RECLAMATION

Managing Water in the West

Technical Memorandum No. MERL-08-10

Hole Erosion Tests for Wolf Creek Dam

U.S Army Corps of Engineers, Nashville District
Russell County, Kentucky

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Materials Engineering Research Laboratory & Hydraulics Laboratory
Denver, Colorado

May 2008

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Materials Engineering and Research Laboratory, 86-68180

Technical Memorandum No. MERL-08-10

Hole Erosion Tests for Wolf Creek Dam
U.S Army Corps of Engineers, Nashville District
Russell County, Kentucky

Prepared: Tony L. Wahl, P.E., and Zeynep Erdogan — Date: 5/28/08
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68460
Civil Engineer, Materials Engineering and Research Laboratory, 86-68180

Checked: Zeynep Erdogan — Date: 5/28/08
Civil Engineer, Materials Engineering and Research Laboratory, 86-68180

Technical Approval: William F. Kepler, P.E. — Date: 5/28/08
Supervisory Civil Engineer, Materials Engineering and Research Laboratory 86-68180

Peer Review: Jeffrey A. Farrar, P.E. — Date: 5/28/08
Civil Engineer, Geology, Geophysics, and Seismotectonics, 86-68320

REVISIONS					
Date	Description	Prepared	Checked	Approval	Review

Technical Memorandum No. MERL-08-10

Hole Erosion Tests for Wolf Creek Dam
U.S Army Corps of Engineers, Nashville District
Russell County, Kentucky

Contents

Tables

Figures

Introduction

The work described in this report was undertaken by the Bureau of Reclamation's Technical Service Center in Denver, Colorado at the request of the U.S. Army Corps of Engineers, Nashville District, through Military Interdepartmental Purchase Request (MIPR) Number W38XDD73174836. Hole Erosion Tests (HETs) and other related tests were performed on undisturbed samples obtained from drill holes at Wolf Creek Dam, Russell County, Kentucky, to determine threshold shear stresses and erosion rate coefficients applicable to potential internal erosion and piping of the soils. Initial samples, mostly of clayey fill materials, were obtained in 3-inch diameter steel Shelby tubes in October and November 2007 and were transported by Reclamation personnel to the Denver laboratory in late November 2007. Testing of these samples took place from December 2007 through early March 2008. Additional samples of alluvial origin were delivered to the Denver laboratory in January 2008 in 3-inch diameter PVC split tubes, and testing of these samples took place in March and April 2008.

Wolf Creek Dam History

Wolf Creek Dam is located on the Cumberland River in south central Kentucky [1]. It provides hydropower, flood control, water supply, and water quality benefits for the Cumberland River system and surrounding region. Designed and constructed during the period 1938-1952, the 5,736 foot-long dam is a combination rolled earth fill and concrete gravity structure with a maximum height of 258 feet above the foundation level. A power plant with a capacity of 270,000 kW, is located immediately downstream. Lake Cumberland, created by the dam, impounds 6.1 million ac-ft at its maximum pool elevation. It is the largest reservoir east of the Mississippi River and the ninth largest in the United States.

In 1968, muddy flows in the tailrace and two sinkholes near the downstream toe of the embankment signaled serious reservoir seepage problems. Investigations indicated the problems were due to the karst geology of the site characterized by an extensive interconnected network of solution channels in the limestone foundation. Piping of filling materials in these features and collapse of overburden and embankment into the voids caused the problems. The District immediately began an emergency investigation and grouting program between 1968 and 1970 that is generally credited with saving the dam. However, grouting was not a long-term fix and a more permanent solution was sought. After studying numerous alternatives, between 1975 and 1979 the District constructed a concrete diaphragm wall through the earth embankment into the rock foundation to block the seepage.

Since completion of the wall in 1979, key instrumentation readings, persistent and increasing wet areas, and investigative borings that encountered soft, wet material at depth in the embankment confirm that solution features still exist which have not been cut off. While the original wall interrupted the progression of erosion, seepage has since found new paths under and around the wall and perhaps through defects in the wall itself as erosion of solution features continues. Since March 2005 the reservoir has been operated to maintain lake levels within a lower than normal range.

To address the seepage problems, the District has conducted a risk assessment study and evaluated several alternatives to improve the long-term reliability of the dam. The District has recommended a new concrete diaphragm wall constructed with newer technology to reinforce the purpose of the original wall. The initial phase of construction began in March 2006. In concert with this work, an exploration program was initiated to define and better understand foundation conditions of the project, particularly the nature of alluvial materials in the foundation and the infilled solution features. A total of fourteen exploratory holes were drilled, with samples taken from the embankment, the alluvium, and the infilled solution features. Selected Shelby tube samples from these holes were chosen for hole erosion testing. Results from the tests will primarily be used to determine if assumptions used in the risk assessment are conservative or not conservative. The information may also be useful for the contractors constructing the new diaphragm wall.

Conclusions

The first set of 13 Shelby tubes contained a relatively uniform set of Lean Clays (CL). The majority of the samples were very similar, having 10 to 17 percent sand, liquid limits in the range of 37 to 47, plasticity indices ranging from 18 to 28, and specific gravities ranging from 2.65 to 2.70. Exceptions were one Sandy Lean Clay [s(CL)] with 7 percent gravel and 35 percent sand, and one Fat Clay (CH) with liquid limit of 75, plasticity index of 50, and specific gravity of 2.75. Most of the materials exhibited erosion that placed them in I_{HET} group 4 (moderately slow erosion), with a few dropping into group 3 (moderately fast erosion). One tube containing a Lean Clay with Sand [(CL)s] could not be eroded in either of two tests; this tube had both the lowest moisture content and highest Torvane shear test reading of any sample tested. If it could be tested to the point of progressive erosion, this sample would probably be in I_{HET} group 5 (very slow erosion).

The second set of 7 split tubes exhibited greater variability, with one Sandy Silt (ML), one Clayey Sand (SC), three Lean Clays (CL) with varying amounts of sand, and two Fat Clays (CH). Liquid limits varied from 29 to 71, plasticity indices varied from 10 to 46, and specific gravities were generally in the range of

2.61 to 2.78, although one exceptional specimen had a specific gravity of 2.93. These materials also exhibited more varied erodibility, ranging from moderately fast to very slow, with I_{HET} values ranging from about 3.6 to 5.2. One of the fat clays could not be eroded in any of three tests, each conducted with successively larger pre-drilled holes to increase the applied shear stress; this tube and the other fat clay with I_{HET} = 5.2 also had the two highest Torvane shear test readings from this group of tubes.

Weak correlations of the I_{HET} value and critical shear stress to the Torvane shear strength, plasticity index, and liquid limit were observed. The I_{HET} value and the critical shear stress were also correlated with one another.

Background

Hole Erosion Test

The Hole Erosion Test developed by Wan and Fell (2002, 2004) [2, 3] is one of several methods for evaluating the erodibility of cohesive soils. The HET utilizes an internal flow through a pre-drilled hole, similar to that occurring during piping erosion of embankment dams. The test is used to determine the critical shear stress needed to initiate erosion that enlarges the hole progressively (i.e., continuing without end until complete failure of the sample or removal of the driving head) and a coefficient describing the rate of erosion per unit of applied excess stress. An ASTM standard for the test does not yet exist; in its absence, tests were performed and analyzed using methods consistent with those described by Wan and Fell (2004), and improved through ongoing research at the Bureau of Reclamation (see Appendix D). Recently, the Bureau of Reclamation and others have investigated alternative methods for analyzing the data collected during HETs, focusing on a model developed by Bonelli et al. (2006) [4] and Bonelli and Brivois (2007) [5]. The data reported here were analyzed primarily using the Wan and Fell (2004) procedures, although they were also checked for consistency using the Bonelli method when applicable.

The Hole Erosion Test is conducted in a laboratory setting using undisturbed tube samples or soil specimens compacted into standard Proctor molds with a length of 116.4 mm (4–19/32 inches). A 6 mm-diameter hole is pre-drilled through the centerline axis. The hole is cleaned and scarified with a rifle cleaning brush, and the specimen is then installed into a test apparatus in which water flows through the hole under a constant hydraulic gradient that can be increased incrementally until progressive, accelerating erosion is produced. With soils of unknown erodibility, tests are started at 50 mm head and the head is then repeatedly doubled until progressive erosion is observed. When erosion is observed, the test is continued at a constant hydraulic gradient for as long as 45 minutes. As the hole enlarges, the shear stress applied to the interior surface of the hole increases, causing the erosion rate to also increase. Measurements of the accelerating flow rate during the test and the initial and final diameter of the erosion hole can be used to compute the applied hydraulic stresses and erosion rates, from which the erodibility parameters of interest can be determined. A successful interpretation of the data can only be made if the progressive, accelerating erosion phase is reached and maintained for a sufficient length of time to define the slope of the rising erosion rate versus shear stress curve.

HET Erodibility Parameters

HET data are used to determine two parameters of a simple detachment-driven erosion equation describing the growth of the erosion hole:

$$\dot{m} = C_e(\tau - \tau_c)$$

where $\dot{m}$ is the rate of mass removal per unit of surface area (kg/s/m^2), τ and τ_c are the applied shear stress and critical shear stress for soil detachment, respectively, and C_e is a proportionality constant, often called the coefficient of soil erosion. Values of C_e in S.I. units are kg/s/m^2/Pa, which simplifies to seconds per meter (s/m). The coefficient of soil erosion has been found to vary over several orders of magnitude in soils of engineering interest. For convenience, an Erosion Rate Index (I_{HET}) is often computed:

$$I_{HET} = -\log_{10} C_e$$

Typical values of this index range from less than 2 to above 6, with larger values indicating decreasing erosion rate. The fractional part of the index is often dropped and the test result reported as a simple integer “group number”. Soils with group numbers less than 2 are usually so rapidly eroded that they cannot be effectively tested in the HET device. Wan and Fell (2004) tested 13 soils representing a variety of cohesive soils commonly found in embankment dams, and proposed the descriptions shown in Table 1 for soils in each range of I_{HET} values.

Table 1. — Descriptive terms related to the erosion rate index (Wan and Fell 2004).

Group Number	Values of I_{HET}	Description
1	< 2	Extremely rapid
2	2 – 3	Very rapid
3	3 – 4	Moderately rapid
4	4 – 5	Moderately slow
5	5 – 6	Very slow
6	> 6	Extremely slow

It should be emphasized that the value of I_{HET} provides information on only the rate coefficient, which should be indicative of the rate at which an internal erosion failure will progress, *once the threshold for erosion is exceeded*. It does not give information about the critical stress, τ_c, required to initiate a progressive erosion failure. Attempts have been made to correlate the values of C_e and τ_c with one another, but the relationship between them appears to be weak. The 13 soils tested by Wan and Fell (2004) exhibited critical shear stress values ranging from less than 6.4 Pa to greater than 153 Pa (the largest stress that could be produced through a 6 mm hole under their maximum head of 1200 mm). Samples that did not erode at the maximum head were considered to be in I_{HET} group 6.

Recent experience and ongoing research at the Bureau of Reclamation suggests that I_{HET} group 5 is probably the upper limit for soil-like materials. During the course of this project, Reclamation constructed a new HET facility in the hydraulics laboratory where the ceiling height permits testing at heads up to about 5400 mm. Many samples that initially resisted erosion at up to 1600 mm head were found to have I_{HET} values of 4 or 5 when they eroded at heads between 1600 and 5400 mm. In fact, in more than 50 HETs run by Reclamation since 2007 on a wide variety of soils, the highest definitive I_{HET} value obtained has been about 5.2. It has been estimated that a pressure head of about 100 m of water may be needed to initiate erosion of an I_{HET} group 6 material (Wahl et al. 2008) [6].

Analysis of HET Data

Figure 1 shows the time history of a successful hole erosion test. The flow rate and head data can be used to compute flow friction factors and make estimates of the evolution of the hole diameter over the course of the test. The computed hole diameters can then be used in turn to compute applied shear stresses and resulting erosion rates. Figure 2 shows the resulting plot of erosion rate versus applied stress. The slope of the right half of the "V" in Figure 2 indicates the erosion rate coefficient, while the X-intercept of the regression line indicates the critical shear stress. The left half of the "V" illustrates a period of declining erosion rate over time that occurs early in many tests, when the applied shear stress is below the threshold value required to cause progressive erosion. Cleanout of disturbed material from the hole allows some erosion to occur, but until the threshold stress is reached, the rate of erosion decreases with time, even though enlargement of the hole is causing a gradual increase in stress. When the stress exceeds the critical value, the erosion rate will begin to increase and the flow rate will accelerate. A more detailed description of HET data analysis procedures is contained in Appendix D, including the alternative method (Bonelli et al. 2006) which fits the dimensionless discharge (Q/Q_0 where Q_0 is the starting flow rate) to a theoretical model describing the exponential growth of dimensionless discharge as a function of time. Determination of the time constant for the model allows one to compute the coefficient of soil erosion.

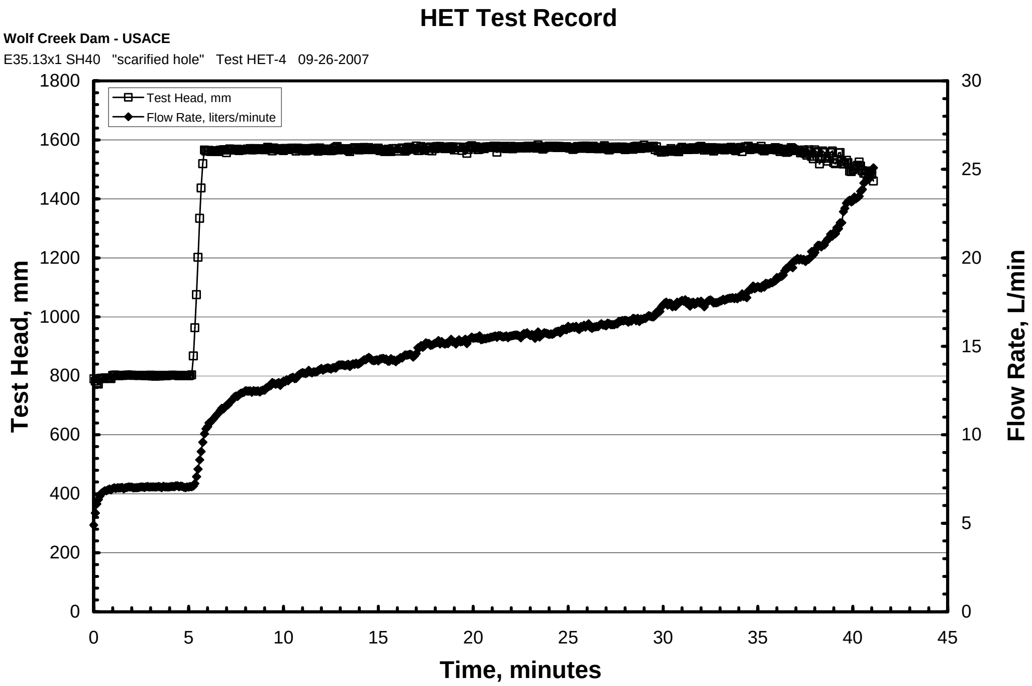


Figure 1. — Typical time-history of a Hole Erosion Test.

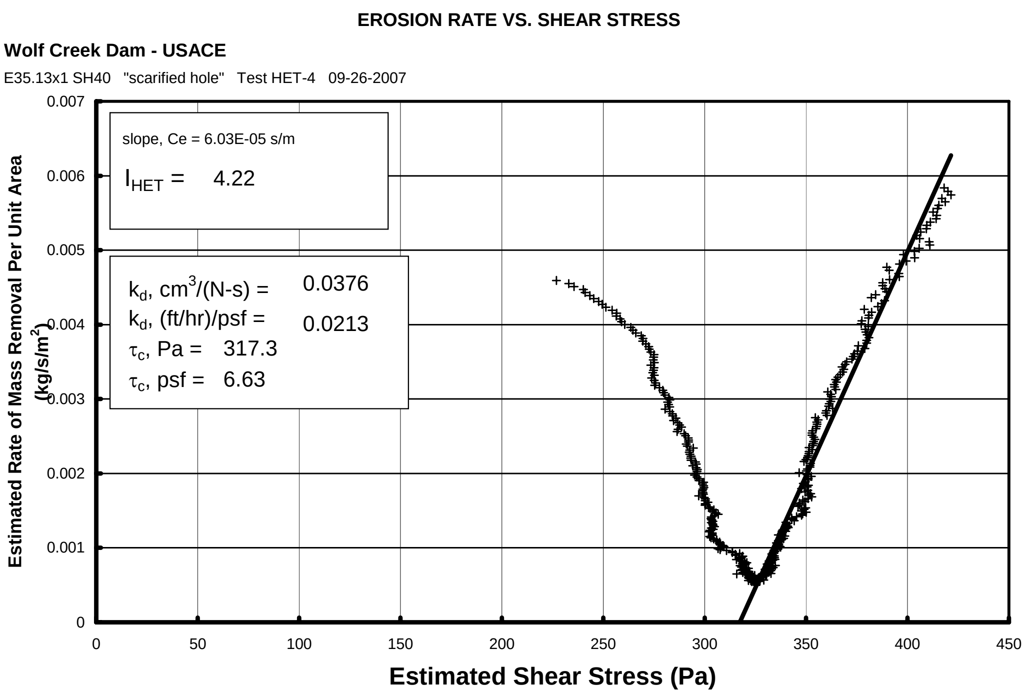


Figure 2. — Computed erosion rates versus applied shear stress during a Hole Erosion Test.

Testing Program

Sample Handling

Thirteen 3-inch o.d. steel Shelby tubes were transported from Wolf Creek Dam in Kentucky to Reclamation's laboratories in Denver, Colorado by automobile, arriving November 30, 2007. Samples were protected from excessive vibration and freezing during transport and were immediately stored in Reclamation's 75% humidity room upon arrival.

Individual samples were cut using a water-cooled chop saw from the approximate middle of each 2-ft long tube to produce 4.5-inch long samples for HET testing. Sample orientation was preserved so that all samples were tested in the HET with the top of each sample located upstream. Material was collected from the exposed faces of the remainder of the cut tubes for determination of basic physical properties including initial moisture content, and Torvane shear measurements were also made immediately after cutting. Torvane shear measurements were generally made from the surface remaining after cutting; in a few cases a fresh surface was prepared when the cut face appeared to have been significantly disturbed. Additional HET samples were then cut from remaining tube sections when possible and were stored in double Ziplock bags in the 75% humidity room to prevent moisture loss until tests could be conducted. In general, tubes were cut open in groups of one to three at a time and the majority of testing was conducted on each opened tube before new tubes were opened. In-place density of the HET samples was determined from measurements of the sample dimensions and the initial test specimen mass.

Seven 3-inch i.d. PVC split tubes were received in Denver on January 31, 2008. These samples had been wrapped in foil inside of the tubes and waxed on the tube ends. To prepare them for testing, each tube was installed into a 4-inch i.d. PVC pipe sleeve, and the annulus between the 3-inch split tube and 4-inch non-split tube was filled with wax. Specimens were then cut from the tubes in the same manner described above. A new set of adapter plates was constructed to allow installation of the 4-inch PVC pipe sections into the HET device. The adapter included provision for installation of end plates upstream and downstream from the samples. These are often used with highly erodible soils to prevent excessive scour erosion at the entrance and exit of the pre-drilled hole, but a downstream end plate was necessary with these specimens to prevent them from simply sliding out of the split tube due to hydrostatic forces, since the foil wrapper slipped easily inside of the PVC tubes.

Physical Properties

Basic physical properties of the samples were determined from the tube ends exposed during the cutting of HET samples. Parameters determined included the following:

- particle size distribution
- USCS classification (laboratory method)
- moisture content
- Atterberg limits
- specific gravity

HET test specimens were also weighed and measured before testing to allow computation of the wet and dry density of each specimen.

The following laboratory tests and standards [7] were used, which are generally in accord with ASTM procedures:

- Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) ASTM D2487
- Specific Gravity of Soils (USBR 5320, Method A)
- Gradation Analysis of Gravel Size Fraction of Soils (USBR 5325)
- Gradation Analysis of Fines and Sand Size Fraction of Soils, Including Hydrometer Analysis (USBR 5330)
- Liquid Limit of Soils by the Three-Point Method (USBR 5355)
- Plastic Limit and Plasticity Index of Soils (USBR 5360)
- Hole erosion test (HET), an on-going internal erosion research project. Details of HET procedures are given in Appendix D.

Torvane Shear

Torvane shear measurements were made on the exposed faces of the ends of tubes remaining after HET specimens were cut. The use of the water-cooled band saw seemed to leave a cut face that was suitable for this testing in most cases. On a few occasions a new surface was exposed before testing. The average of four measurements was computed. It was difficult at times to perform the tests due to the relatively dry condition of some of the soils, which caused a rapid failure that was difficult to control. The standard 1-inch diameter vane was used when possible, but when soil strength required it, the smaller vane was used, for which a 2.5 multiplier is applied to the raw instrument reading. It was our perception that the smaller vane generally produced significantly higher strength values, after application of the multiplier.

Hole Erosion Testing

Figure 3 shows the standard and high-head HET test facilities in the Bureau of Reclamation laboratory in Denver, Colorado. Flow rate through the specimen is measured by a custom 10° V-notch weir calibrated in place. Measurements of differential head across the specimen and head on the weir are recorded by a computerized data acquisition system that records data at 5 second intervals throughout a test. The maximum test head using the facility in Fig. 3(a) is about 1600 mm, limited by laboratory ceiling height and flow capability. The maximum head used by Wan and Fell (2004) was 1200 mm. During the course of the testing program, the high-head HET facility was constructed, allowing testing at heads up to 5400 mm.

(a) (b)

Figure 3. — The standard HET apparatus in the soils laboratory (a) is limited to about 1600 mm net head, while the new high-head facility (b) can produce a maximum head of about 5400 mm..

Samples were removed from high humidity storage immediately before testing. Initial mass was recorded, then the standard 6-mm (1/4-inch) diameter hole was drilled using a drill press and fluted wood auger bit. Drilling was performed as carefully as possible to minimize disturbance of the sample. Following drilling, the hole was carefully cleaned and scarified using a 0.22-in. diameter brush, the mass was recorded, and the sample was then installed into the HET apparatus. Testing then proceeded as described previously and in Appendix D, with the test head initially set to 50 mm, or to a higher starting value once some experience was gained with the soils. The test head was generally doubled until progressive erosion was observed.

The first seven tests were performed using the standard facility, limited to 1600 mm of head. Most of these initial samples exhibited little or no erosion, even at the maximum head available in the standard facility. In some cases minor erosion did occur, and flow rates increased slowly but did not actually accelerate within a reasonable testing period (more than 5 hours in one case). Such behavior is caused by the erosion of weaker material disturbed during the hole-drilling operation. When the flow does not accelerate, it indicates that the stress is not high enough to erode the stronger, undisturbed material. When progressive erosion cannot be produced, typical practice has been to characterize such soils as being in I_{HET} group 6, with a critical shear stress that is unknown, but greater than the maximum stress applied. Of the first seven tests, only HET-4 successfully produced progressive erosion. In one test (HET-5), we even tried starting the test with a larger (9.5 mm) pre-drilled hole to increase the applied stress.

After the high-head HET facility was put into operation we were able to produce progressive erosion of almost all tested samples. Although several samples required 3200 mm or more of head to produce progressive erosion, all were found to be in I_{HET} group 5 or lower, and the highest I_{HET} value obtained was about 5.2. No samples demonstrated an erosion rate slow enough to definitely qualify for group 6, although a handful of samples did not erode even at the maximum possible test head, nor when tested with a larger pre-drilled hole. Ongoing research [5] suggests that a pressure head as high as 100 m might be needed to initiate progressive erosion of a true I_{HET} group 6 material. Such a material is likely to be a lithified or cemented material rather than a soil.

Results

Table 2 provides a summary of the physical properties of the specimens, Torvane shear strength test results, and HET results. Details of individual hole erosion tests including test narratives are given in Appendix B.

The first set of 13 Shelby tubes contained a relatively uniform set of Lean Clays (CL), most having 10 to 17 percent sand, liquid limits in the range of 37 to 47, plasticity indices ranging from 18 to 28, and specific gravities ranging from 2.65 to 2.70. A few of the tubes contained soils with more than 15 percent coarse-grained material, causing them to be classified as Lean Clay with Sand [(CL)s] or as Sandy Lean Clay [s(CL)]. The greatest deviations from the "average" soil were one Sandy Lean Clay [s(CL)] with 7 percent gravel, 35 percent sand, LL=28, PI=15, and one Fat Clay (CH), LL=75, PI=50, and specific gravity of 2.75. Most of the materials exhibited erosion that placed them in I_{HET} group 4 (moderately slow erosion), with a few dropping into group 3 (moderately fast erosion). One tube containing a Lean Clay with Sand [(CL)s] could not be eroded in either of two tests; this tube had both the lowest moisture content and highest Torvane shear test reading of any sample tested.

The second set of 7 PVC split tubes exhibited greater material variability, with one Sandy Silt (ML), one Clayey Sand (SC), three Lean Clays (CL) with varying amounts of sand, and two Fat Clays (CH). Liquid limits varied from 29 to 71, plasticity indices varied from 10 to 46, and specific gravities were generally in the range of 2.61 to 2.78, with one specimen having an unusually high specific gravity of 2.93. These materials also exhibited more varied erodibility, ranging from moderately fast to very slow (I_{HET} values ranging from about 3.6 to 5.2). One of the fat clays could not be eroded in any of three tests, each conducted with successively larger pre-drilled holes to increase the applied shear stress; this tube and the other fat clay in this set (I_{HET} = 5.2) also had the two highest Torvane shear test readings from this group of tubes. The materials that could not be eroded in these tests should also be classified in I_{HET} group 5 with I_{HET} values likely to be slightly above 5.2. Based on the tests reported here, ongoing research at the Bureau of Reclamation, and a review of the work of other investigators studying and measuring soil erodibility with a variety of devices [8], it seems likely that I_{HET} group 6 consists solely of rock-like (lithified or cemented) materials.

The I_{HET} value and critical shear stress were observed to be weakly related to the Torvane shear strength, plasticity index, and liquid limit. The I_{HET} value and the critical shear stress were correlated to one another, as expected, although there is significant scatter around the best-fit line. Figures 4, 5, 6, and 7 show the HET results graphically. Figure 8 shows the results ranked in order of decreasing erosion rate or increasing value of I_{HET}.

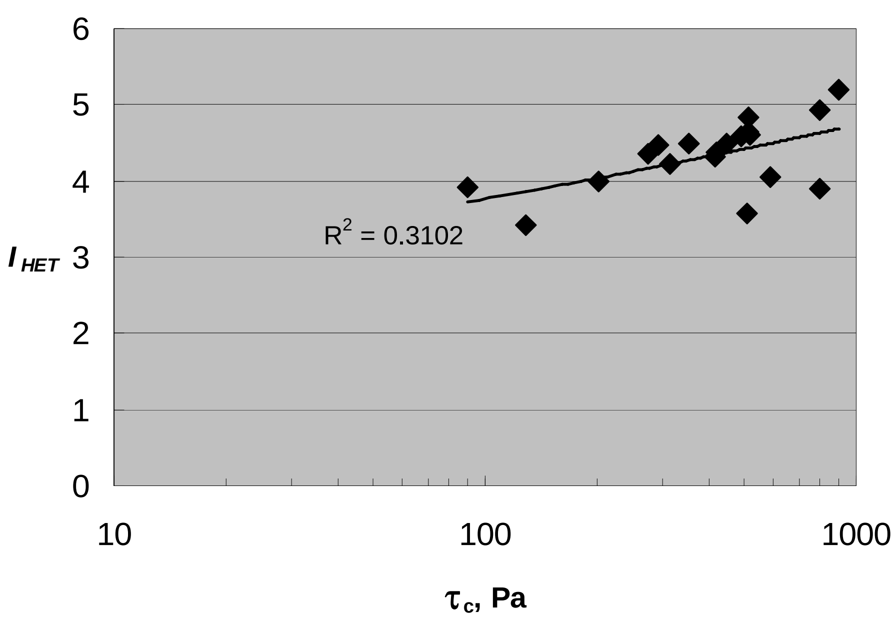


Figure 4. — Erosion rate index values and critical shear stresses.

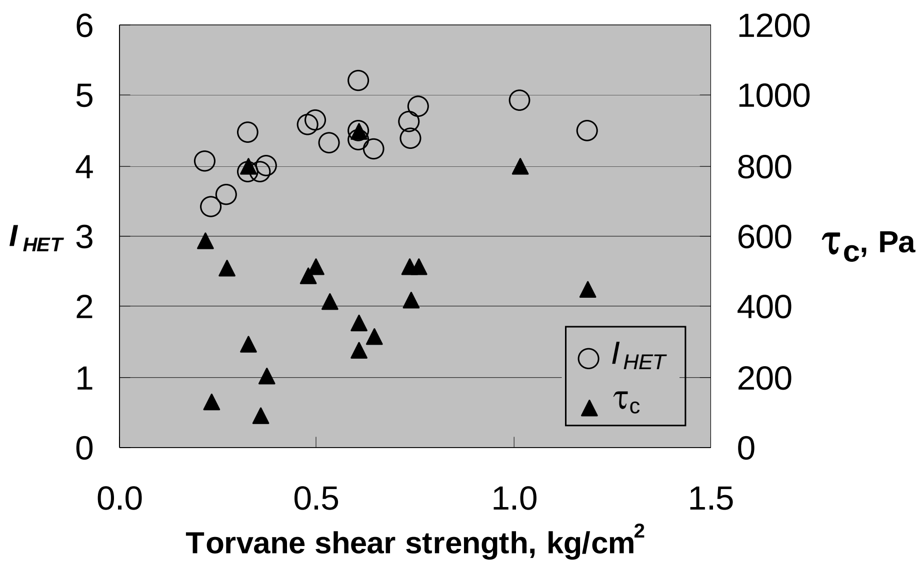


Figure 5. — Erosion rate index values and critical shear stresses versus measured value of Torvane shear strength.

