River Project
COORDINATES: N 473,325 E 1,122,537
TOTAL DEPTH: 61.5
DEPTH TO BEDROCK: 60.8

STATE: Montana
GROUND ELEVATION: 4144.2
ANGLE FROM HORIZONTAL: 90 AZIMUTH:
HOLE LOGGED BY: J. Lasater
REVIEWED BY: K. Scannella

FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.
s(CL)gc	100, 48, 0, 43, 0, 100, 0, 38, 54, 74	ts, Qgt
(GC)sc	100, 44	Qgf

NOTES

LOCATION:
Emergency spillway, upstream of crest.

PURPOSE OF HOLE:
To collect undisturbed samples for laboratory testing and additional geologic data in order to better estimate potential erosion rates for materials within the spillway at Willow Creek Dam, MT.

DRILL EQUIPMENT:
Truck-mounted CME-85 rotary drill rig; 6-1/4 inch I.D. hollow stem auger (HSA); 5-foot-long, 5.38 inch I.D. split tube sample barrel; 2-1/2 foot long, 5.07 inch I.D. acrylic undisturbed sample tube.

DRILLER:
Sean Rafferty, Sam Watt; USBR

DRILLING METHOD:
0.0 to 4.0 feet - Advanced hole with 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

4.0 to 9.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

9.0 to 14.0 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

14.0 to 17.5 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

17.5 to 17.5 feet - Single SPT with 6-1/4 inch HSA and 1-3/8 inch I.D. SPT barrel to break through rock layer.

17.5 to 21.5 feet - 6-1/4 inch HSA with centerbit assembly

21.5 to 24.0 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

24.0 to 29.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

29.0 to 34.0 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

34.0 to 42.8 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample

CLASSIFICATION AND PHYSICAL CONDITION

0.0 to 1.1 feet - TOPSOIL:

0.0 to 1.1 feet - CLAYEY SAND WITH GRAVEL (SC)g:
Approximately 50% sand, approximately 35% plastic fines, approximately 15% igneous and sedimentary gravel; 5% cobbles by volume; maximum particle size recovered 3-1/2 inches; subangular to subrounded; brown-light brown; dry strong reaction to HCl; consistency firm-hard; no cementation; hard; slow dilatency; high toughness; poorly sorted; high dry strength.

Total sample (by volume): Approximately 5% metasedimentary and igneous cobbles, subangular to subrounded; 2-3-1/2 inches, hard.

1.1 to 44.0 feet - QUATERNARY GLACIAL TILL (Qgt):

1.1 to 14.0 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 35-40 % metasedimentary and igneous gravel; approximately 30-40% plastic fines; approximately 20-35% sand; metasedimentary and igneous gravel; maximum particle size recovered 4-1/2 inches; angular to subrounded; brown-light brown; dry from 1.1 to 9.0 feet, moist from 9.0 to 14.0 feet; strong reaction to HCl; consistency firm-hard; no cementation; hard; slow-none dilatency; high toughness; poorly sorted; high dry strength.

Total sample (by volume): Approximately 5-10% metasedimentary and igneous cobbles, angular to subrounded, 2-4-1/2 inches, hard.

LAB TEST DATA: 0.0 to 4.0 feet - 36% sand, 35% fines, 29% gravel; LL=22.0, PI=8.4; Laboratory classification is Clayey Sand with Gravel (SC)g

LAB TEST DATA: 7.1 to 8.5 feet - 39% gravel, 32% fines, 29% sand; LL=21.1, PI=8.2; Laboratory classification is Clayey Gravel with Sand (GC)s

9.0 to 17.5 feet - SANDY LEAN CLAY WITH COBBLES s(CL)c:
Approximately 60% plastic fines; approximately 30% sand; approximately 10% metasedimentary and igneous gravel; maximum particle size recovered 4 inches; angular to subrounded; brown; moist; strong reaction to HCl; consistency firm-hard; no cementation; hard; slow-none dilatency; high toughness; poorly sorted; high dry strength.

Total sample (by volume): Approximately 20-25% metasedimentary and igneous cobbles, subangular to subrounded, 2-4 inches, hard.

17.5 to 21.5 feet - NO RECOVERY:

21.5 to 24.0 feet - SANDY LEAN CLAY WITH GRAVEL AND COBBLES s(CL)gc:
Approximately 40% non plasitc fines; approximately 35% sand; approximately 25% metasedimentary and igneous gravel; maximum particle size recovered 4 inches; angular

FEATURE: Willow Creek Dam
LOCATION: Emergency spillway
BEGUN: 5/20/15 **FINISHED:** 5/26/15
DEPTH AND ELEV. OF WATER LEVEL AND DATE MEASURED: 10.1 (4134.1) 5/26/15

PROJECT: Sun River Project
COORDINATES: N 473,325 E 1,122,537
TOTAL DEPTH: 61.5
DEPTH TO BEDROCK: 60.8

STATE: Montana
GROUND ELEVATION: 4144.2
ANGLE FROM HORIZONTAL: 90 **AZIMUTH:**
HOLE LOGGED BY: J. Lasater
REVIEWED BY: K. Scannella

DEPTH	FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.
	(GC)sc	80	Qgf
55	(GC)sc	74	Qgf
60	(GC)sc	68	Qgf
	cs		Ktm

BOTTOM OF HOLE

NOTES

tube.

42.8 to 49.0 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

49.0 to 59.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

59.0 to 61.5 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

DRILLING COMMENTS:
17.5 to 21.5 feet - Centerbit assembly was used to break through a boulder which had stopped advancement.

24.0 to 29.0 feet - No sample recovery due to the coarse nature of the material. Cobbles and boulders were likely pushed ahead of augers, preventing sample collection.

HOLE COMPLETION:
Drill holes backfilled from the bottom of the hole at 61.5 feet to ground surface with 33, 50 pound bags of 3/8 inch bentonite chips.

CLASSIFICATION AND PHYSICAL CONDITION

to subrounded; brown; wet; weak reaction to HCl; consistency soft; no cementation; hard; rapid dilatency; low toughness; moderately sorted; low dry strength.

Total sample (by volume): Approximately 5% metasedimentary and igneous cobbles, angular to subrounded, 2-4 inches, hard.

LAB TEST DATA: 21.5 to 24.0 feet - 49% gravel, 31 % sand, 20% fines; LL=23.1, PI=7.6; Laboratory classification is Clayey Gravel with Sand and Cobbles (GC)sc

24.0 to 29.0 feet - NO RECOVERY:

29.0 to 42.8 feet - SANDY LEAN CLAY WITH GRAVEL AND COBBLES s(CL)gc:
Approximately 50% plastic fines; approximately 30% metasedimentary and igneous gravel; approximately 20% sand; maximum particle size recovered 4 inches; angular to subrounded; brown; moist; weak reaction to HCL; consistency firm-hard; no cementation; hard; slow-none dilatency; high toughness; poorly sorted; high dry strength.

Total sample (by volume): Approximately 5% metasedimentary and igneous cobbles, angular to subrounded, 2-4 inches, hard.

LAB TEST DATA: 29.0 to 39.0 feet - 49% gravel, 31% sand, 20% fines; LL=21.8, PI=8.6; Laboratory classification is Clayey Gravel with Sand and Cobbles (GC)sc

LAB TEST DATA: 36.3 to 38.8 feet - 62% gravel, 27% sand, 11% fines; LL=19.2, PI=4.6; Laboratory classification is Poorly Graded Gravel with Clay with Sand and Cobbles (GP-GC)sc

LAB TEST DATA: 41.1 to 42.5 feet - 60% gravel, 29% sand, 11% fines; LL=19.2, PI=4.7; Laboratory classification is Poorly Graded Gravel with Clay with Sand and Cobbles (GP-GC)sc

42.8 to 60.8 feet - GLACIAL FLUVIAL (Qgf):

42.8 to 44.0 feet - GRAVELLY LEAN CLAY WITH SAND g(CL)sc:
Approximately 45% plastic fines; approximately 40% metasedimentary and igneous gravel; approximately 15% sand; 5% cobbles by volume; maximum particle size recovered 3-1/2 inches; subangular to subrounded; brown; wet; strong reaction to HCl; consistency soft; no cementation; hard; slow-none dilatency; high toughness; moderately to well sorted; high dry strength.

Total sample (by volume): Approximately 5% metasedimentary and igneous cobbles; subangular to subrounded, 2-3-1/2 inches, hard.

44.0 to 59.0 feet - CLAYEY GRAVEL WITH SAND AND COBBLES(GC)sc:
Approximately 55% metasedimentary and igneous gravel; approximately 30% plastic fines; approximately 15% sand;

GEOLOGIC LOG OF DRILL HOLE: DH15-202WC

FEATURE: Willow Creek Dam	**PROJECT:** Sun River Project	**STATE:** Montana
LOCATION: Emergency spillway	**COORDINATES:** N 473,325 E 1,122,537	**GROUND ELEVATION:** 4144.2
BEGUN: 5/20/15 **FINISHED:** 5/26/15	**TOTAL DEPTH:** 61.5	**ANGLE FROM HORIZONTAL:** 90 **AZIMUTH:**
DEPTH AND ELEV. OF WATER LEVEL AND DATE MEASURED: 10.1 (4134.1) 5/26/15	**DEPTH TO BEDROCK:** 60.8	**HOLE LOGGED BY:** J. Lasater **REVIEWED BY:** K. Scannella

NOTES	DEPTH	FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.	CLASSIFICATION AND PHYSICAL CONDITION

maximum particle size recovered 4-1/2 inches; subangular to rounded; brown; wet; strong reaction to HCl; consistency firm-hard; no cementation; hard; slow dilatency; high toughness; poorly sorted; high dry strength.

Total sample (by volume): Approximately 15% metasedimentary and igneous cobbles, subangular to rounded, 2-4-1/2 inches, hard.

LAB TEST DATA: 42.8 to 49.0 feet - 52% gravel, 31% sand, 17% fines; LL=19.1, PI=4.9; Laboratory classification is Silty, Clayey Gravel with Sand and Cobbles (GC-GM)sc

LAB TEST DATA: 56.3 to 58.8 feet - 60% gravel, 31% sand, 9% fines; PI=N/P; Laboratory classification is Poorly Graded Gravel with Silt and sand(GP-GM)s

59.0 to 60.8 feet - SILTY SAND WITH GRAVEL (SM)g:
Approximately 70% sand; approximately 15% non plastic fines; approximately 15% metasedimentary and igneous gravel; maximum particle size recovered 2 inches; subangular to rounded; brown; wet; weak reaction to HCl; consistency firm-hard; no cementation; hard; rapid dilatency; low toughness; well sorted; low dry strength.

60.8 to 61.5 feet - TWO MEDICINE FORMATION (Ktm):

60.8 to 61.2 feet - CLAYSTONE:
Brown claystone; strong reaction to HCl; moderately bedded; very intensely weathered to decomposed (W8-W9); soft-very soft (H6-H7); no fractures discernible (FD0-FD1) ; moist; moderate to rapid slaking.

61.2 to 61.5 feet - CLAYSTONE:
Green gray claystone; strong reaction to HCl; moderately bedded; very intensely weathered to decomposed (W8-W9); soft-very soft (H6-H7); well indurated; no fractures discernible (FD0-FD1); moist; moderate to rapid slaking.

GEOLOGIC LOG OF DRILL HOLE: DH15-203WC

FEATURE: Willow Creek Dam
LOCATION: Emergency spillway
BEGUN: 6/3/15 **FINISHED:** 6/5/15
DEPTH AND ELEV. OF WATER LEVEL AND DATE MEASURED: 16.5 (4119.4) 6/5/15

PROJECT: Sun River Project
COORDINATES: N 473,326 E 1,122,525
TOTAL DEPTH: 28.4
DEPTH TO BEDROCK: Not Encountered

STATE: Montana
GROUND ELEVATION: 4135.9
ANGLE FROM HORIZONTAL: 90 **AZIMUTH:**
HOLE LOGGED BY: C. Sullivan
REVIEWED BY: K. Scanella

NOTES

LOCATION:
Emergency spillway, downstream of crest adjacent to DH79-103.

PURPOSE OF HOLE:
To collect undisturbed samples for laboratory testing and additional geologic data in order to better estimate potential erosion rates for materials within the spillway at Willow Creek Dam, MT.

DRILL EQUIPMENT:
Truck-mounted CME-85 rotary drill rig; 6-1/4 inch I.D. hollow stem auger (HSA); 5-foot-long, 5.38 inch I.D. split tube sample barrel; 2-1/2 foot long, 5.07 inch I.D. acrylic undisturbed sample tube.

DRILLER:
Sam Watt; USBR

DRILLING METHOD:
0.0 to 5.0 feet - Advanced hole with 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

5.0 to 10.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

10.0 to 15.0 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

15.0 to 20.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

20.0 to 22.7 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

22.7 to 25.0 feet - 6-1/4 inch HSA with centerbit assembly.

25.0 to 28.4 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

DRILLING FLUID:
0.0 to 17.5 feet - None.

17.5 to 28.4 feet - Reservoir water.

DEPTH	FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.
0–2.6	(GC)sc		ts
2.6–28.4 (5, 10, 15, 20, 25)	(GC)sc		Qgt

BOTTOM OF HOLE

CLASSIFICATION AND PHYSICAL CONDITION

0.0 to 2.6 feet - TOPSOIL:
0.0 to 2.6 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 50% coarse to fine, hard, subangular to subrounded, predominately sedimentary (sandstone, limestone, siltstone) gravel; about 30% coarse to fine, hard, subrounded to rounded sand; about 20% fines with low plasticity, medium to high dry strength, no dilatency, low to medium toughness; maximum particle size recovered 4 inches; top 1.8 foot containing grass roots; dry, moderately firm; organic smell; medium brown with cream colored siltstone clasts; weak to strong reaction to HCl.

Total sample (by volume): Approximately 20-30% metasedimentary and igneous cobbles, subangular to subrounded, 4 inches, hard.

2.6 to 28.4 feet - QUATERNARY GLACIAL TILL (Qgt):

2.6 to 19.5 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 45-60% coarse to fine, hard, subangular to subrounded gravel; approximately 20-35% coarse to fine, hard, subrounded to rounded sand; about 15-25% fines with low to medium plasticity, medium to high dry strength, no dilatency, low to medium toughness; maximum particle size recovered 4 inches; dry to 16.5 feet; moist to 20.0 feet; dense heterogeneous nature; no cementation; tan to cream color when dry; weak to strong reaction to HCl.

Total sample (by volume): Approximately 20-30% metasedimentary and igneous cobbles, subangular to subrounded, 4 inches, hard.

LAB TEST DATA: 0.0 to 5.0 feet - 40% fines, 33% gravel, 27%sand; LL=34.7, PI=15.2; Laboratory classification is Clayey Gravel with sand (GC)s

LAB TEST DATA: 5.0 to 10.0 feet - 40% fines, 30% sand, 30% gravel; LL=30.8, PI=17.9; Laboratory classification is Clayey Sand with Gravel and Cobbles (SC)gc

LAB TEST DATA: 10.o to 15.0 feet - 54% gravel, 27% fines, 19% sand; LL=30.8, PI=19.1; Laboratory classification is Clayey Gravel with Sand and Cobbles (GC)sc

LAB TEST DATA: 15.0 to 20.0 feet - 37% gravel, 32% sand, 31% fines; LL=29.1, PI=16.8; Laboratory classification is Clayey Gravel with Sand and Cobbles (GC)sc

19.5 to 21.8 feet - SILTY SAND (SM):
Approximately 65% coarse to fine, hard, subrounded to rounded sand; 25% nonplastic fines, no dry strength, slow dilatency; approximately 10% fine, hard, subangular to subrounded gravel; maximum particle size recovered 1/4 inch; wet; soft; light brown; no reaction to HCl.

21.8 to 22.3 feet - CLAYEY SAND WITH GRAVEL (SC)g:
Approximately 50% coarse to fine, hard, subangular to

GEOLOGIC LOG OF DRILL HOLE: DH15-203WC

FEATURE: Willow Creek Dam
LOCATION: Emergency spillway
BEGUN: 6/3/15 **FINISHED:** 6/5/15
DEPTH AND ELEV. OF WATER LEVEL AND DATE MEASURED: 16.5 (4119.4) 6/5/15

PROJECT: Sun River Project
COORDINATES: N 473,326 E 1,122,525
TOTAL DEPTH: 28.4
DEPTH TO BEDROCK: Not Encountered

STATE: Montana
GROUND ELEVATION: 4135.9
ANGLE FROM HORIZONTAL: 90 **AZIMUTH:**
HOLE LOGGED BY: C. Sullivan
REVIEWED BY: K. Scanella

NOTES	DEPTH	FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.	CLASSIFICATION AND PHYSICAL CONDITION

DRILLING COMMENTS:
Moderately hard to align augers at top of hole and advance the drill string. Drilling was rough and slow with a large rock impeding progress at 2.5 feet. The cobbles and/or boulders within the foundation materials are estimated to be between 10 and 15% of the total mass. A partially exposed surface boulder within 25 feet of the rig was measured at 3.5x2.8 feet.

HOLE COMPLETION:
Drill holes backfilled from the bottom of the hole at 28.4 feet to ground surface with 33, 50 pound bags of 3/8 inch bentonite chips.

rounded sand; approximately 20% coarse to fine, hard, subangular to subrounded gravel; approximately 30% low plasticity fines, low dry strength, no dilatency, low toughness; maximum particle size recovered 1 inch; wet; moderately soft; medium brown; weak reaction to HCl.

22.3 to 28.4 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 55% coarse to fine, hard, subangular to subrounded gravel; approximately 25% coarse to fine, hard, subrounded to rounded sand; approximately 20% fines with medium plasticity, medium dry strength, no dilatancy, low toughness; maximum particle size recovered 3 inches; wet; dense heterogeneous nature; no cementation; light to medium brown; weak to strong reaction to HCl.

Total sample (by volume): Approximately 20-30% metasedimentary and igneous cobbles, subangular to subrounded, 4 inches, hard.

GEOLOGIC LOG OF DRILL HOLE: DH15-204WC

FEATURE: Willow Creek Dam
LOCATION: Emergency spillway
BEGUN: 6/6/15 **FINISHED:** 6/9/15
DEPTH AND ELEV. OF WATER LEVEL AND DATE MEASURED: 19.0 (4111.8) 6/9/15

PROJECT: Sun River Project
COORDINATES: N 473,325 E 1,122,524
TOTAL DEPTH: 44.0
DEPTH TO BEDROCK: Not Encountered

STATE: Montana
GROUND ELEVATION: 4130.8
ANGLE FROM HORIZONTAL: 90 **AZIMUTH:**
HOLE LOGGED BY: C. Sullivan
REVIEWED BY: K. Scanella

NOTES	DEPTH	FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.	CLASSIFICATION AND PHYSICAL CONDITION
	0.0–1.1	Topsoil		ts	
	1.1–44.0	(GC)sc		Qgt	
		BOTTOM OF HOLE			

NOTES

LOCATION:
Emergency spillway, downstream of crest.

PURPOSE OF HOLE:
To collect undisturbed samples for laboratory testing and additional geologic data in order to better estimate potential erosion rates for materials with in the spillway at Willow Creek Dam, MT.

DRILL EQUIPMENT:
Truck-mounted CME-85 rotary drill rig; 6-1/4 inch I.D. hollow stem auger (HSA); 5 foot long, 5.38 inch I.D. split tube sample barrel; 2-1/2 foot long, 5.07 inch I.D. acrylic undisturbed sample tube.

DRILLER:
Sam Watt; USBR

DRILLING METHOD:
0.0 to 9.0 feet - Advanced hole with 6-1/4 HSA with 5.38 inch split tube sample barrel.

9.0 to 14.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

14.0 to 24.0 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

24.0 to 29.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

29.0 to 41.5 feet - 6-1/4 inch HSA with 5.38 inch split tube sample barrel.

41.5 to 44.0 feet - 6-1/4 inch HSA with 5.07 inch acrylic undisturbed sample tube.

DRILLING FLUID:
0.0 to 19.0 feet - None.

19.0 to 44.0 feet - Reservoir water.

DRILLING COMMENTS:
Moderately hard to align augers at top of hole and advance the drill string. Drilling was rough and slow with a large rock impeding progress at 2.3

CLASSIFICATION AND PHYSICAL CONDITION

0.0 to 1.1 feet - TOPSOIL:

0.0 to 1.1 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 50% coarse to fine, hard, subangular to subrounded, predominately sedimentary (sandstone, limestone, siltstone) origin gravel; approximately 30% coarse to fine, hard, subrounded to rounded, sedimentary sand; approximately 20% fines with low plasticity, medium to high dry strength, no dilatency, low to medium toughness; maximum particle size recovered 4 inches; top 1.1 feet containing grass roots; dry, moderately firm; organic smell; medium brown with cream colored siltstone clasts; weak to strong reaction to HCl.