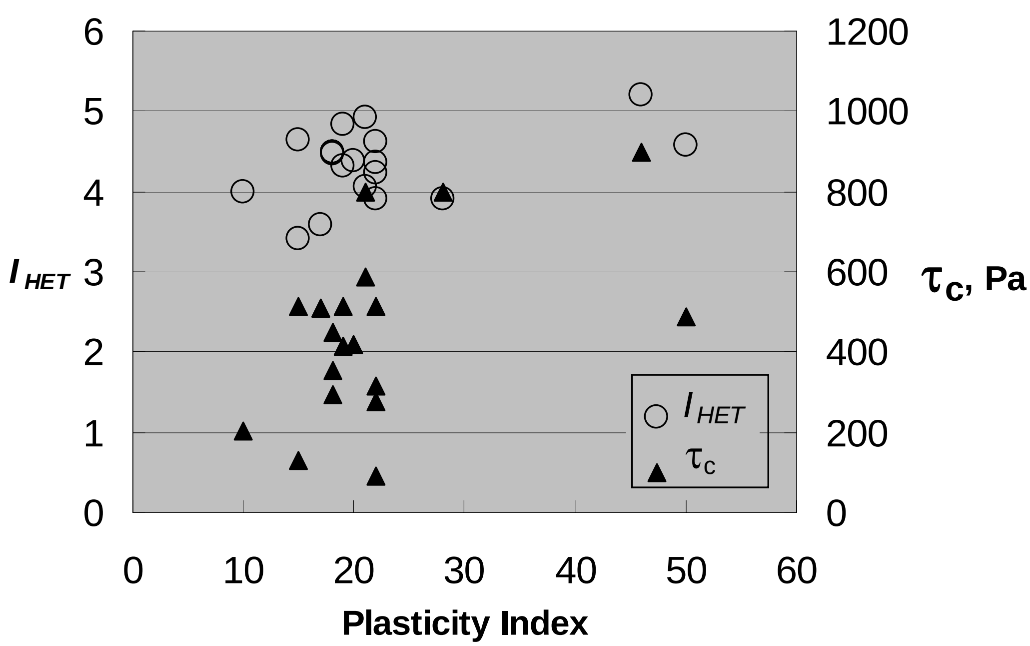


Figure 6. — Erosion rate index values and critical shear stresses versus plasticity index.

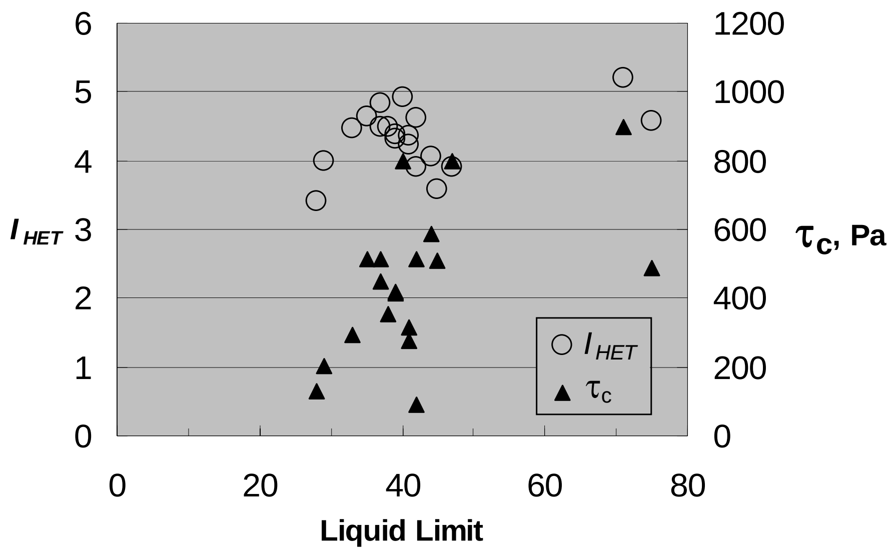


Figure 7. — Erosion rate index values and critical shear stresses versus the liquid limit.

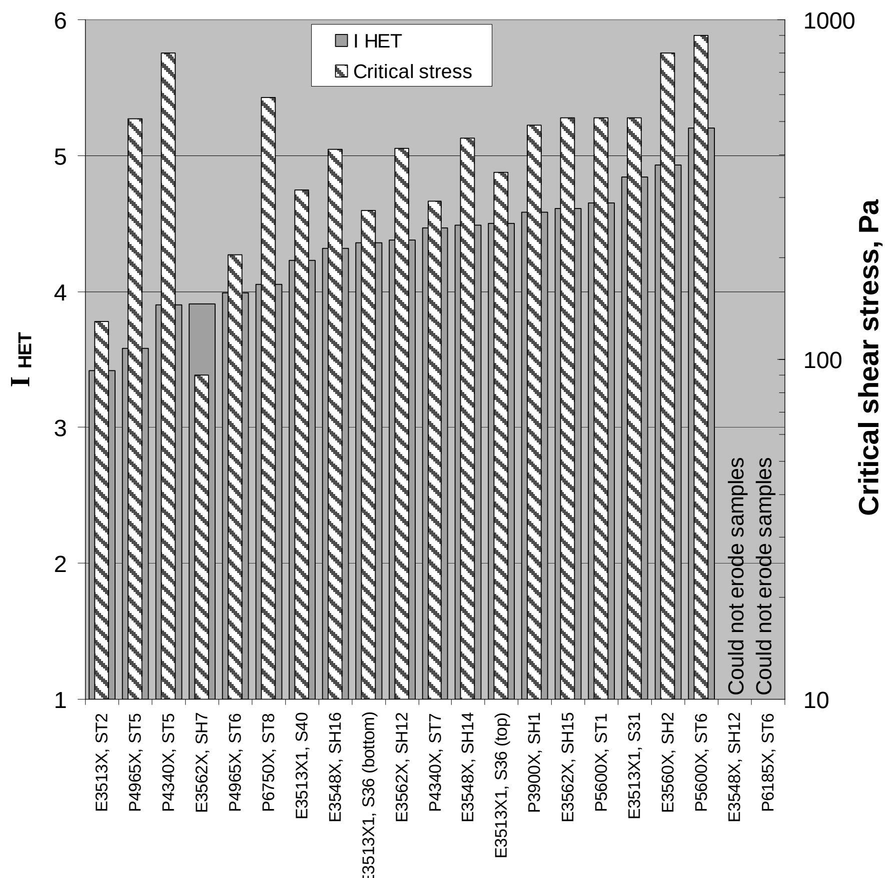


Figure 8. — Erosion rate index values and critical shear stresses ranked in order of decreasing erosion rate (increasing value of I_{HET}).

Table 2. — Summary of physical properties of tube specimens, Torvane shear strength test results, and hole erosion test results.

Sample No	Depth Interval	Initial Moisture Content	Avg. Dry Density	USCS Classification	Gravel	Sand	Silt	Clay	Liquid Limit LL	Plasticity Index PI	Specific Gravity	Torvane Shear Strength	HET Results I_{HET}	HET Results τ_c
					> 4.76 mm	0.075-4.76 mm	0.005-0.075 mm	< 0.005 mm						
	ft	%	lbf/ft^3		%	%	%	%	%	%		kg/cm^2		Pa
3-inch diameter Shelby tubes														
E3562X, SH15	211-213	23.2	98.3	Lean Clay - CL	0.0	11	48	41	42	22	2.70	0.74	4.61	515
E3513X1, S40	222-224	23.4	100.5	Lean Clay - CL	0.0	13	50	37	41	22	2.69	0.65	4.23	316
E3548X, SH16	221-223	23.1	102.8	Lean Clay - CL	0.0	14	50	36	39	19	2.70	0.54	4.32	416
P3900X, SH1	163.5-165.5	37.0	84.9	Fat Clay - CH	0.0	7.6	45	47	75	50	2.75	0.48	4.58	488
E3548X, SH12	211-213	20.7	102.2	Lean Clay with Sand - (CL)s	0.1	15	52	33	40	19	2.67	1.73	could not erode	> 900
E3513X, ST2	194 - 196	29.3	93.8	Sandy Lean Clay - s(CL)	7.3	35	36	22	28	15	2.65	0.23	3.42	129
E3513X1, S31	204 - 206	23.9	102.8	Lean Clay - CL	0.3	10	48	42	37	19	2.68	0.76	4.84	514
E3513X1, S36	214 (Top)	25.0	98.2	Lean Clay - CL	0.2	7.7	49	43	38	18	2.65	0.61	4.50	355
	216 (Bottom)	23.8	105.4	Lean Clay - CL	0.0	13	48	39	41	22	2.70	0.61	4.36	275
E3548X, SH14	217 - 219	21.6	101.7	Lean Clay with Sand - (CL)s	0.3	17	50	33	37	18	2.69	1.19	4.49	449
E3560X, SH2	209 - 211	22.1	104.5	Lean Clay - CL	0.2	12	47	40	40	21	2.68	1.02	4.93	799
E3562X, SH12	205 - 207	23.2	98.9	Lean Clay - CL	0.0	13	46	41	39	20	2.67	0.74	4.38	419
E3562X, SH7	195 - 197	34.6	84.2	Lean Clay - CL	0.0	13	47	40	42	22	2.69	0.36	3.91	90
P4340X, ST5	138.5 - 140.5	27.0	97.1	Lean Clay - CL	0.0	13	47	40	47	28	2.68	0.33	3.90	800
3-inch diameter split tubes														
P4340X, ST7	145.8-146.6	21.7	105.1	Lean Clay with Sand - (CL)s	0.0	20	53	27	33	18	2.61	0.33	4.47	292
P4965X, ST5	137.2-138.0	30.2	92.0	Sandy Silt - ML	0.0	42	40	18	45	17	2.93	0.27	3.58	510
P4965X, ST6	141.0-142.0	22.8	100.6	Lean Clay with Sand - (CL)s	0.0	29	46	25	29	10	2.67	0.37	3.99	203
P5600X, ST1	100.5-101.5	17.2	106.9	Clayey Sand - SC	1.5	52	23	24	35	15	2.69	0.50	4.65	513
P5600X, ST6	110.2-110.9	32.2	84.7	Fat Clay - CH	0.0	1.1	52	47	71	46	2.78	0.61	5.20	900
P6185X, ST6	100.2-101.1	31.4	89.6	Fat Clay - CH	0.0	2.3	49	49	57	32	2.73	0.59	could not erode	> 1600
P6750X, ST8	87.2-88.3	25.5	93.2	Sandy Lean Clay - s(CL)	14	27	35	24	44	21	2.71	0.22	4.05	589

References

[1] http://www.lrn.usace.army.mil/WolfCreek/seepage.htm

[2] Wan, C.F., and Fell, R., 2004. Investigation of rate of erosion of soils in embankment dams. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 4, pp. 373-380.

[3] Wan, C.F., and Fell, R., 2002. *Investigation of internal erosion and piping of soils in embankment dams by the slot erosion test and the hole erosion test*, UNICIV Report No. R-412, The University of New South Wales, Sydney, Australia.

[4] Bonelli, S., Brivois, O., Borghi, R., and Benahmed, N., 2006. On the modelling of piping erosion. *Comptes Rendus Mecanique* 334, Elsevier SAS, pp. 555-559.

[5] Bonelli, S., and Brivois, O., 2007. The scaling law in the hole erosion test with a constant pressure drop. *International Journal for Numerical and Analytical Methods in Geomechanics*, Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/nag.683.

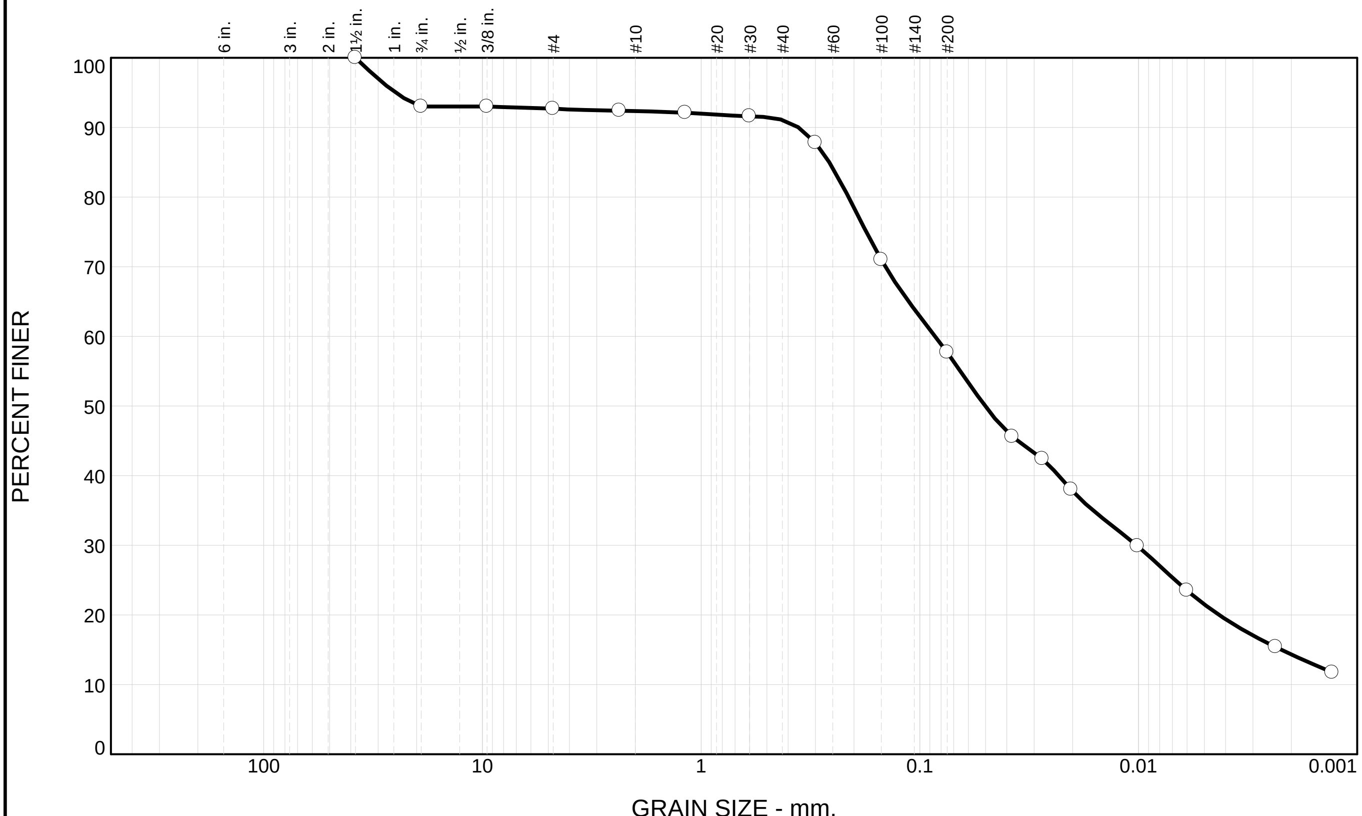
[6] Wahl, T.L., Regazzoni, P.-L., and Erdogan, Z., 2008. Determining erosion indices of cohesive soils with the hole erosion test and jet erosion test. U.S. Dept. of the Interior, Bureau of Reclamation, Dam Safety Office Research Report, in press.

[7] Earth Manual, Part 2, 3rd Edition, U.S. Department of the Interior, Bureau of Reclamation, Denver, CO, 1990.

[8] Briaud, Jean-Louis, 2008. Case histories in soil and rock erosion. 9th Ralph B. Peck Lecture. *Journal of Geotechnical and Geoenvironmental Engineering*, in press.

Appendix A: Physical Properties Test Reports

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	7.0	0.3	0.3	1.3	33.4	36.2	21.5

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
1.5	100.0		
.75	93.0		
.375	93.0		
#4	92.7		
#8	92.4		
#16	92.1		
#30	91.6		
#50	87.8		
#100	71.0		
#200	57.7		

* (no specification provided)

Material Description

Sandy lean clay

Atterberg Limits

PL= 15 LL= 28 PI= 13

Coefficients

D_{85}= 0.2595 D_{60}= 0.0851 D_{50}= 0.0503
D_{30}= 0.0102 D_{15}= 0.0022 D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-6(5)

Remarks

Initial Moisture Content=29.3%
Specific Gravity=2.65

Sample Number: E3513x, ST2 **Depth:** 195.5-195.75 ft
Location: Sta 35+13 **Date:** 03/17/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam

Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+13
Depth: 195.5-195.75 ft **Sample Number:** E3513x, ST2
Material Description: Sandy lean clay
Date: 03/17/2008 **PL:** 15 **LL:** 28 **PI:** 13
USCS Classification: CL **AASHTO Classification:** A-6(5)
Testing Remarks: Initial Moisture Content=29.3%
Specific Gravity=2.65

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	100.0
.75	93.0
.375	93.0
#4	92.7
#8	92.4
#16	92.1
#30	91.6
#50	87.8
#100	71.0
#200	57.7

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 92.7
Weight of hydrometer sample =92.7
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.0
Specific gravity of solids = 2.65
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	21.1	51.4	45.6	0.0135	51.4	7.9	0.0378	45.6
2.00	21.2	48.2	42.4	0.0134	48.2	8.4	0.0275	42.4
4.00	21.1	43.8	38.0	0.0135	43.8	9.1	0.0203	38.0
19.00	20.1	35.9	29.9	0.0136	35.9	10.4	0.0101	29.9
60.00	19.3	29.7	23.5	0.0138	29.7	11.4	0.0060	23.5
435.00	19.2	21.6	15.4	0.0138	21.6	12.8	0.0024	15.4
1545.00	18.0	18.2	11.7	0.0140	18.2	13.3	0.0013	11.7

Fractional Components

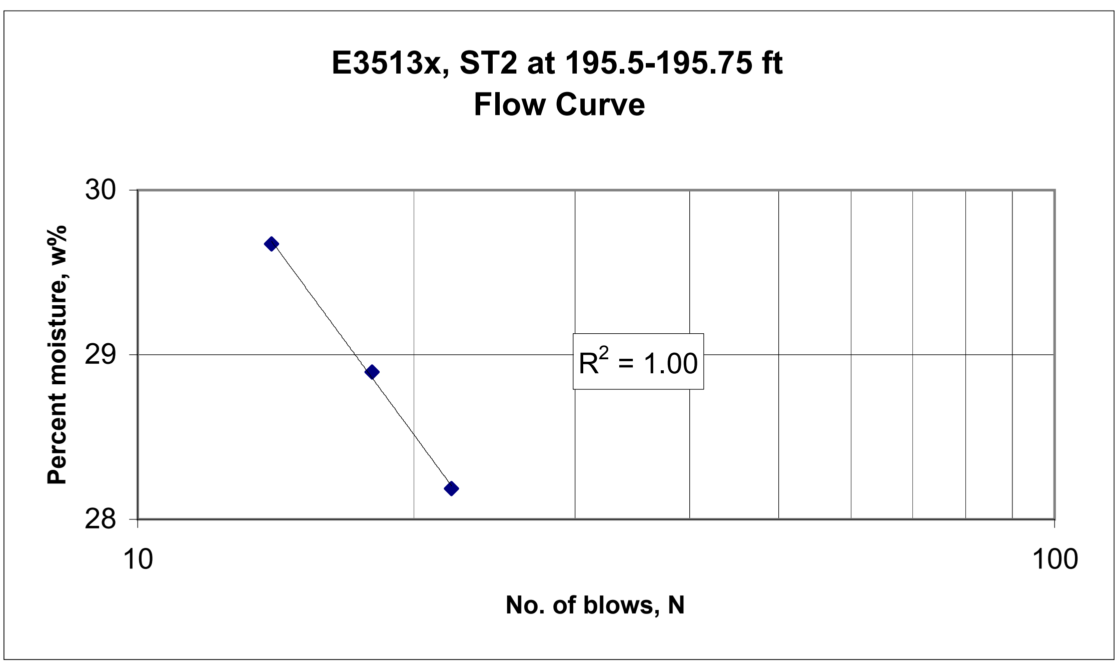
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	7.0	0.3	7.3	0.3	1.3	33.4	35.0	36.2	21.5	57.7

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
	0.0022	0.0043	0.0102	0.0503	0.0851	0.2117	0.2595	0.3583	24.9537

Fineness Modulus
0.86

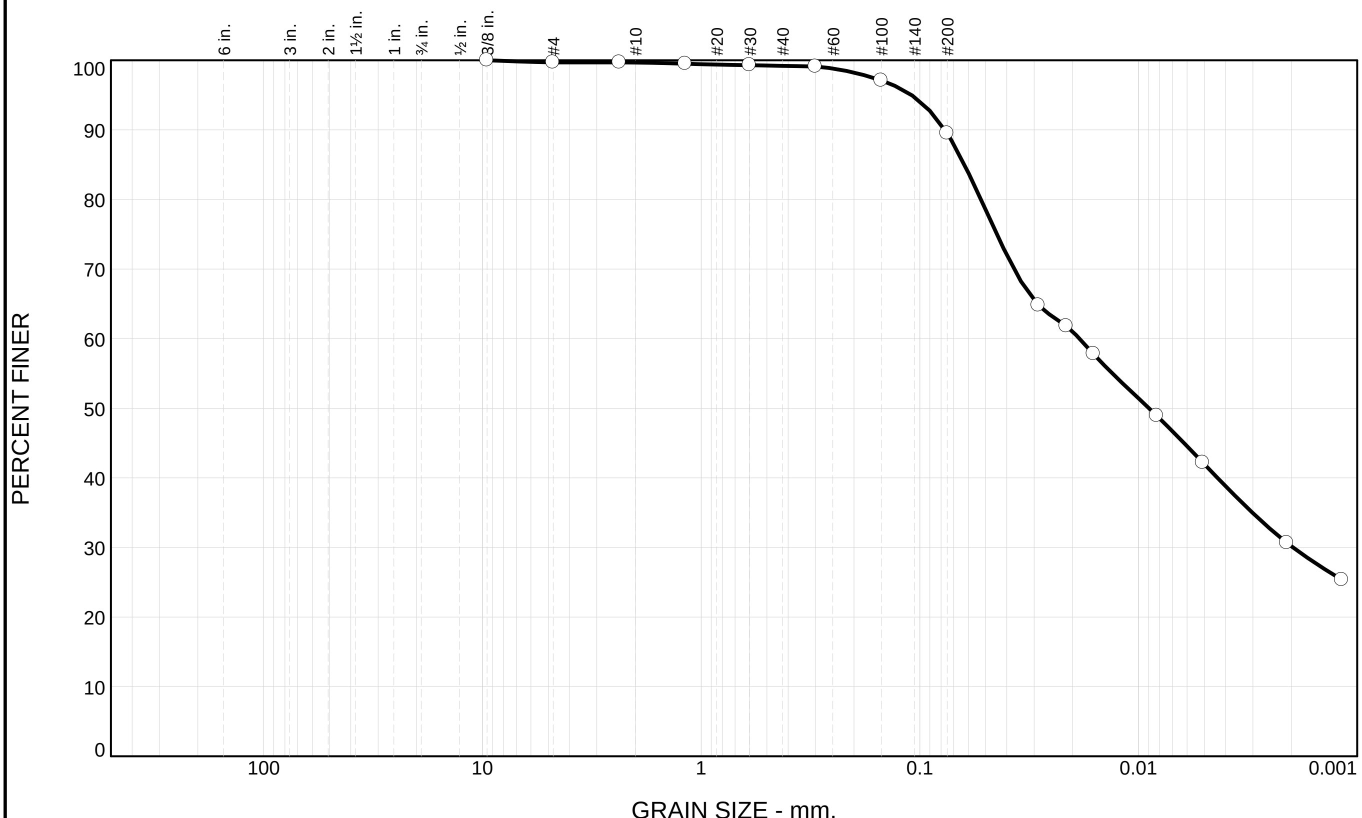
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	E3513x, ST2 at 195.5-195.75 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	3/17/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	108	S-41	S-20	S-29	S-26
No. of blows	N/A	N/A	22	18	14
Mass of dish+wet soil (g)	14.944	18.559	23.229	22.741	24.332
Mass of dish+dry soil (g)	13.822	17.113	19.917	19.498	20.974
Mass of dish (g)	6.333	7.614	8.166	8.274	9.658
Mass of water (g)	1.122	1.446	3.312	3.243	3.358
Mass of dry soil (g)	7.489	9.499	11.751	11.224	11.316
% moisture	15.0	15.2	28.2	28.9	29.7
Average plastic limit	15				

LL = 28 **PL = 15** **PI = 13** **Fi = -7.6**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.3	0.0	0.5	9.7	47.5	42.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.375	100.0		
#4	99.7		
#8	99.7		
#16	99.5		
#30	99.3		
#50	99.1		
#100	97.1		
#200	89.5		

* (no specification provided)

Material Description

Lean clay

Atterberg Limits

PL= 18 LL= 37 PI= 19

Coefficients

D_{85}= 0.0625 D_{60}= 0.0186 D_{50}= 0.0090
D_{30}= 0.0020 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-6(17)

Remarks

Initial Moisture Content=23.9%
Specific Gravity=2.68

Sample Number: E3513x1, S31 **Depth:** 204.2-206.0 ft
Location: Sta 35+13 **Date:** 03/17/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+13
Depth: 204.2-206.0 ft
Sample Number: E3513x1, S31
Material Description: Lean clay
Date: 03/17/2008 **PL:** 18 **LL:** 37 **PI:** 19
USCS Classification: CL **AASHTO Classification:** A-6(17)
Testing Remarks: Initial Moisture Content=23.9%
Specific Gravity=2.68

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	100.0
#4	99.7
#8	99.7
#16	99.5
#30	99.3
#50	99.1
#100	97.1
#200	89.5

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 99.7
Weight of hydrometer sample =99.7
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.0
Specific gravity of solids = 2.68
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	21.3	71.0	65.2	0.0133	71.0	4.7	0.0287	64.8
2.00	21.2	68.0	62.2	0.0133	68.0	5.1	0.0214	61.8
4.00	21.1	64.0	58.2	0.0133	64.0	5.8	0.0161	57.8
19.42	20.0	55.3	49.3	0.0135	55.3	7.2	0.0082	48.9
60.00	19.2	48.7	42.5	0.0137	48.7	8.3	0.0051	42.2
435.00	19.1	37.1	30.9	0.0137	37.1	10.2	0.0021	30.7
1545.00	17.9	32.0	25.5	0.0139	32.0	11.0	0.0012	25.4

Fractional Components

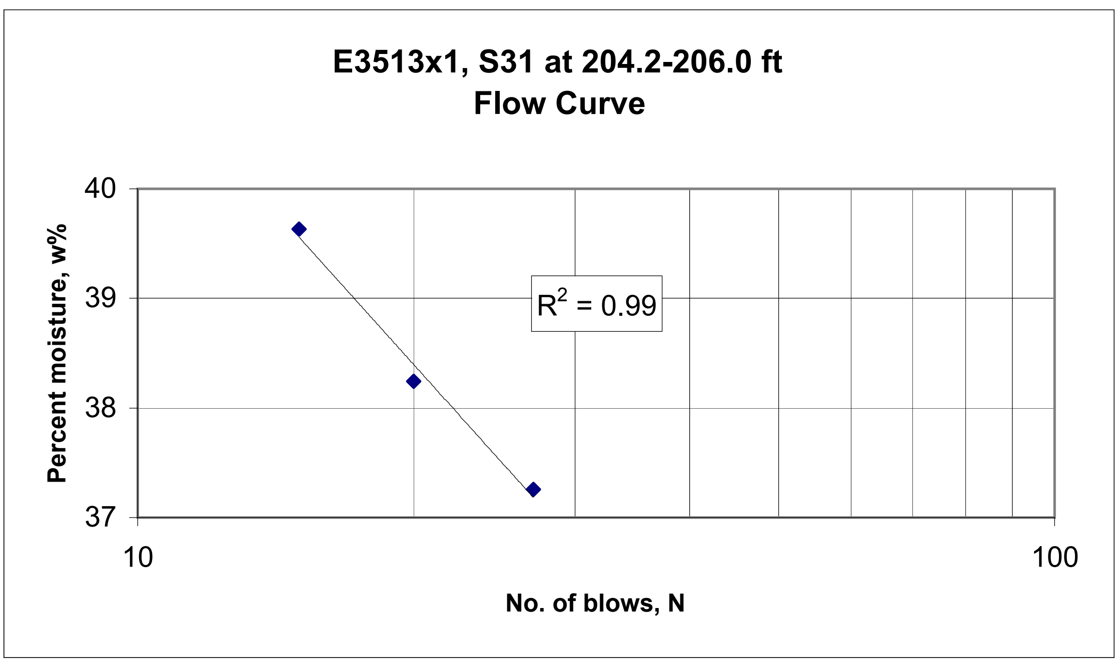
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.3	0.3	0.0	0.5	9.7	10.2	47.5	42.0	89.5

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0020	0.0090	0.0186	0.0526	0.0625	0.0768	0.1089

Fineness Modulus
0.06

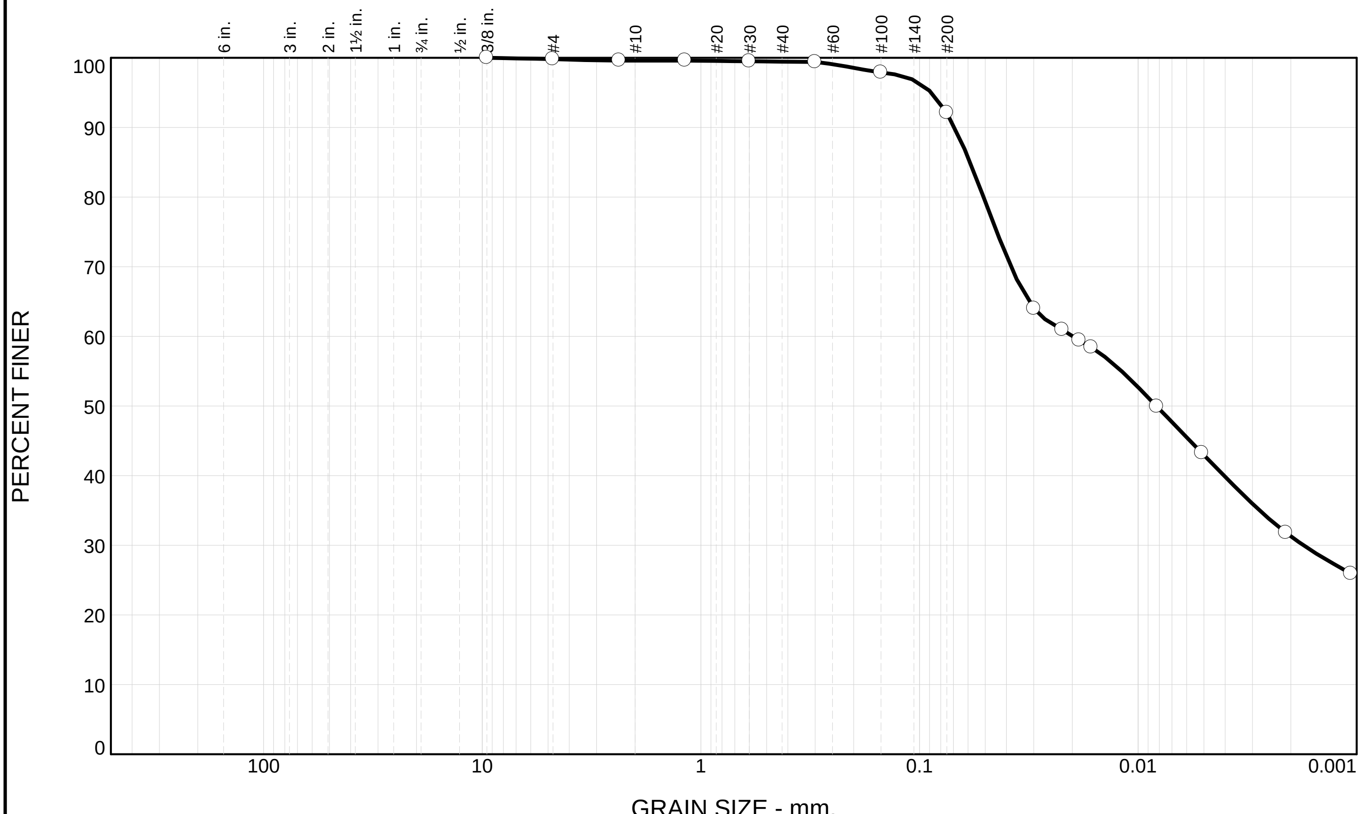
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	E3513x1, S31 at 204.2-206.0 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	3/17/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	133	S-56	99	S-68	87
No. of blows	N/A	N/A	27	20	15
Mass of dish+wet soil (g)	14.099	14.205	21.841	24.900	20.300
Mass of dish+dry soil (g)	12.972	13.209	17.616	20.312	16.312
Mass of dish (g)	6.742	7.674	6.276	8.316	6.250
Mass of water (g)	1.127	0.996	4.225	4.588	3.988
Mass of dry soil (g)	6.230	5.535	11.340	11.996	10.062
% moisture	18.1	18.0	37.3	38.2	39.6
Average plastic limit	18				