Total sample (by volume): Approximately 20-30% metasedimentary and igneous cobbles, subangular to subrounded, 4 inches, hard.

1.1 to 44.0 feet - QUATERNARY GLACIAL TILL (Qgt):
1.1 to 19.0 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 45-55% coarse to fine, hard, subangular to subrounded gravel; approximately 20-35% coarse to fine, hard subrounded to rounded sand; approximately 15-25% fines with low to medium plasticity, medium to high dry strength, no dilatency, low to medium toughness; maximum particle size recovered 4-3/4 inches; dry to 16.4; moist to 19.0 feet; dense heterogeneous nature; no cementation; tan to cream color when dry, then light brown; weak reaction to HCl.

Total sample (by volume): Approximately 20-30% metasedimentary and igneous cobbles, subangular to subrounded, 4 inches, hard.

<u>LAB TEST DATA:</u> 0.0 to 9.0 feet - 53% fines, 30% sand, 17% gravel; LL=29.7, PI=16.5; Laboratory classification is Sandy Lean Clay with Gravel and Cobbles s(CL)gc

<u>LAB TEST DATA:</u> 11.5 to 14.0 feet - 34% gravel, 30% fines, 26% sand; LL=32.9, PI=20.4; Laboratory classification is Clayey Gravel with sand (GC)s

19.0 to 21.4 feet - SILTY GRAVEL WITH SAND AND COBBLES (GM)sc:
Approximately 45% coarse to fine, hard, subrounded to rounded gravel; approximately 35% coarse to fine, hard, subangular to subrounded sand, approximately 20% nonplastic fines, no dry strength, slow dilatency; maximum particle size recovered 3.4 inches; wet; predominately soft; light brown; no reaction to HCl.

Total sample (by volume): Approximately 20-30% metasedimentary and igneous cobbles, subrounded to rounded, 4 inches, hard.

21.4 to 22.6 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 50% coarse to fine, hard, subangular to subrounded gravel; approximately 25% coarse to fine,

FEATURE: Willow Creek Dam	PROJECT: Sun River Project	STATE: Montana
LOCATION: Emergency spillway	COORDINATES: N 473,325 E 1,122,524	GROUND ELEVATION: 4130.8
BEGUN: 6/6/15 FINISHED: 6/9/15	TOTAL DEPTH: 44.0	ANGLE FROM HORIZONTAL: 90 AZIMUTH:
DEPTH AND ELEV. OF WATER	DEPTH TO BEDROCK: Not Encountered	HOLE LOGGED BY: C. Sullivan
LEVEL AND DATE MEASURED: 19.0 (4111.8) 6/9/15		REVIEWED BY: K. Scanella

NOTES	DEPTH	FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.	CLASSIFICATION AND PHYSICAL CONDITION

NOTES

feet. Cutting head was blocked by a cobble at 6.0 feet.

2.3 to 19 feet - Drilling was rough and slow with large rocks encountered and eventually recovered at 13.2, 14.7, 17.5, and 18.0 feet with the largest measuring 6x5x3 inches.

HOLE COMPLETION:
Drill holes backfilled from the bottom of the hole to ground surface with 33, 50 pound bags of 3/8 inch bentonite chips.

CLASSIFICATION AND PHYSICAL CONDITION

hard, subangular to subrounded sand; approximately 25% medium plasticity fines, medium dry strength, no dilatency, medium toughness; maximum particle size recovered 3 inches; wet; moderately soft; medium brown; weak reaction to HCl.

Total sample (by volume): Approximately 20-30% metasedimentary and igneous cobbles, subangular to subrounded, 4 inches, hard.

22.6 to 24.0 feet - CLAYEY GRAVEL WITH SAND (GC)s:
Approximately 55% coarse to fine, hard, subangular to subrounded gravel; approximately 25% coarse to fine, hard, subrounded to rounded sand; approximately 20% fines with low plasticity, low to medium dry strength, no dilatency, low toughness; maximum particle size recovered 2.1 inches; wet; dense heterogeneous nature; no cementation; light to medium brown; weak to strong reaction to HCl.

LAB TEST DATA: 14.0 to 24.0 feet - 41% gravel, 32% sand, 27% fines; LL=23.0, PI=10.4; Laboratory classification is Clayey Gravel with Sand and Cobbles (GC)sc

24.0 to 29.0 feet - SILTY SAND WITH GRAVEL (SM)g:
Approximately 45% coarse to fine, hard, subrounded to rounded sand; approximately 35% coarse to fine, hard, subangular to subrounded gravel; approximately 20% nonplastic fines, no dry strength, slow dilatency; maximum particle size recovered 1.8 inches; wet; predominately soft; light brown; no reaction to HCl.

LAB TEST DATA: 24.0 to 26.5 feet - 48% sand, 26% gravel, 26% fines; LL=19.3, PI=5.3; Laboratory classification is Silty, Clayey Sand with Gravel(SC-SM)g

29.0 to 29.8 feet - POORLY GRADED GRAVEL WITH SAND AND COBBLES (GP)sc:
Approximately 55% coarse to fine, hard, subangular to subrounded gravel; approximately 40% coarse to fine, hard, subrounded to rounded sand; approximately 5% nonplastic fines; maximum particle size recovered, 4.2 inches; wet; dense heterogeneous nature; no cementation; light to medium brown; weak reaction to HCl.

Total sample (by volume): Approximately 20-30% metasedimentary and igneous cobbles, subangular to subrounded, 4 inches, hard.

29.8 to 41.5 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc:
Approximately 45% coarse to fine, hard, subangular to rounded gravel; approximately 30% coarse to fine, hard, subangular to subrounded sand; approximately 25% medium plasticity fines, medium dry strength, no dilatency, medium toughness; maximum particle size recovered 5x4.5x3 inches; wet, moderately soft; medium brown; weak reaction to HCl.

Total sample (by volume): Approximately 20-30%

FEATURE: Willow Creek Dam	PROJECT: Sun River Project	STATE: Montana
LOCATION: Emergency spillway	COORDINATES: N 473,325 E 1,122,524	GROUND ELEVATION: 4130.8
BEGUN: 6/6/15 FINISHED: 6/9/15	TOTAL DEPTH: 44.0	ANGLE FROM HORIZONTAL: 90 AZIMUTH:
DEPTH AND ELEV. OF WATER LEVEL AND DATE MEASURED: 19.0 (4111.8) 6/9/15	DEPTH TO BEDROCK: Not Encountered	HOLE LOGGED BY: C. Sullivan REVIEWED BY: K. Scanella

NOTES	DEPTH	FLD. CLASS/LITH.	% CORE RECOVERY	GEOL. UNIT SYM.	CLASSIFICATION AND PHYSICAL CONDITION
					metasedimentary and igneous cobbles, subangular to rounded, 4 inches, hard.
					LAB TEST DATA: 29.0 to 31.5 feet - 44% gravel, 43% sand, 13% fines; LL=16.5, PI=2.3; Laboratory classification is Silty Gravel with Sand and Cobbles(GM)sc
					LAB TEST DATA: 31.5 to 41.5 feet - 47% gravel, 32% sand, 21% fines; LL=23.9, PI=10.3; Laboratory classification is Clayey Gravel with Sand and Cobbles (GC)sc
					41.5 to 42.3 feet - POORLY GRADED SAND (SP): Approximately 85% coarse to fine, hard, subangular to subrounded sand; approximately 10% nonplastic fines; approximately 5% fine, hard, subangular grave; maximum particle size recovered 3/8 inch; wet; dense heterogeneous nature; no cementation; light to medium brown; weak reaction to HCl.
					42.3 to 44.0 feet - CLAYEY GRAVEL WITH SAND AND COBBLES (GC)sc: Approximately 45% coarse to fine, hard, subangular to rounded gravel; approximately 30% coarse to fine, hard, subangular to subrounded sand; approximately 25% medium plasticity fines, medium dry strength, no dilatency, medium toughness; maximum particle size recovered 3-1/2 inches; wet; moderately soft; medium brown; weak reaction to HCl.
					Total sample (by volume): Approximately 20-30% metasedimentary and igneous cobbles, subangular to rounded, 4 inches, hard.
					LAB TEST DATA: 41.5 to 43.3 feet - 53% sand, 34% gravel, 13% fines; PI=N/P; Laboratory classification is Silty Sand with Gravel (SM)g

SUMMARY OF PHYSICAL PROPERTIES TEST RESULTS

DATE 11/9/2015

PROJECT Sun River Project FEATURE Willow Creek Dam SHEET 1 OF 1

SAMPLE LOCATION	SAMPLE TYPE	DEPTH (feet) From	DEPTH (feet) To	CLASSIFICATION	PARTICLE - SIZE FRACTION (%) Fines (passing #200) (<0.075 mm)	Sand (#200 to #4)	Gravel (#4 to 3 inch)	Cobbles (3 inch to 5 inch)	Oversize (>5 inch)	CONSISTANCY LIMITS Liquid Limit %	Plasticity Index %	COEFFICIENTS Coefficient of Uniformity $C_u = D_{60} / D_{10}$	Coefficient of Curvature $C_c = D_{30}^2 / (D_{60} \times D_{10})$
DH-15-201	ENTIRE BOX	0.0	15.0	(GC)sc	35.6	26.0	32.4	6.0	0.0	25	12		
DH-15-201	COMBINED	23.0	33.6	(GC)sc	13.8	23.2	25.0	38.0	0.0	22	8		
DH-15-201	[1]TUBE	25.5	27.3	(GC)s	25.5	25.6	48.9	0.0	0.0	26	11	3092.65	0.59
DH-15-201	COMBINED	49.0	62.3	(SC-SM)gc	23.8	39.6	34.6	2.0	0.0	19	6		
DH-15-201	[1]TUBE	51.3	52.4	(GC-GM)s	15.7	38.0	46.3	0.0	0.0	19	4	413.99	1.19
DH-15-202	PARTIAL BOX	0.0	4.0	(SC)g	35.1	36.2	28.7	0.0	0.0	22	8		
DH-15-202	TUBE	7.1	8.5	(GC)s	31.8	28.9	39.3	0.0	0.0	21	8		
DH-15-202	[1]TUBE	7.1	8.5	(GC)s	35.6	23.7	40.7	0.0	0.0	23	11	*NA	NA
DH-15-202	PARTIAL BOX	21.5	24.0	(GC)sc	18.5	29.5	46.0	6.0	0.0	23	8		
DH-15-202	COMBINED	29.0	39.0	(GC)sc	18.2	28.6	45.2	8.0	0.0	22	9		
DH-15-202	TUBE	36.3	38.8	(GP-GC)sc	9.3	24.9	54.8	11.0	0.0	19	5		
DH-15-202	[1]TUBE	36.3	38.8	(GP-GC)s	9.5	23.7	66.8	0.0	0.0	21	7	247.42	5.89
DH-15-202	TUBE	41.1	42.5	(GP-GC)sc	8.2	22.4	46.4	23.0	0.0	19	5		
DH-15-202	COMBINED	42.8	49.0	(GC-GM)sc	14.8	27.4	45.8	12.0	0.0	19	5		
DH-15-202	TUBE	56.3	58.8	(GP-GM)s	9.3	30.8	59.9	0.0	0.0	**NP	NP		
DH-15-202	[1]TUBE	56.3	58.8	(GP-GM)s	10.2	27.6	62.2	0.0	0.0	18	0	206.68	6.78
DH-15-203	PARTIAL BOX	0.0	5.0	(GC)s	32.7	26.9	40.4	0.0	0.0	35	15		
DH-15-203	[1]TUBE	5.0	7.5	(SC)g	43.4	31.1	25.5	0.0	0.0	27	14	293.17	0.37
DH-15-203	COMBINED	5.0	10.0	(SC)gc	29.1	21.2	21.7	28.0	0.0	31	18		
DH-15-203	PARTIAL BOX	10.0	15.0	(GC)sc	23.2	17.3	46.5	13.0	0.0	31	19		
DH-15-203	COMBINED	15.0	20.0	(GC)sc	27.8	29.3	33.9	9.0	0.0	29	17		
DH-15-204	ENTIRE BOX	0.0	9.0	s(CL)gc	43.8	25.0	14.2	17.0	0.0	30	17		
DH-15-204	TUBE	11.5	14.0	(GC)s	40.1	26.0	33.9	0.0	0.0	33	20		
DH-15-204	COMBINED	14.0	24.0	(GC)sc	23.1	28.3	35.6	13.0	0.0	23	10		
DH-15-204	TUBE	24.0	26.5	(SC-SM)g	26.1	47.7	26.2	0.0	0.0	19	5		
DH-15-204	[1]TUBE	24.0	24.4	SM	31.0	63.8	5.2	0.0	0.0	NP	NP	85.30	7.78
DH-15-204	[1]TUBE	25.3	25.7	(GC-GM)sc	14.9	27.1	30.2	27.8	0.0	18	4	1285.69	2.60
DH-15-204	PARTIAL BOX	29.0	31.5	(GM)sc	10.1	32.9	34.0	23.0	0.0	17	2		
DH-15-204	COMBINED	31.5	41.5	(GC)sc	19.5	30.3	43.2	7.0	0.0	24	10		
DH-15-204	PARTIAL BOX	41.5	43.3	(SM)g	13.4	52.8	33.8	0.0	0.0	NP	NP		

[1] Indicates that physical property testing was performed on JET Test specimen remnants.
*NA = Not Applicable. D_{10} is not quantified.
**NP = Non-Plastic

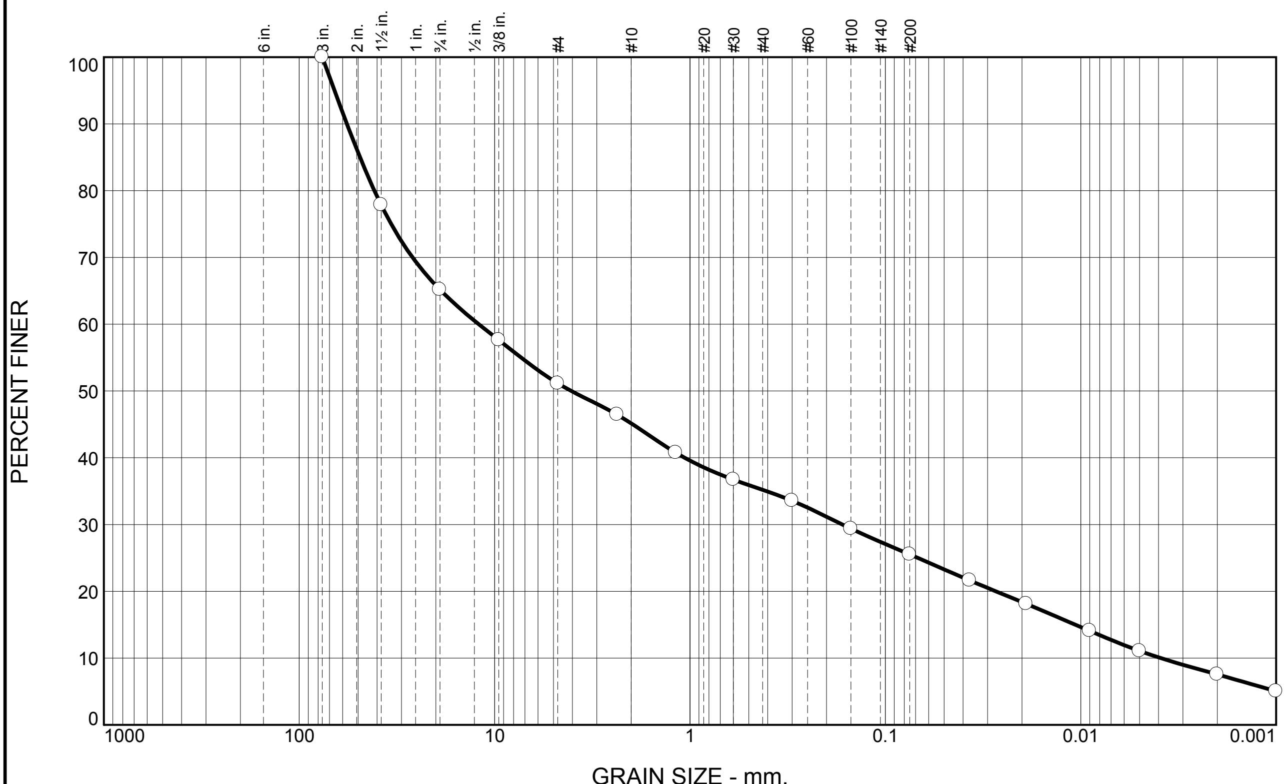
SUMMARY OF TUBE DENSITY TEST RESULTS

PROJECT Sun River Project FEATURE Willow Creek Dam DATE 11/9/2015 SHEET 1 OF 1

SAMPLE LOCATION	DEPTH OF TUBE PUSH INTERVAL (feet)		IN-PLACE UNIT WEIGHT		
	From	To	In-Situ Wet Unit Weight lbf/ft^3	In-Situ Dry Unit Weight lbf/ft^3	In-Situ Water Content %
DH-15-201	19.0	24.0	124.7	114.7	8.7
DH-15-201	24.0	27.5	138.8	122.4	13.4
DH-15-201	29.0	34.0	132.2	117.9	12.1
DH-15-201	61.5	62.5	126.2	113.4	11.3
DH-15-202	4.0	9.0	114.6	107.1	7.0
DH-15-202	34.0	39.0	154.0	143.0	7.7
DH-15-202	39.0	42.8	137.5	127.7	7.7
DH-15-202	49.0	54.0	131.8	*NA	NA
DH-15-202	54.0	59.0	150.4	NA	NA
DH-15-203	5.0	7.5	109.8	104.8	4.8
DH-15-203	7.5	10.0	114.8	NA	NA
DH-15-203	15.0	17.5	88.2	80.5	9.6
DH-15-203	17.5	20.0	122.7	116.5	5.3
DH-15-204	11.5	14.0	105.2	96.6	8.9
DH-15-204	24.0	26.5	135.2	114.9	17.7

*NA = Not Applicable. Field moisture samples were not obtained.

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	34.8	14.1	5.9	10.0	9.7	18.0	7.5

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
3 in	100.0		
1-1/2 in	77.9		
3/4 in	65.2		
3/8 in	57.6		
#4	51.1		
#8	46.5		
#16	40.8		
#30	36.7		
#50	33.5		
#100	29.4		
#200	25.5		
0.037 mm	21.6		
0.019 mm	18.1		
0.009 mm	14.1		
0.005 mm	11.1		
00.002 mm	7.5		
0.001 mm	5.0		

* (no specification provided)

Material Description

Clayey gravel with sand

Atterberg Limits

PL= 15 LL= 26 PI= 11

Coefficients

D_{90}= 57.0409 D_{85}= 48.8851 D_{60}= 12.0524
D_{50}= 4.0524 D_{30}= 0.1658 D_{15}= 0.0107
D_{10}= 0.0039 C_u= 3092.65 C_c= 0.59

Classification

USCS= GC AASHTO= A-2-6(0)

Remarks

Source of Sample: DH-15-201 **Depth:** 25.5 - 27.3 feet
Sample Number: 4Z-11 (as-received) **Date:** 9/24/15

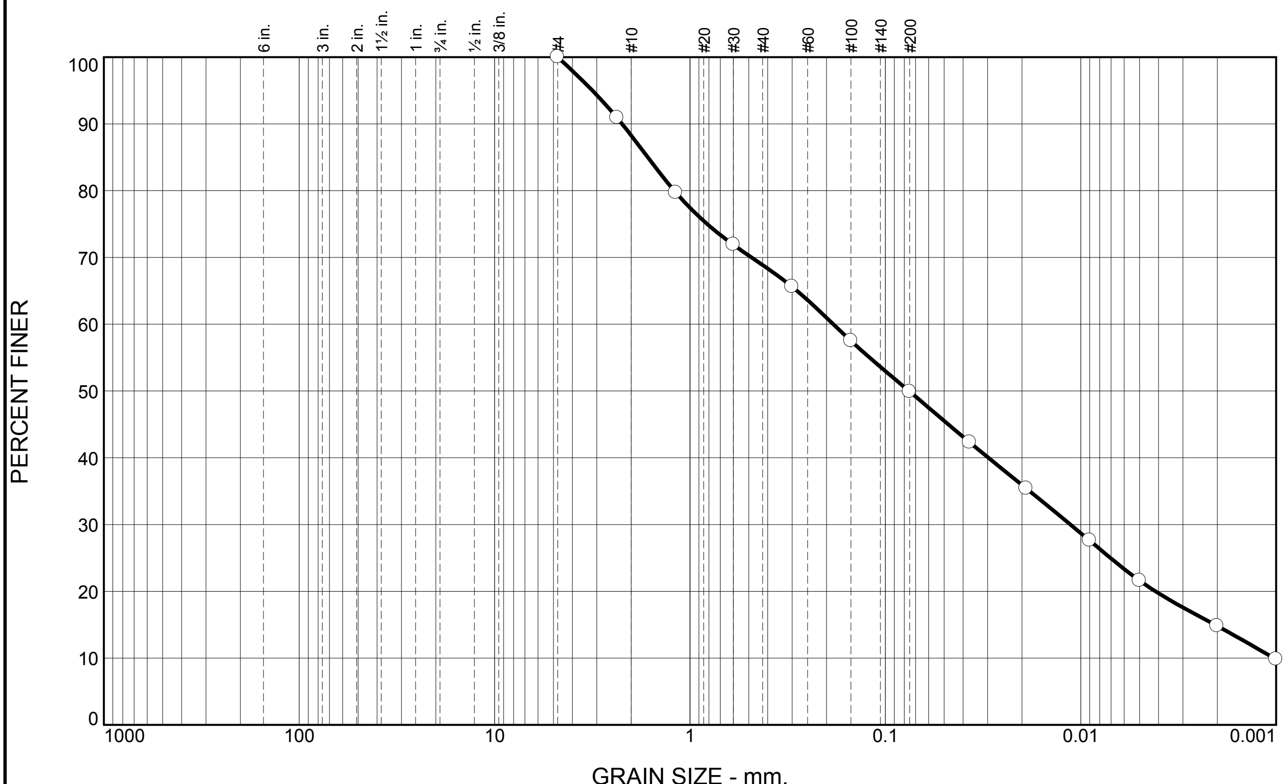
BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam
Project No: 4Z **Figure** 1

Tested By: TC **Checked By:** LJH

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	11.7	19.4	19.0	35.1	14.8

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	90.9		
#16	79.7		
#30	71.9		
#50	65.6		
#100	57.5		
#200	49.9		
0.037 mm	42.3		
0.019 mm	35.4		
0.009 mm	27.6		
0.005 mm	21.6		
0.002 mm	14.8		
0.001 mm	9.8		

* (no specification provided)

Material Description

Clayey sand

Atterberg Limits

PL= 15 LL= 26 PI= 11

Coefficients

D_{90}= 2.2270 D_{85}= 1.6446 D_{60}= 0.1848
D_{50}= 0.0757 D_{30}= 0.0113 D_{15}= 0.0021
D_{10}= 0.0010 C_u= 179.84 C_c= 0.67

Classification

USCS= SC AASHTO= A-6(2)

Remarks

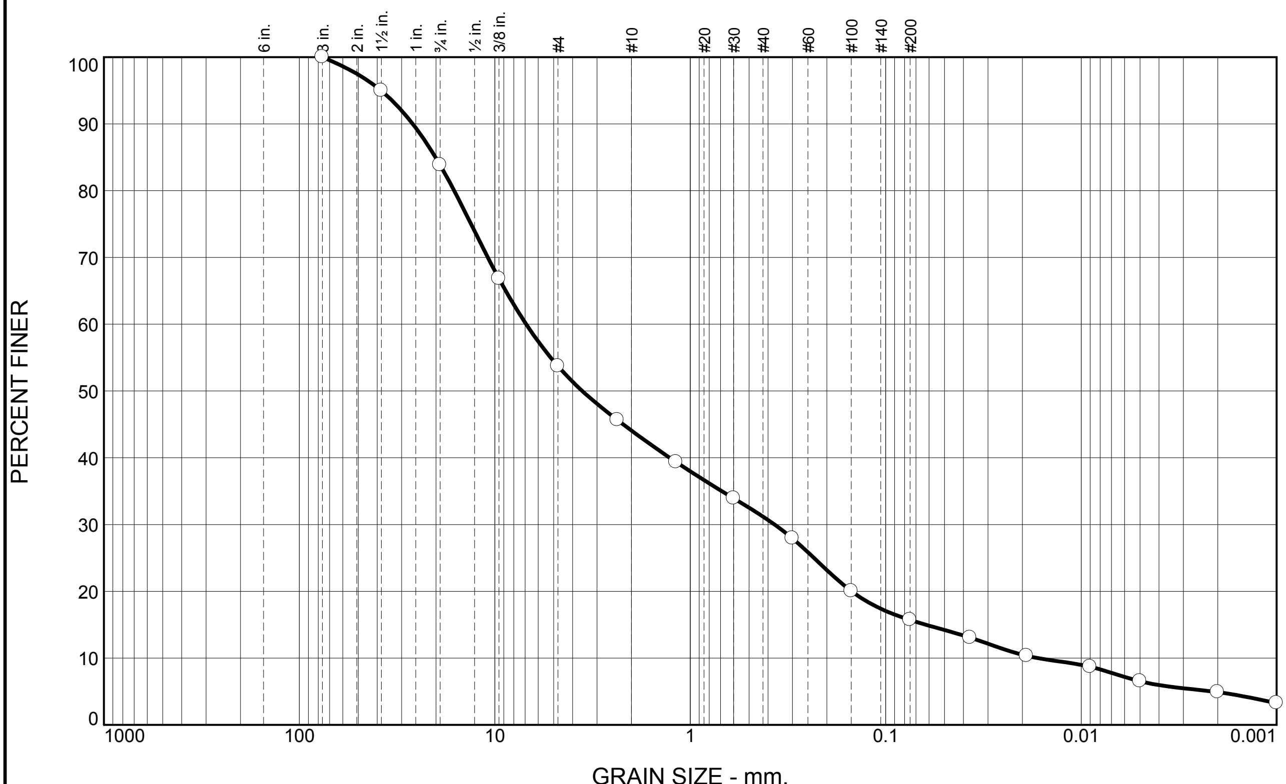
The as-received sample contained 48.9% gravel by mass. Information presented here pertains only to the minus #4 fraction of the material for project purposes.

Source of Sample: DH-15-201 **Depth:** 25.5 - 27.3 feet
Sample Number: 4Z-11 (minus #4) **Date:** 9/24/15

BUREAU OF RECLAMATION Denver, Colorado	**Client:** **Project:** Willow Creek Dam **Project No:** 4Z **Figure** 2

Tested By: TC **Checked By:** LJH

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	16.2	30.1	9.6	12.9	15.5	10.8	4.9

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
3 in	100.0		
1-1/2 in	95.0		
3/4 in	83.8		
3/8 in	66.8		
#4	53.7		
#8	45.7		
#16	39.4		
#30	33.9		
#50	27.9		
#100	20.0		
#200	15.7		
0.037 mm	13.1		
0.019 mm	10.3		
0.009 mm	8.7		
0.005 mm	6.5		
0.002 mm	4.9		
0.001 mm	3.3		

* (no specification provided)

Material Description

Silty clayey gravel with sand

Atterberg Limits

PL= 15 LL= 19 PI= 4

Coefficients

D_{90}= 26.3034 D_{85}= 20.1088 D_{60}= 6.9092
D_{50}= 3.5696 D_{30}= 0.3701 D_{15}= 0.0624
D_{10}= 0.0167 C_u= 413.99 C_c= 1.19

Classification

USCS= GC-GM AASHTO= A-1-b

Remarks

Source of Sample: DH-15-201 **Depth:** 51.3 - 52.4 feet
Sample Number: 4Z-17 (as-received) **Date:** 9/24/15

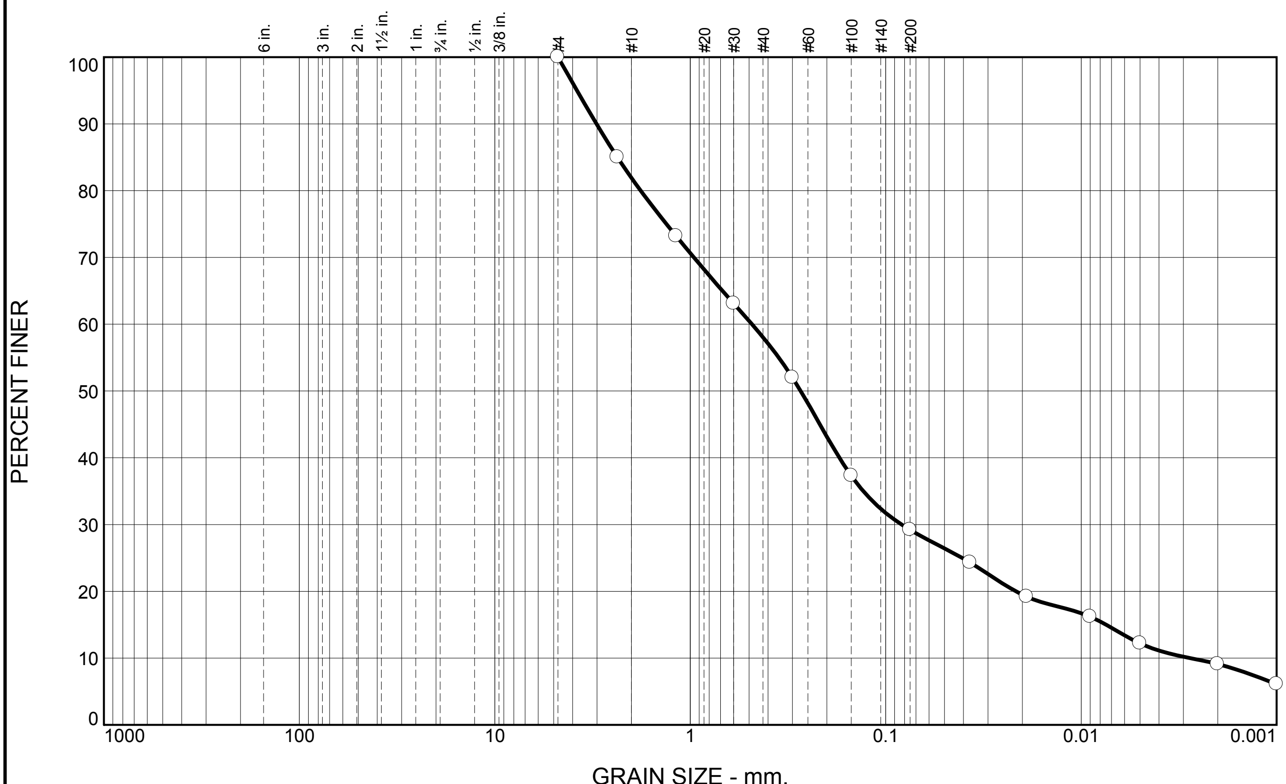
BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam
Project No: 4Z **Figure** 3

Tested By: TC **Checked By:** LJH

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	18.1	23.8	28.9	20.1	9.1

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	85.0		
#16	73.2		
#30	63.1		
#50	52.0		
#100	37.3		
#200	29.2		
0.037 mm	24.3		
0.019 mm	19.2		
0.009 mm	16.2		
0.005 mm	12.2		
0.002 mm	9.1		
0.001 mm	6.1		

* (no specification provided)

Material Description

Silty, clayey sand

Atterberg Limits

PL= 15 LL= 19 PI= 4

Coefficients

D_{90}= 3.0185 D_{85}= 2.3600 D_{60}= 0.4838
D_{50}= 0.2723 D_{30}= 0.0829 D_{15}= 0.0075
D_{10}= 0.0028 C_u= 174.11 C_c= 5.12

Classification

USCS= SC-SM AASHTO= A-2-4(0)

Remarks

The as-received sample contained 36.3% gravel by mass. Information presented here pertains only to the minus #4 fraction of the material for project purposes.

Source of Sample: DH-15-201 **Depth:** 51.3 - 52.4 feet
Sample Number: 4Z-17 (minus (#4)) **Date:** 9/24/15

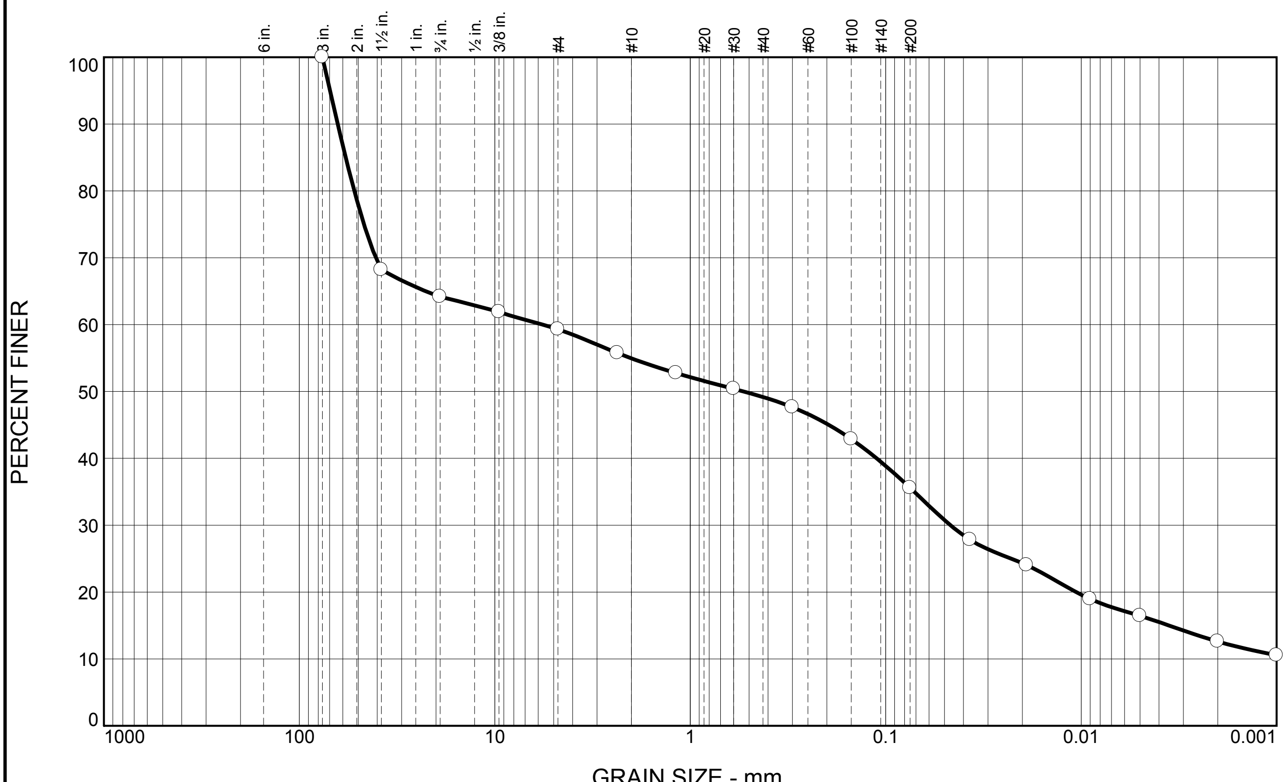
BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam
Project No: 4Z **Figure** 4

Tested By: TC **Checked By:** LJH

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	35.8	4.9	4.3	5.8	13.6	23.0	12.6

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
3 in	100.0		
1-1/2 in	68.2		
3/4 in	64.2		
3/8 in	61.9		
#4	59.3		
#8	55.8		
#16	52.8		
#30	50.4		
#50	47.6		
#100	42.9		
#200	35.6		
0.037 mm	27.8		
0.019 mm	24.0		
0.009 mm	19.0		
0.005 mm	16.4		
0.002 mm	12.6		
0.001 mm	10.5		

* (no specification provided)

Material Description

Clayey gravel with sand

Atterberg Limits

PL= 12 LL= 23 PI= 11

Coefficients

D_{90}= 63.6722 D_{85}= 57.9348 D_{60}= 5.6794
D_{50}= 0.5350 D_{30}= 0.0466 D_{15}= 0.0036
D_{10}= C_u= C_c=

Classification

USCS= GC AASHTO= A-6(0)

Remarks

Source of Sample: DH-15-202 **Depth:** 7.1 - 8.5 feet
Sample Number: 4Z-24 (as-received) **Date:** 9/24/15

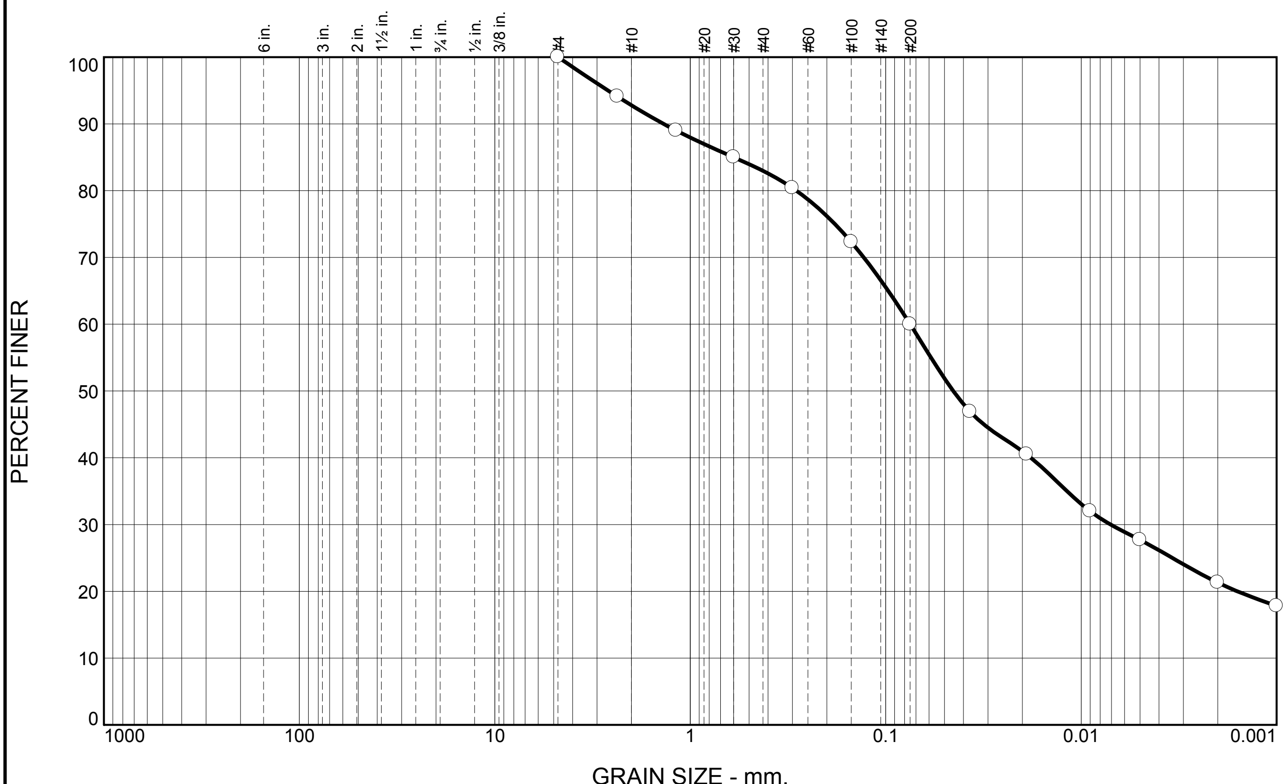
BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam
Project No: 4Z **Figure** 5

Tested By: TC **Checked By:** LJH

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	7.2	9.8	23.0	38.7	21.3

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	94.1		
#16	89.0		
#30	85.0		
#50	80.4		
#100	72.3		
#200	60.0		
0.037 mm	46.9		
0.019 mm	40.5		
0.009 mm	32.0		
0.005 mm	27.7		
0.002 mm	21.3		
0.001 mm	17.8		

* (no specification provided)

Material Description

Sandy lean clay

Atterberg Limits

PL= 12 LL= 23 PI= 11

Coefficients

D_{90}= 1.3691 D_{85}= 0.6000 D_{60}= 0.0750
D_{50}= 0.0451 D_{30}= 0.0071 D_{15}=
D_{10}= C_u= C_c=

Classification

USCS= CL AASHTO= A-6(3)

Remarks

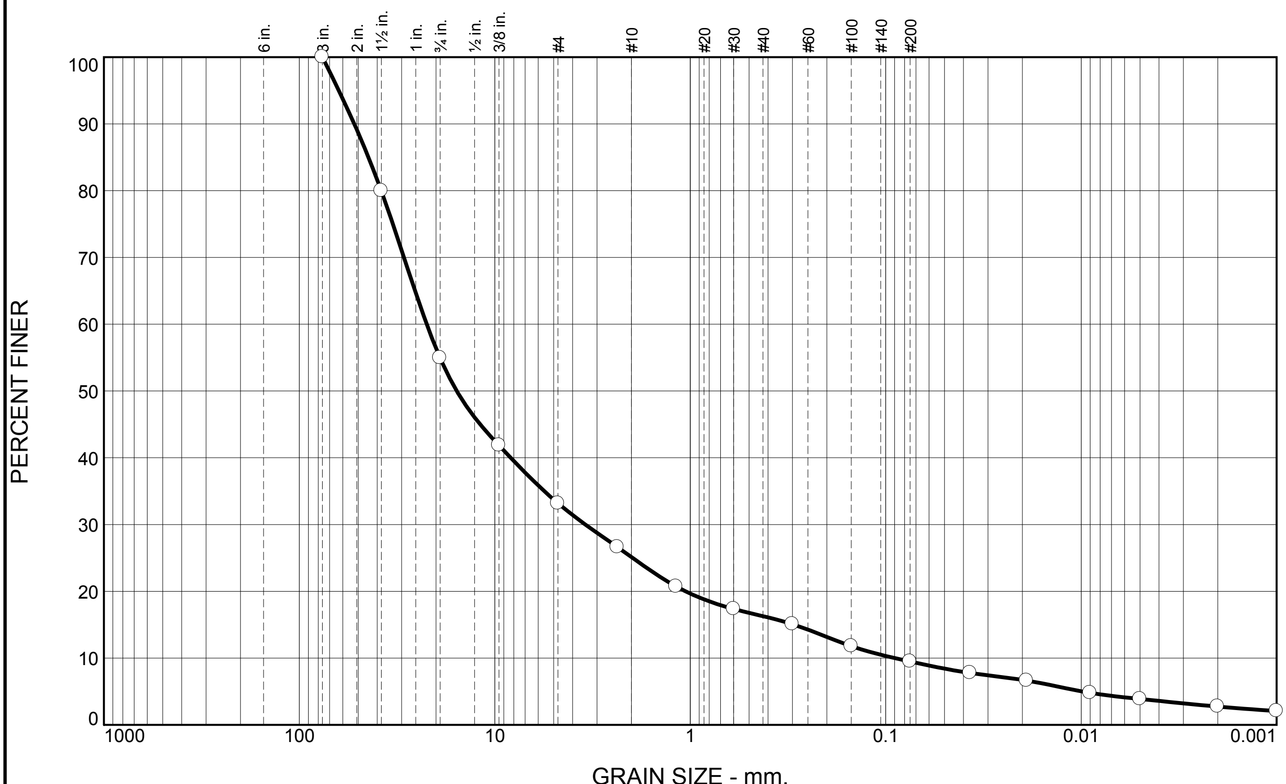
The as-received sample contained 40.7% gravel by mass. Information presented here pertains only to the minus #4 fraction of the material for project purposes.