LL = 37 **PL = 18** **PI = 19** **Fi = -9.3**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.2	0.2	0.2	7.3	49.1	43.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.375	100.0		
#4	99.8		
#8	99.6		
#16	99.6		
#30	99.5		
#50	99.4		
#100	97.9		
#200	92.1		

* (no specification provided)

Material Description

Lean clay

Atterberg Limits

PL= 20 LL= 38 PI= 18

Coefficients

D_{85}= 0.0587 D_{60}= 0.0199 D_{50}= 0.0082
D_{30}= 0.0018 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-6(17)

Remarks

Initial Moisture Content=25.0%
Specific Gravity=2.65

Sample Number: E3513x1, S36 **Depth:** 214.6 ft (Top)
Location: Sta 35+13 **Date:** 03/12/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/6/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+13
Depth: 214.6 ft (Top) **Sample Number:** E3513x1, S36
Material Description: Lean clay
Date: 03/12/2008 **PL:** 20 **LL:** 38 **PI:** 18
USCS Classification: CL **AASHTO Classification:** A-6(17)
Testing Remarks: Initial Moisture Content=25.0%
Specific Gravity=2.65

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	100.0
#4	99.8
#8	99.6
#16	99.6
#30	99.5
#50	99.4
#100	97.9
#200	92.1

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 99.8
Weight of hydrometer sample =99.8
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.0
Specific gravity of solids = 2.65
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	20.1	70.0	64.0	0.0136	70.0	4.8	0.0299	64.0
2.00	20.0	67.0	61.0	0.0136	67.0	5.3	0.0222	61.0
3.00	19.9	65.5	59.4	0.0137	65.5	5.6	0.0186	59.4
4.00	19.8	64.5	58.4	0.0137	64.5	5.7	0.0164	58.4
20.00	19.3	56.1	49.9	0.0138	56.1	7.1	0.0082	49.9
60.00	19.0	49.5	43.3	0.0138	49.5	8.2	0.0051	43.3
435.00	18.8	38.1	31.8	0.0139	38.1	10.0	0.0021	31.8
1890.00	18.4	32.3	25.9	0.0139	32.3	11.0	0.0011	25.9

Fractional Components

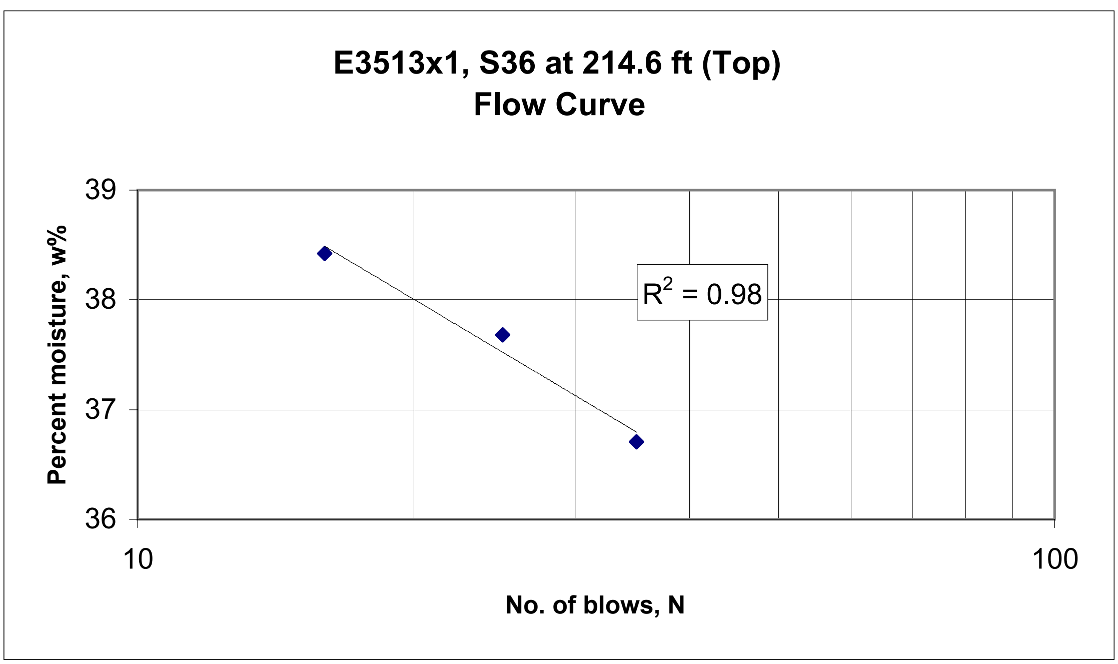
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.2	0.2	0.2	0.2	7.3	7.7	49.1	43.0	92.1

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0018	0.0082	0.0199	0.0509	0.0587	0.0690	0.0882

Fineness Modulus
0.04

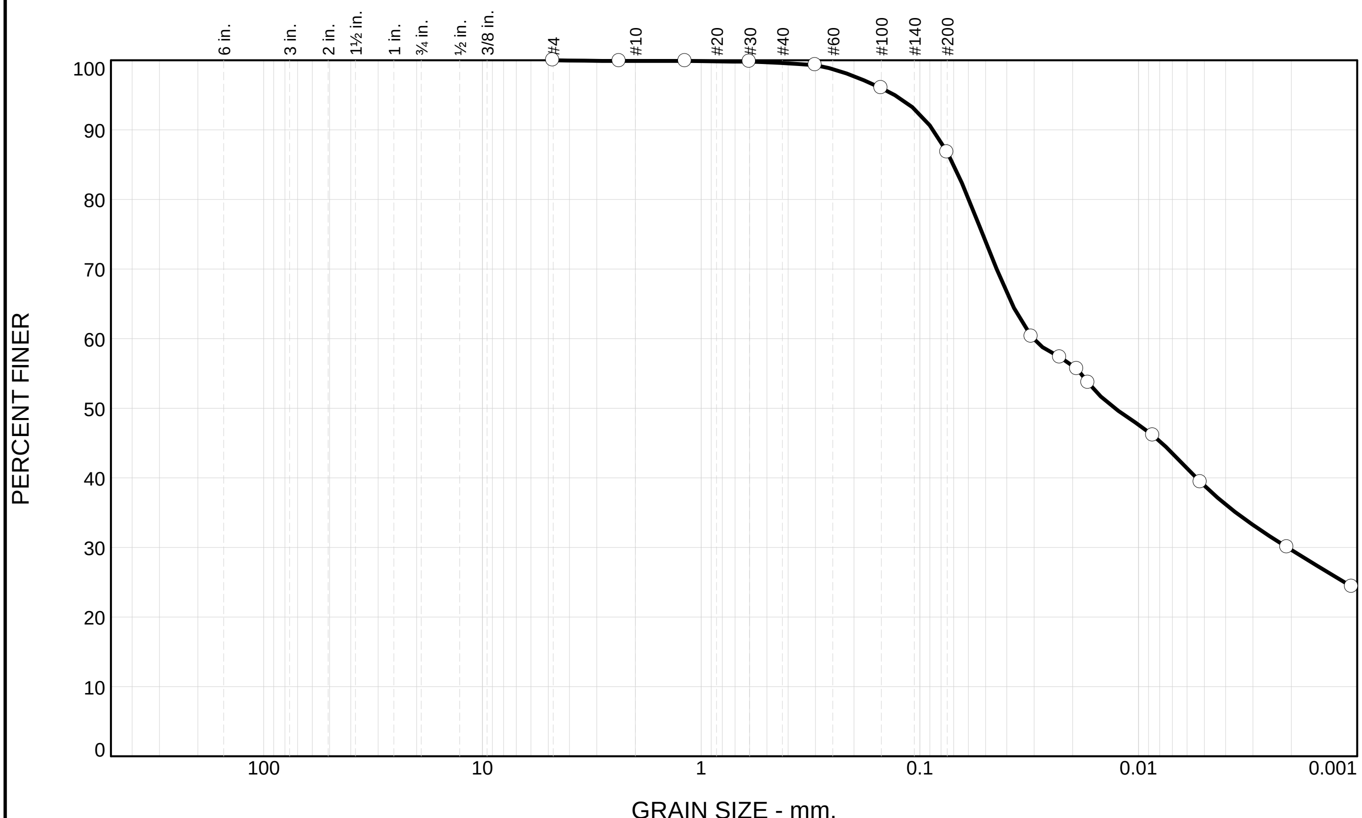
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	E3513x1, S36 at 214.6 ft (Top)				
Feature	Wolf Creek Dam				
Project	USACE				
Date	3/15/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	S-1	104	53	S-30	118
No. of blows	N/A	N/A	35	25	16
Mass of dish+wet soil (g)	19.439	16.502	22.419	26.596	26.350
Mass of dish+dry soil (g)	17.822	14.806	18.099	21.989	20.638
Mass of dish (g)	9.326	6.444	6.330	9.762	5.771
Mass of water (g)	1.617	1.696	4.320	4.607	5.712
Mass of dry soil (g)	8.496	8.362	11.769	12.227	14.867
% moisture	19.0	20.3	36.7	37.7	38.4
Average plastic limit	20				

LL = 38 **PL = 20** **PI = 18** **Fi = -5.0**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.1	0.3	12.8	47.9	38.9

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	99.9		
#16	99.9		
#30	99.8		
#50	99.3		
#100	96.0		
#200	86.8		

* (no specification provided)

Material Description

Lean clay

Atterberg Limits

PL= 19 LL= 41 PI= 22

Coefficients

D_{85}= 0.0701 D_{60}= 0.0303 D_{50}= 0.0128
D_{30}= 0.0021 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-7-6(19)

Remarks

Initial Moisture Content=23.8%
Specific Gravity=2.70

Sample Number: E3513x1, S36 **Depth:** 215.4 ft (Bottom)
Location: Sta 35+13 **Date:** 03/12/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+13
Depth: 215.4 ft (Bottom) **Sample Number:** E3513x1, S36
Material Description: Lean clay
Date: 03/12/2008 **PL:** 19 **LL:** 41 **PI:** 22
USCS Classification: CL **AASHTO Classification:** A-7-6(19)
Testing Remarks: Initial Moisture Content=23.8%
Specific Gravity=2.70

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	100.0
#8	99.9
#16	99.9
#30	99.8
#50	99.3
#100	96.0
#200	86.8

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =100
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.0
Specific gravity of solids = 2.70
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	20.2	67.0	61.0	0.0134	67.0	5.3	0.0309	60.3
2.00	20.1	64.0	58.0	0.0134	64.0	5.8	0.0229	57.3
3.00	20.1	62.3	56.3	0.0134	62.3	6.1	0.0191	55.7
4.00	20.1	60.3	54.3	0.0134	60.3	6.4	0.0170	53.7
19.00	19.4	52.8	46.6	0.0135	52.8	7.6	0.0086	46.1
60.00	18.9	46.1	39.8	0.0136	46.1	8.7	0.0052	39.4
435.00	19.1	36.6	30.4	0.0136	36.6	10.3	0.0021	30.0
1880.00	18.5	31.0	24.6	0.0137	31.0	11.2	0.0011	24.4

Fractional Components

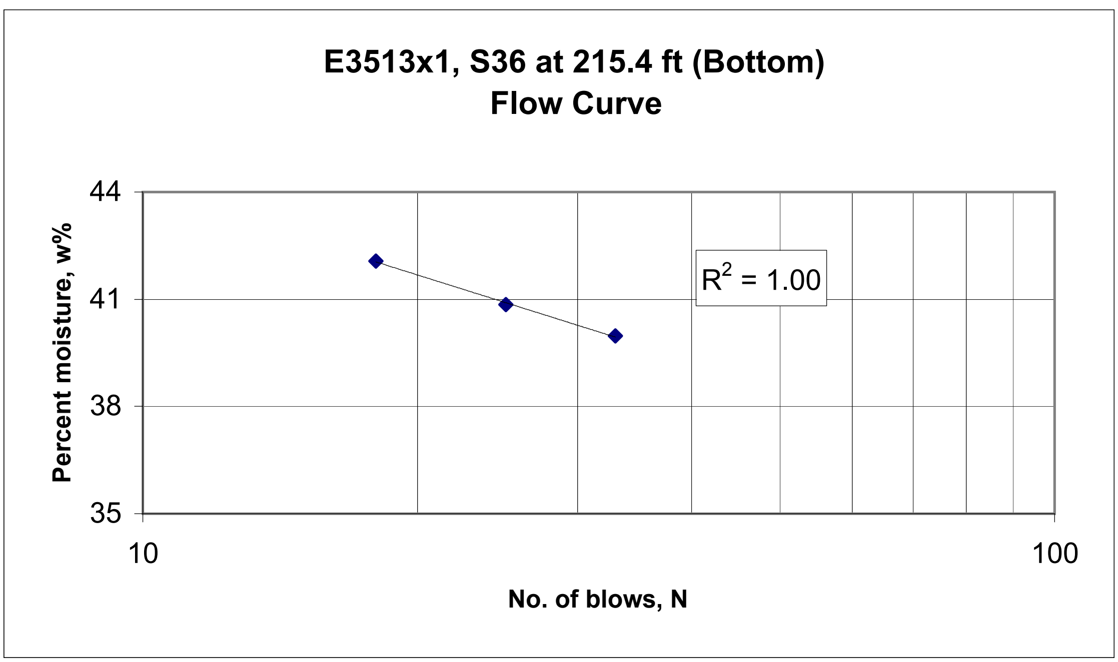
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.1	0.3	12.8	13.2	47.9	38.9	86.8

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0021	0.0128	0.0303	0.0597	0.0701	0.0868	0.1302

Fineness Modulus
0.05

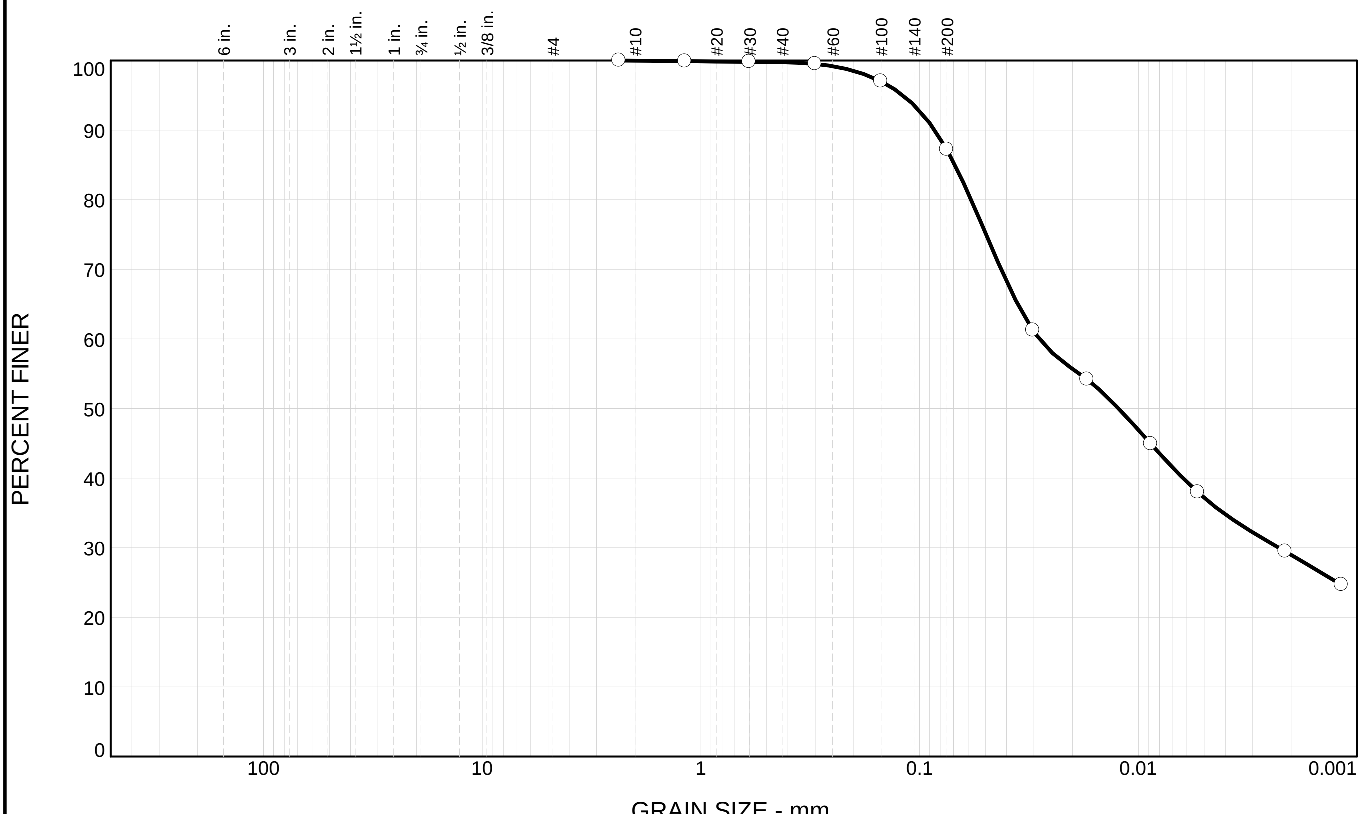
Soil Consistency Test (Three-Point Liquid Limit Method)						
Sample No.	E3513x1, S36 at 215.4 ft (Bottom)					
Feature	Wolf Creek Dam					
Project	USACE					
Date	3/15/2008					
Test		Plastic Limit		Liquid Limit		
Trial No.		1	2	1	2	3
Dish No.		116	120	S66	136	57
No. of blows		N/A	N/A	33	25	18
Mass of dish+wet soil (g)		11.496	12.623	23.789	22.898	20.030
Mass of dish+dry soil (g)		10.581	11.727	19.452	18.271	15.928
Mass of dish (g)		5.679	6.993	8.602	6.942	6.179
Mass of water (g)		0.915	0.896	4.337	4.627	4.102
Mass of dry soil (g)		4.902	4.734	10.850	11.329	9.749
% moisture		18.7	18.9	40.0	40.8	42.1
Average plastic limit		19				

LL = 41 **PL = 19** **PI = 22** **Fi = -8.0**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.2	12.6	50.0	37.2

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#8	100.0		
#16	99.9		
#30	99.8		
#50	99.5		
#100	97.0		
#200	87.2		

* (no specification provided)

Material Description

Lean clay

Atterberg Limits

PL= 19 LL= 41 PI= 22

Coefficients

D_{85}= 0.0689 D_{60}= 0.0284 D_{50}= 0.0123
D_{30}= 0.0023 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO=

Remarks

Specific Gravity=2.69
As-received moisture content=23.4%

Sample Number: E3513x1, S40 **Depth:** 222.6-223.4 ft
Location: Sta 35+13 **Date:** 12/17/2007

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+13
Depth: 222.6-223.4 ft **Sample Number:** E3513x1, S40
Material Description: Lean clay
Date: 12/17/2007 **PL:** 19 **LL:** 41 **PI:** 22
USCS Classification: CL
Testing Remarks: Specific Gravity=2.69
As-received moisture content=23.4%

Sieve Test Data

Sieve Opening Size	Percent Finer
#8	100.0
#16	99.9
#30	99.8
#50	99.5
#100	97.0
#200	87.2

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =99.42
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.69
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	22.0	67.0	61.4	0.0132	67.0	5.3	0.0303	61.2
4.00	19.5	60.5	54.4	0.0136	60.5	6.4	0.0171	54.2
19.00	19.5	51.2	45.1	0.0136	51.2	7.9	0.0087	44.9
60.00	18.2	44.5	38.1	0.0138	44.5	9.0	0.0053	38.0
435.00	18.5	35.9	29.5	0.0137	35.9	10.4	0.0021	29.5
1545.00	18.0	31.2	24.7	0.0138	31.2	11.2	0.0012	24.7

Fractional Components

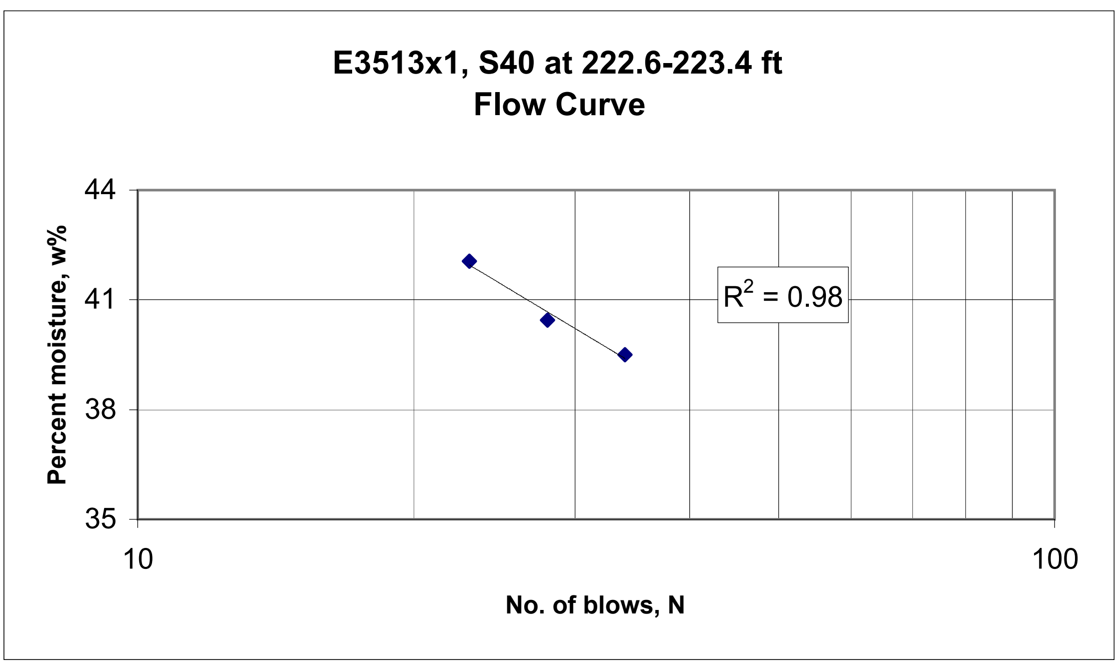
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	0.2	12.6	12.8	50.0	37.2	87.2

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0023	0.0123	0.0284	0.0581	0.0689	0.0852	0.1190

Fineness Modulus
0.04

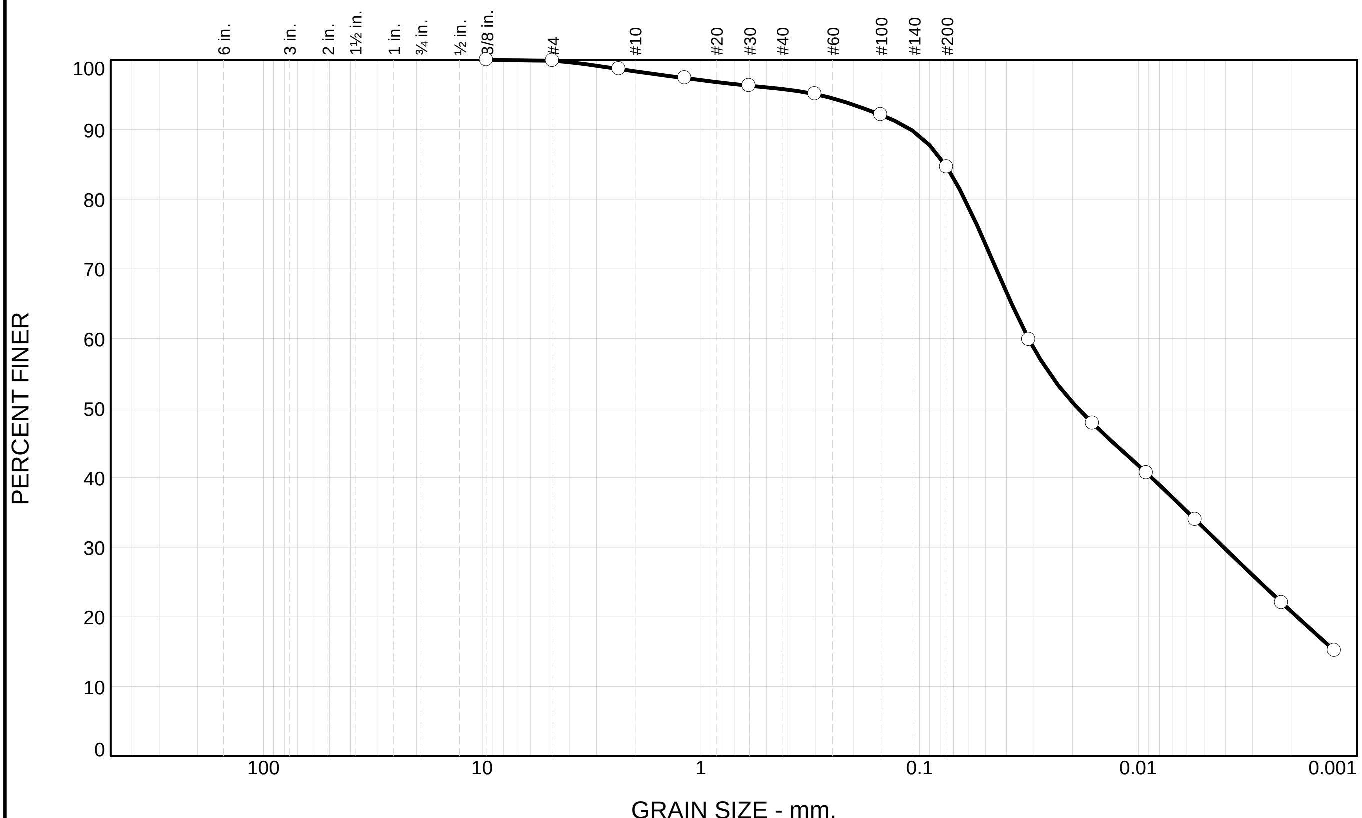
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	E3513x1, S40 at 222.6-223.4 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	12/13/2007				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	108	S-28	112	S-65	S-41
No. of blows	N/A	N/A	34	28	23
Mass of dish+wet soil (g)	13.521	15.696	19.741	29.183	24.512
Mass of dish+dry soil (g)	12.362	14.503	15.800	23.458	19.509
Mass of dish (g)	6.333	8.228	5.824	9.305	7.614
Mass of water (g)	1.159	1.193	3.941	5.725	5.003
Mass of dry soil (g)	6.029	6.275	9.976	14.153	11.895
% moisture	19.2	19.0	39.5	40.5	42.1
Average plastic limit	19				

LL = 41 **PL = 19** **PI = 22** **Fi = -15.1**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.1	1.5	2.6	11.2	51.9	32.7

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.375	100.0		
#4	99.9		
#8	98.7		
#16	97.4		
#30	96.3		
#50	95.1		
#100	92.1		
#200	84.6		

* (no specification provided)

Material Description

Lean clay with sand

Atterberg Limits

PL= 21 LL= 40 PI= 19

Coefficients

D_{85}= 0.0765 D_{60}= 0.0318 D_{50}= 0.0189
D_{30}= 0.0041 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO=

Remarks

Initial Moisture Content=20.74%
Specific Gravity=2.67

Sample Number: E3548x, SH12 **Depth:** 211.2-212.2 ft
Location: Sta 35+48 **Date:** 01/13/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam

Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+48
Depth: 211.2-212.2 ft **Sample Number:** E3548x, SH12
Material Description: Lean clay with sand
Date: 01/13/2008 **PL:** 21 **LL:** 40 **PI:** 19
USCS Classification: CL
Testing Remarks: Initial Moisture Content=20.74%
Specific Gravity=2.67

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	100.0
#4	99.9
#8	98.7
#16	97.4
#30	96.3
#50	95.1
#100	92.1
#200	84.6

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 99.9
Weight of hydrometer sample =99.64
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.5
Specific gravity of solids = 2.67
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	19.8	66.0	59.9	0.0136	66.5	5.4	0.0316	59.8
5.25	19.6	54.0	47.9	0.0136	54.5	7.4	0.0161	47.8
19.00	19.4	46.9	40.7	0.0137	47.4	8.5	0.0092	40.7
60.00	19.3	40.2	34.0	0.0137	40.7	9.6	0.0055	33.9
450.00	19.0	28.3	22.1	0.0137	28.8	11.6	0.0022	22.0
1545.00	17.6	21.7	15.2	0.0140	22.2	12.7	0.0013	15.1