Source of Sample: DH-15-202 **Depth:** 7.1 - 8.5 feet
Sample Number: 4Z-24 (minus #4) **Date:** 9/24/15

BUREAU OF RECLAMATION Denver, Colorado	**Client:** **Project:** Willow Creek Dam **Project No:** 4Z **Figure** 6

Tested By: TC **Checked By:** LJH

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	45.1	21.7	8.1	8.8	6.8	6.8	2.7

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
3 in	100.0		
1-1/2 in	80.0		
3/4 in	54.9		
3/8 in	41.9		
#4	33.2		
#8	26.6		
#16	20.7		
#30	17.4		
#50	15.1		
#100	11.8		
#200	9.5		
0.037 mm	7.8		
0.019 mm	6.6		
0.009 mm	4.8		
0.005 mm	3.9		
0.002 mm	2.7		
0.001 mm	2.1		

* (no specification provided)

Material Description

Poorly graded gravel with silty clay and sand

Atterberg Limits

PL= 14 LL= 21 PI= 7

Coefficients

D_{90}= 52.4003 D_{85}= 44.3266 D_{60}= 22.3006
D_{50}= 15.6585 D_{30}= 3.4413 D_{15}= 0.2950
D_{10}= 0.0901 C_u= 247.42 C_c= 5.89

Classification

USCS= GP-GC AASHTO= A-2-4(0)

Remarks

Source of Sample: DH-15-202 **Depth:** 36.3 - 38.8 feet
Sample Number: 4Z-28 (as-received) **Date:** 9/24/15

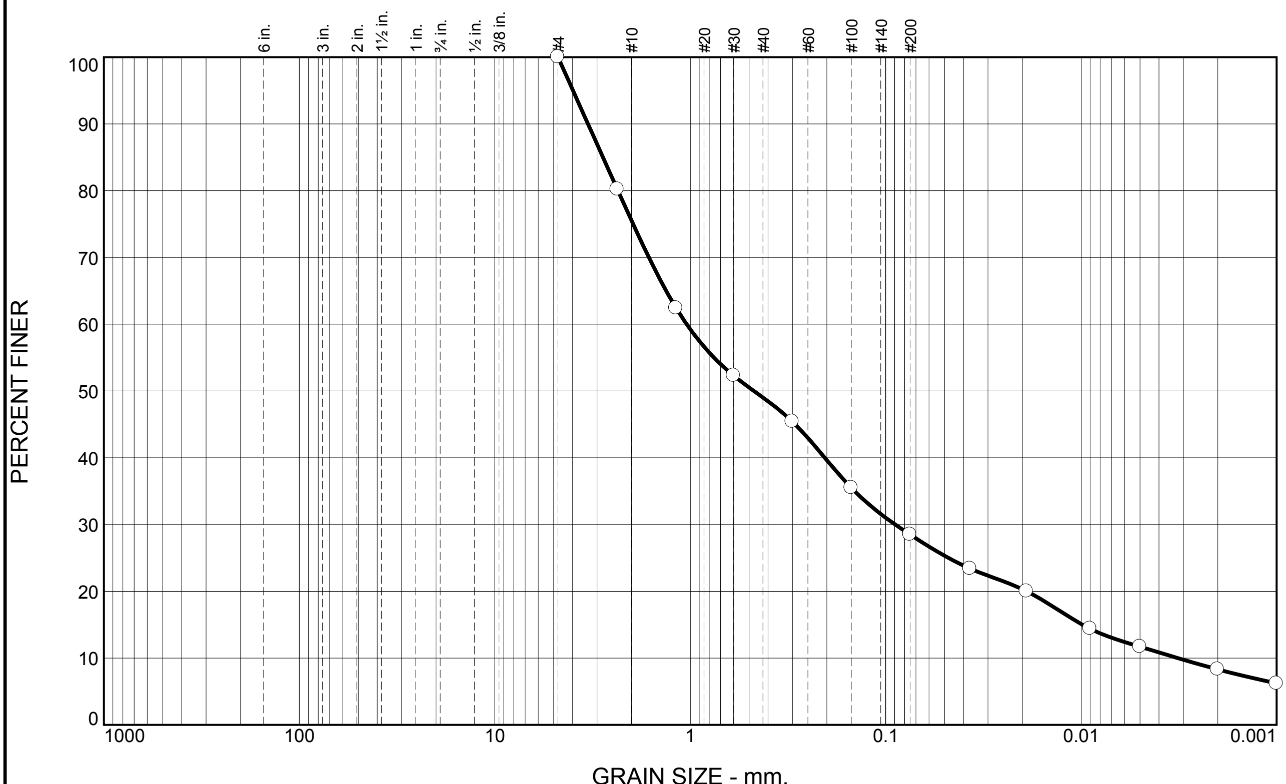
BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam
Project No: 4Z **Figure** 7

Tested By: TC **Checked By:** LJH

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	24.4	26.6	20.5	20.2	8.3

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	80.2		
#16	62.4		
#30	52.3		
#50	45.4		
#100	35.5		
#200	28.5		
0.037 mm	23.4		
0.019 mm	20.0		
0.009 mm	14.4		
0.005 mm	11.7		
0.002 mm	8.3		
0.001 mm	6.2		

* (no specification provided)

Material Description

Silty, clayey sand

Atterberg Limits

PL= 14 LL= 21 PI= 7

Coefficients

D_{90}= 3.3378 D_{85}= 2.7972 D_{60}= 1.0434
D_{50}= 0.4725 D_{30}= 0.0894 D_{15}= 0.0098
D_{10}= 0.0032 C_u= 325.63 C_c= 2.39

Classification

USCS= SC-SM AASHTO= A-2-4(0)

Remarks

The as-received sample contained 66.8% gravel by mass. Information presented here pertains only to the minus #4 fraction of the material for project purposes.

Source of Sample: DH-15-202 **Depth:** 36.3 - 38.8 feet
Sample Number: 4Z-28 (minus #4) **Date:** 9/24/15

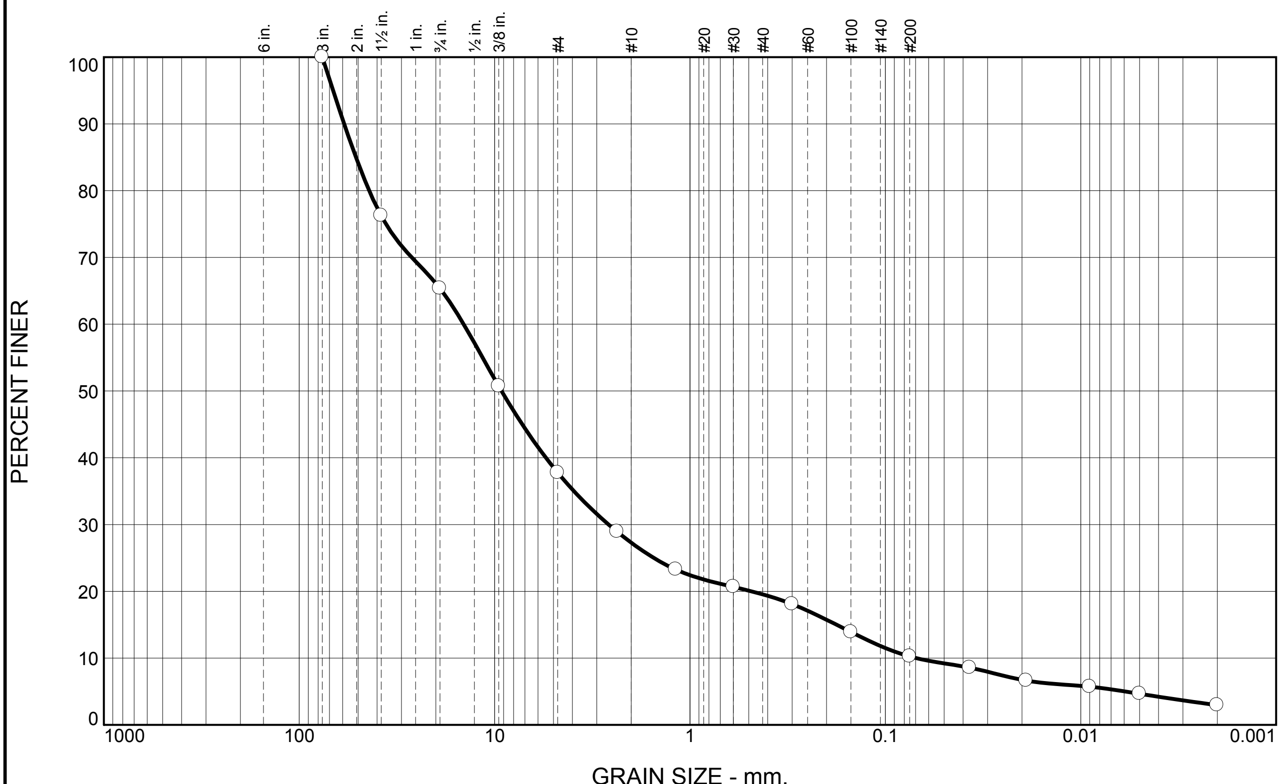
BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam
Project No: 4Z **Figure** 8

Tested By: TC **Checked By:** LJH

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	34.6	27.6	10.5	7.8	9.3	7.3	2.9

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
3 in	100.0		
1-1/2 in	76.3		
3/4 in	65.4		
3/8 in	50.7		
#4	37.8		
#8	28.9		
#16	23.2		
#30	20.7		
#50	18.1		
#100	13.9		
#200	10.2		
0.037 mm	8.6		
0.019 mm	6.6		
0.009 mm	5.7		
0.005 mm	4.7		
0.002 mm	2.9		

* (no specification provided)

Material Description

Poorly graded gravel with silt and sand

Atterberg Limits

PL= 18 LL= 18 PI= 0

Coefficients

D_{90}= 58.9225 D_{85}= 51.2802 D_{60}= 14.4097
D_{50}= 9.2191 D_{30}= 2.6101 D_{15}= 0.1781
D_{10}= 0.0697 C_u= 206.68 C_c= 6.78

Classification

USCS= GP-GM AASHTO= A-1-a

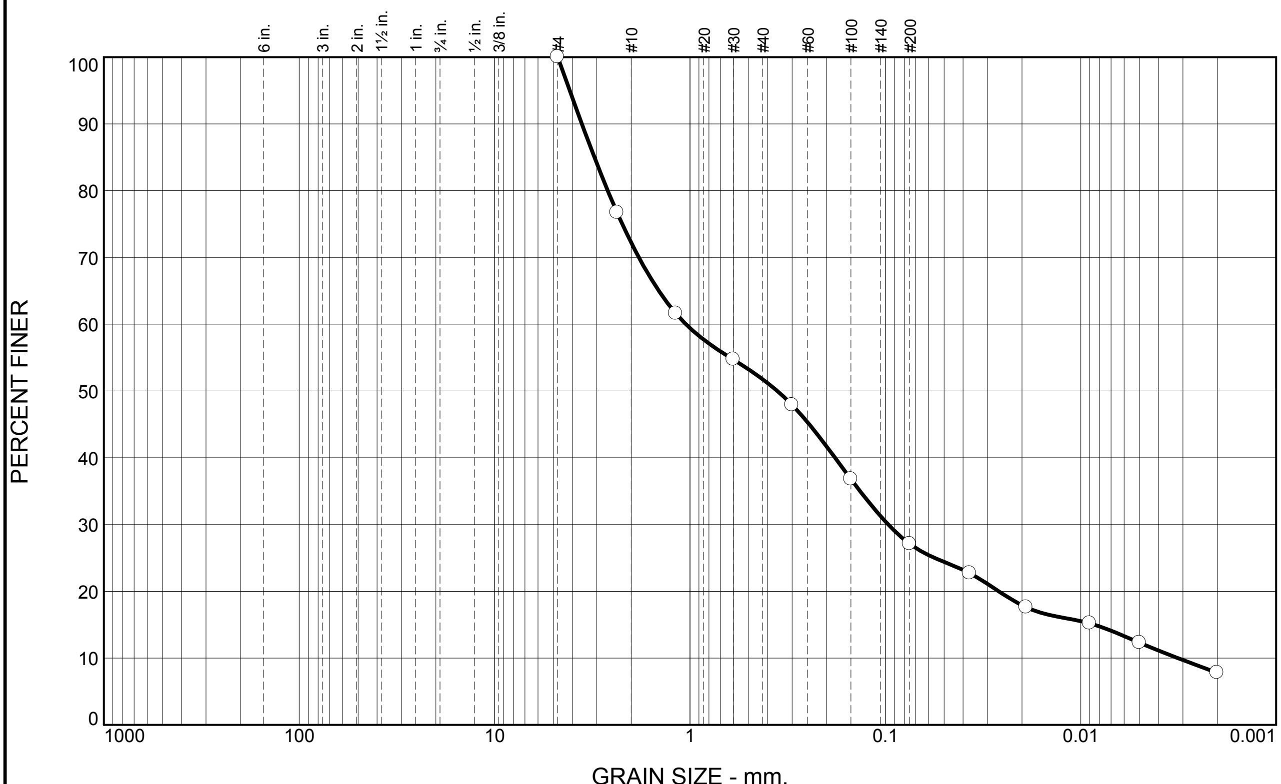
Remarks

Source of Sample: DH-15-202 **Depth:** 56.3 - 58.8 feet
Sample Number: 4Z-33 (as-received) **Date:** 11/4/15

BUREAU OF RECLAMATION Denver, Colorado	**Client:** **Project:** Willow Creek Dam **Project No:** 4Z **Figure**

Tested By: LH **Checked By:** TC

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	27.8	20.4	24.7	19.3	7.8

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	76.7		
#16	61.6		
#30	54.7		
#50	47.9		
#100	36.8		
#200	27.1		
0.037 mm	22.7		
0.019 mm	17.6		
0.009 mm	15.2		
0.005 mm	12.3		
0.002 mm	7.8		

* (no specification provided)

Material Description

Silty sand

Atterberg Limits

PL= 18 LL= 18 PI= 0

Coefficients

D_{90}= 3.5762 D_{85}= 3.0841 D_{60}= 1.0493
D_{50}= 0.3574 D_{30}= 0.0967 D_{15}= 0.0085
D_{10}= 0.0032 C_u= 329.30 C_c= 2.79

Classification

USCS= SM AASHTO= A-2-4(0)

Remarks

The as-received sample contained 62.2% gravel by mass. Information presented here pertains only to the minus #4 fraction of the material for project purposes.

Source of Sample: DH-15-202 **Depth:** 56.3 - 58.8 feet
Sample Number: 4Z-33 (minus #4) **Date:** 11/4/15

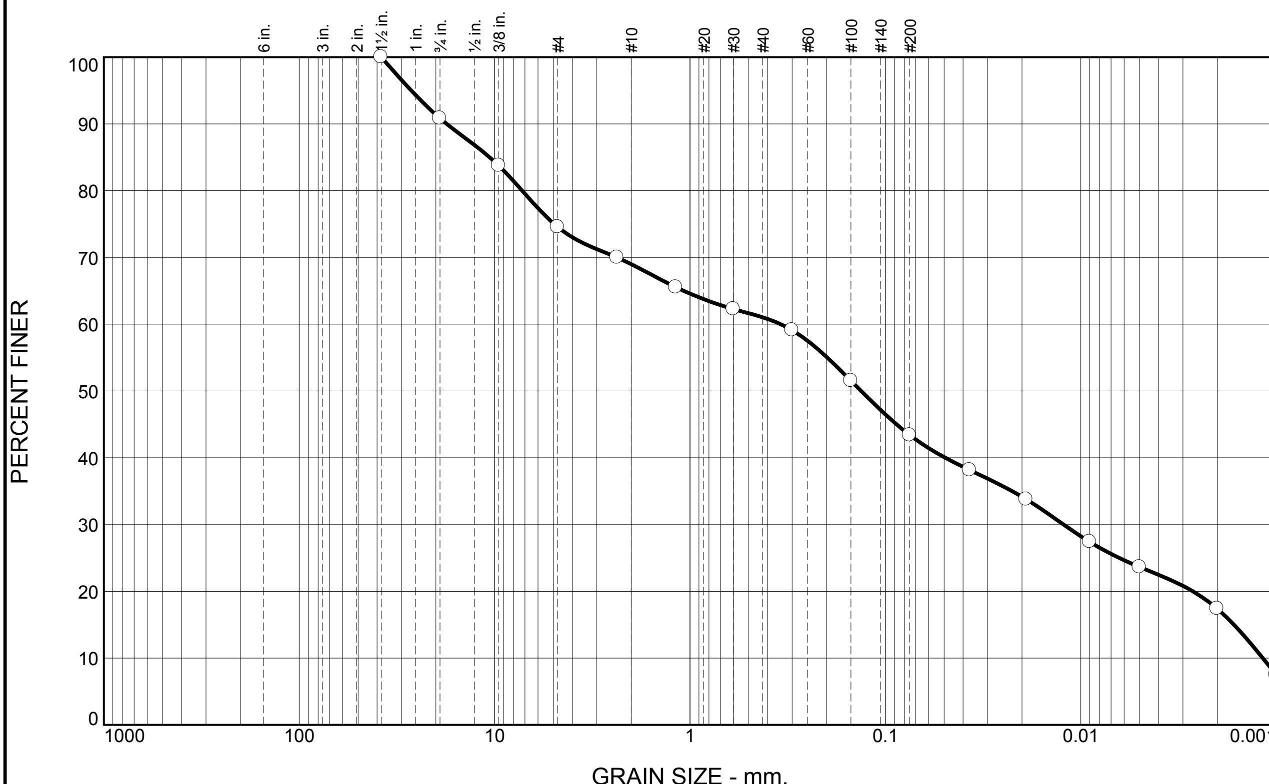
BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam
Project No: 4Z **Figure**

Tested By: LJH **Checked By:** TC

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	9.2	16.3	5.5	8.0	17.6	26.0	17.4

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
1-1/2 in	100.0		
3/4 in	90.8		
3/8 in	83.8		
#4	74.5		
#8	70.0		
#16	65.5		
#30	62.3		
#50	59.1		
#100	51.5		
#200	43.4		
0.037 mm	38.2		
0.019 mm	33.8		
0.009 mm	27.4		
0.005 mm	23.6		
0.002 mm	17.4		
0.001 mm	7.5		

* (no specification provided)

Material Description

Clayey sand with gravel

Atterberg Limits

PL= 13 LL= 27 PI= 14

Coefficients

D_{90}= 17.5942 D_{85}= 10.6092 D_{60}= 0.3430
D_{50}= 0.1330 D_{30}= 0.0122 D_{15}= 0.0016
D_{10}= 0.0012 C_u= 293.17 C_c= 0.37

Classification

USCS= SC AASHTO= A-6(2)

Remarks

Source of Sample: DH-15-203 **Depth:** 5.0 - 7.5 feet
Sample Number: 4Z-36 (as-received) **Date:** 11/4/15

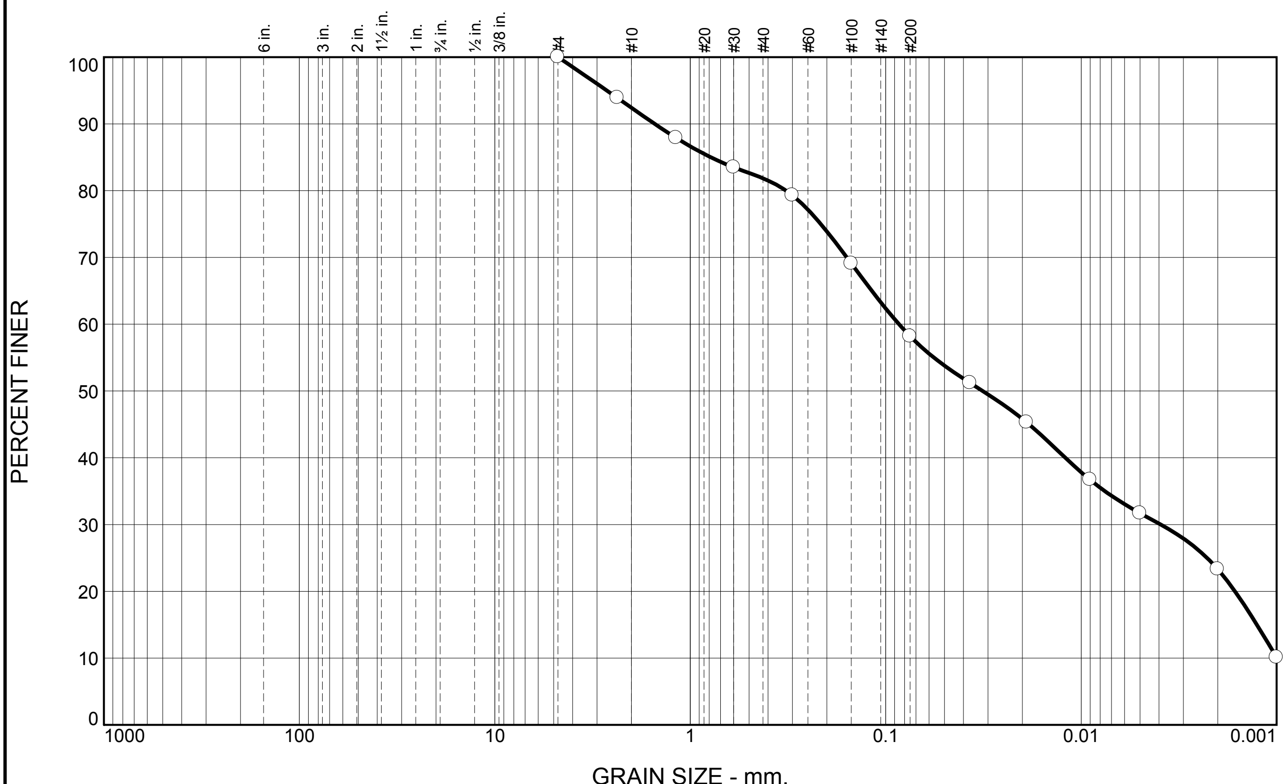
BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam
Project No: 4Z **Figure**

Tested By: LJH **Checked By:** TC

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	7.6	10.5	23.7	34.9	23.3

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	93.9		
#16	87.9		
#30	83.5		
#50	79.3		
#100	69.1		
#200	58.2		
0.037 mm	51.2		
0.019 mm	45.3		
0.009 mm	36.7		
0.005 mm	31.7		
0.002 mm	23.3		
0.001 mm	10.1		

* (no specification provided)

Material Description

Sandy lean clay

Atterberg Limits

PL= 13 LL= 27 PI= 14

Coefficients

D_{90}= 1.5199 D_{85}= 0.7843 D_{60}= 0.0855
D_{50}= 0.0319 D_{30}= 0.0039 D_{15}= 0.0013
D_{10}= C_u= C_c=

Classification

USCS= CL AASHTO= A-6(5)

Remarks

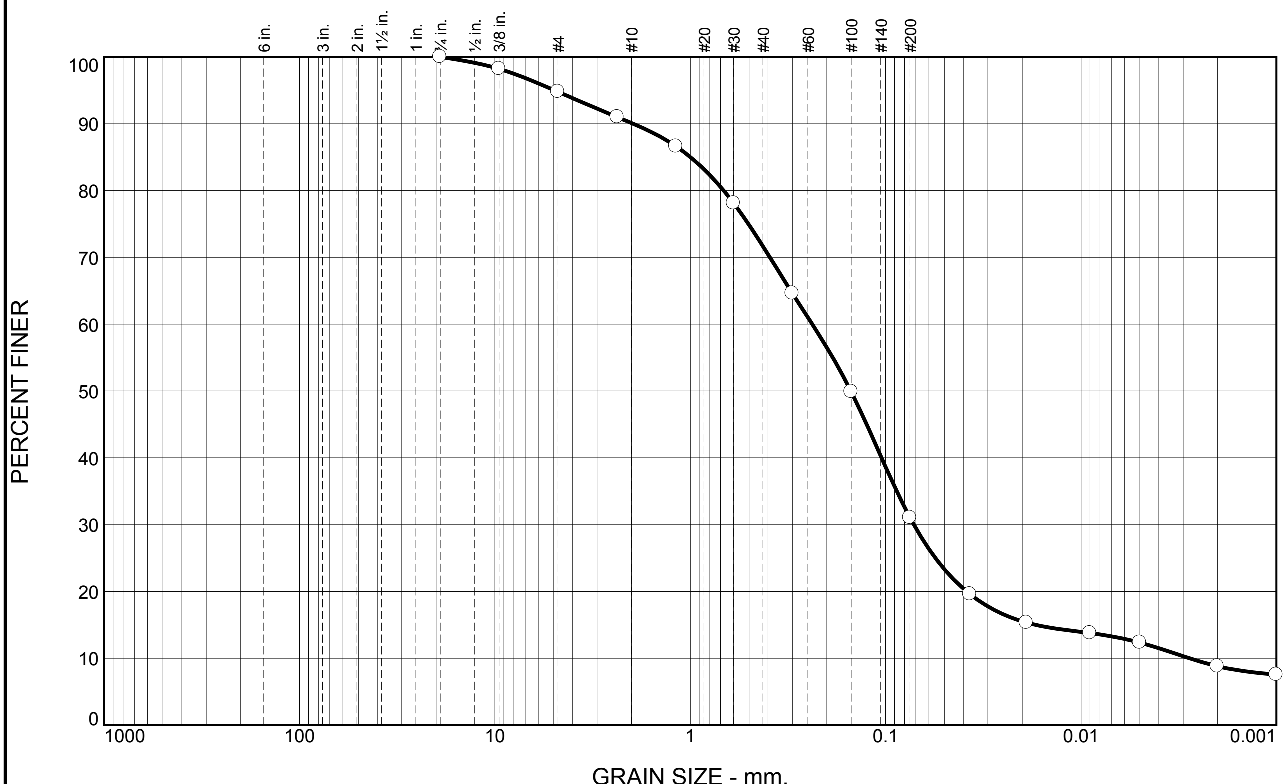
The as-received sample contained 25.5% gravel by mass. Information presented here pertains only to the minus #4 fraction of the material for project purposes.

Source of Sample: DH-15-203 **Depth:** 5.0 - 7.5 feet
Sample Number: 4Z-36 (minus #4) **Date:** 11/4/15

BUREAU OF RECLAMATION **Denver, Colorado**	**Client:** **Project:** Willow Creek Dam **Project No:** 4Z **Figure**

Tested By: LJH **Checked By:** TC

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	5.2	4.7	18.4	40.7	22.2	8.8

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
3/4 in	100.0		
3/8 in	98.2		
#4	94.8		
#8	91.0		
#16	86.6		
#30	78.1		
#50	64.6		
#100	49.9		
#200	31.0		
0.037 mm	19.6		
0.019 mm	15.3		
0.009 mm	13.8		
0.005 mm	12.3		
0.002 mm	8.8		
0.001 mm	7.5		

* (no specification provided)

Material Description

Silty sand

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 1.9613 D_{85}= 0.9977 D_{60}= 0.2376
D_{50}= 0.1507 D_{30}= 0.0717 D_{15}= 0.0171
D_{10}= 0.0028 C_u= 85.30 C_c= 7.78

Classification

USCS= SM AASHTO= A-2-4(0)

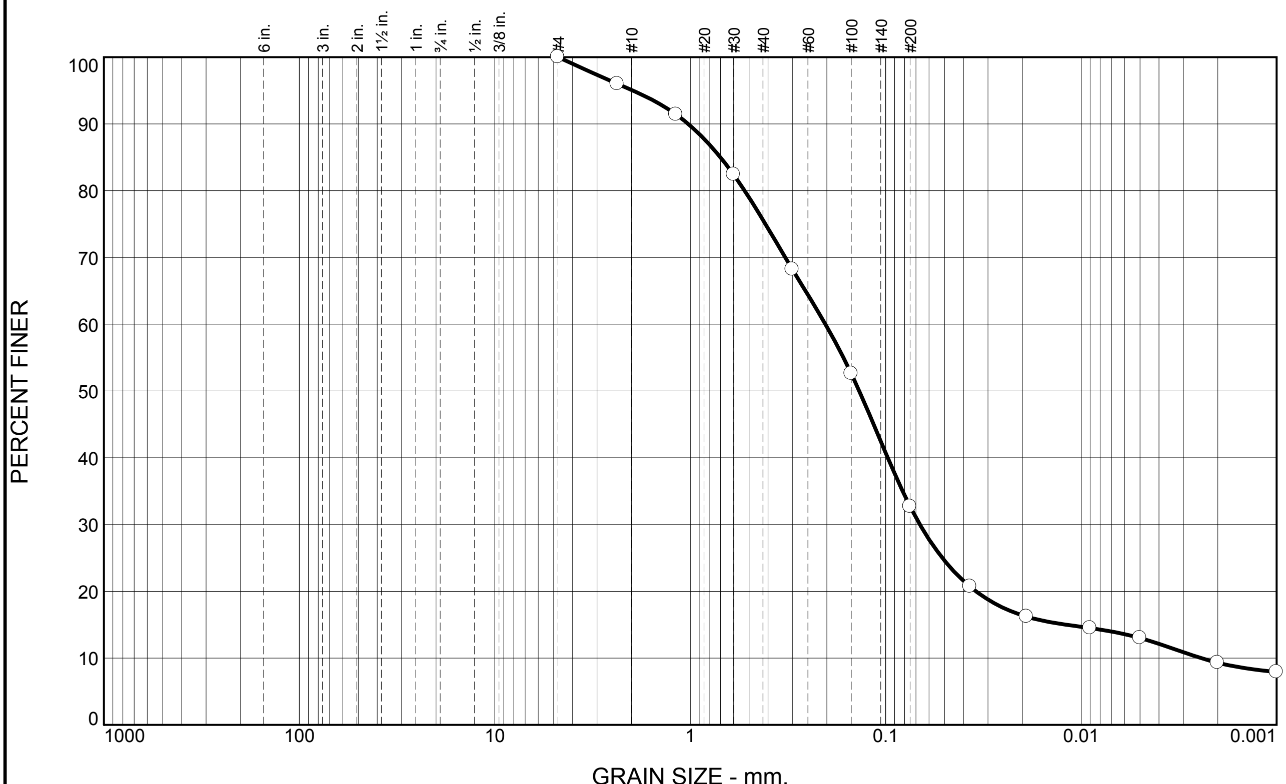
Remarks

Source of Sample: DH-15-204 **Depth:** 24.0 - 24.4 feet
Sample Number: 4Z-49A (as-received) **Date:** 11/4/15

BUREAU OF RECLAMATION Denver, Colorado	**Client:** **Project:** Willow Creek Dam **Project No:** 4Z **Figure**

Tested By: LJH **Checked By:** TC

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	4.9	19.5	42.9	23.4	9.3

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	96.0		
#16	91.4		
#30	82.4		
#50	68.2		
#100	52.6		
#200	32.7		
0.037 mm	20.7		
0.019 mm	16.2		
0.009 mm	14.5		
0.005 mm	13.0		
0.002 mm	9.3		
0.001 mm	7.9		

* (no specification provided)

Material Description

Silty sand

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{90}= 1.0255 D_{85}= 0.7012 D_{60}= 0.2036
D_{50}= 0.1366 D_{30}= 0.0668 D_{15}= 0.0120
D_{10}= 0.0024 C_u= 83.72 C_c= 9.03

Classification

USCS= SM AASHTO= A-2-4(0)

Remarks

The as-received sample contained 5.2% gravel by mass. Information presented here pertains only to the minus #4 fraction of the material for project purposes.

Source of Sample: DH-15-204 **Depth:** 24.0 - 24.4 feet
Sample Number: 4Z-49A (minus #4) **Date:** 11/4/15

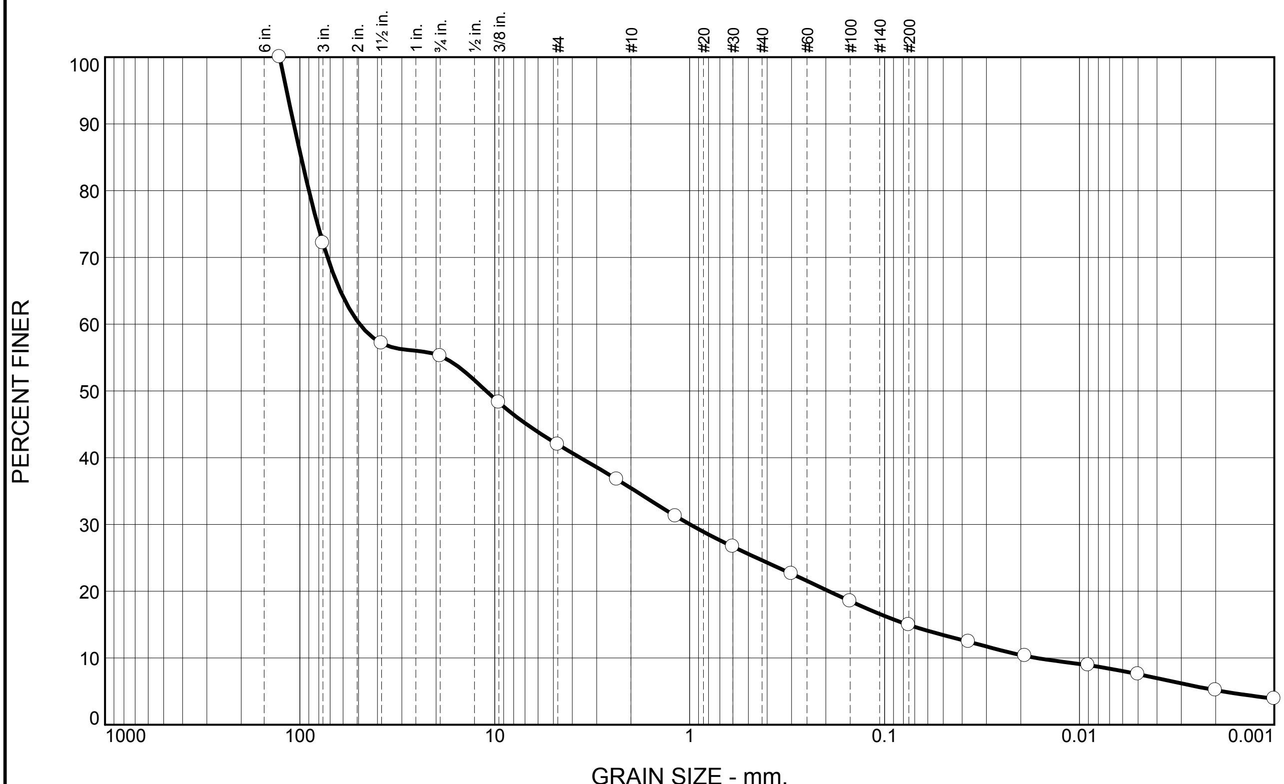
BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam
Project No: 4Z **Figure**

Tested By: LJH **Checked By:** TC

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
27.8	17.0	13.2	6.6	10.8	9.7	9.7	5.2

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
5 in	100.0		
3 in	72.2		
1-1/2 in	57.2		
3/4 in	55.2		
3/8 in	48.3		
#4	42.0		
#8	36.8		
#16	31.2		
#30	26.7		
#50	22.6		
#100	18.5		
#200	14.9		
0.037 mm	12.4		
0.019 mm	10.3		
0.009 mm	8.9		
0.005 mm	7.6		
0.002 mm	5.2		
0.001 mm	3.9		

* (no specification provided)

Material Description

Silty, clayey gravel with sand and cobble

Atterberg Limits

PL= 14 LL= 18 PI= 4

Classification

USCS= GC-GM AASHTO= A-1-b

Remarks

Source of Sample: DH-15-204 **Depth:** 25.3 - 25.7 feet
Sample Number: 4Z-49B (as-received) **Date:** 11/4/15

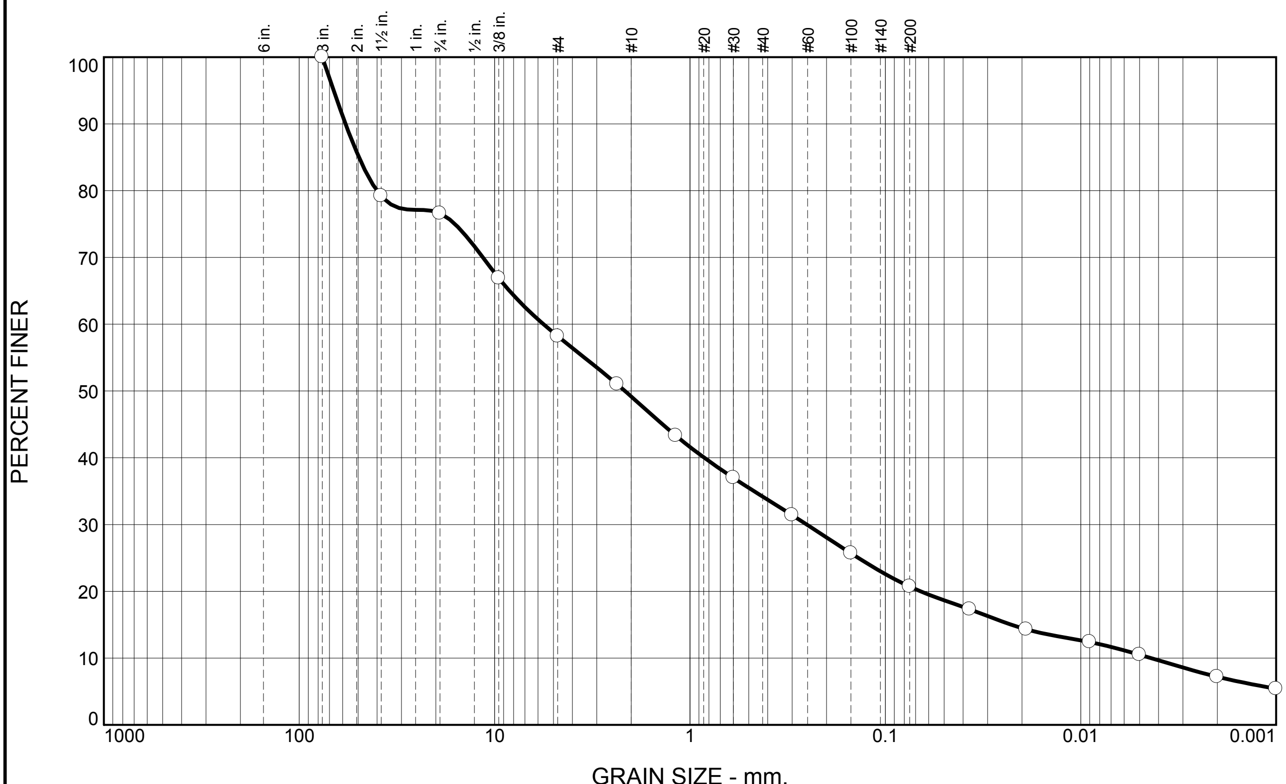
BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam
Project No: 4Z **Figure**