Fractional Components

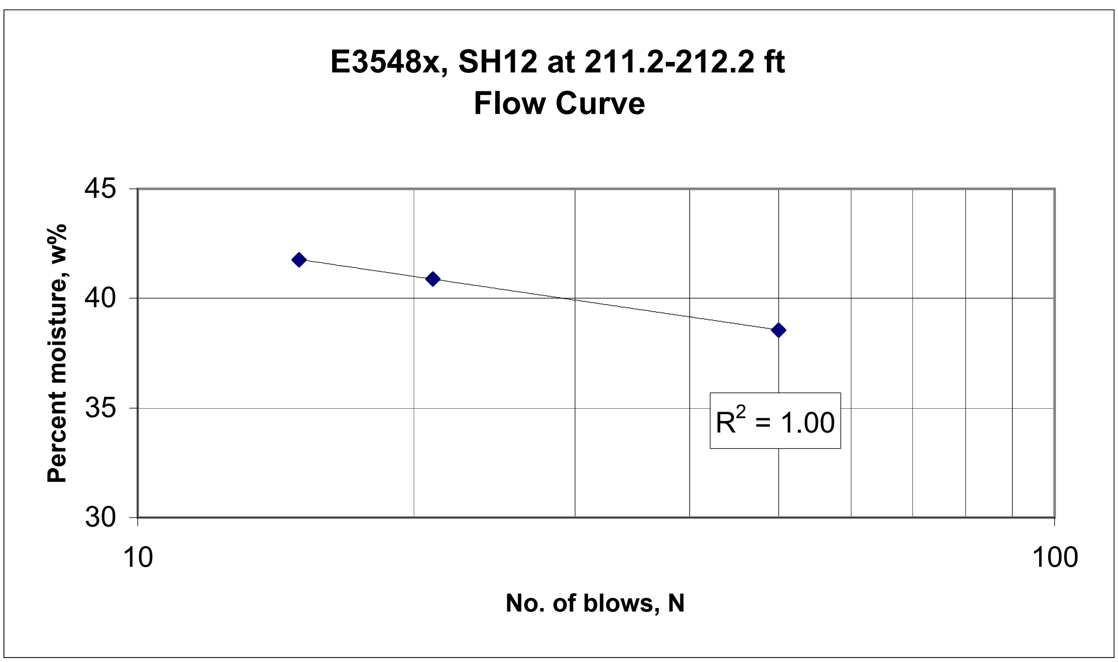
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.1	0.1	1.5	2.6	11.2	15.3	51.9	32.7	84.6

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
		0.0019	0.0041	0.0189	0.0318	0.0621	0.0765	0.1096	0.2900

Fineness Modulus
0.21

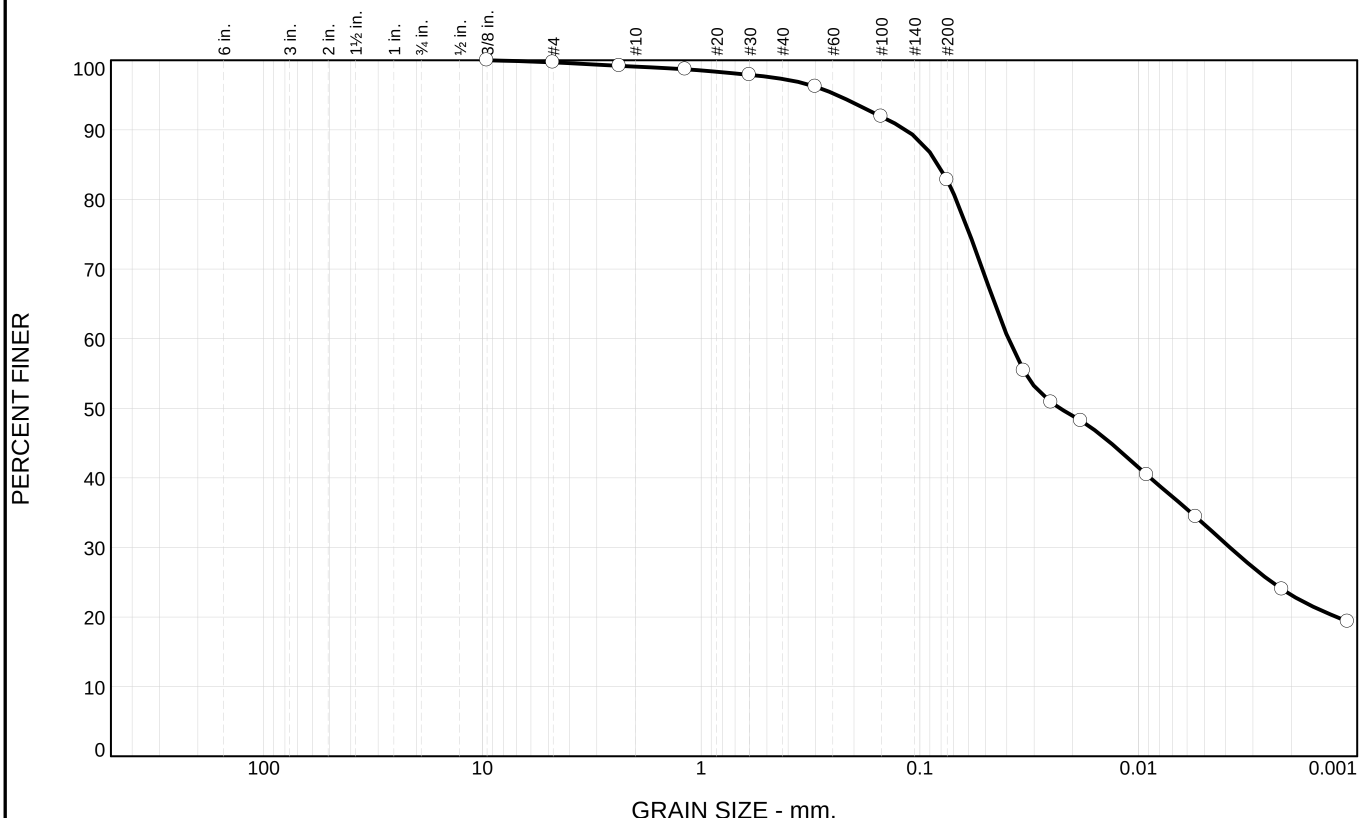
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	E3548x, SH12 at 211.2-212.2 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	1/7/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	92	108	125	S-49	128
No. of blows	N/A	N/A	21	15	50
Mass of dish+wet soil (g)	13.431	14.629	20.130	26.396	22.923
Mass of dish+dry soil (g)	12.173	13.168	15.988	21.485	18.500
Mass of dish (g)	6.266	6.334	5.858	9.726	7.029
Mass of water (g)	1.258	1.461	4.142	4.911	4.423
Mass of dry soil (g)	5.907	6.834	10.130	11.759	11.471
% moisture	21.3	21.4	40.9	41.8	38.6
Average plastic limit	21				

LL = 40 **PL = 21** **PI = 19** **Fi = -6.1**



Remarks: Soil smells like bleach (O_3).

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.3	0.6	1.8	14.5	49.5	33.3

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.375	100.0		
#4	99.7		
#8	99.2		
#16	98.7		
#30	97.9		
#50	96.2		
#100	91.9		
#200	82.8		

* (no specification provided)

Material Description

Lean clay with sand

Atterberg Limits

PL= 19 LL= 37 PI= 18

Coefficients

D_{85}= 0.0821 D_{60}= 0.0394 D_{50}= 0.0229
D_{30}= 0.0038 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-6(14)

Remarks

Initial Moisture Content=21.6%
Specific Gravity=2.69

Sample Number: E3548x, SH14 **Depth:** 217.3-218.5 ft
Location: Sta 35+48 **Date:** 03/12/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+48
Depth: 217.3-218.5 ft **Sample Number:** E3548x, SH14
Material Description: Lean clay with sand
Date: 03/12/2008 **PL:** 19 **LL:** 37 **PI:** 18
USCS Classification: CL **AASHTO Classification:** A-6(14)
Testing Remarks: Initial Moisture Content=21.6%
Specific Gravity=2.69

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	100.0
#4	99.7
#8	99.2
#16	98.7
#30	97.9
#50	96.2
#100	91.9
#200	82.8

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 99.7
Weight of hydrometer sample =99.7
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.0
Specific gravity of solids = 2.69
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	19.7	62.0	55.9	0.0135	62.0	6.1	0.0335	55.4
2.00	19.7	57.4	51.3	0.0135	57.4	6.9	0.0251	50.8
4.00	19.5	54.8	48.7	0.0136	54.8	7.3	0.0183	48.2
19.00	19.2	47.0	40.8	0.0136	47.0	8.6	0.0092	40.4
60.00	18.8	41.0	34.7	0.0137	41.0	9.6	0.0055	34.4
435.00	18.8	30.5	24.2	0.0137	30.5	11.3	0.0022	24.0
1870.00	18.4	25.9	19.5	0.0138	25.9	12.0	0.0011	19.4

Fractional Components

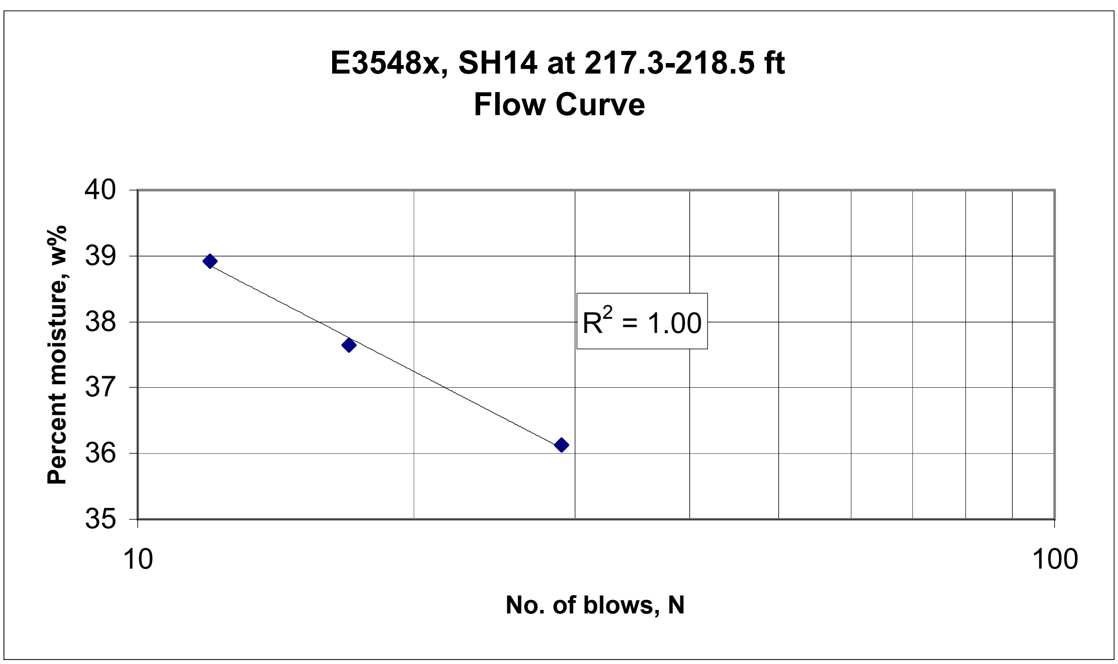
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.3	0.3	0.6	1.8	14.5	16.9	49.5	33.3	82.8

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
		0.0012	0.0038	0.0229	0.0394	0.0682	0.0821	0.1158	0.2395

Fineness Modulus
0.16

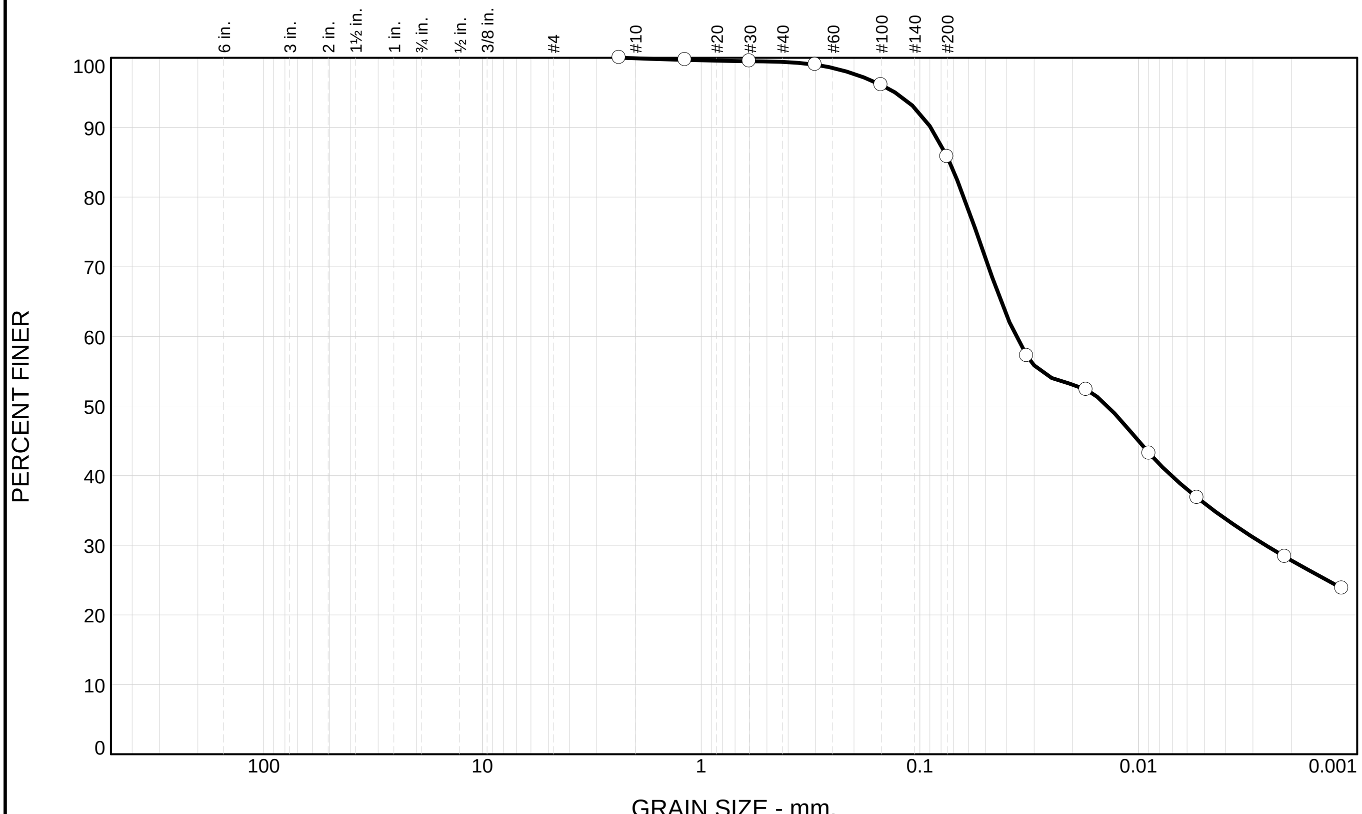
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	E3548x, SH14 at 217.3-218.5 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	3/17/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	108	S-41	S-20	S-29	S-26
No. of blows	N/A	N/A	29	17	12
Mass of dish+wet soil (g)	14.541	14.515	21.881	20.764	24.468
Mass of dish+dry soil (g)	13.209	13.209	18.120	17.636	19.869
Mass of dish (g)	6.167	6.341	7.709	9.327	8.052
Mass of water (g)	1.332	1.306	3.761	3.128	4.599
Mass of dry soil (g)	7.042	6.868	10.411	8.309	11.817
% moisture	18.9	19.0	36.1	37.6	38.9
Average plastic limit	19				

LL = 37 **PL = 19** **PI = 18** **Fi = -7.2**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.1	0.5	13.6	49.8	36.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#8	100.0		
#16	99.7		
#30	99.5		
#50	99.0		
#100	96.1		
#200	85.8		

* (no specification provided)

Material Description

Lean clay

Atterberg Limits

PL= 20 LL= 39 PI= 19

Coefficients

D_{85}= 0.0730 D_{60}= 0.0363 D_{50}= 0.0139
D_{30}= 0.0026 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO=

Remarks

Moisture Content=23.06%
Specific Gravity=2.70

Sample Number: E3548x, SH16 **Depth:** 221.7-222.4 ft
Location: Sta 35+48 **Date:** 01/06/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+48
Depth: 221.7-222.4 ft **Sample Number:** E3548x, SH16
Material Description: Lean clay
Date: 01/06/2008 **PL:** 20 **LL:** 39 **PI:** 19
USCS Classification: CL
Testing Remarks: Moisture Content=23.06%
Specific Gravity=2.70

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	
#8	100.0
#16	99.7
#30	99.5
#50	99.0
#100	96.1
#200	85.8

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =100
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.5
Specific gravity of solids = 2.70
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	19.4	64.0	57.8	0.0135	64.5	5.7	0.0324	57.2
4.00	19.4	59.1	52.9	0.0135	59.6	6.5	0.0173	52.3
19.00	18.2	50.1	43.7	0.0138	50.6	8.0	0.0089	43.2
60.00	17.5	43.8	37.2	0.0139	44.3	9.0	0.0054	36.8
435.00	18.1	35.1	28.7	0.0138	35.6	10.5	0.0021	28.3
1545.00	18.2	30.5	24.1	0.0138	31.0	11.2	0.0012	23.8

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.1	0.5	13.6	14.2	49.8	36.0	85.8

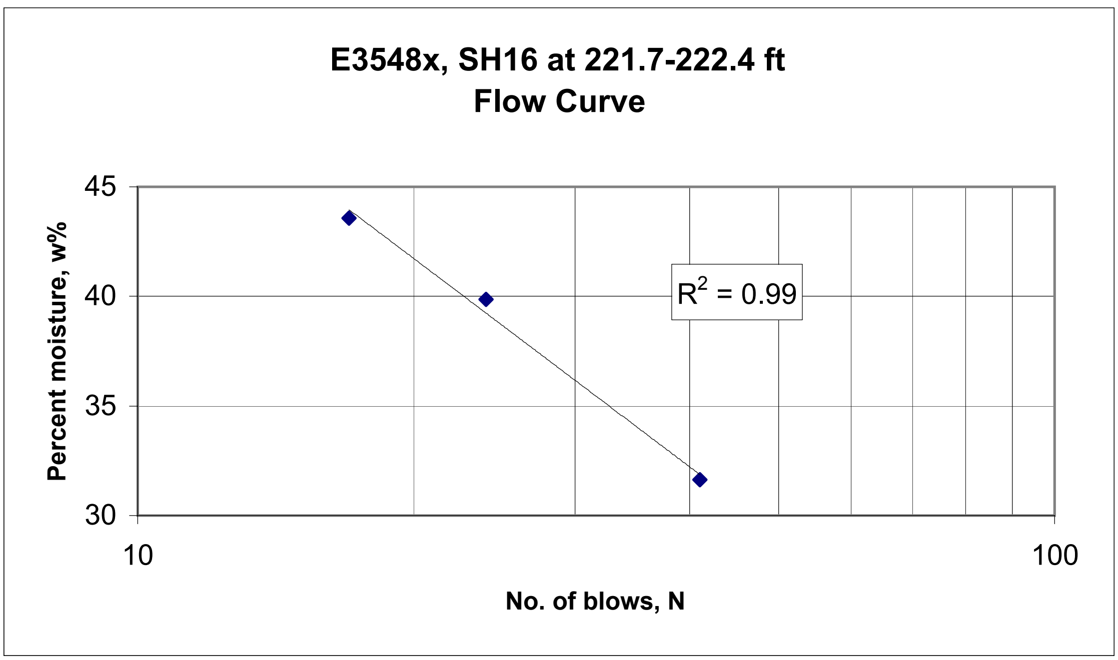
D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0026	0.0139	0.0363	0.0630	0.0730	0.0891	0.1292

Fineness Modulus
0.06

Soil Consistency Test (Three-Point Liquid Limit Method)

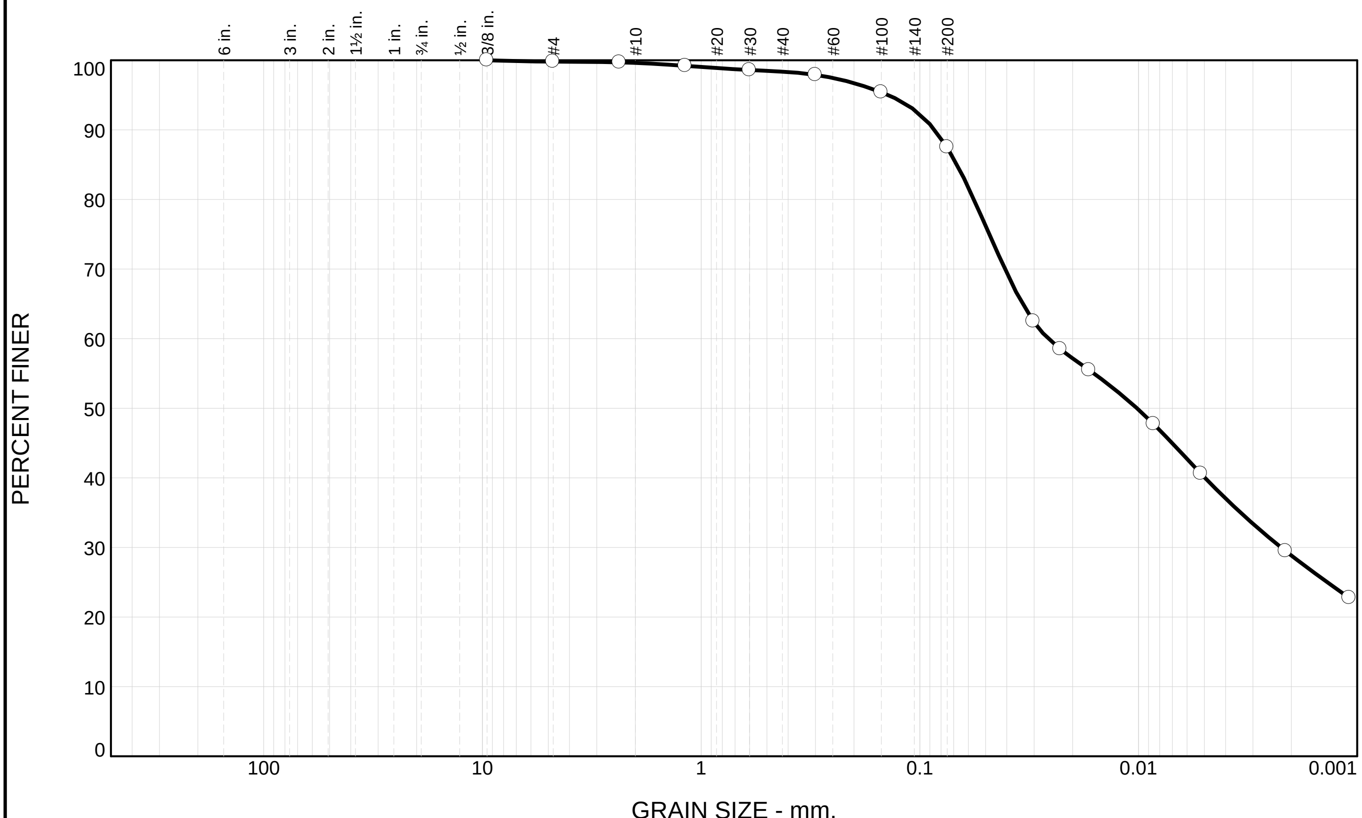
Sample No.	E3548x, SH16 at 221.7-222.4 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	1/6/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	131	116	139	S-30	144
No. of blows	N/A	N/A	17	41	24
Mass of dish+wet soil (g)	12.727	11.366	24.344	26.392	21.195
Mass of dish+dry soil (g)	11.774	10.431	18.903	21.544	17.000
Mass of dish (g)	6.987	5.680	6.415	6.217	6.477
Mass of water (g)	0.953	0.935	5.441	4.848	4.195
Mass of dry soil (g)	4.787	4.751	12.488	15.327	10.523
% moisture	19.9	19.7	43.6	31.6	39.9
Average plastic limit	20				

LL = 39 **PL = 20** **PI = 19** **Fi = -31.6**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.2	0.2	1.2	10.9	47.4	40.1

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.375	100.0		
#4	99.8		
#8	99.7		
#16	99.2		
#30	98.6		
#50	97.9		
#100	95.4		
#200	87.5		

* (no specification provided)

Material Description

Lean clay

Atterberg Limits

PL= 19 LL= 40 PI= 21

Coefficients

D_{85}= 0.0676 D_{60}= 0.0259 D_{50}= 0.0102
D_{30}= 0.0022 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-6(19)

Remarks

Initial Moisture Content=22.1%
Specific Gravity=2.68

Sample Number: E3560x, SH2 **Depth:** 209.3-210.5 ft
Location: Sta 35+60 **Date:** 03/12/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+60
Depth: 209.3-210.5 ft **Sample Number:** E3560x, SH2
Material Description: Lean clay
Date: 03/12/2008 **PL:** 19 **LL:** 40 **PI:** 21
USCS Classification: CL **AASHTO Classification:** A-6(19)
Testing Remarks: Initial Moisture Content=22.1%
Specific Gravity=2.68

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	100.0
#4	99.8
#8	99.7
#16	99.2
#30	98.6
#50	97.9
#100	95.4
#200	87.5

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 99.8
Weight of hydrometer sample =99.8
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.0
Specific gravity of solids = 2.68
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	19.8	69.0	62.9	0.0136	69.0	5.0	0.0303	62.5
2.00	19.7	65.0	58.9	0.0136	65.0	5.6	0.0228	58.5
4.00	19.6	62.0	55.9	0.0136	62.0	6.1	0.0168	55.5
19.00	19.1	54.3	48.1	0.0137	54.3	7.4	0.0085	47.7
60.00	18.7	47.2	40.9	0.0137	47.2	8.6	0.0052	40.6
435.00	18.7	36.0	29.7	0.0137	36.0	10.4	0.0021	29.5
1860.00	18.3	29.3	22.9	0.0138	29.3	11.5	0.0011	22.8

Fractional Components

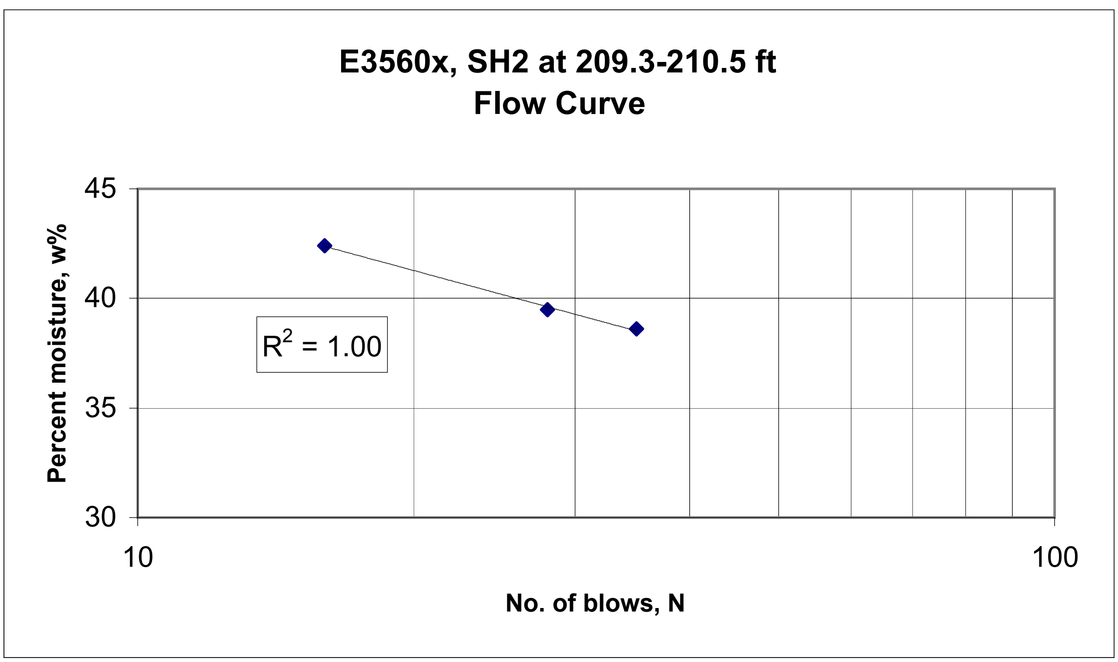
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.2	0.2	0.2	1.2	10.9	12.3	47.4	40.1	87.5

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0022	0.0102	0.0259	0.0566	0.0676	0.0854	0.1395

Fineness Modulus
0.09

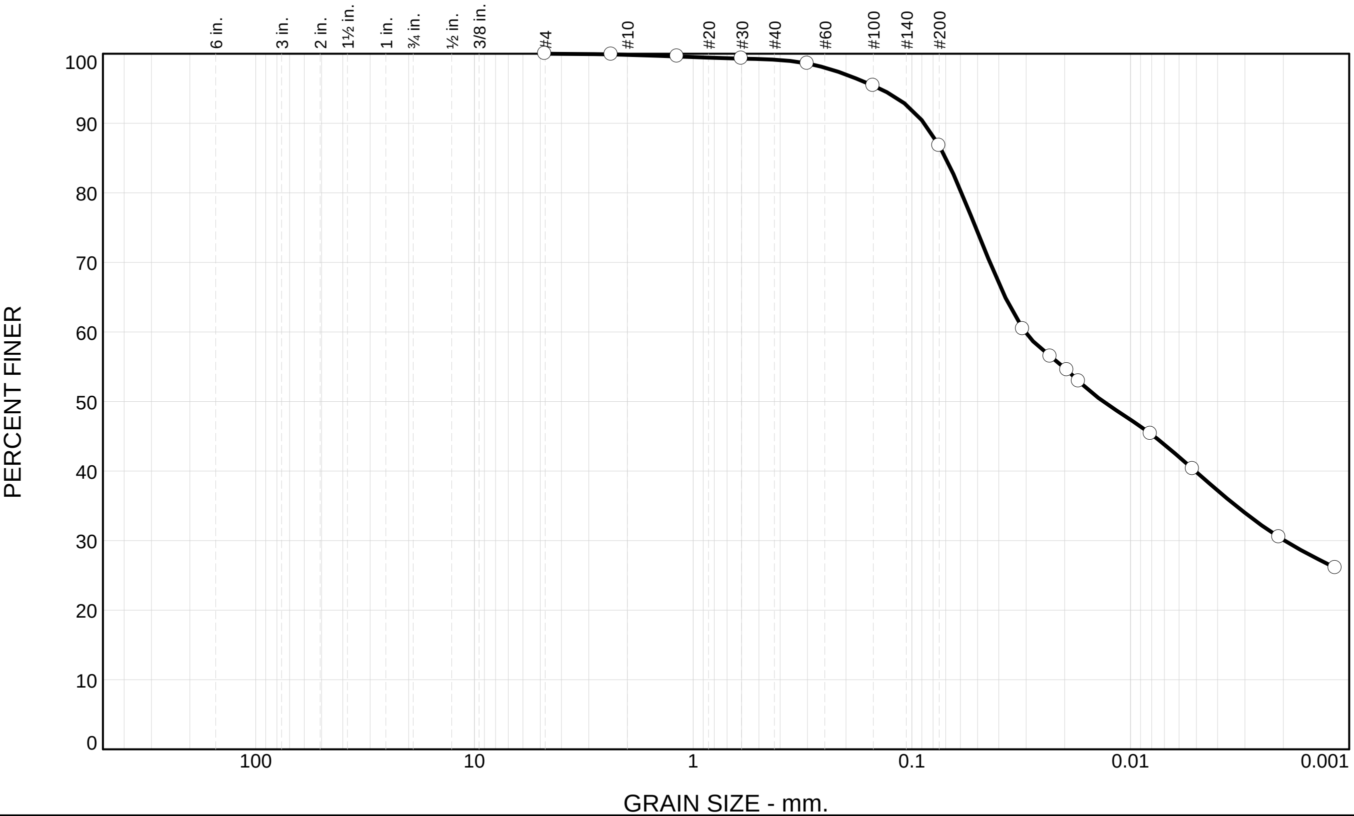
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	E3560x, SH2 at 209.3-210.5 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	3/15/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	139	S57	S-12	39	54
No. of blows	N/A	N/A	35	28	16
Mass of dish+wet soil (g)	13.537	16.106	26.212	20.368	16.848
Mass of dish+dry soil (g)	12.404	14.824	21.636	16.367	13.660
Mass of dish (g)	6.415	8.052	9.784	6.233	6.143
Mass of water (g)	1.133	1.282	4.576	4.001	3.188
Mass of dry soil (g)	5.989	6.772	11.852	10.134	7.517
% moisture	18.9	18.9	38.6	39.5	42.4
Average plastic limit	19				

LL = 40 **PL = 19** **PI = 21** **Fi = -11.3**



Remarks: Soil smells like bleach (O_3).

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.2	0.6	12.4	46.9	39.9

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	99.9		
#16	99.6		
#30	99.3		
#50	98.6		
#100	95.4		
#200	86.8		

* (no specification provided)

Material Description

Lean clay

Atterberg Limits

PL= 20 LL= 42 PI= 22

Coefficients

D_{85}= 0.0699 D_{60}= 0.0303 D_{50}= 0.0133
D_{30}= 0.0020 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-7-6(20)

Remarks

Initial Moisture Content=34.6%
Specific Gravity=2.69

Sample Number: E3562x, SH7 **Depth:** 195.2-197.0 ft
Location: Sta 35+62 **Date:** 03/17/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+62
Depth: 195.2-197.0 ft **Sample Number:** E3562x, SH7
Material Description: Lean clay
Date: 03/17/2008 **PL:** 20 **LL:** 42 **PI:** 22
USCS Classification: CL **AASHTO Classification:** A-7-6(20)
Testing Remarks: Initial Moisture Content=34.6%
Specific Gravity=2.69

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	100.0
#8	99.9
#16	99.6
#30	99.3
#50	98.6
#100	95.4
#200	86.8

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =100
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.0
Specific gravity of solids = 2.69
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	20.1	67.0	61.0	0.0135	67.0	5.3	0.0310	60.4
2.00	20.2	63.0	57.0	0.0134	63.0	6.0	0.0232	56.5
3.00	20.2	61.0	55.0	0.0134	61.0	6.3	0.0195	54.5
4.00	20.1	59.4	53.4	0.0135	59.4	6.6	0.0172	52.9
22.00	19.2	52.0	45.8	0.0136	52.0	7.8	0.0081	45.4
60.00	18.6	47.0	40.7	0.0137	47.0	8.6	0.0052	40.3
435.00	19.1	37.0	30.8	0.0136	37.0	10.2	0.0021	30.5
1520.00	19.3	32.5	26.3	0.0136	32.5	11.0	0.0012	26.1

Fractional Components

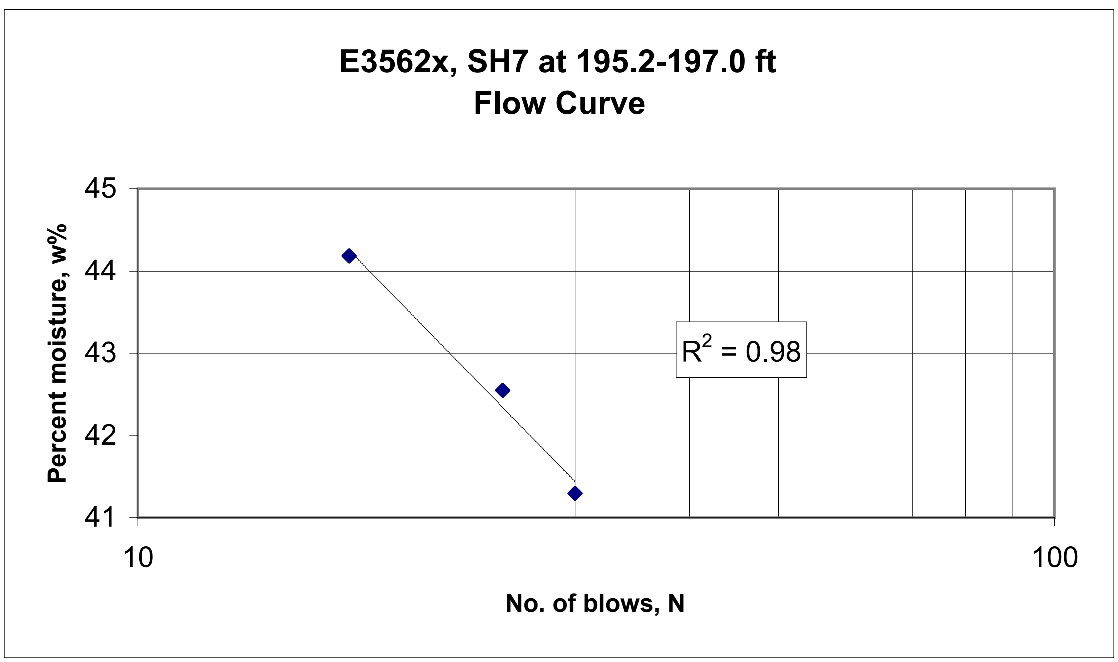
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.2	0.6	12.4	13.2	46.9	39.9	86.8

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0020	0.0133	0.0303	0.0592	0.0699	0.0876	0.1406

Fineness Modulus
0.07

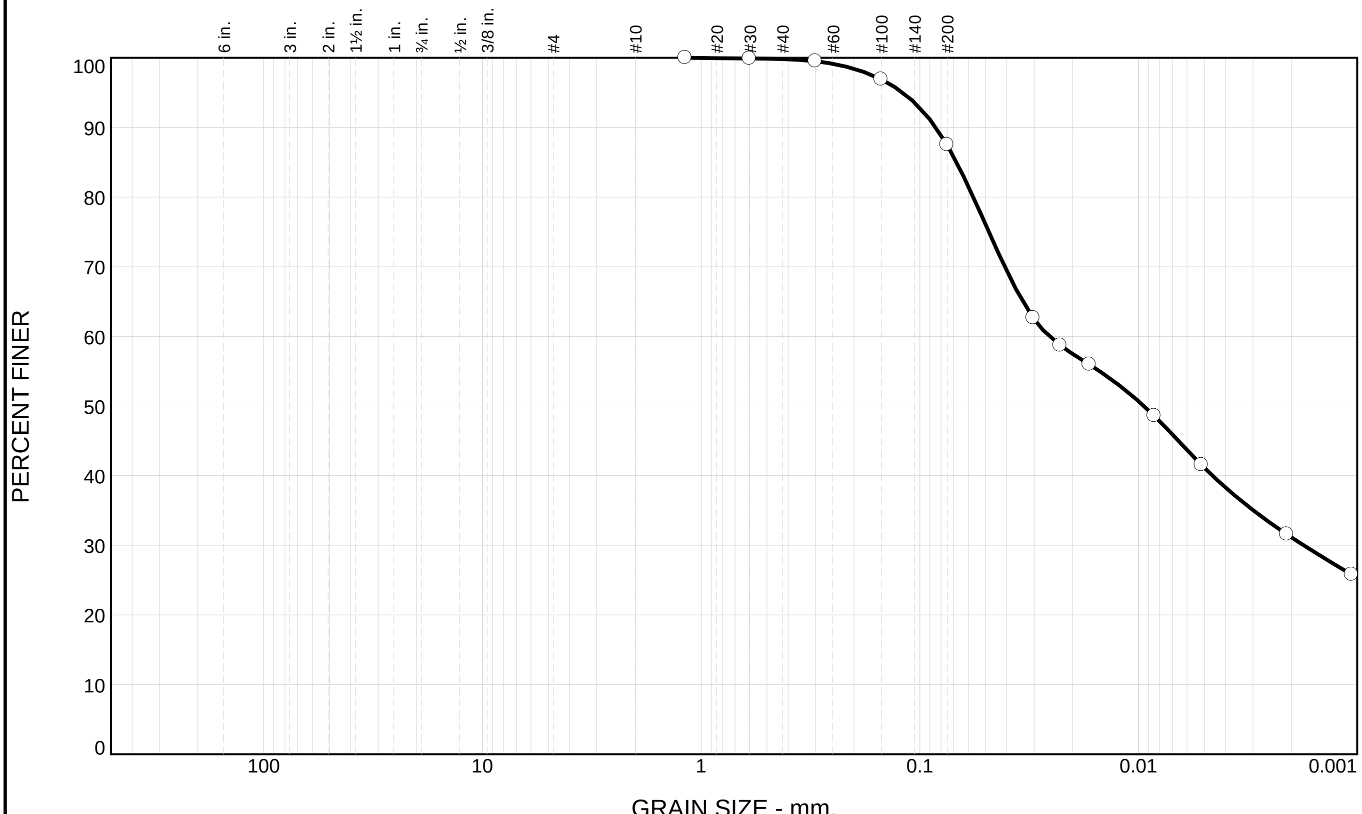
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	E3562x, SH7 at 195.2-197.0 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	3/17/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	130	S-40	120	72	55
No. of blows	N/A	N/A	30	25	17
Mass of dish+wet soil (g)	13.272	16.618	23.360	19.071	20.102
Mass of dish+dry soil (g)	12.045	15.264	18.576	15.244	15.880
Mass of dish (g)	5.962	8.580	6.992	6.249	6.325
Mass of water (g)	1.227	1.354	4.784	3.827	4.222
Mass of dry soil (g)	6.083	6.684	11.584	8.995	9.555
% moisture	20.2	20.3	41.3	42.5	44.2
Average plastic limit	20				

LL = 42 **PL = 20** **PI = 22** **Fi = -11.4**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.2	12.3	46.4	41.1

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#16	100.0		
#30	99.9		
#50	99.5		
#100	96.9		
#200	87.5		

* (no specification provided)

Material Description

Lean Clay

Atterberg Limits

PL= 19 LL= 39 PI= 20

Coefficients

D_{85}= 0.0679 D_{60}= 0.0256 D_{50}= 0.0094
D_{30}= 0.0018 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-6(18)

Remarks

Initial Moisture Content=23.2%
Specific Gravity=2.67

Sample Number: E3562x, SH12 **Depth:** 205.4-206.6 ft
Location: Sta 35+62

Date: 03/12/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+62
Depth: 205.4-206.6 ft **Sample Number:** E3562x, SH12
Material Description: Lean Clay
Date: 03/12/2008 **PL:** 19 **LL:** 39 **PI:** 20
USCS Classification: CL **AASHTO Classification:** A-6(18)
Testing Remarks: Initial Moisture Content=23.2%
Specific Gravity=2.67

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	
#8	
#16	100.0
#30	99.9
#50	99.5
#100	96.9
#200	87.5

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =100
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.0
Specific gravity of solids = 2.67
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	19.9	69.0	62.9	0.0136	69.0	5.0	0.0303	62.7
2.00	20.0	65.0	59.0	0.0136	65.0	5.6	0.0228	58.7
4.00	19.8	62.3	56.2	0.0136	62.3	6.1	0.0168	56.0
19.00	19.3	55.0	48.8	0.0137	55.0	7.3	0.0085	48.6
60.00	18.9	48.0	41.7	0.0138	48.0	8.4	0.0052	41.5
435.00	18.8	38.0	31.7	0.0138	38.0	10.1	0.0021	31.6
1880.00	18.3	32.3	25.9	0.0139	32.3	11.0	0.0011	25.8

Fractional Components

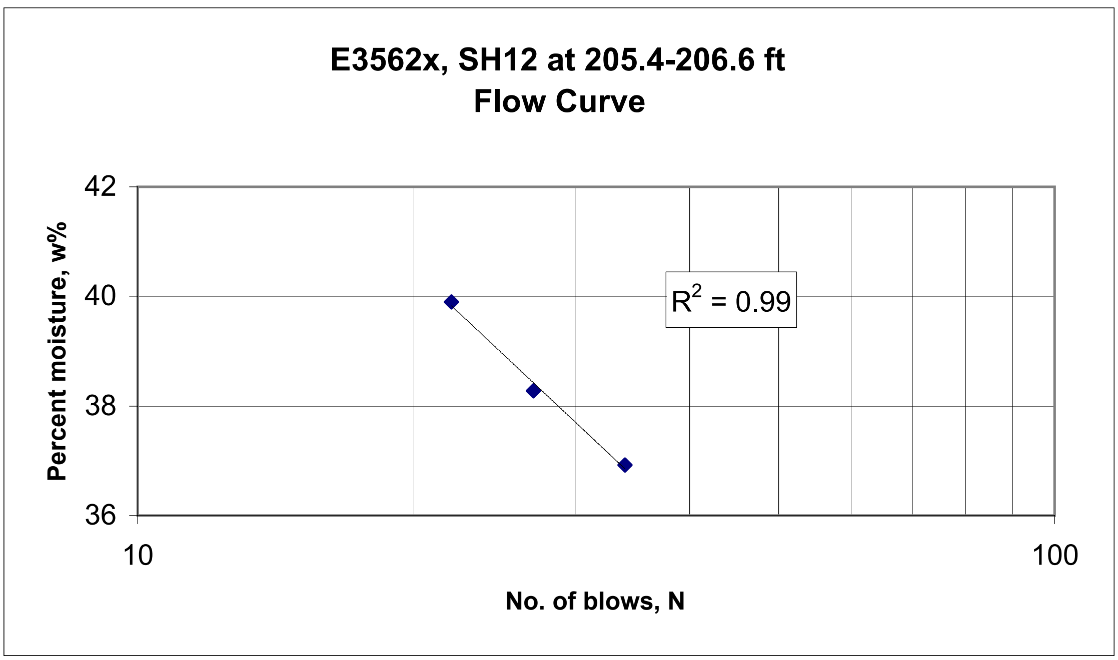
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	0.2	12.3	12.5	46.4	41.1	87.5

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0018	0.0094	0.0256	0.0569	0.0679	0.0844	0.1195

Fineness Modulus
0.04

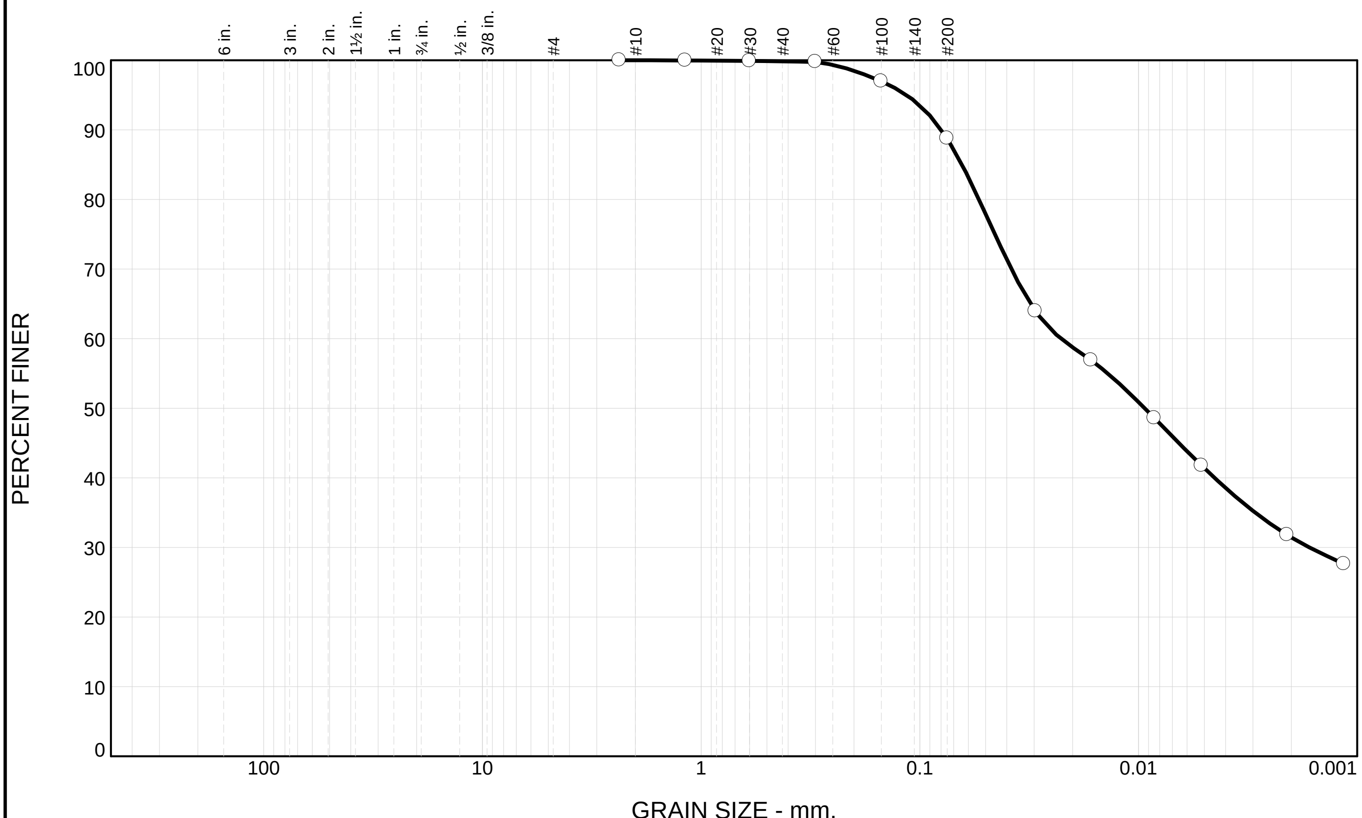
Soil Consistency Test (Three-Point Liquid Limit Method)						
Sample No.	E3562x, SH12 at 205.4-206.6 ft					
Feature	Wolf Creek Dam					
Project	USACE					
Date	3/15/2008					
Test		Plastic Limit		Liquid Limit		
Trial No.		1	2	1	2	3
Dish No.		S-26	72	S7	121	73
No. of blows		N/A	N/A	34	27	22
Mass of dish+wet soil (g)		17.465	13.640	26.029	22.160	20.085
Mass of dish+dry soil (g)		16.213	12.469	21.599	17.897	16.176
Mass of dish (g)		9.658	6.249	9.600	6.761	6.380
Mass of water (g)		1.252	1.171	4.430	4.263	3.909
Mass of dry soil (g)		6.555	6.220	11.999	11.136	9.796
% moisture		19.1	18.8	36.9	38.3	39.9
Average plastic limit		19				

LL = 39 **PL = 19** **PI = 20** **Fi = -15.7**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.2	11.0	47.4	41.4

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#8	100.0		
#16	100.0		
#30	99.9		
#50	99.8		
#100	97.0		
#200	88.8		

* (no specification provided)

Material Description

Lean clay

Atterberg Limits

PL= 20 LL= 42 PI= 22

Coefficients

D_{85}= 0.0641 D_{60}= 0.0226 D_{50}= 0.0094
D_{30}= 0.0017 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO=

Remarks

Specific Gravity=2.70
As-received moisture content=23.2%

Sample Number: E3562x, SH15 **Depth:** 211.6-212.4 ft
Location: Sta 35+62 **Date:** 12/17/2007

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 35+62
Depth: 211.6-212.4 ft **Sample Number:** E3562x, SH15
Material Description: Lean clay
Date: 12/17/2007 **PL:** 20 **LL:** 42 **PI:** 22
USCS Classification: CL
Testing Remarks: Specific Gravity=2.70
As-received moisture content=23.2%

Sieve Test Data

Sieve Opening Size	Percent Finer
#8	100.0
#16	100.0
#30	99.9
#50	99.8
#100	97.0
#200	88.8

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =98.86
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.70
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	19.8	70.0	63.9	0.0135	70.0	4.8	0.0296	63.9
4.00	19.7	63.0	56.9	0.0135	63.0	6.0	0.0165	56.9
19.00	18.7	54.9	48.6	0.0137	54.9	7.3	0.0085	48.6
60.00	18.1	48.2	41.8	0.0138	48.2	8.4	0.0051	41.8
435.00	18.2	38.2	31.8	0.0138	38.2	10.0	0.0021	31.8
1545.00	17.9	34.1	27.6	0.0138	34.1	10.7	0.0011	27.6

Fractional Components

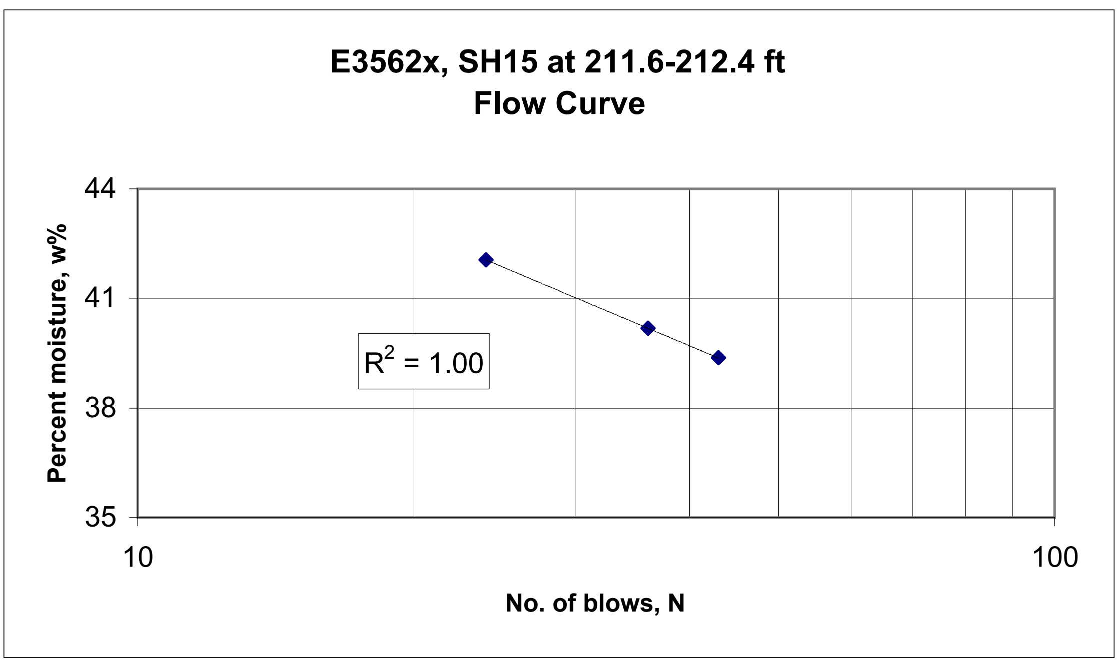
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	0.2	11.0	11.2	47.4	41.4	88.8

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0017	0.0094	0.0226	0.0537	0.0641	0.0797	0.1150

Fineness Modulus
0.03

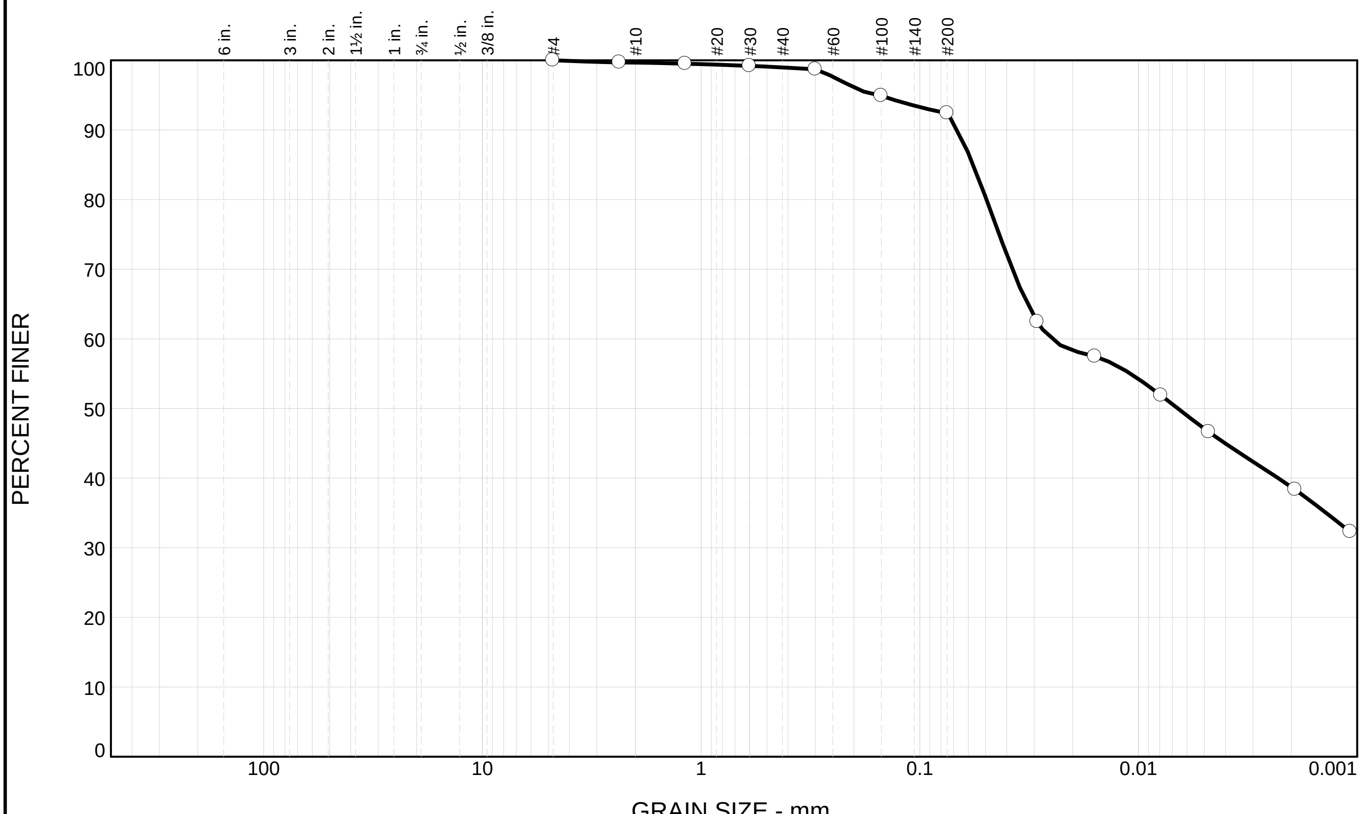
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	E3562x, SH15 at 211.6-212.4 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	3/16/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	S-65	S-41	87	121	128
No. of blows	N/A	N/A	43	36	24
Mass of dish+wet soil (g)	15.737	14.142	19.990	19.248	25.351
Mass of dish+dry soil (g)	14.693	13.073	16.109	15.669	19.927
Mass of dish (g)	9.305	7.614	6.251	6.762	7.028
Mass of water (g)	1.044	1.069	3.881	3.579	5.424
Mass of dry soil (g)	5.388	5.459	9.858	8.907	12.899
% moisture	19.4	19.6	39.4	40.2	42.0
Average plastic limit	19				

LL = 42 **PL = 19** **PI = 22** **Fi = -10.6**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.3	0.7	6.6	45.3	47.1

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	99.7		
#16	99.5		
#30	99.2		
#50	98.7		
#100	94.9		
#200	92.4		

* (no specification provided)

Material Description

Fat clay

Atterberg Limits

PL= 25 LL= 75 PI= 50

Coefficients

D_{85}= 0.0570 D_{60}= 0.0250 D_{50}= 0.0066
D_{30}= D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CH AASHTO=

Remarks

Moisture Content=36.99%
Specific Gravity=2.75

Sample Number: P3900x, SH1 **Depth:** 164.1-164.9 ft
Location: Sta 39+00 **Date:** 01/06/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam

Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 39+00
Depth: 164.1-164.9 ft **Sample Number:** P3900x, SH1
Material Description: Fat clay
Date: 01/06/2008 **PL:** 25 **LL:** 75 **PI:** 50
USCS Classification: CH
Testing Remarks: Moisture Content=36.99%
Specific Gravity=2.75

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	100.0
#8	99.7
#16	99.5
#30	99.2
#50	98.7
#100	94.9
#200	92.4

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =100
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.5
Specific gravity of solids = 2.75
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	19.4	70.0	63.8	0.0133	70.5	4.7	0.0290	62.5
4.00	19.0	65.0	58.8	0.0134	65.5	5.6	0.0158	57.5
19.00	18.4	59.4	53.0	0.0135	59.9	6.5	0.0079	51.9
60.00	17.6	54.2	47.7	0.0137	54.7	7.3	0.0048	46.6
435.00	18.2	45.6	39.2	0.0136	46.1	8.7	0.0019	38.3
1545.00	18.3	39.4	33.0	0.0135	39.9	9.8	0.0011	32.3

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.3	0.7	6.6	7.6	45.3	47.1	92.4

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
				0.0066	0.0250	0.0496	0.0570	0.0673	0.1583

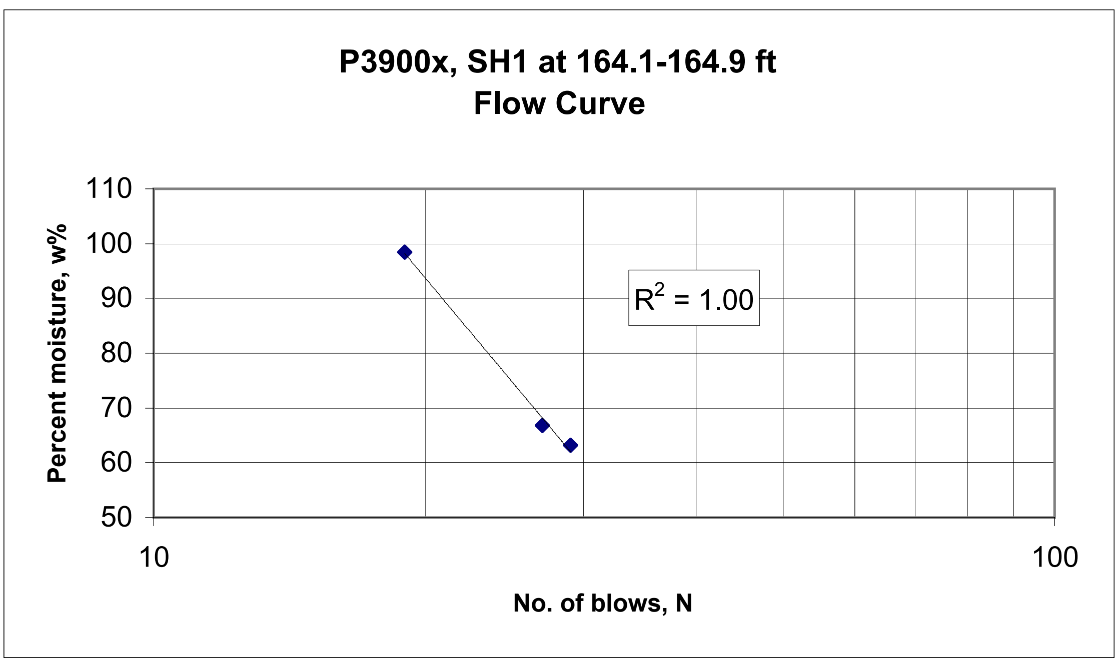
Fineness Modulus
0.08

Soil Consistency Test (Three-Point Liquid Limit Method)