Tested By: LJH **Checked By:** TC

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	23.4	18.4	9.0	15.0	13.5	13.5	7.2

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
3 in	100.0		
1-1/2 in	79.2		
3/4 in	76.6		
3/8 in	66.9		
#4	58.2		
#8	51.0		
#16	43.3		
#30	37.0		
#50	31.4		
#100	25.7		
#200	20.7		
0.037 mm	17.3		
0.019 mm	14.3		
0.009 mm	12.4		
0.005 mm	10.5		
0.002 mm	7.2		
0.001 mm	5.4		

* (no specification provided)

Material Description

Silty, clayey gravel with sand

Atterberg Limits

PL= 14 LL= 18 PI= 4

Coefficients

D_{90}= 57.9752 D_{85}= 49.5053 D_{60}= 5.6198
D_{50}= 2.1542 D_{30}= 0.2528 D_{15}= 0.0227
D_{10}= 0.0044 C_u= 1285.69 C_c= 2.60

Classification

USCS= GC-GM AASHTO= A-1-b

Remarks

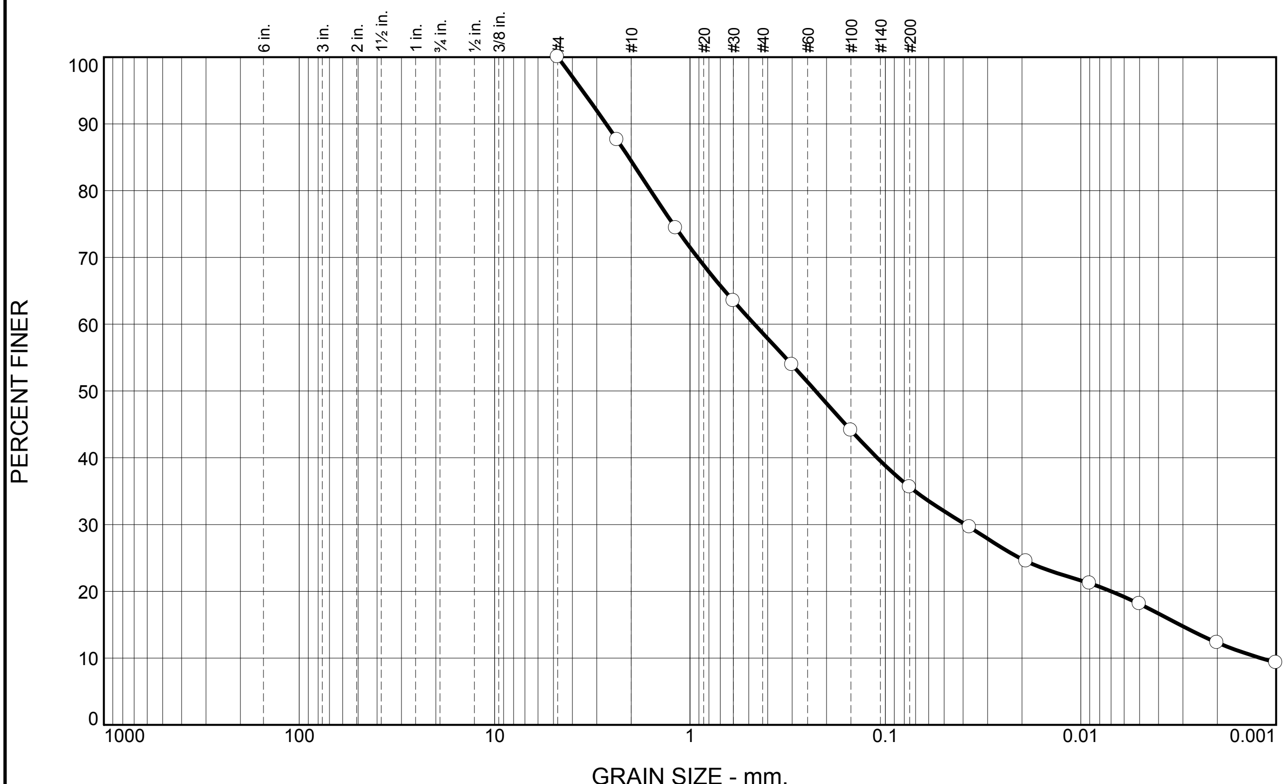
The as-received sample contained 27.8% cobble by mass. Information presented here pertains only to the minus 3 inch fraction of the material for project and USCS classification

Source of Sample: DH-15-204 **Depth:** 25.3 - 25.7 feet
Sample Number: 4Z-49B (minus 3") **Date:** 11/4/15

BUREAU OF RECLAMATION	Client:
	Project: Willow Creek Dam
Denver, Colorado	Project No: 4Z Figure

Tested By: LJH **Checked By:** TC

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	15.6	25.7	23.1	23.3	12.3

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	87.6		
#16	74.4		
#30	63.5		
#50	53.9		
#100	44.1		
#200	35.6		
0.037 mm	29.6		
0.019 mm	24.5		
0.009 mm	21.2		
0.005 mm	18.1		
0.002 mm	12.3		
0.001 mm	9.3		

* (no specification provided)

Material Description

Silty, clayey sand

Atterberg Limits

PL= 14 LL= 18 PI= 4

Coefficients

D_{90}= 2.6869 D_{85}= 2.0586 D_{60}= 0.4681
D_{50}= 0.2277 D_{30}= 0.0389 D_{15}= 0.0031
D_{10}= 0.0012 C_u= 390.13 C_c= 2.69

Classification

USCS= SC-SM AASHTO= A-4(0)

Remarks

The as-received sample contained 27.8% cobble and 30.2% gravel by mass. Information presented here pertains only to the minus #4 fraction of the material for project purposes.

Source of Sample: DH-15-204 **Depth:** 25.3 - 25.7 feet
Sample Number: 4Z-49B (minus #4) **Date:** 11/4/15

BUREAU OF RECLAMATION

Denver, Colorado

Client:
Project: Willow Creek Dam

Project No: 4Z **Figure**

Tested By: LJH **Checked By:** TC

Appendix B – Erosion Test Data and Photos

Submerged Jet Erosion Test Summary

Sample Number **4Z-**	Sampling Location	Depth ft			Comments
11	DH-15-201	25.5	-	27.3	Good jet test - highest erosion resistance of all jet tests performed
17	DH-15-201	51.3	-	52.4	Successful jet test. Very rapid erosion
24	DH-15-202	7.1	-	8.5	Two jet tests attempted, eroding in opposite directions from depth 8.08'. One hit cobble just below cut surface almost immediately; the other hit a second cobble after about 2.5 minutes. Insufficient data for analysis in both cases.
28	DH-15-202	36.3	-	38.8	Successful jet test with rapid erosion
33	DH-15-202	56.3	-	58.8	Successful jet test with rapid erosion
36	DH-15-203	5.0	-	7.5	Successful jet test with very rapid erosion - highest erosion rate of all jet tests
49A	DH-15-204	24.0	-	26.5	Two jet tests performed (one from top of tube-A, one from bottom of tube-B)
49B		26.5			

Sample Number **4Z-**	Jet Test ID	Elev. (Approx.)	USCS	LL	PI	% gravel/cobble + #4 %	%clay <0.002 mm - #4 sample %	%clay <0.002 mm all %	k_d ft/hr/psf	τ_c psf
11	WCDS-1	4118.5	(GC)s	26	11	49	14.8	7.5	0.4	6.10E-02
17	WCDS-2	4092.7	(GC-GM)s	19	4	46	9.1	4.9	12.3	6.12E-09
24	WCDS-3	4136.9	(GC)s	23	11	41	21.3	12.6		
24	WCDS-4	4136.9	(GC)s	23	11	41	21.3	12.6		
28	WCDS-5	4107.7	(GP-GC)s	21	7	67	8.3	2.7	6.8	2.82E-03
33	WCDS-6	4087.7	(GP-GM)s	18	0	62	7.8	2.9	3.0	1.49E-02
36	WCDS-7	4128.0	(SC)g	27	14	26	23.3	17.4	110.2	1.88E-03
49A	WCDS-9	4109.0	SM	18	4	5.2	9.3	8.8	9.1	3.70E-04
49B	WCDS-8	4106.5	(GC-GM)s	18	4	58	12.3	5.2	1.2	3.68E-02

SUBMERGED JET TEST DATA

PROJECT Willow Creek Dam spillway

DATE 9/9/2015

SAMPLE / LOCATION DH-15-201 26.88'-27.31' (4Z-11)

OPERATOR TLW

ZERO POINT GAGE READING (on deflector plate)

TEST # WCDS-1

PRELIMINARY HEAD SETTING (IN.) **33.5**

POINT GAGE RDG @ NOZZLE **1.238**

NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.162

RESULTS

$k_d =$	0.377 ft/hr/psf
$\tau_c =$	0.06098495 psf

$k_d =$	0.666 $cm^3/(N\text{-}s)$
$\tau_c =$	2.920 Pa

SCOUR DEPTH READINGS			
TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		**1.076**	0.000
0.5	**0.5**	**1.072**	0.004
3	**2.5**	**1.064**	0.012
7	**4**	**1.042**	0.034
15	**8**	**1.031**	0.045
33	**18**	**0.974**	0.102

HEAD SETTING	
TIME (MIN)	HEAD (IN.)
0	**33.50**
0.5	**33.50**
3	**33.50**
7	**33.50**
15	**33.50**
33	**33.50**

COMMENTS

This sample was a glacial till with large amounts of subangular to subrounded gravel, in-filled by a silty/clayey cohesive soil. This test was run with the sample tilted up to an angle of 45° to enable loosened gravel particles to be easily flushed out of the scour hole.

An additional data point was collected at t=67 minutes (Δt=34 min), pt. gage=0.962 ft, but there were loose gravel pieces lining the interior of the hole. No loose gravel pieces were present at any of the earlier time steps.

D:\Erosion\Willow Creek\Jet Tests\[WCDS-1, 4Z-11, DH-15-201 26.88-27.31.xlsm]Data

TEST # WCDS-1 **SAMPLE** DH-15-201 26.88'-27.31' (4Z-11)

SUBMERGED JET TEST DATA

PROJECT Willow Creek Dam spillway

DATE 9/10/2015

SAMPLE / LOCATION DH-15-201 52.19'-52.58'

OPERATOR TLW

ZERO POINT GAGE READING (on deflector plate)

TEST # WCDS-2

PRELIMINARY HEAD SETTING (IN.) **39**

POINT GAGE RDG @ NOZZLE **1.238**

NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.189

RESULTS

k_d =	12.252	ft/hr/psf
τ_c =	6.1247E-09	psf

k_d =	21.666	$cm^3/(N\text{-}s)$
τ_c =	2.932E-07	Pa

SCOUR DEPTH READINGS			
TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		**1.049**	0.000
1	**1**	**1.016**	0.033
3	**2**	**0.917**	0.132
4	**1**	**0.809**	0.240
5	**1**	**0.769**	0.280

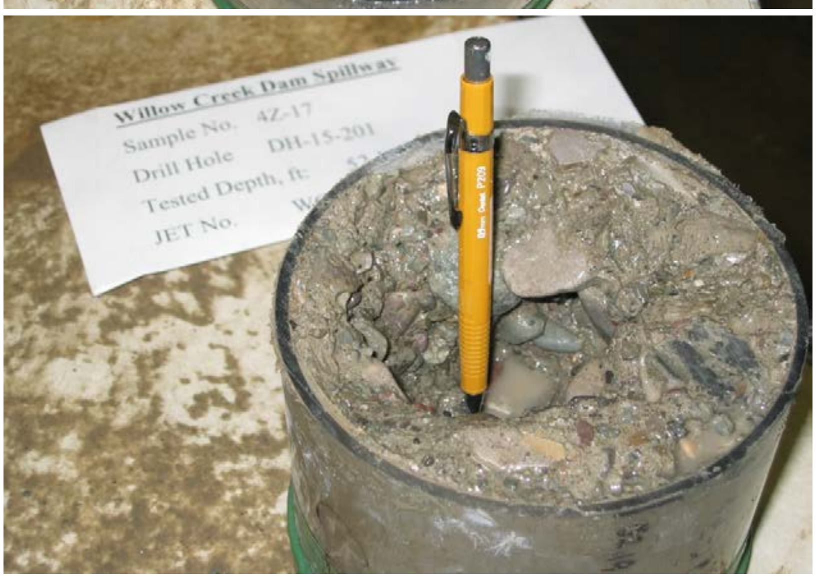
HEAD SETTING	
TIME (MIN)	HEAD (IN.)
0	**39.00**
1	**39.00**
3	**39.00**
4	**39.00**
5	**39.00**

COMMENTS

This sample was a glacial till with large amounts of subangular to subrounded gravel, in-filled by silty/clayey cohesive soil. This test was run with the sample tilted up to an angle of 45° to enable loosened gravel particles to be easily flushed out of the scour hole. Flushing did not occur as readily as desired, and loose gravel pieces were manually lifted out of the hole at t=3, 4, and 5 minutes. Erosion of in-filled material between gravel pieces was very rapid.

D:\Erosion\Willow Creek\Jet Tests\[WCDS-2, 4Z-17, DH-15-201 52.19-52.58.xlsm]Data

TEST # WCDS-2 **SAMPLE** DH-15-201 52.19'-52.58'



SUBMERGED JET TEST DATA

PROJECT Willow Creek Dam spillway

DATE 9/11/2015

SAMPLE / LOCATION DH-15-202 8.08'-8.46' (4Z-24)

OPERATOR TLW

ZERO POINT GAGE READING (on deflector plate)

TEST # WCDS-3

PRELIMINARY HEAD SETTING (IN.) **39**

POINT GAGE RDG @ NOZZLE **1.238**

NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.256

RESULTS

k_d =	##########	ft/hr/psf
τ_c =	6.7275E-20	psf

k_d =	##########	$cm^3/(N\text{-}s)$
τ_c =	3.221E-18	Pa

SCOUR DEPTH READINGS			
TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		**0.982**	0.000
1	**1**	**0.982**	0.000

HEAD SETTING	
TIME (MIN)	HEAD (IN.)
0	**39.00**
1	**39.00**

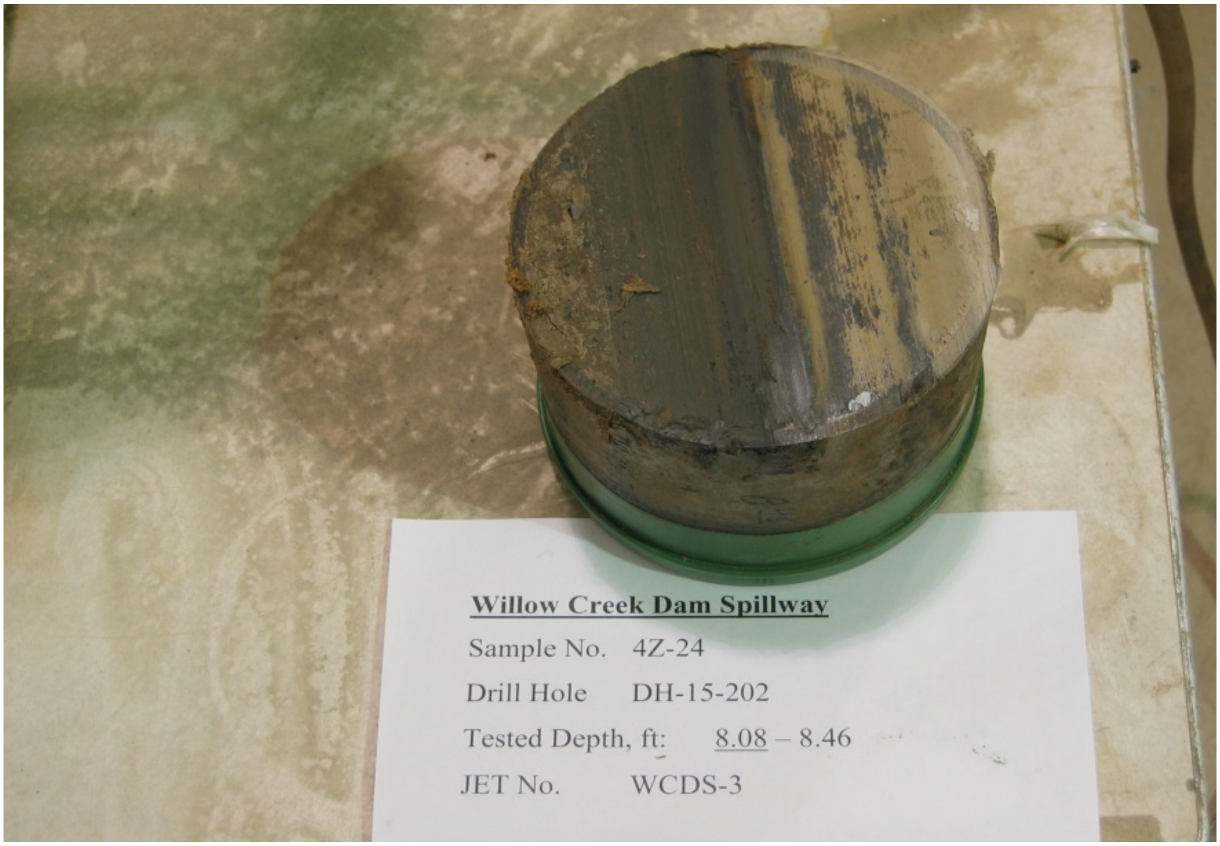
COMMENTS

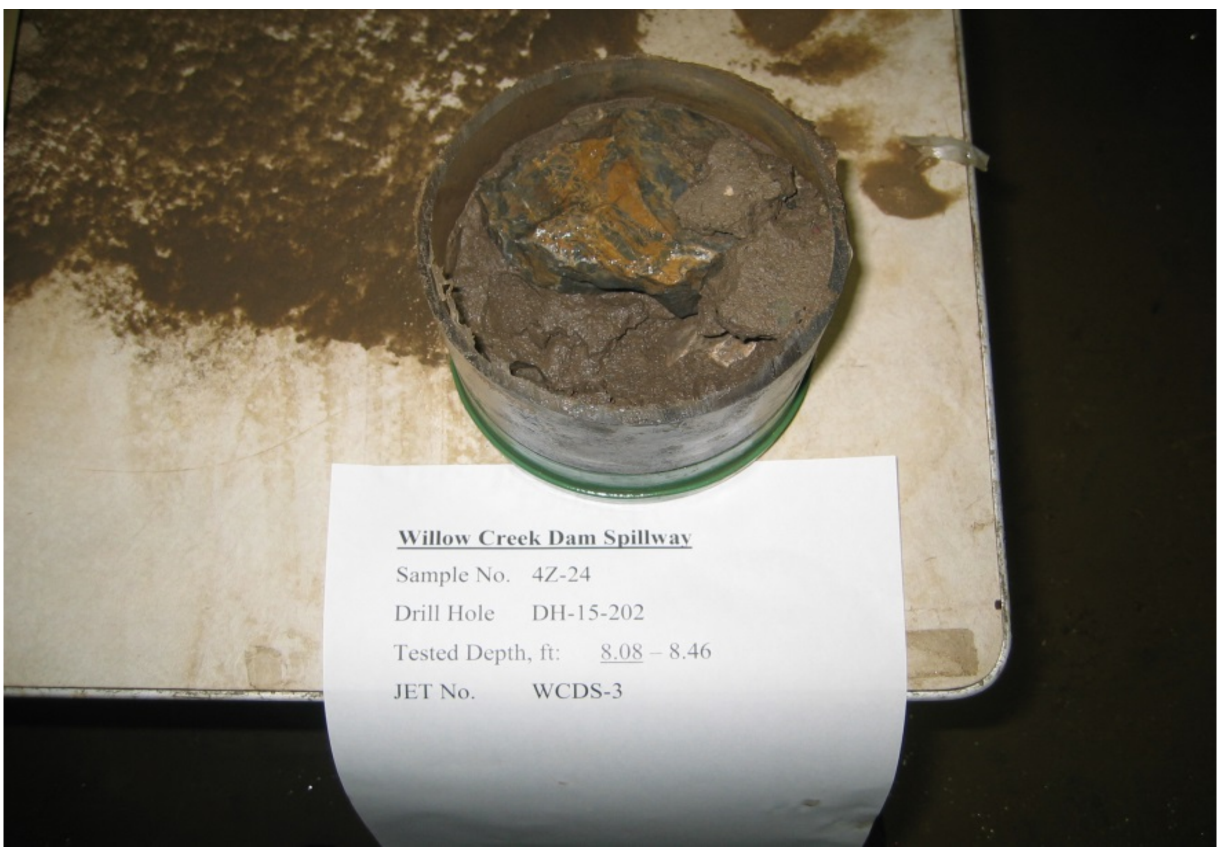
This sample was a glacial till with large amounts of subangular to subrounded gravel, in-filled by silty/clayey cohesive soil. This test was run with the sample tilted up to an angle of 45° to enable loosened gravel particles to be easily flushed out of the scour hole.