Sample No.	P3900x, SH1 at 164.1-164.9 ft
Feature	Wolf Creek Dam
Project	USACE
Date	1/6/2008

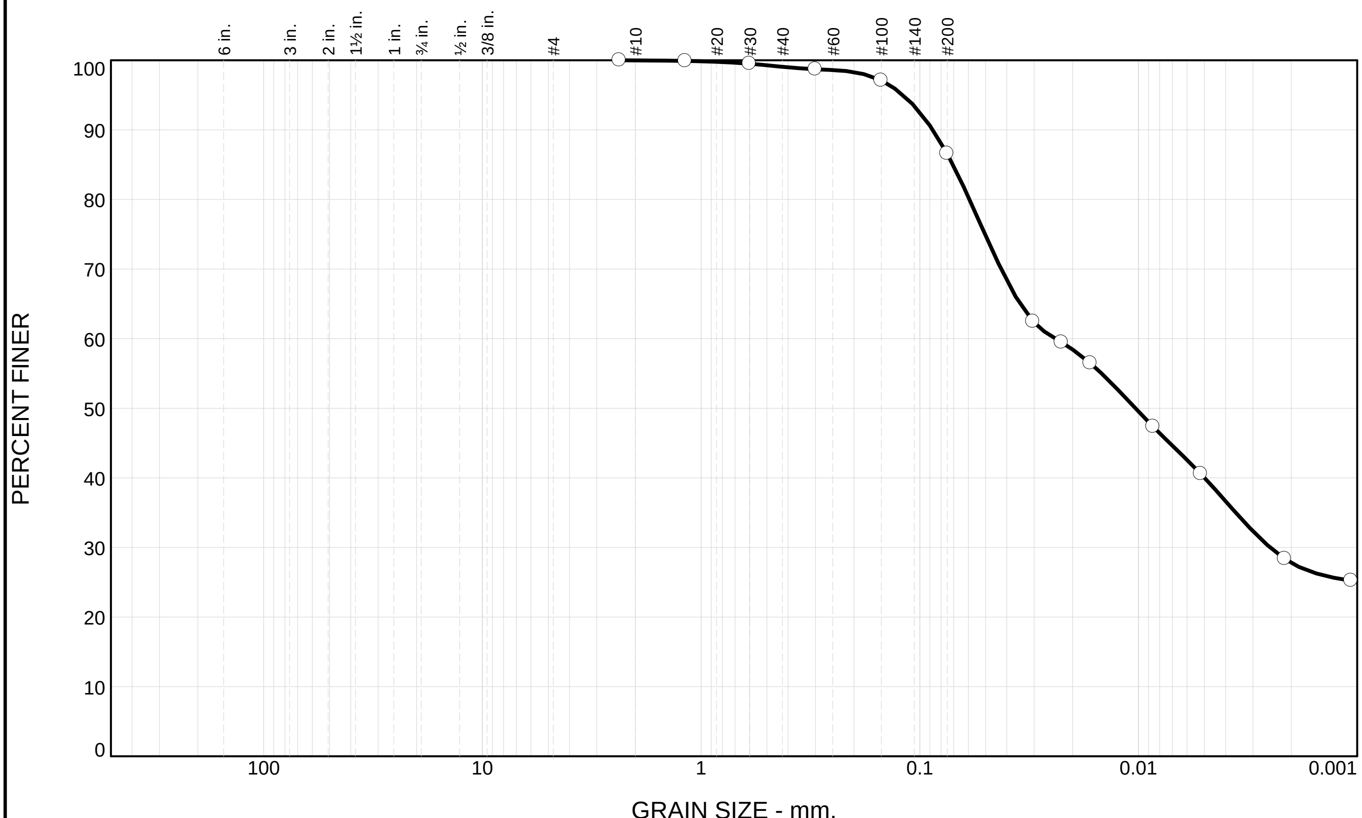
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	51	S-11	133	62	78
No. of blows	N/A	N/A	29	19	27
Mass of dish+wet soil (g)	12.348	17.201	21.060	22.903	18.230
Mass of dish+dry soil (g)	11.117	15.715	15.513	16.386	13.407
Mass of dish (g)	6.113	9.650	6.742	9.764	6.185
Mass of water (g)	1.231	1.486	5.547	6.517	4.823
Mass of dry soil (g)	5.004	6.065	8.771	6.622	7.222
% moisture	24.6	24.5	63.2	98.4	66.8
Average plastic limit	25				

LL = 75 **PL = 25** **PI = 50** **Fi = -196.6**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.9	12.5	46.6	40.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#8	100.0		
#16	99.9		
#30	99.5		
#50	98.7		
#100	97.1		
#200	86.6		

* (no specification provided)

Material Description

Lean clay

Atterberg Limits

PL= 19 LL= 47 PI= 28

Coefficients

D_{85}= 0.0705 D_{60}= 0.0240 D_{50}= 0.0103
D_{30}= 0.0025 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-7-6(25)

Remarks

Initial Moisture Content=27.0%
Specific Gravity=2.68

Sample Number: P4340x, ST5 **Depth:** 138.8-140.0 ft
Location: Sta 43+40 **Date:** 03/12/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 43+40
Depth: 138.8-140.0 ft **Sample Number:** P4340x, ST5
Material Description: Lean clay
Date: 03/12/2008 **PL:** 19 **LL:** 47 **PI:** 28
USCS Classification: CL **AASHTO Classification:** A-7-6(25)
Testing Remarks: Initial Moisture Content=27.0%
Specific Gravity=2.68

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	
#8	100.0
#16	99.9
#30	99.5
#50	98.7
#100	97.1
#200	86.6

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =100
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.0
Specific gravity of solids = 2.68
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	19.6	69.0	62.9	0.0136	69.0	5.0	0.0303	62.5
2.00	19.6	66.0	59.9	0.0136	66.0	5.5	0.0225	59.5
4.00	19.5	63.0	56.9	0.0136	63.0	6.0	0.0166	56.5
19.00	19.1	53.9	47.7	0.0137	53.9	7.5	0.0086	47.4
60.00	18.6	47.2	40.9	0.0138	47.2	8.6	0.0052	40.6
435.00	18.6	34.9	28.6	0.0138	34.9	10.6	0.0021	28.4
1860.00	18.3	31.8	25.4	0.0138	31.8	11.1	0.0011	25.2

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	0.9	12.5	13.4	46.6	40.0	86.6

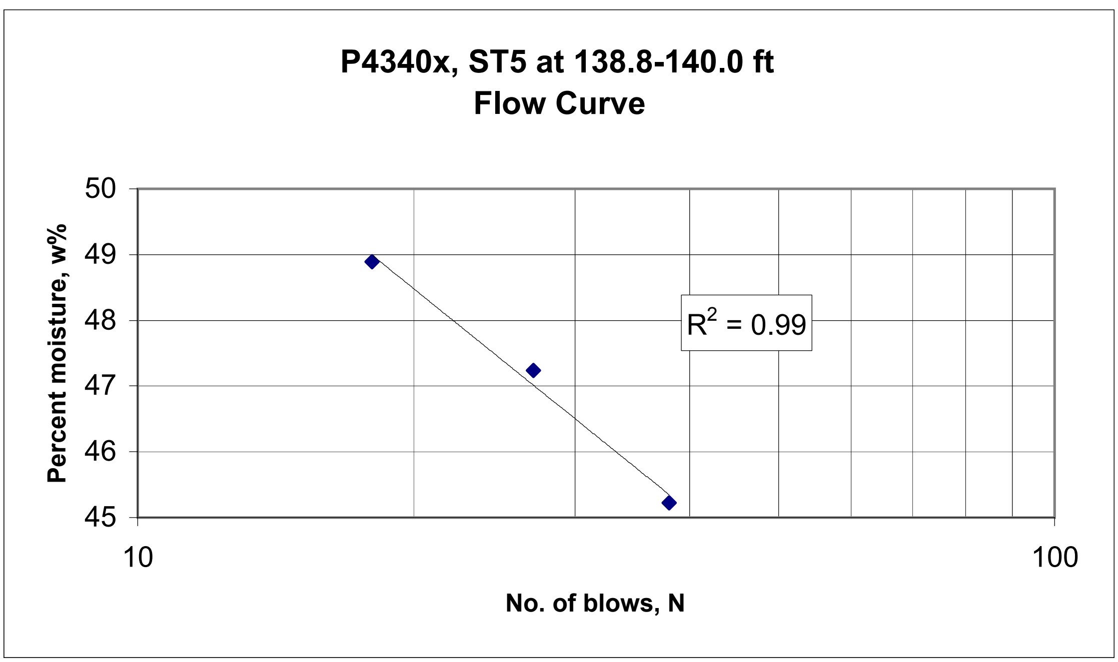
D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0025	0.0103	0.0240	0.0593	0.0705	0.0871	0.1192

Fineness Modulus
0.05

Soil Consistency Test (Three-Point Liquid Limit Method)

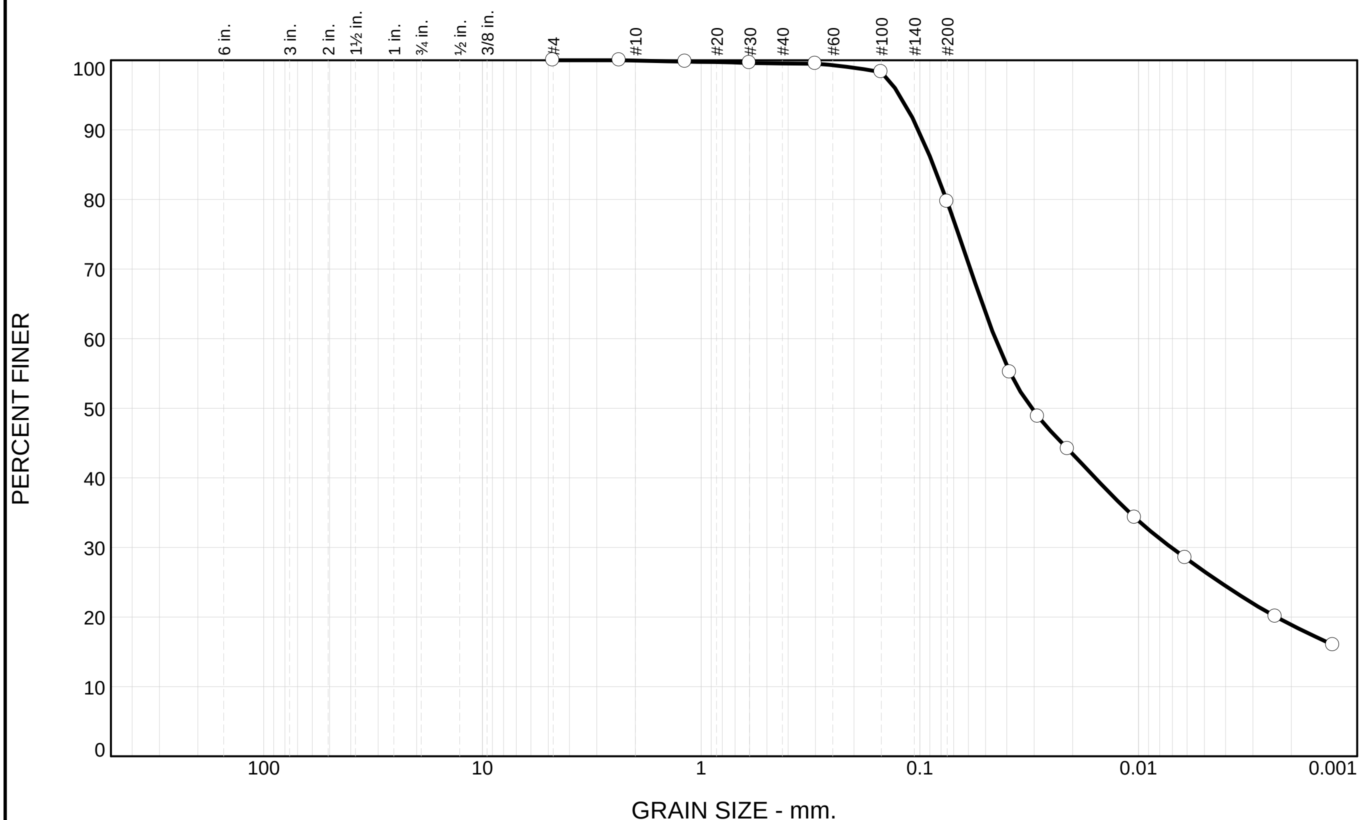
Sample No.	P4340x, ST5 at 138.8-140.0 ft					
Feature	Wolf Creek Dam					
Project	USACE					
Date	3/17/2008					
Test	Plastic Limit		Liquid Limit			
Trial No.	1	2	1	2	3	
Dish No.	156	62	139	140	116	
No. of blows	N/A	N/A	38	27	18	
Mass of dish+wet soil (g)	12.327	10.812	20.301	19.447	19.523	
Mass of dish+dry soil (g)	11.365	10.067	15.977	15.275	14.977	
Mass of dish (g)	6.384	6.217	6.416	6.443	5.679	
Mass of water (g)	0.962	0.745	4.324	4.172	4.546	
Mass of dry soil (g)	4.981	3.850	9.561	8.832	9.298	
% moisture	19.3	19.4	45.2	47.2	48.9	
Average plastic limit	19					

LL = 47 **PL = 19** **PI = 28** **Fi = -11.2**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.5	19.8	53.1	26.6

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	100.0		
#16	99.8		
#30	99.6		
#50	99.5		
#100	98.3		
#200	79.7		

* (no specification provided)

Material Description

Lean clay with sand

Atterberg Limits

PL= 15 LL= 33 PI= 18

Coefficients

D_{85}= 0.0868 D_{60}= 0.0452 D_{50}= 0.0308
D_{30}= 0.0071 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-6(13)

Remarks

Initial Moisture Content=21.7%
Specific Gravity=2.61

Sample Number: P4340x, ST7 **Depth:** 145.8-146.6 ft
Location: Sta 43+40 **Date:** 04/18/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 43+40
Depth: 145.8-146.6 ft   **Sample Number:** P4340x, ST7
Material Description: Lean clay with sand
Date: 04/18/2008   **PL:** 15   **LL:** 33   **PI:** 18
USCS Classification: CL   **AASHTO Classification:** A-6(13)
Testing Remarks: Initial Moisture Content=21.7%
Specific Gravity=2.61

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	100.0
#8	100.0
#16	99.8
#30	99.6
#50	99.5
#100	98.3
#200	79.7

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =80.1
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.61
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	21.5	49.5	43.8	0.0136	49.5	8.2	0.0388	55.2
2.00	21.3	44.5	38.7	0.0136	44.5	9.0	0.0288	48.8
4.00	21.3	40.8	35.0	0.0136	40.8	9.6	0.0211	44.2
19.00	20.3	33.2	27.2	0.0138	33.2	10.9	0.0104	34.3
60.00	19.4	28.8	22.6	0.0139	28.8	11.6	0.0061	28.5
445.00	18.9	22.2	15.9	0.0140	22.2	12.7	0.0024	20.1
1545.00	19.2	18.9	12.7	0.0140	18.9	13.2	0.0013	16.0

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	0.5	19.8	20.3	53.1	26.6	79.7

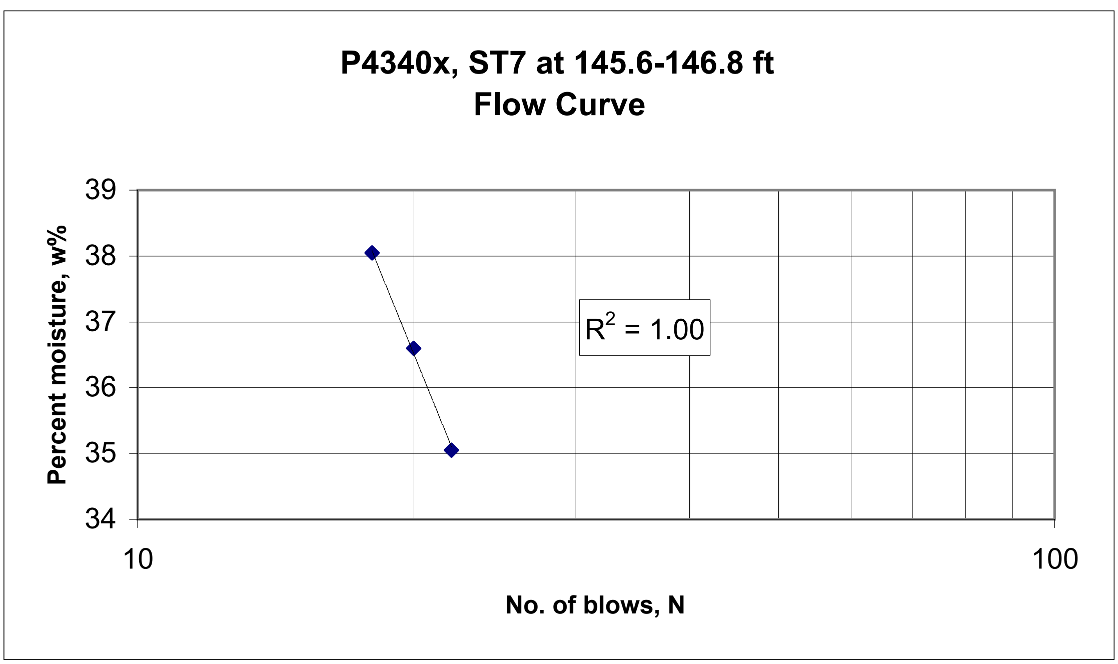
D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
		0.0023	0.0071	0.0308	0.0452	0.0756	0.0868	0.1016	0.1236

Fineness Modulus
0.03

Soil Consistency Test (Three-Point Liquid Limit Method)

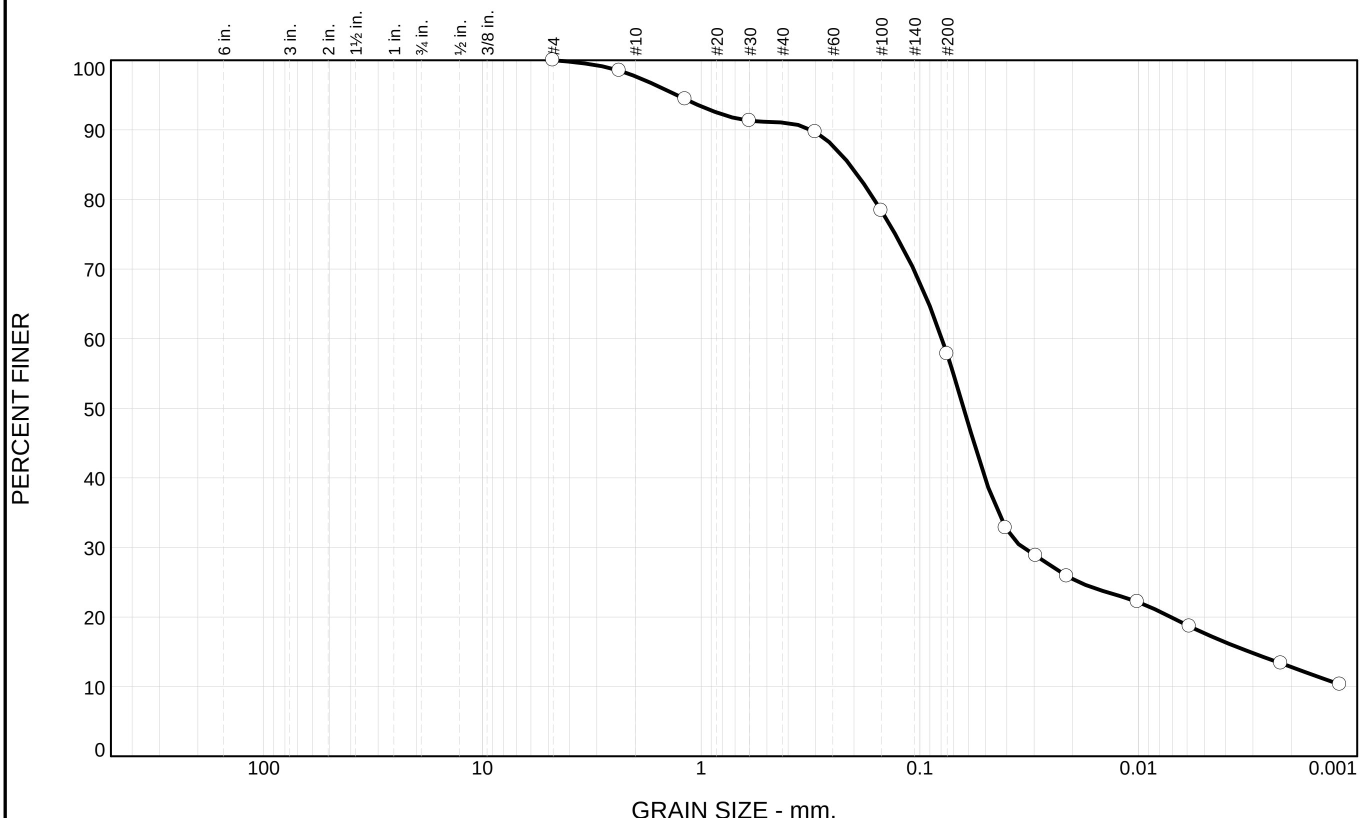
Sample No.	P4340x, ST7 at 145.6-146.8 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	4/18/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	S-40	S-1	S-20	S-2	S-58
No. of blows	N/A	N/A	22	20	18
Mass of dish+wet soil (g)	15.931	16.916	23.545	21.838	20.984
Mass of dish+dry soil (g)	14.942	15.900	19.553	18.155	17.326
Mass of dish (g)	8.579	9.325	8.165	8.091	7.711
Mass of water (g)	0.989	1.016	3.992	3.683	3.658
Mass of dry soil (g)	6.363	6.575	11.388	10.064	9.615
% moisture	15.5	15.5	35.1	36.6	38.0
Average plastic limit	15				

LL = 33 **PL = 15** **PI = 18** **Fi = -34.3**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	2.3	6.6	33.3	40.1	17.7

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	98.5		
#16	94.4		
#30	91.3		
#50	89.7		
#100	78.4		
#200	57.8		

* (no specification provided)

Material Description

Sandy silt

Atterberg Limits

PL= 27 LL= 45 PI= 17

Coefficients

D_{85}= 0.2089 D_{60}= 0.0792 D_{50}= 0.0630
D_{30}= 0.0339 D_{15}= 0.0031 D_{10}=
C_u= C_c=

Classification

USCS= ML AASHTO= A-7-6(9)

Remarks

Initial Moisture Content=30.2%
Specific Gravity=2.93

Sample Number: P4965x, ST5 **Depth:** 137.2-138.0 ft
Location: Sta 49+65
Date: 04/18/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 49+65
Depth: 137.2-138.0 ft **Sample Number:** P4965x, ST5
Material Description: Sandy silt
Date: 04/18/2008 **PL:** 27 **LL:** 45 **PI:** 17
USCS Classification: ML **AASHTO Classification:** A-7-6(9)
Testing Remarks: Initial Moisture Content=30.2%
Specific Gravity=2.93

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	100.0
#8	98.5
#16	94.4
#30	91.3
#50	89.7
#100	78.4
#200	57.8

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =81.6
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.93
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	21.6	34.0	28.3	0.0124	34.0	10.7	0.0405	32.8
2.00	21.4	30.6	24.9	0.0124	30.6	11.3	0.0294	28.8
4.00	21.3	28.1	22.3	0.0124	28.1	11.7	0.0212	25.9
19.00	20.0	25.2	19.2	0.0126	25.2	12.2	0.0101	22.2
60.00	19.3	22.3	16.1	0.0127	22.3	12.6	0.0058	18.7
435.00	19.4	17.7	11.5	0.0127	17.7	13.4	0.0022	13.4
1545.00	19.7	15.0	8.9	0.0127	15.0	13.8	0.0012	10.3

Fractional Components

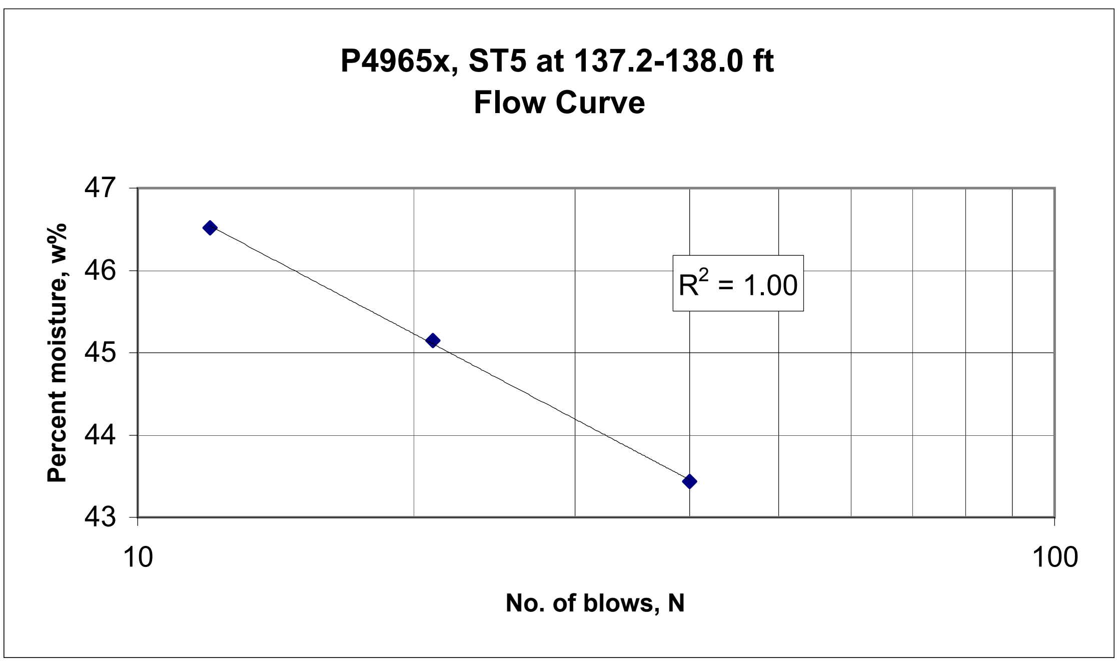
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	2.3	6.6	33.3	42.2	40.1	17.7	57.8

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
	0.0031	0.0071	0.0339	0.0630	0.0792	0.1615	0.2089	0.3123	1.2939

Fineness Modulus
0.48

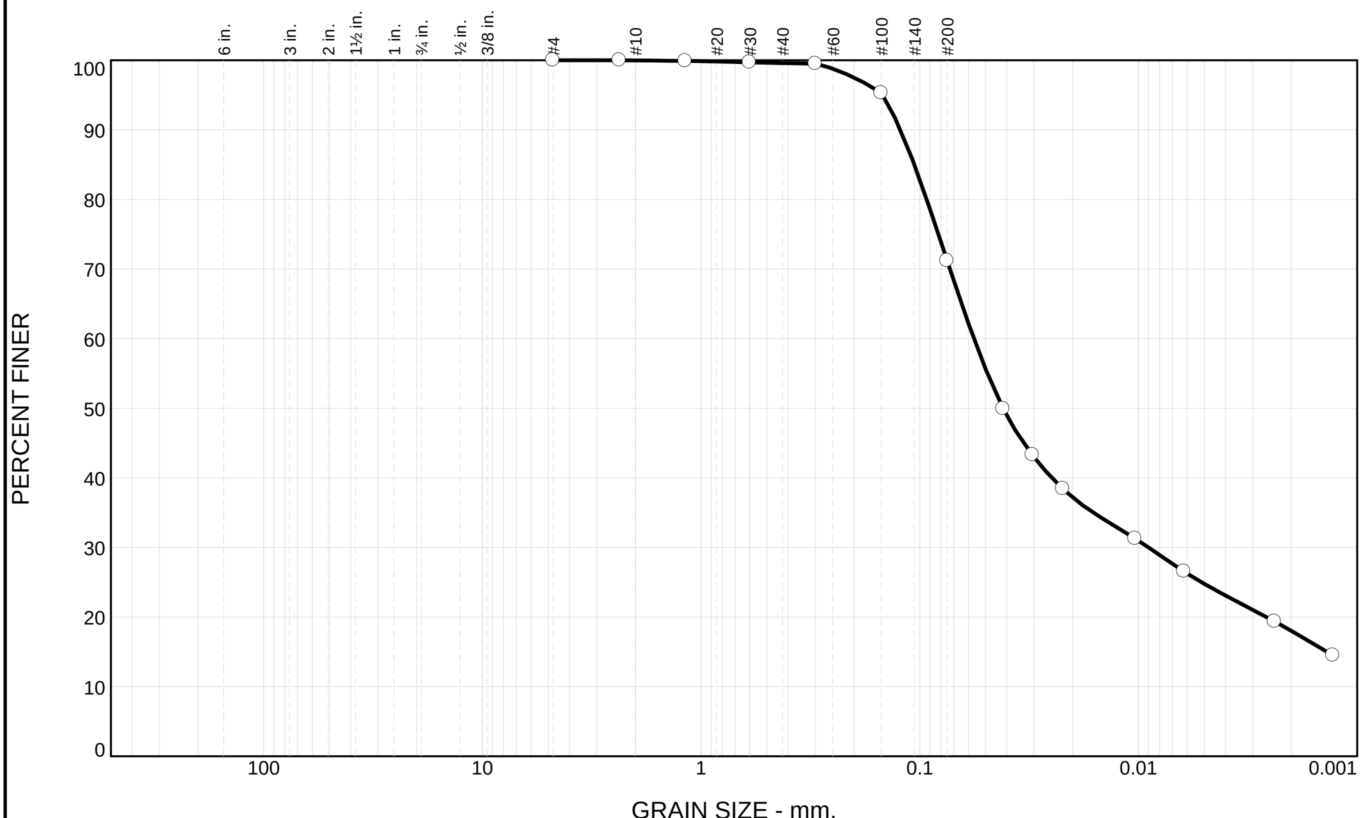
Soil Consistency Test (Three-Point Liquid Limit Method)						
Sample No.	P4965x, ST5 at 137.2-138.0 ft					
Feature	Wolf Creek Dam					
Project	USACE					
Date	4/18/2008					
Test	Plastic Limit		Liquid Limit			
Trial No.	1	2	1	2	3	
Dish No.	S-57	55	117	S-61	93	
No. of blows	N/A	N/A	40	21	12	
Mass of dish+wet soil (g)	15.798	14.171	19.295	23.551	20.912	
Mass of dish+dry soil (g)	14.138	12.493	15.176	18.852	16.286	
Mass of dish (g)	8.054	6.326	5.693	8.444	6.341	
Mass of water (g)	1.660	1.678	4.119	4.699	4.626	
Mass of dry soil (g)	6.084	6.167	9.483	10.408	9.945	
% moisture	27.3	27.2	43.4	45.1	46.5	
Average plastic limit	27					