A large cobble was encountered immediately after starting the test (was lurking just below cut surface)

D:\Erosion\Willow Creek\Jet Tests\[WCDS-3, 4Z-24, DH-15-202 8.08-8.46.xlsm]Data

TEST # WCDS-3 **SAMPLE** DH-15-202 8.08'-8.46' (4Z-24)





SUBMERGED JET TEST DATA

PROJECT Willow Creek Dam spillway

DATE 9/11/2015

SAMPLE / LOCATION DH-15-202 8.08'-7.70'

OPERATOR TLW

ZERO POINT GAGE
READING (on deflector plate)

TEST # WCDS-4

PRELIMINARY HEAD SETTING (IN.) **20.5**

POINT GAGE RDG @ NOZZLE **1.238**

NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.210

RESULTS

$k_d =$	##########	ft/hr/psf
$\tau_c =$	3.5362E-20	psf

$k_d =$	##########	$cm^3/(N\text{-}s)$
$\tau_c =$	1.693E-18	Pa

SCOUR DEPTH READINGS			
TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		**1.028**	0.000
1	**1**	**1.024**	0.004
2.5	**1.5**	**0.839**	0.189

HEAD SETTING	
TIME (MIN)	HEAD (IN.)
0	**20.50**
1	**20.50**
2.5	**20.50**

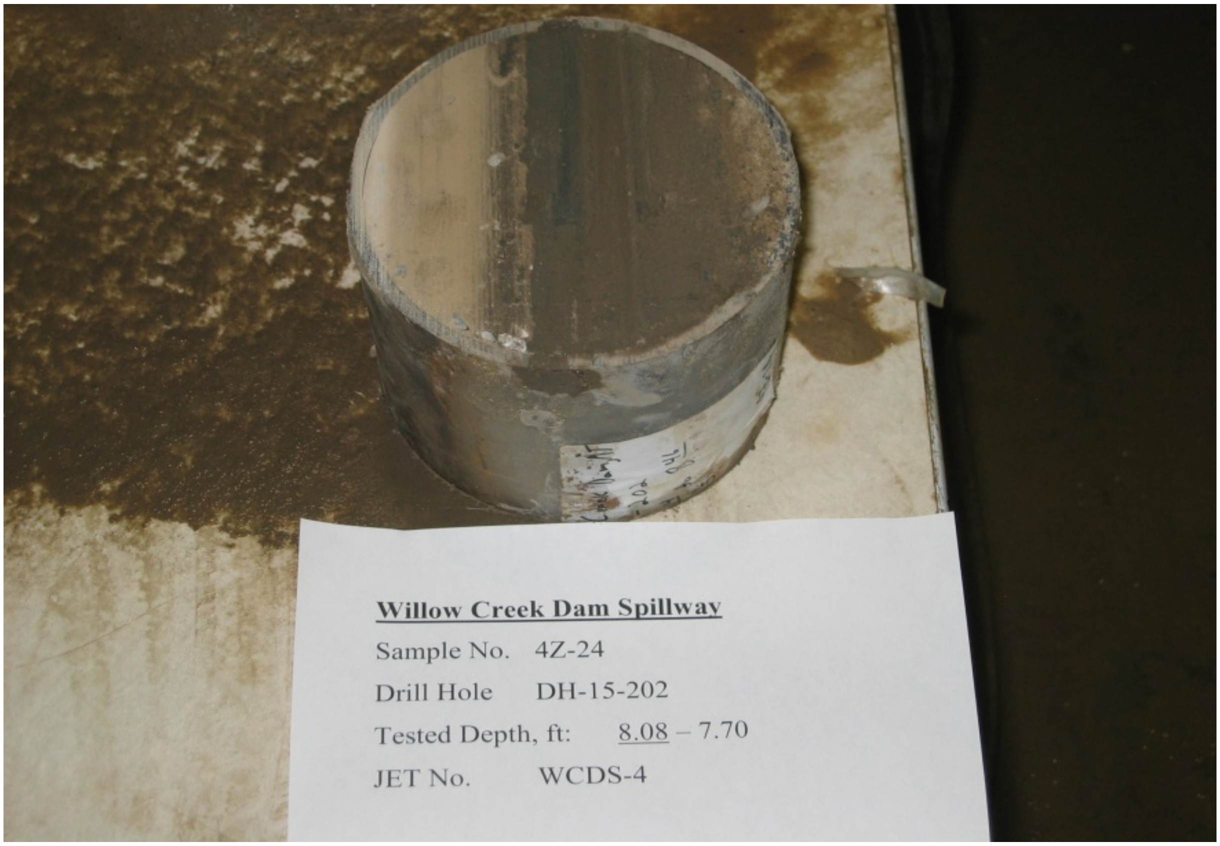
COMMENTS

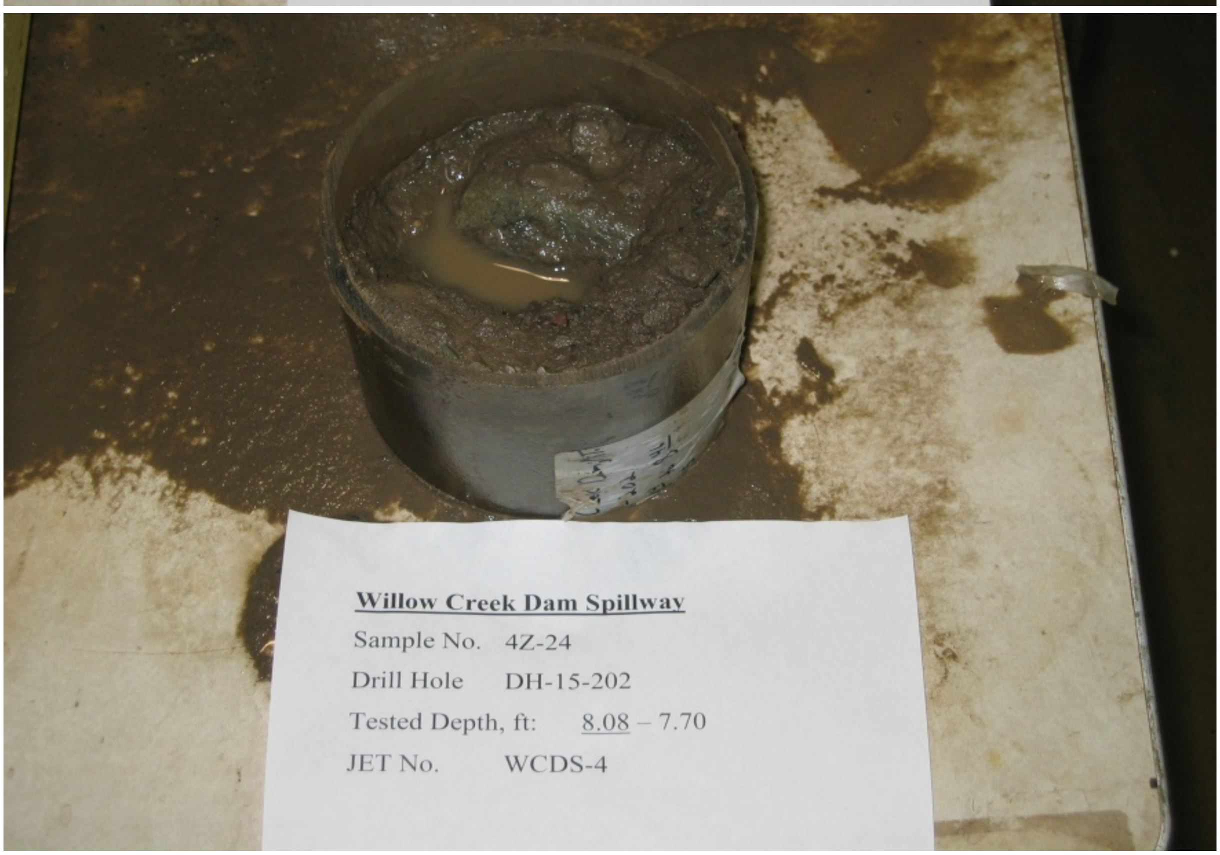
This sample was a glacial till with large amounts of subangular to subrounded gravel, in-filled by silty/clayey cohesive soil. This test was run with the sample tilted up to an angle of 45° to enable loosened gravel particles to be easily flushed out of the scour hole.

Scour stopped after t=2.5 minutes when a cobble was encountered in the middle of the sample.

D:\Erosion\Willow Creek\Jet Tests\[WCDS-4, 4Z-24, DH-15-202 8.08-7.70.xlsm]Data

TEST # WCDS-4 **SAMPLE** DH-15-202 8.08'-7.70'





SUBMERGED JET TEST DATA

PROJECT Willow Creek Dam spillway

DATE 9/14/2015

SAMPLE / LOCATION DH-15-202 37.30'-37.70'

OPERATOR TLW

ZERO POINT GAGE READING (on deflector plate)

TEST # WCDS-5

PRELIMINARY HEAD SETTING (IN.) 11.5

POINT GAGE RDG @ NOZZLE 1.238

NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.179

RESULTS

$k_d =$	6.755	ft/hr/psf
$\tau_c =$	0.00281656	psf

$k_d =$	11.945	$cm^3/(N\text{-}s)$
$\tau_c =$	1.349E-01	Pa

SCOUR DEPTH READINGS			
TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		1.059	0.000
0.5	0.5	1.056	0.003
1	0.5	1.020	0.039
2	1	0.982	0.077
4	2	0.967	0.092
8	4	0.958	0.101

HEAD SETTING	
TIME (MIN)	HEAD (IN.)
0	11.50
0.5	11.50
1	11.50
2	11.50
4	11.50
8	11.50

COMMENTS

This sample was a glacial till with large amounts of subangular to subrounded gravel, in-filled by silty/clayey cohesive soil. This test was run with the sample tilted up to an angle of 45° to enable loosened gravel particles to be easily flushed out of the scour hole. Some loose gravel pieces were manually removed at t=2 and t=4 minutes.

D:\Erosion\Willow Creek\Jet Tests\[WCDS-5, 4Z-28, DH-15-202 37.30-37.70.xlsm]Data

TEST # WCDS-5 **SAMPLE** DH-15-202 37.30'-37.70'

SUBMERGED JET TEST DATA

PROJECT Willow Creek Dam spillway

DATE 9/14/2015

SAMPLE / LOCATION DH-15-202 58.41'-58.81'

OPERATOR TLW

ZERO POINT GAGE READING (on deflector plate)

TEST # WCDS-6

PRELIMINARY HEAD SETTING (IN.) **11.5**

POINT GAGE RDG @ NOZZLE **1.238**

NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.197

RESULTS

k_d = 2.953 ft/hr/psf	k_d = 5.223 $cm^3/(N\text{-}s)$
τ_c = 0.01488725 psf	τ_c = 7.128E-01 Pa

SCOUR DEPTH READINGS

TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		**1.041**	0.000
1	**1**	**1.023**	0.018
2	**1**	**1.011**	0.030
4	**2**	**0.997**	0.044
8	**4**	**0.976**	0.065
13	**5**	**0.967**	0.074

HEAD SETTING

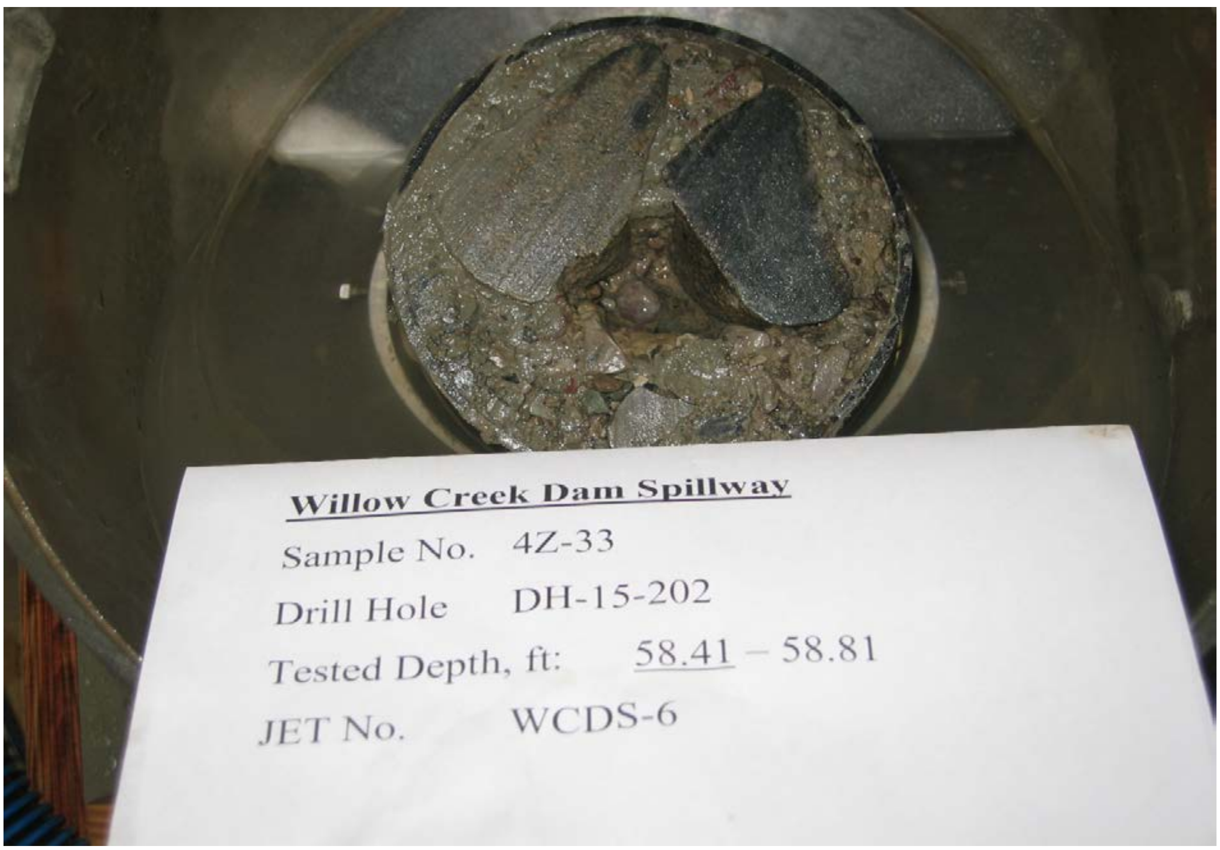
TIME (MIN)	HEAD (IN.)
0	**11.50**
1	**11.50**
2	**11.50**
4	**11.50**
8	**11.50**
13	**11.50**

COMMENTS

This sample was a glacial till with large amounts of subangular to subrounded gravel, in-filled by silty/clayey cohesive soil. This test was run with the sample tilted up to an angle of 45° to enable loosened gravel particles to be easily flushed out of the scour hole.

D:\Erosion\Willow Creek\Jet Tests\[WCDS-6, 4Z-33, DH-15-202 58.41-58.81.xlsm]Data

TEST # WCDS-6 **SAMPLE** DH-15-202 58.41'-58.81'



SUBMERGED JET TEST DATA

PROJECT Willow Creek Dam spillway

DATE 9/17/2015

SAMPLE / LOCATION DH-15-203 5.4'-5.0'

OPERATOR TLW

ZERO POINT GAGE READING (on deflector plate) ________

TEST # WCDS-7

PRELIMINARY HEAD SETTING (IN.) **16.5**

POINT GAGE RDG @ NOZZLE **1.238**

NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.182

RESULTS

$k_d =$	110.207	ft/hr/psf
$\tau_c =$	0.00188228	psf

$k_d =$	194.884	$cm^3/(N\text{-}s)$
$\tau_c =$	9.012E-02	Pa

SCOUR DEPTH READINGS

TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		**1.056**	0.000
0.25	**0.25**	**0.933**	0.123
0.5	**0.25**	**0.888**	0.168
0.75	**0.25**	**0.868**	0.188