LL = 44.66 **PL = 27.25** **PI = 17.41** **Fi = -5.9**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.4	28.4	46.4	24.8

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#8	100.0		
#16	99.9		
#30	99.7		
#50	99.5		
#100	95.3		
#200	71.2		

* (no specification provided)

Material Description

Lean clay with sand

Atterberg Limits

PL= 19 LL= 29 PI= 10

Coefficients

D_{85}= 0.1059 D_{60}= 0.0566 D_{50}= 0.0417
D_{30}= 0.0090 D_{15}= 0.0014 D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-4(5)

Remarks

Initial Moisture Content=22.8%
Specific Gravity=2.67

Sample Number: P4965x, ST6 **Depth:** 141.0-142.0 ft
Location: Sta 49+65 **Date:** 04/18/2008

BUREAU OF RECLAMATION	**Client:** U.S. Army Corps of Engineers **Project:** Foundation Grouting Wolf Creek Dam **Project No:** 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 49+65
Depth: 141.0-142.0 ft
Sample Number: P4965x, ST6
Material Description: Lean clay with sand
Date: 04/18/2008 **PL:** 19 **LL:** 29 **PI:** 10
USCS Classification: CL
AASHTO Classification: A-4(5)
Testing Remarks: Initial Moisture Content=22.8%
Specific Gravity=2.67

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	100.0
#8	100.0
#16	99.9
#30	99.7
#50	99.5
#100	95.3
#200	71.2

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =68.0
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.67
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	21.6	39.8	34.1	0.0133	39.8	9.8	0.0416	49.9
2.00	21.4	35.3	29.6	0.0133	35.3	10.5	0.0306	43.3
4.00	21.3	32.0	26.2	0.0133	32.0	11.0	0.0222	38.4
20.00	20.5	27.3	21.4	0.0135	27.3	11.8	0.0104	31.3
60.00	19.4	24.3	18.1	0.0137	24.3	12.3	0.0062	26.5
435.00	18.9	19.5	13.2	0.0138	19.5	13.1	0.0024	19.4
1545.00	19.2	16.1	9.9	0.0137	16.1	13.7	0.0013	14.5

Fractional Components

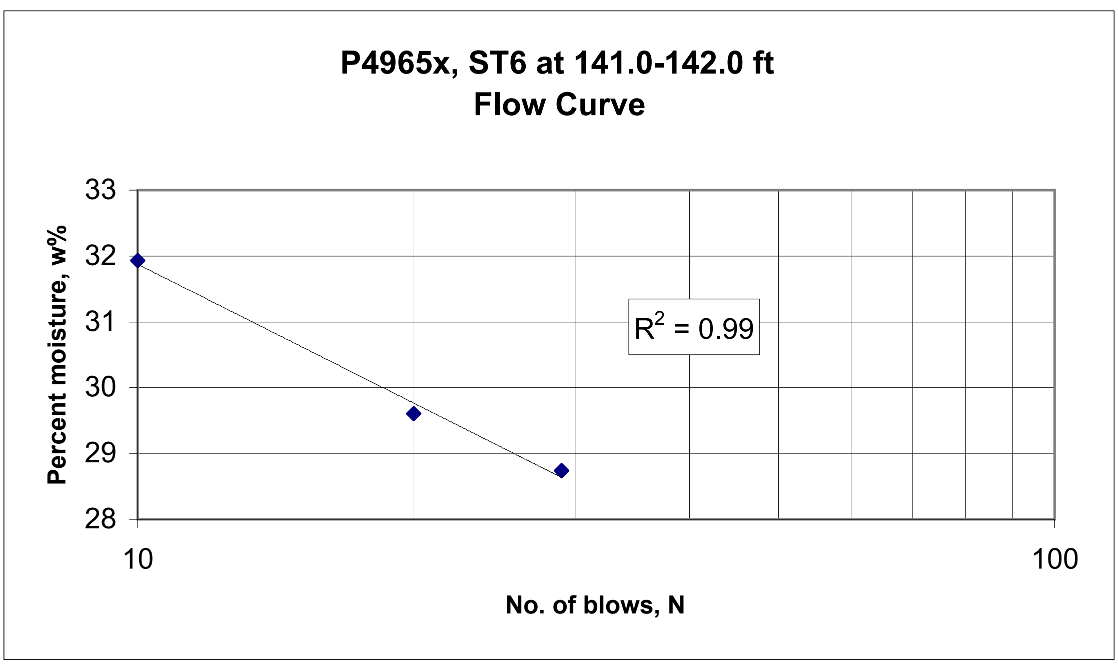
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	0.4	28.4	28.8	46.4	24.8	71.2

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
	0.0014	0.0026	0.0090	0.0417	0.0566	0.0930	0.1059	0.1226	0.1479

Fineness Modulus
0.06

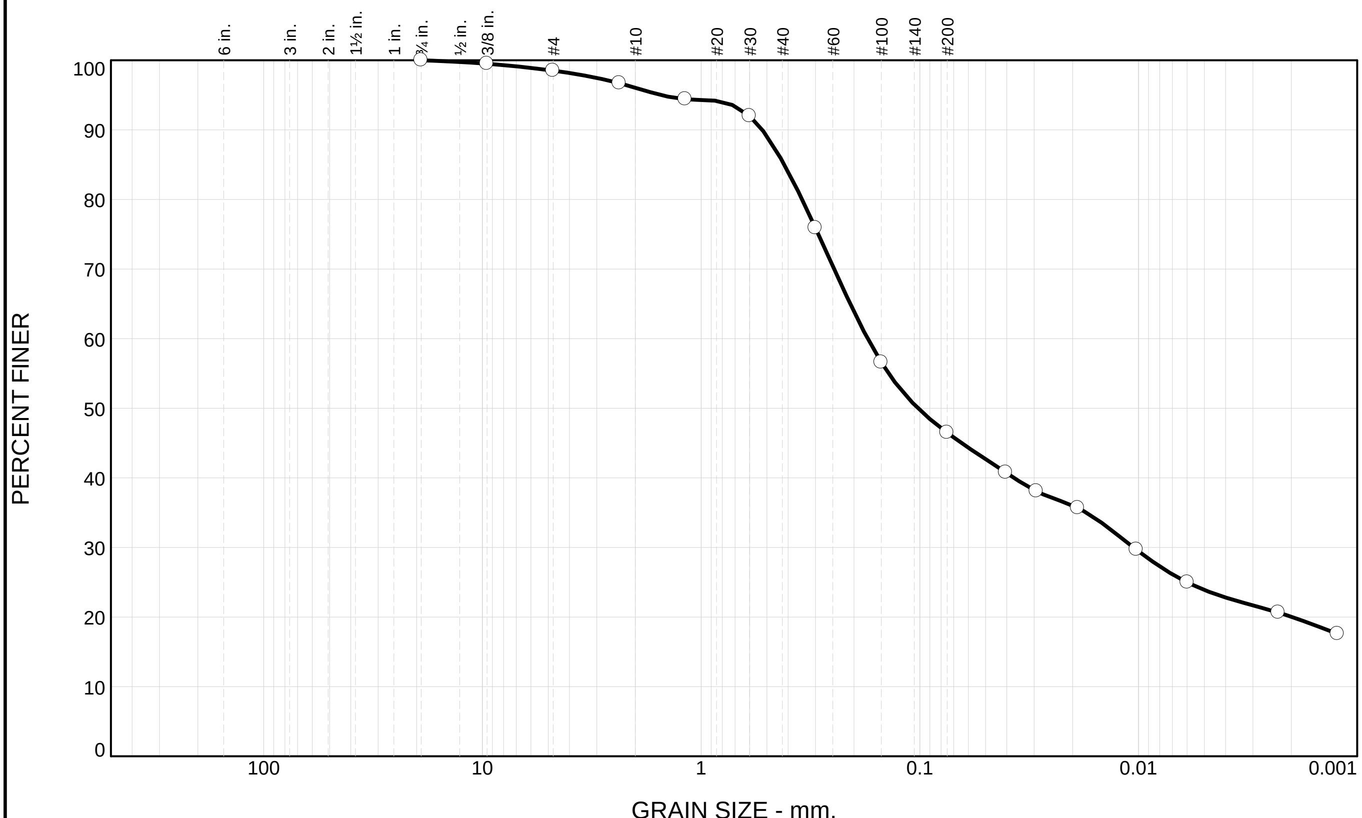
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	P4965x, ST6 at 141.0-142.0 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	4/18/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	118	89	S-29	73	62
No. of blows	N/A	N/A	29	20	10
Mass of dish+wet soil (g)	14.209	15.544	20.392	20.890	21.488
Mass of dish+dry soil (g)	12.870	14.087	17.687	17.575	17.792
Mass of dish (g)	5.771	6.231	8.274	6.379	6.216
Mass of water (g)	1.339	1.457	2.705	3.315	3.696
Mass of dry soil (g)	7.099	7.856	9.413	11.196	11.576
% moisture	18.9	18.5	28.7	29.6	31.9
Average plastic limit	18.7				

LL = 29.1 **PL = 18.7** **PI = 10.4** **Fi = -7.0**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	1.5	2.4	10.6	39.0	22.6	23.9

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.75	100.0		
.375	99.5		
#4	98.5		
#8	96.7		
#16	94.4		
#30	92.0		
#50	75.9		
#100	56.6		
#200	46.5		

* (no specification provided)

Material Description

Clayey sand

Atterberg Limits

PL= 20.6 LL= 35.4 PI= 14.8

Coefficients

D_{85}= 0.4163 D_{60}= 0.1731 D_{50}= 0.1020
D_{30}= 0.0105 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= SC AASHTO= A-6(3)

Remarks

Initial Moisture Content=17.2%
Specific Gravity=2.69

Sample Number: P5600x, ST1 **Depth:** 100.5-101.5 ft
Location: Sta 56+00 **Date:** 04/24/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 56+00
Depth: 100.5-101.5 ft
Sample Number: P5600x, ST1
Material Description: Clayey sand
Date: 04/24/2008 **PL:** 20.6 **LL:** 35.4 **PI:** 14.8
USCS Classification: SC **AASHTO Classification:** A-6(3)
Testing Remarks: Initial Moisture Content=17.2%
Specific Gravity=2.69

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	100.0
.375	99.5
#4	98.5
#8	96.7
#16	94.4
#30	92.0
#50	75.9
#100	56.6
#200	46.5

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 98.5
Weight of hydrometer sample =88
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.69
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	21.4	42.5	36.8	0.0133	42.5	9.3	0.0405	40.8
2.00	21.2	40.1	34.3	0.0133	40.1	9.7	0.0293	38.1
5.00	20.9	38.0	32.2	0.0133	38.0	10.1	0.0189	35.7
19.00	20.0	32.8	26.8	0.0135	32.8	10.9	0.0102	29.7
60.00	19.3	28.7	22.5	0.0136	28.7	11.6	0.0060	25.0
435.00	18.8	24.9	18.6	0.0137	24.9	12.2	0.0023	20.6
1545.00	19.5	22.0	15.9	0.0136	22.0	12.7	0.0012	17.6

Fractional Components

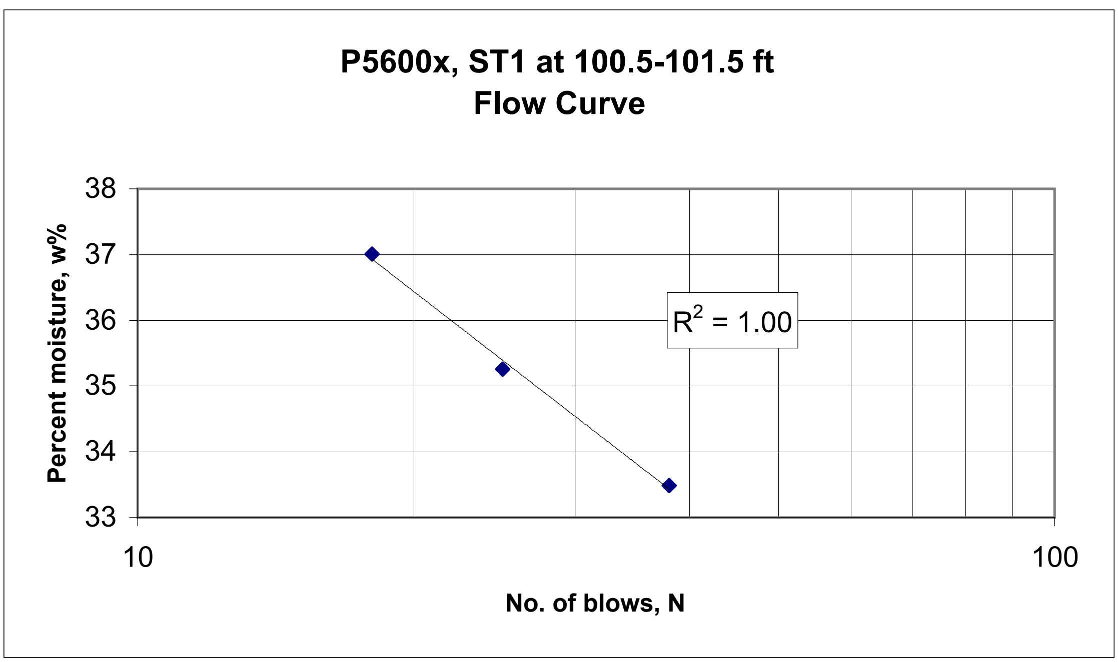
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	1.5	1.5	2.4	10.6	39.0	52.0	22.6	23.9	46.5

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
		0.0020	0.0105	0.1020	0.1731	0.3453	0.4163	0.5253	1.5214

Fineness Modulus
0.86

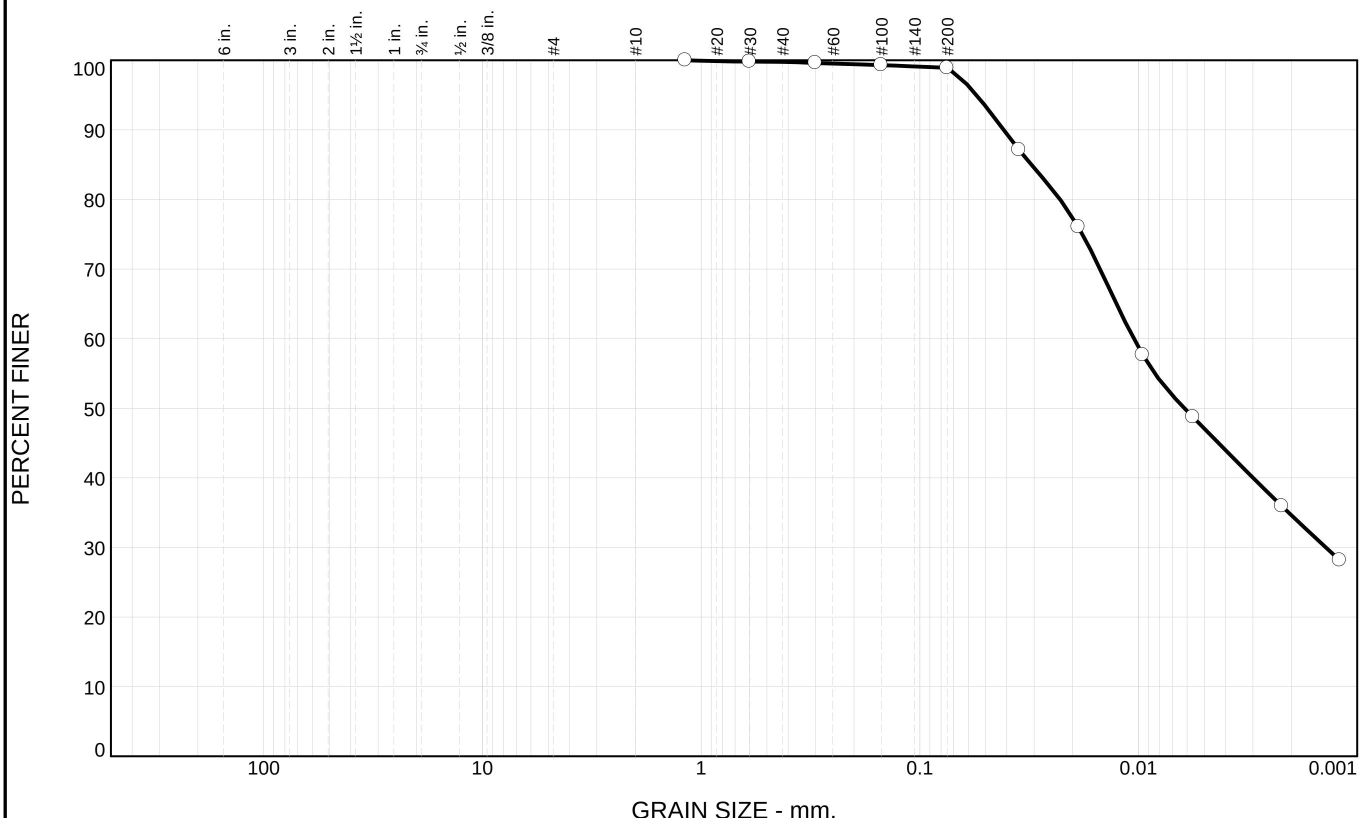
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	P5600x, ST1 at 100.5-101.5 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	4/21/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	144	S-42	99	S-15	S-41
No. of blows	N/A	N/A	38	25	18
Mass of dish+wet soil (g)	17.135	19.371	19.087	23.567	21.400
Mass of dish+dry soil (g)	15.309	17.646	15.873	19.630	17.676
Mass of dish (g)	6.478	9.212	6.276	8.464	7.613
Mass of water (g)	1.826	1.725	3.214	3.937	3.724
Mass of dry soil (g)	8.831	8.434	9.597	11.166	10.063
% moisture	20.7	20.5	33.5	35.3	37.0
Average plastic limit	20.6				

LL = 35.4 **PL = 20.6** **PI = 14.8** **Fi = -10.8**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.2	0.9	51.8	47.1

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#16	100.0		
#30	99.8		
#50	99.6		
#100	99.3		
#200	98.9		

* (no specification provided)

Material Description

Fat clay

Atterberg Limits

PL= 25 LL= 71 PI= 46

Coefficients

D_{85}= 0.0309 D_{60}= 0.0105 D_{50}= 0.0062
D_{30}= 0.0014 D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CH AASHTO= A-7-6(53)

Remarks

Initial Moisture Content=32.2%
Specific Gravity=2.78

Sample Number: P5600x, ST6 **Depth:** 110.2-110.9 ft
Location: Sta 56+00 **Date:** 04/24/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 56+00
Depth: 110.2-110.9 ft **Sample Number:** P5600x, ST6
Material Description: Fat clay
Date: 04/24/2008 **PL:** 25 **LL:** 71 **PI:** 46
USCS Classification: CH **AASHTO Classification:** A-7-6(53)
Testing Remarks: Initial Moisture Content=32.2%
Specific Gravity=2.78

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	
#8	
#16	100.0
#30	99.8
#50	99.6
#100	99.3
#200	98.9

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =53.9
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.78
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	21.5	54.0	48.3	0.0129	54.0	7.4	0.0352	87.1
4.00	20.9	48.0	42.2	0.0130	48.0	8.4	0.0189	76.1
19.00	20.0	38.0	32.0	0.0131	38.0	10.1	0.0096	57.7
60.00	19.3	33.2	27.0	0.0133	33.2	10.9	0.0056	48.7
435.00	18.9	26.2	19.9	0.0133	26.2	12.0	0.0022	36.0
1545.00	19.3	21.8	15.6	0.0133	21.8	12.7	0.0012	28.2

Fractional Components

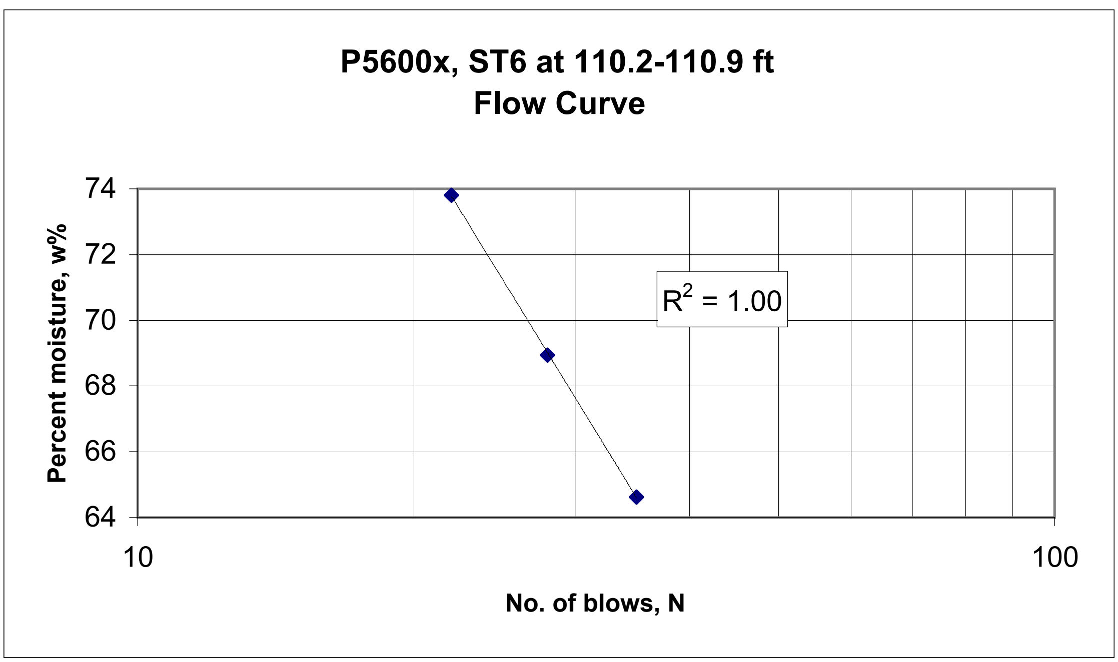
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	0.2	0.9	1.1	51.8	47.1	98.9

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0014	0.0062	0.0105	0.0228	0.0309	0.0414	0.0550

Fineness Modulus
0.01

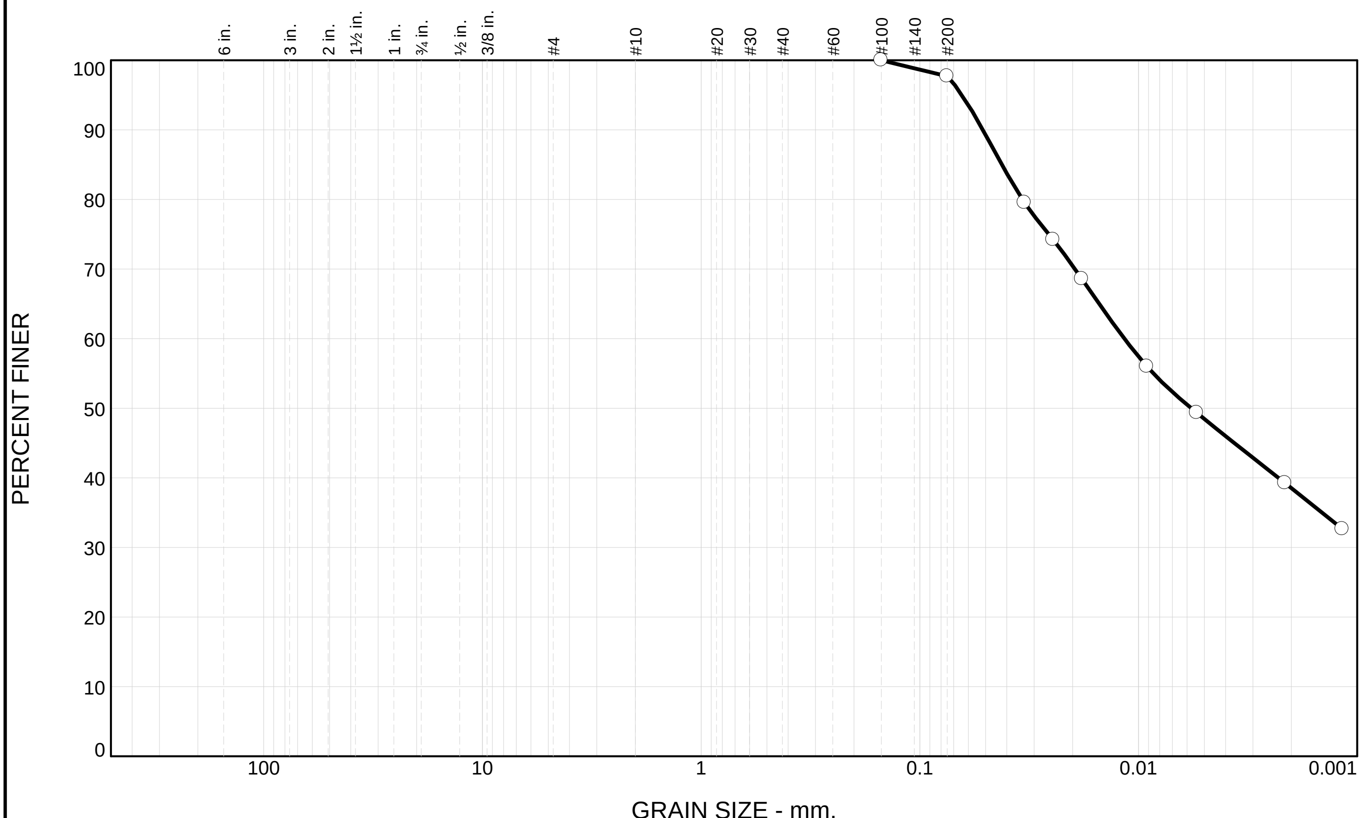
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	P5600x, ST6 at 110.2-110.9 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	4/21/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	121	S-7	130	87	104
No. of blows	N/A	N/A	35	28	22
Mass of dish+wet soil (g)	15.373	17.469	20.782	17.937	16.638
Mass of dish+dry soil (g)	13.613	15.886	14.964	13.167	12.309
Mass of dish (g)	6.762	9.601	5.962	6.249	6.443
Mass of water (g)	1.760	1.583	5.818	4.770	4.329
Mass of dry soil (g)	6.851	6.285	9.002	6.918	5.866
% moisture	25.7	25.2	64.6	69.0	73.8
Average plastic limit	25.4				

LL = 71.2 **PL = 25.4** **PI = 45.8** **Fi = -45.5**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.0	2.3	49.2	48.5

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#100	100.0		
#200	97.7		

* (no specification provided)

Material Description

Fat clay

Atterberg Limits

PL= 25.4 LL= 56.9 PI= 31.5

Coefficients

D_{85}= 0.0421 D_{60}= 0.0116 D_{50}= 0.0057
D_{30}= D_{15}= D_{10}=
C_u= C_c=

Classification

USCS= CH AASHTO= A-7-6(36)

Remarks

Initial Moisture Content=31.4%
Specific Gravity=2.73

Sample Number: P6185x, ST6 **Depth:** 100.2-101.1 ft
Location: Sta 61+85 **Date:** 04/24/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 61+85
Depth: 100.2-101.1 ft **Sample Number:** P6185x, ST6
Material Description: Fat clay
Date: 04/24/2008 **PL:** 25.4 **LL:** 56.9 **PI:** 31.5
USCS Classification: CH **AASHTO Classification:** A-7-6(36)
Testing Remarks: Initial Moisture Content=31.4%
Specific Gravity=2.73

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	
#8	
#16	
#30	
#50	
#100	100.0
#200	97.7

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =67.1
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.73
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	21.6	60.0	54.3	0.0131	60.0	6.5	0.0332	79.5
2.00	21.5	56.4	50.7	0.0131	56.4	7.0	0.0246	74.2
4.00	21.3	52.6	46.8	0.0131	52.6	7.7	0.0182	68.6
19.00	20.4	44.2	38.2	0.0133	44.2	9.0	0.0091	56.0
60.00	19.3	39.9	33.7	0.0134	39.9	9.8	0.0054	49.4
435.00	18.8	33.1	26.8	0.0135	33.1	10.9	0.0021	39.3
1545.00	19.2	28.5	22.3	0.0135	28.5	11.6	0.0012	32.6

Fractional Components

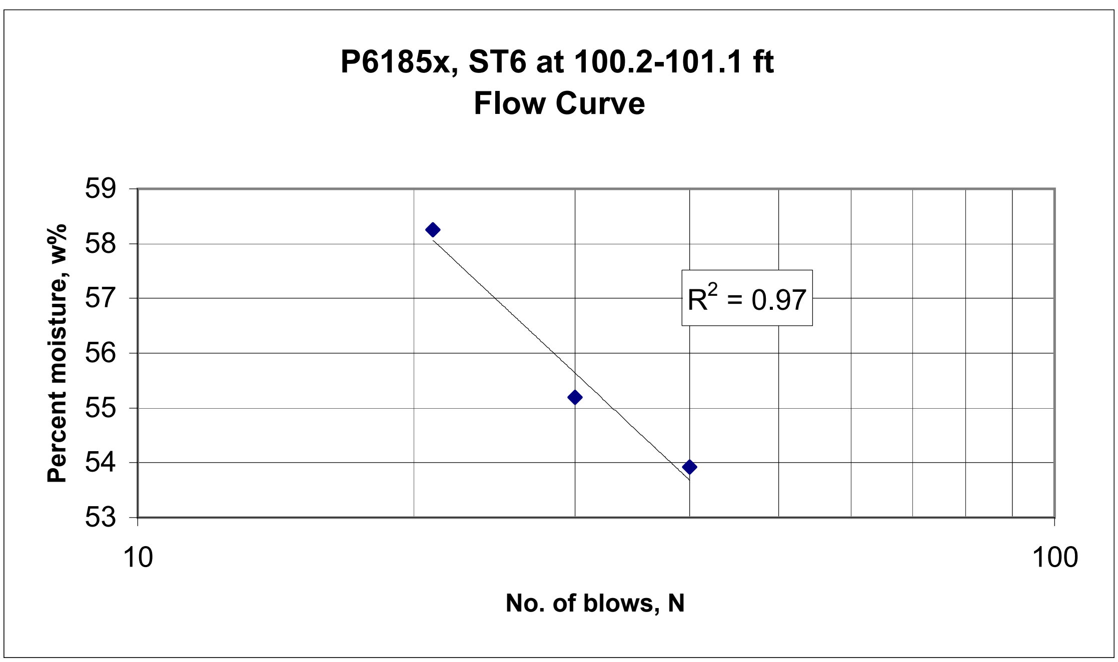
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	0.0	2.3	2.3	49.2	48.5	97.7