HEAD SETTING

TIME (MIN)	HEAD (IN.)
0	**16.50**
0.25	**16.50**
0.5	**16.50**
0.75	**16.50**

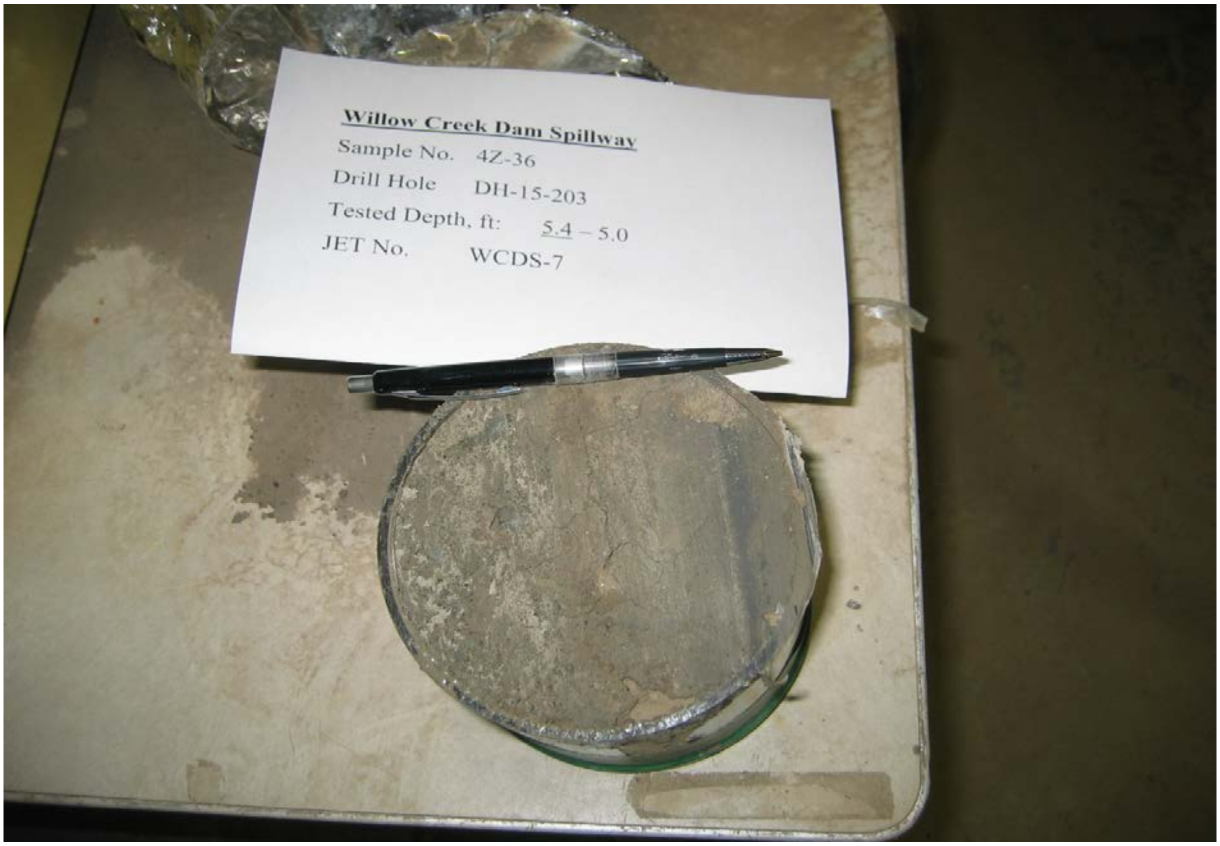
COMMENTS

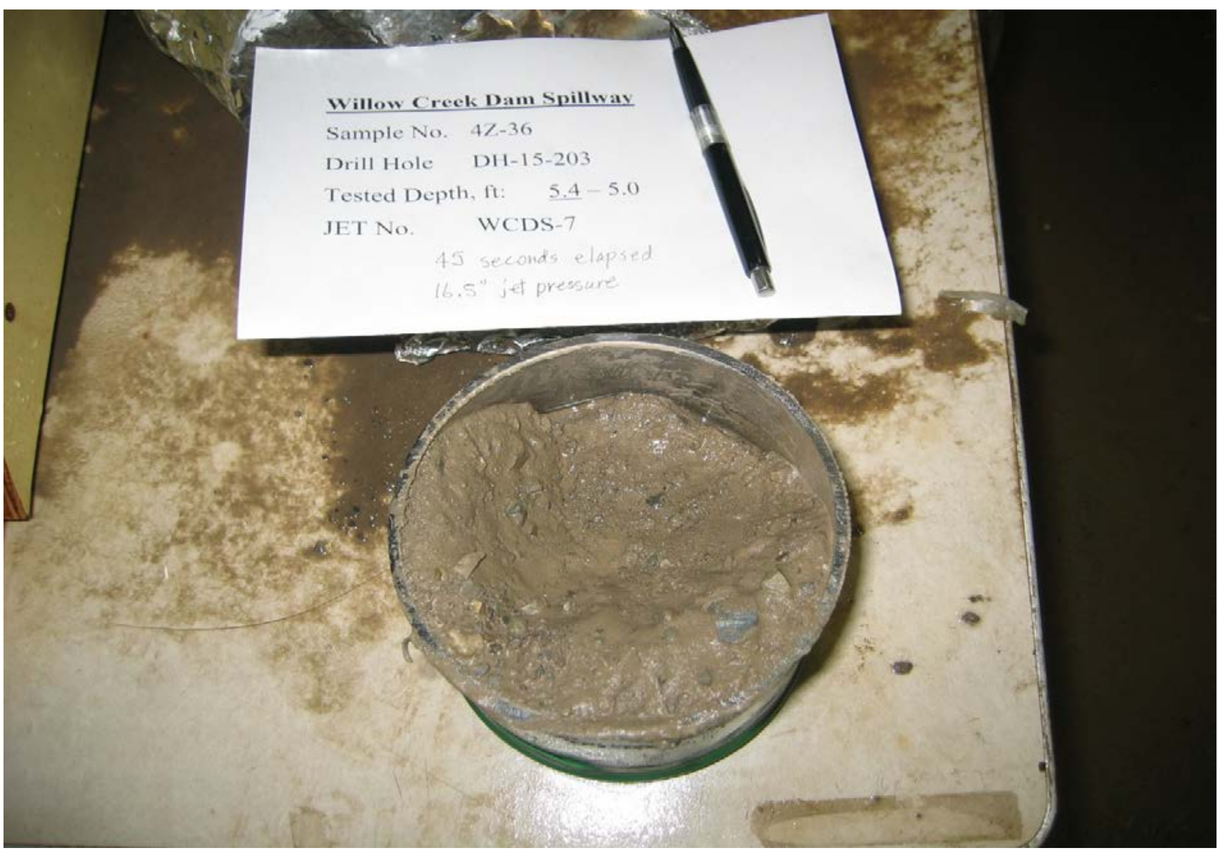
This sample was a glacial till with large amounts of subangular to subrounded gravel, in-filled by silty/clayey cohesive soil. This test was run with the sample tilted up to an angle of 45° to enable loosened gravel particles to be easily flushed out of the scour hole.

The scour hole was not cleansing itself effectively when the test was stopped after 45 seconds. Gravel pieces were accumulating quickly at the bottom of the scour hole.

D:\Erosion\Willow Creek\Jet Tests\[WCDS-7, 4Z-36, DH-15-203 5.4-5.0.xlsm]Data

TEST # WCDS-7 **SAMPLE** DH-15-203 5.4'-5.0'





SUBMERGED JET TEST DATA

PROJECT Willow Creek Dam spillway

DATE 9/18/2015

SAMPLE / LOCATION DH-15-204 25.33'-25.72' (4Z-49B)

OPERATOR TLW

ZERO POINT GAGE READING (on deflector plate) ____

TEST # WCDS-8

PRELIMINARY HEAD SETTING (IN.) **17.5**

POINT GAGE RDG @ NOZZLE **1.238**

NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.198

RESULTS

k_d =	1.193	ft/hr/psf
τ_c =	0.03683759	psf

k_d =	2.109	cm^3/(N-s)
τ_c =	1.764E+00	Pa

SCOUR DEPTH READINGS			
TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		**1.040**	0.000
1	**1**	**1.038**	0.002
8	**7**	**1.025**	0.015
16	**8**	**0.972**	0.068

HEAD SETTING	
TIME (MIN)	HEAD (IN.)
0	**17.50**
1	**17.50**
8	**17.50**
16	**17.50**

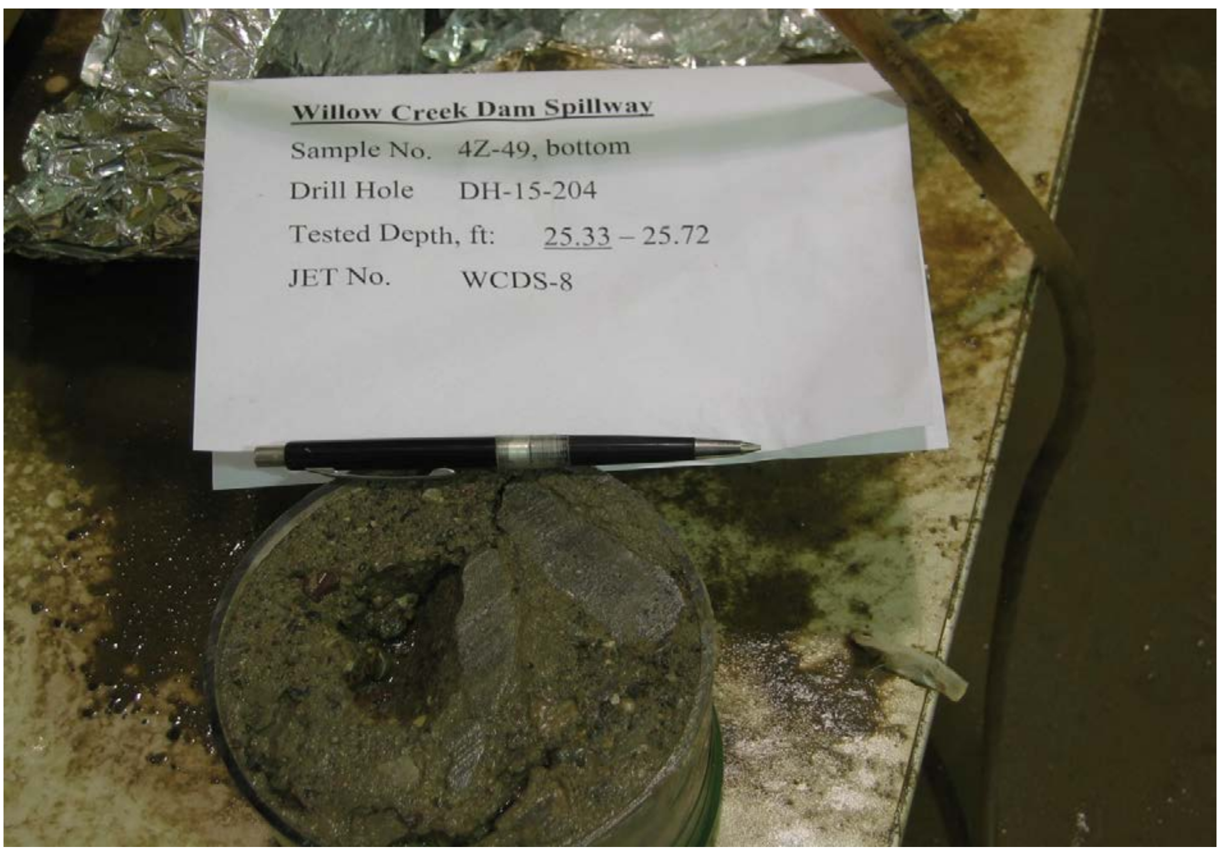
COMMENTS

This sample was a glacial till with large amounts of subangular to subrounded gravel, in-filled by silty/clayey cohesive soil. This test was run with the sample tilted up to an angle of 45° to enable loosened gravel particles to be easily flushed out of the scour hole.

This sample was labeled "B" when Tyler Chatfield ran the subsequent gradation test

D:\Erosion\Willow Creek\Jet Tests\[WCDS-8, 4Z-49B, DH-15-204 25.33-25.72.xlsm]Data

TEST # WCDS-8 **SAMPLE** DH-15-204 25.33'-25.72' (4Z-49B)



SUBMERGED JET TEST DATA

PROJECT Willow Creek Dam spillway

DATE 9/18/2015

SAMPLE / LOCATION DH-15-204 25.33'-25.72' (4Z-49A)

OPERATOR TLW

ZERO POINT GAGE READING (on deflector plate)

TEST # WCDS-9

PRELIMINARY HEAD SETTING (IN.) **17.5**

POINT GAGE RDG @ NOZZLE **1.238**

NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.175

RESULTS

k_d =	9.055 ft/hr/psf
τ_c =	0.00037001 psf

k_d =	16.012 $cm^3/(N\text{-}s)$
τ_c =	1.772E-02 Pa

SCOUR DEPTH READINGS

TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		**1.063**	0.000
1	**1**	**1.059**	0.004
4	**3**	**1.057**	0.006
8	**4**	**1.031**	0.032
12	**4**	**0.830**	0.233
13	**1**	**0.790**	0.273

HEAD SETTING

TIME (MIN)	HEAD (IN.)
0	**17.50**
1	**17.50**
4	**17.50**
8	**17.50**
12	**17.50**
13	**17.50**

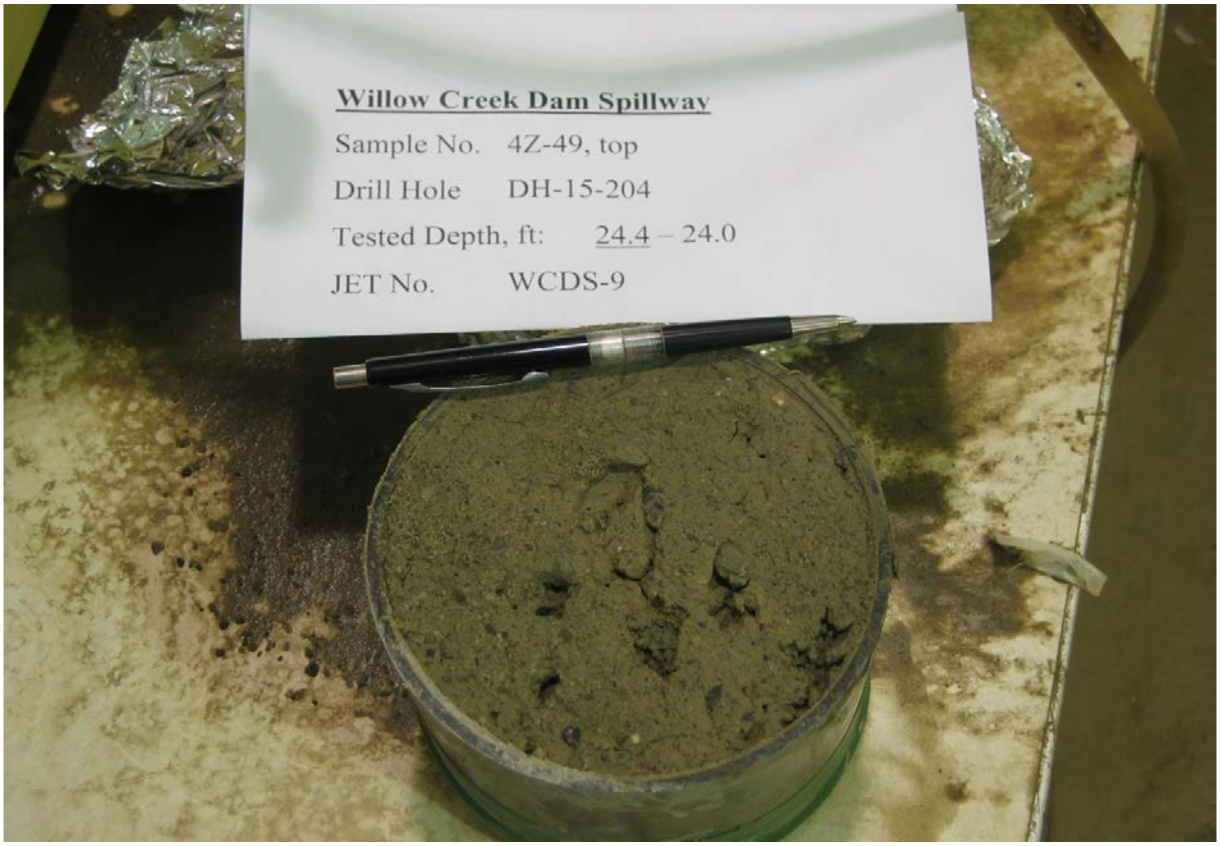
COMMENTS

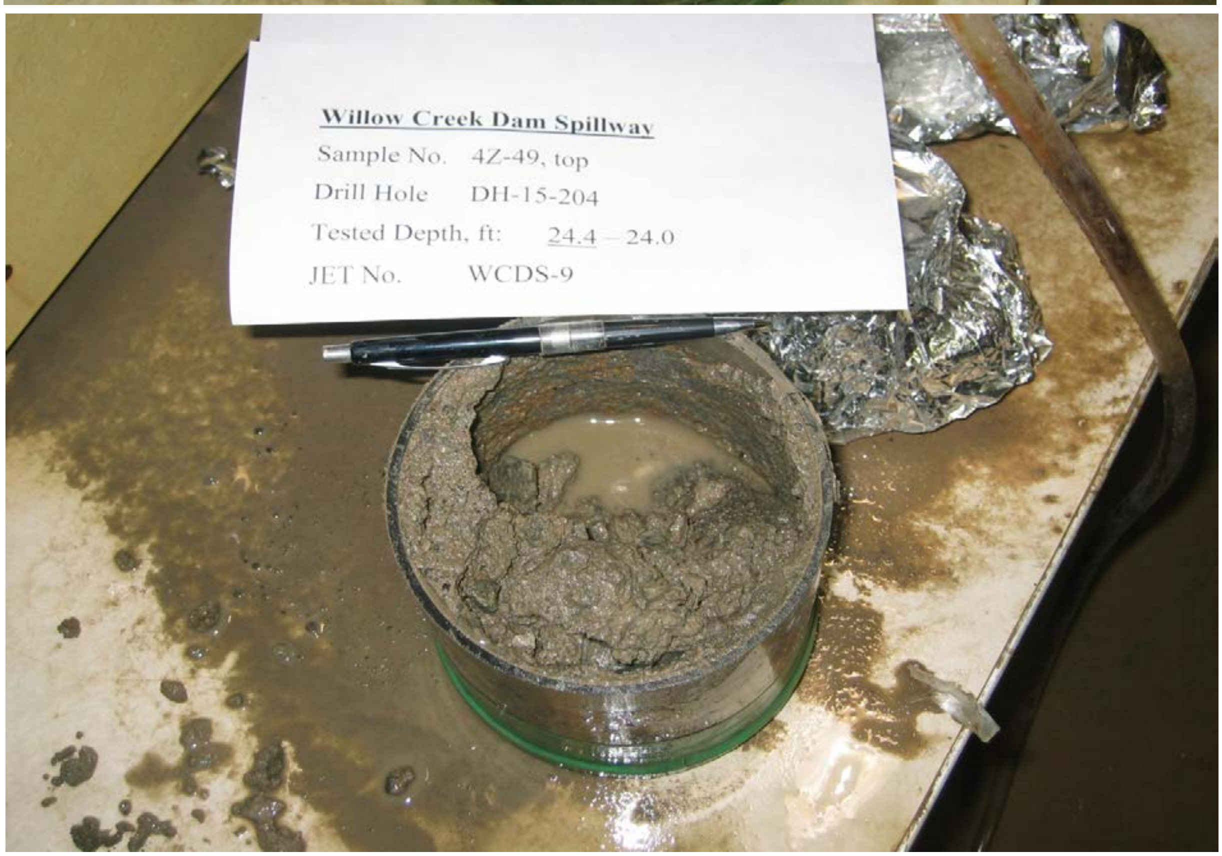
This sample was a glacial till with large amounts of subangular to subrounded gravel, in-filled by silty/clayey cohesive soil. This test was run with the sample tilted up to an angle of 45° to enable loosened gravel particles to be easily flushed out of the scour hole.

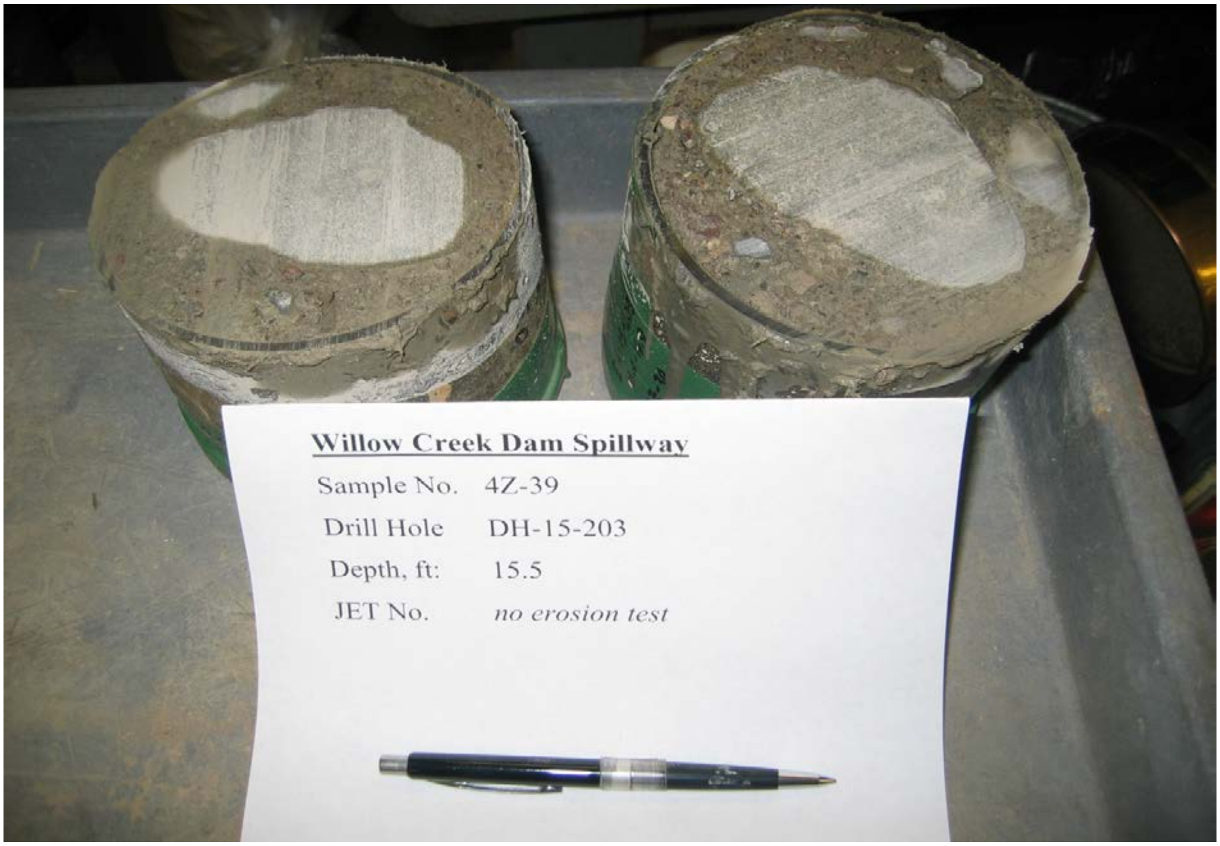
Labeled "A" when sent for subsequent gradation test

D:\Erosion\Willow Creek\Jet Tests\[WCDS-9, 4Z-49A, DH-15-204 24.4-24.0.xlsm]Data

TEST # WCDS-9 **SAMPLE** DH-15-204 25.33'-25.72' (4Z-49A)






Willow Creek Dam Spillway
Sample No. 4Z-39
Drill Hole DH-15-203
Depth, ft: 15.5
JET No. no erosion test