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
				0.0057	0.0116	0.0340	0.0421	0.0515	0.0641

Fineness Modulus
0.00

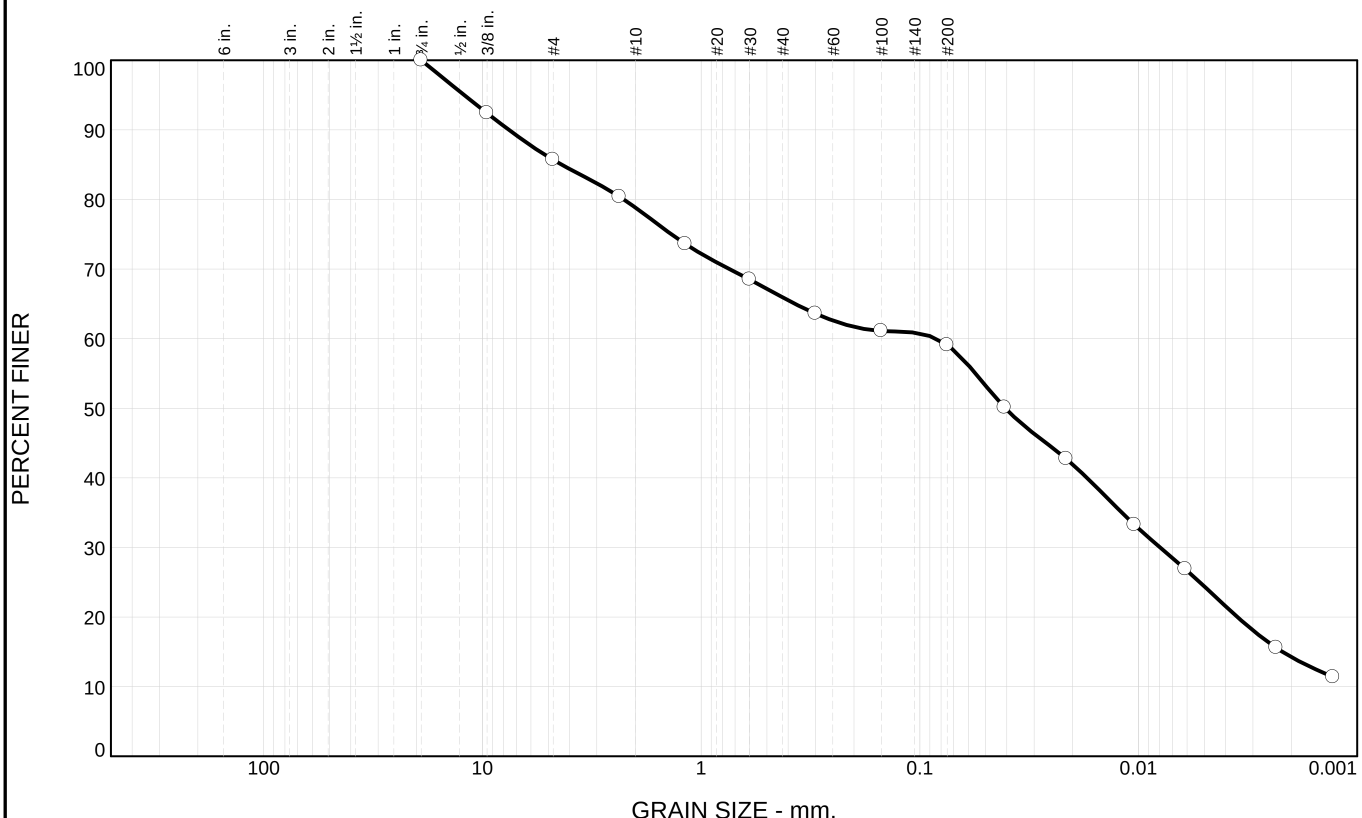
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	P6185x, ST6 at 100.2-101.1 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	4/21/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	139	72	156	116	54
No. of blows	N/A	N/A	40	30	21
Mass of dish+wet soil (g)	14.734	15.392	16.754	17.435	18.180
Mass of dish+dry soil (g)	13.044	13.549	13.121	13.254	13.749
Mass of dish (g)	6.416	6.248	6.384	5.679	6.143
Mass of water (g)	1.690	1.843	3.633	4.181	4.431
Mass of dry soil (g)	6.628	7.301	6.737	7.575	7.606
% moisture	25.5	25.2	53.9	55.2	58.3
Average plastic limit	25.4				

LL = 56.9 **PL = 25.4** **PI = 31.5** **Fi = -15.6**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	14.3	6.8	12.9	6.9	34.7	24.4

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.75	100.0		
.375	92.4		
#4	85.7		
#8	80.4		
#16	73.6		
#30	68.5		
#50	63.6		
#100	61.1		
#200	59.1		

* (no specification provided)

Material Description

Sandy lean clay

Atterberg Limits

PL= 22.9 LL= 43.6 PI= 20.7

Coefficients

D_{85}= 4.3423 D_{60}= 0.0838 D_{50}= 0.0407
D_{30}= 0.0080 D_{15}= 0.0022 D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-7-6(10)

Remarks

Initial Moisture Content=25.5%
Specific Gravity=2.71

Sample Number: P6750x, ST8 **Depth:** 87.2-88.3 ft
Location: Sta 67+50 **Date:** 04/24/2008

BUREAU OF RECLAMATION

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project No: 71N **Figure**

GRAIN SIZE DISTRIBUTION TEST DATA

5/1/2008

Client: U.S. Army Corps of Engineers
Project: Foundation Grouting Wolf Creek Dam
Project Number: 71N
Location: Sta 67+50
Depth: 87.2-88.3 ft   **Sample Number:** P6750x, ST8
Material Description: Sandy lean clay
Date: 04/24/2008   **PL:** 22.9   **LL:** 43.6   **PI:** 20.7
USCS Classification: CL   **AASHTO Classification:** A-7-6(10)
Testing Remarks: Initial Moisture Content=25.5%
Specific Gravity=2.71

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	100.0
.375	92.4
#4	85.7
#8	80.4
#16	73.6
#30	68.5
#50	63.6
#100	61.1
#200	59.1

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 85.7
Weight of hydrometer sample =57.9
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.71
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	21.6	40.0	34.3	0.0131	40.0	9.7	0.0410	50.1
4.00	21.4	35.0	29.3	0.0132	35.0	10.6	0.0214	42.7
19.00	20.1	28.8	22.8	0.0134	28.8	11.6	0.0104	33.3
60.00	19.3	24.6	18.4	0.0135	24.6	12.3	0.0061	26.9
451.00	19.1	16.9	10.7	0.0136	16.9	13.5	0.0023	15.6
1545.00	19.2	14.0	7.8	0.0135	14.0	14.0	0.0013	11.4

Fractional Components

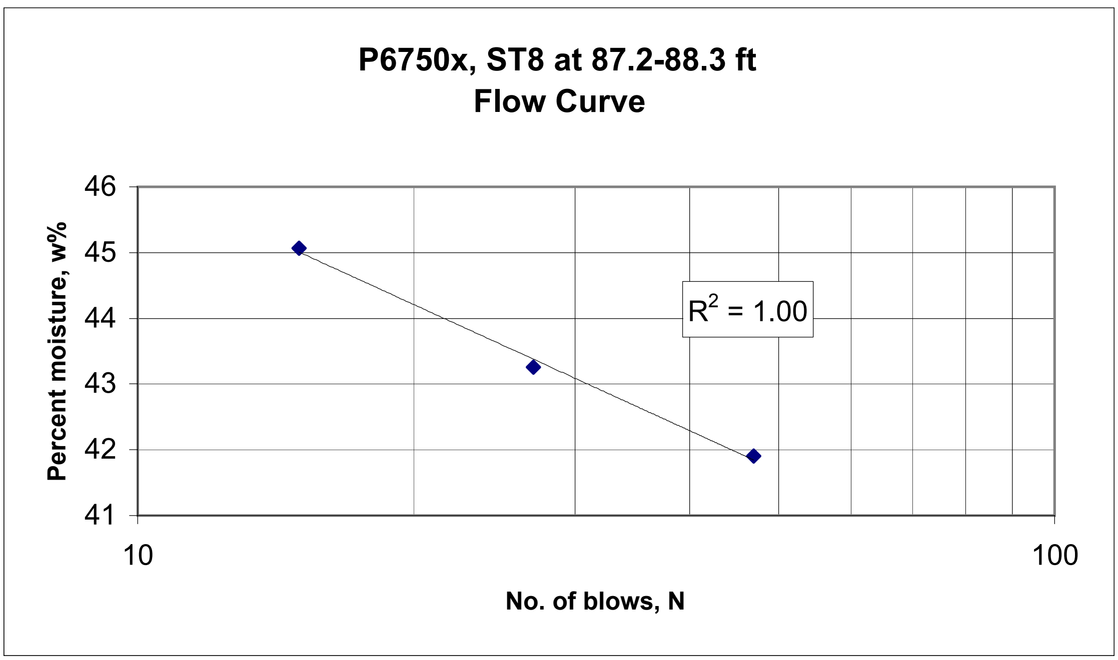
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	14.3	14.3	6.8	12.9	6.9	26.6	34.7	24.4	59.1

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
	0.0022	0.0035	0.0080	0.0407	0.0838	2.2570	4.3423	7.5686	12.1184

Fineness Modulus
1.75

Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	P6750x, ST8 at 87.2-88.3 ft				
Feature	Wolf Creek Dam				
Project	USACE				
Date	4/21/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	S-26	133	S-12	136	108
No. of blows	N/A	N/A	47	27	15
Mass of dish+wet soil (g)	18.877	13.871	23.051	20.922	20.303
Mass of dish+dry soil (g)	17.138	12.556	19.133	16.701	15.963
Mass of dish (g)	9.659	6.743	9.784	6.942	6.333
Mass of water (g)	1.739	1.315	3.918	4.221	4.340
Mass of dry soil (g)	7.479	5.813	9.349	9.759	9.630
% moisture	23.3	22.6	41.9	43.3	45.1
Average plastic limit	22.9				

LL = 43.6 **PL = 22.9** **PI = 20.7** **Fi = -6.4**



Remarks:

Appendix B: Hole Erosion Test Data Records and Analysis Charts

Sample No	USCS	Test Sequence Number	Depth Interval ft	Initial Moisture Content %	Dry Unit Weight lbf/ft^3	Maximum HET head mm	Initial Hole Diameter mm	Final Hole Diameter mm	Wan & Fell I_{HET}	Wan & Fell τ_c Pa	Bonelli I_{HET}	Bonelli τ_c Pa	Remarks
E3562X, SH15	CL	1	211.8-212.2	23.2	97.7	800	6.35	6.6		> 143			Did not achieve true progressive erosion. Erodibility parameters computed from observed cleanout erosion, but hole stabilized afterward, so true values are probably higher. **Maximum stress applied was approximately 143 Pa.**
		3	212.3-212.7	23.2	99.8	1585	6.35	7.0		> 236			Did not achieve progressive erosion. Some cleanout erosion observed, but hole stabilized. There was an anomalous jump in flow near end of test, but no observed erosion corresponding to it. **Maximum stress applied was approximately 236 Pa.**
		11	211.1-211.5	23.2	97.3	3400	6.35	8.5	4.57	514	4.65	517	Good test.
E3513X1, S40	CL	2	222.8-223.2	23.4	101.0	1585	6.35			> 223			Did not achieve progressive erosion. Some cleanout erosion observed, but hole stabilized. **Maximum stress applied was approximately 223 Pa.**
		4	223.3-223.7	23.4	100.1	1565	6.35	13.3	4.22	317	4.24	316	Good test. Scarified hole more than in previous tests. Progressive erosion began about 25 minutes after increasing head to 1565 mm.
E3548X, SH16	CL	5	221.8-222.2	23.1	102.3	1575	9.53			> 376			No erosion at maximum head, despite pre-drilling a larger hole. Also tried rescarifying hole after 1 hour and restarting test, but still could not cause erosion. **Maximum applied stress was 376 Pa.**
		9	222.2-222.6	23.1	103.2	3200	6.35	10.5	4.33	411	4.30	422	Good test. Progressive erosion occurred from the beginning. Bonelli analysis and Wan/Fell analysis produce almost the same result.
P3900X, SH1	CH	6	164.3-164.7	37.0	84.8	1590	6.35			approx. 250 or greater			Slow erosion throughout test…ran 5 hours the first day and 30 minutes the second day. Never achieved progressive erosion, although it appeared that it may have been just starting as test was ended. Subjective interpretation suggests critical shear approximately 250 Pa.
		8	uncertain (either directly above or below test 6)	37.0	85.0	3200	6.35	12.5	4.28	488	4.78	insufficient data	Erosion proceeded very rapidly. As erosion was really beginning to accelerate, outflow drain became plugged, submerging V-notch weir. Still able to perform analysis, although more data would have been helpful. Not able to determine critical shear stress by Bonelli method.
E3548X, SH12	(CL)s	7	211.2 - 211.6	20.7	100.6	1590	6.35	7.0		> 215			Soil around entrance of hole cracked during drilling of hole. At start of test this soil spalled off, causing a particle from the upstream face to lodge in the hole entrance at about 2.5 minutes. It was cleared by momentarily reversing the flow. No enlargement of hole occurred after this time, even at maximum test head for a duration of about 2 hours. **Maximum applied stress approx. 215 Pa.**
		10	211.6 - 212.0	20.7	103.8	5300	6.35	8.0		> 900			Very slow increase in flow rate at 3200, 4800, and 5300 mm, but rate of flow change always declining over time. No progressive erosion. **Maximum applied stress = 903 Pa**.

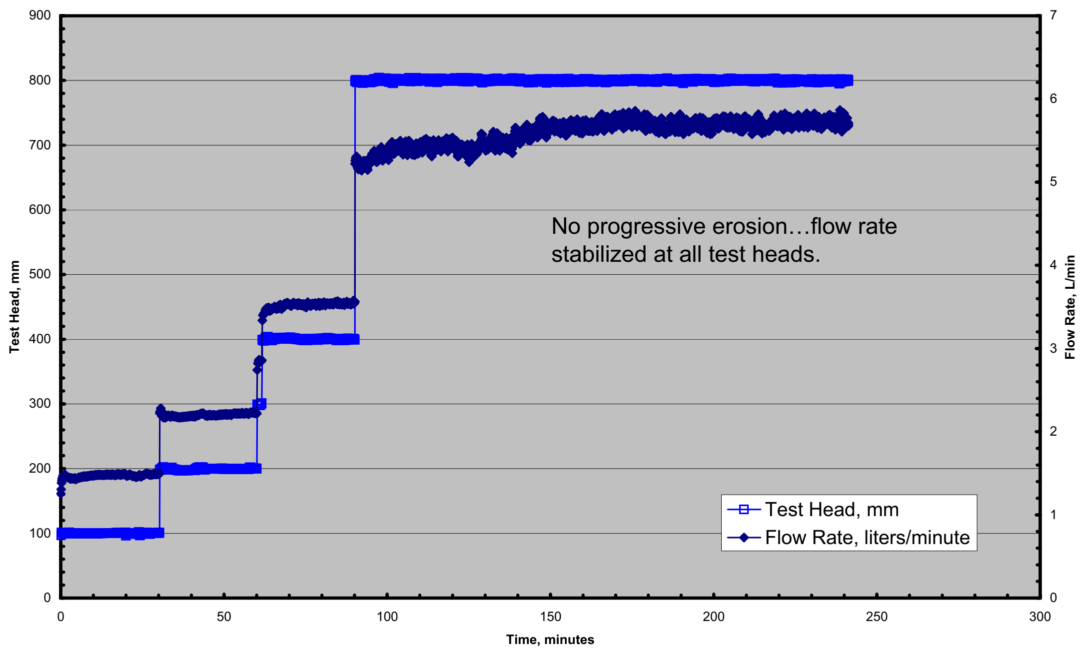
									Wan & Fell		Bonelli		
Sample No	USCS	Test Sequence Number	Depth Interval ft	Initial Moisture Content %	Dry Unit Weight lbf/ft^3	Maximum HET head mm	Initial Hole Diameter mm	Final Hole Diameter mm	I_{HET}	τ_c Pa	I_{HET}	τ_c Pa	Remarks
E3562X, SH12	CL	12	205.6 - 206.0	23.2	98.9	3200	6.35	10.0	4.33	429	4.44	409	Good test.
E3513X1, S36	CL	13	215.0 - 215.4	23.8	105.4	3200	6.35	12.0	4.41	196	4.31	356	Good test. No erosion at 1600 mm; very rapid erosion after increasing head to 3200 mm.
		18	214.6 - 215.0	25.0	98.2	4000	6.35	11.9	4.24	536	4.75	174	Good test, but last incremental head increase may have been a little too large. Erosion was pretty rapid at 4000 mm.
P4340X, ST5	CL	14	139.4 - 139.8	#N/A	#N/A	800	6.35	#N/A					Busted test. Sample failed rapidly through a void along the wall of the tube.
		17	139.0 - 139.4	27.0	96.4	2000	6.35	20.2	3.38	452	3.51	442	Good test, but maybe started with too much head. Erosion was extremely rapid. Final hole is very rough.
		19	140.0 - 140.4	27.0	97.8	5300	6.35	12.0	4.48	1144	4.22	1172	Good test. Eroded nicely after a few minutes at 5300 mm.
E3548X, SH14	(CL)s	15	217.9 - 218.3	27.0	101.7	3200	6.35	9.3	4.52	442	4.46	456	Good test. Eroded nicely when head was increased to 3200 mm.
E3560X, SH2	CL	16	209.9 - 210.3	22.1	104.5	4800	6.35	10.1	5.01	774	4.85	823	Good test. Eroded nicely when head was increased to 4800 mm, but discharge was clear, even when erosion was occurring. Erosion was occurring entirely by detachment of clay chunks (no fines suspended in the flow)
E3562X, SH7	CL	20	195.3 - 195.7	30.1	84.2	750	6.35	12.0	3.86	91.6	3.96	87.9	Good test. Eroded nicely from the very start at 750 mm. Flow tripled in 10 minutes. Soil was somewhat loose against wall of tube, but did not cause a problem running the test.
E3513X, ST2	s(CL)	21	194.7 - 195.1	29.3	94.6	200	8.0	#N/A					Failed test. Drill hit a piece of gravel and deflected, causing initial hole to be crooked, oblong, and about 8 mm diameter. During the test there was extreme scour at upstream and downstream ends, but a small section of hole in middle of specimen did not erode at all (it seems to be through a clay layer, whereas the rest of the specimen is very sandy, with occasional coarse gravel. Top side of hole caved in at u/s end early in the test.
		23	195.1 - 195.5	29.3	92.9	565	8.50	14.9	3.44	128.2	3.41	130.2	Good test. Eroded hole is unusual in shape, but flow was accelerating nicely at the end of the test and hole diameter seems to be about the same throughout the specimen. Initial hole was about 8.5 mm diameter because we hit gravel while drilling.
E3513X1, S31	CL	22	204.4 - 204.8	23.9	102.8	3700	6.35	12.6	4.84	504.7	4.85	523.1	Good test. Flow accelerating at end of test, although discharge only slightly turbid. Most erosion is of flakes or small chunks, not individual fines particles.

Sample No	USCS	Test Sequence Number	Depth Interval ft	Initial Moisture Content %	Dry Unit Weight lbf/ft^3	Maximum HET head mm	Initial Hole Diameter mm	Final Hole Diameter mm	Wan & Fell I_{HET}	Wan & Fell τ_c Pa	Bonelli I_{HET}	Bonelli τ_c Pa	Remarks
P5600x, ST1	SC	24	100.7 - 101.1	17.2	106.3	5370	6.35	6.4		> 752			No progressive erosion at maximum head.
		33	101.1 - 101.5	17.2	107.6	3200	9.53	11.3	4.56	569.7	4.73	456.7	Used a 3/8" hole. Progressive erosion occurred at 3200 mm. At end of test, downstream portion of hole was greatly enlarged and downstream end plate seemed to be limiting the flow. Analysis is sensitive to range of data analyzed.
P5600x, ST6	CH	25	110.3 - 110.7	32.2	84.7	5400	6.35	9.9	5.19	904	5.20	894	Good test. Slow erosion at maximum head. Relatively clear discharge even when erosion was occurring.
P4340x, ST7	(CL)s	26	145.8 - 146.2	21.7	105.8	1700	6.35	9.4	4.29	247	4.75	218	Difficult test to analyze. Erosion did occur, but was erratic. May have been affected by a few pieces of gravel (some visible at downstream face). Analysis was performed using the initial period of progressive erosion, before flow became erratic.
		32	146.2 - 146.6	21.7	104.4	2250	6.35	10.6	4.40	354	4.43	350	Good test, although erosion seemed to pause briefly before accelerating. Good agreement with test 26 result.
P6750x, ST8	s(CL)	27	87.3 - 87.7	25.5	97.8	3200	6.35	13.4	3.68	626	4.41	552	Struck gravel while drilling hole. Hole is angled and maybe slightly enlarged. There was a short period of erosion at 2250 mm head, but the downstream 25-mm end plate quickly became clogged by medium gravel. 3-4 gravel particles were lodged in the orifice when test was finally ended. Analyzed the 3-minute period of erosion that seemed to precede clogging.
		28	87.7 - 88.1	25.5		#N/A							Unsuccessful. Attempted to run without a downstream end plate due to presence of gravel (encountered during hole drilling), but sample immediately slid out of tube when head was applied.
P4965X, ST5	ML	29	137.3 - 137.7	30.2	90.7	1600	6.35	9.3	3.6 to 3.8	59 to 196			Progressive erosion was just beginning at 1600 mm head, when everything suddenly became erratic. Specimen eventually breached along edge of tube. There may have been loose gravel pockets in this specimen. Period of progressive erosion was very short...difficult to analyze.
		34	138.2 - 138.6	30.2	93.2	2250	6.35	18.5	3.53	515	3.62	506	Sample was loose in tube and cracked longitudinally during hole drilling. Progressive erosion began at 2250 mm head, and was marked by several short periods of hole clogging. Final hole is very rough and of variable diameter along its length.
P6185x, ST6	CH	30(a)	100.3 - 100.7	31.4	89.6	5400	6.35	8.0		> 880			No erosion at maximum head.
		30(b)	100.3 - 100.7	31.4	89.6	5400	9.53	11.0		> 1210			Enlarged hole to 3/8" and re-tested. No erosion at maximum head.
		30(c)	100.3 - 100.7	31.4	89.6	5100	12.70	13.0		> 1600			Slight flow increase over ~20 minutes time at max head, but flow was not accelerating and progressive erosion had not yet occurred. Hose on water supply came loose to end test.
P4965X, ST6	(CL)s	31	141.4 - 141.8	22.8	100.6	1125	6.35	13.8	4.02	188.5	3.96	217.5	This was a good test, but at the very end, the downstream part of the hole seemed to fail suddenly. Analyze the portion of the test up to that point, using the measured diameter of the upstream part of the hole.

Wolf Creek Dam - USACE

E35-62x, SH15 Test HET-1 12-05-2007

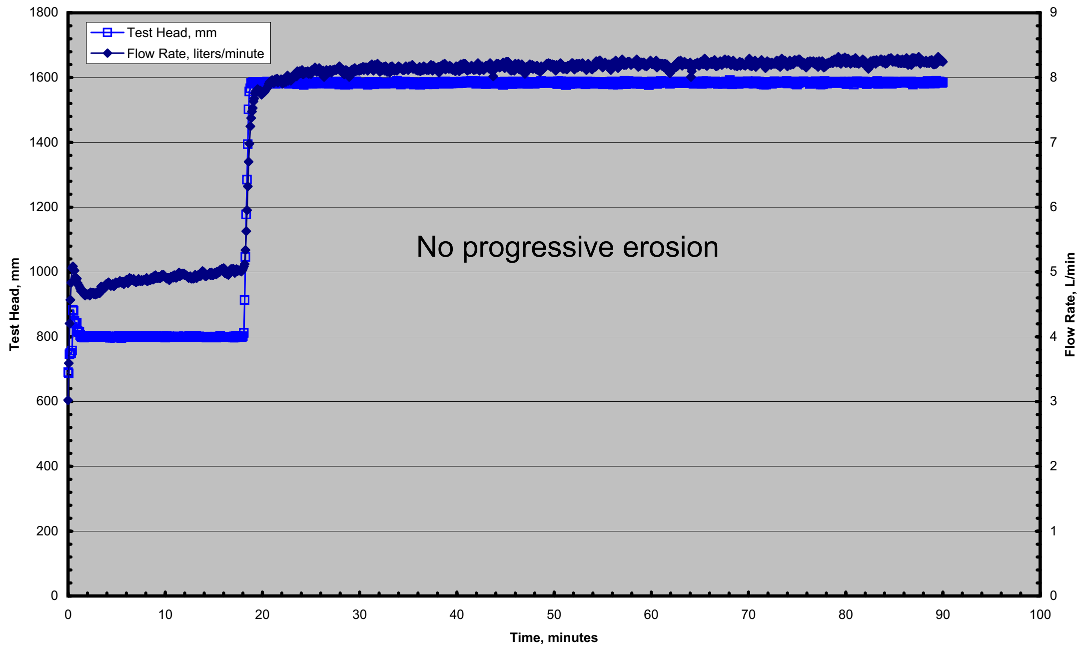
HET Test Record



Wolf Creek Dam - USACE

E35-13x1, S40 Test HET-2 12-07-2007

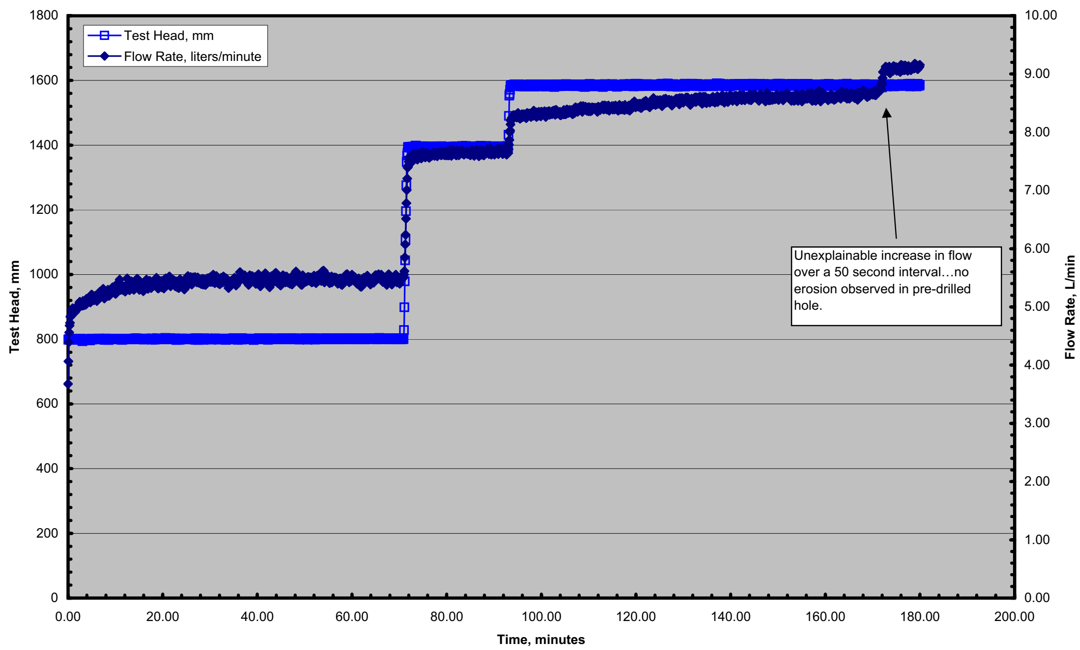
HET Test Record

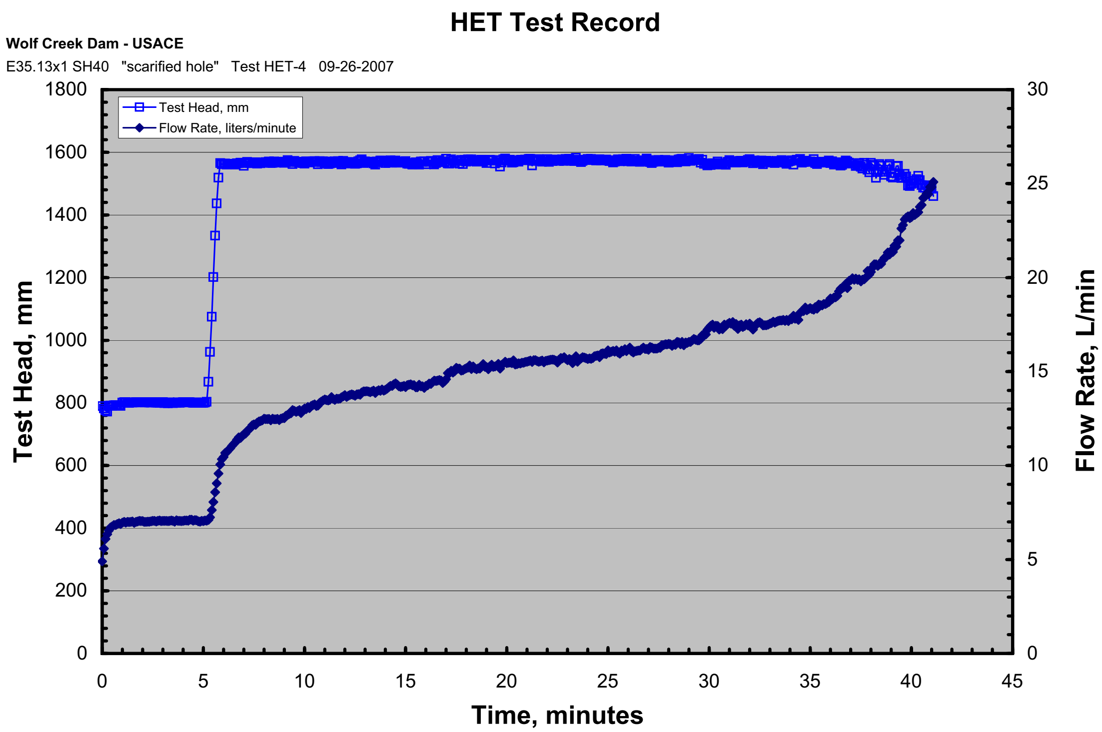


Wolf Creek Dam - USACE

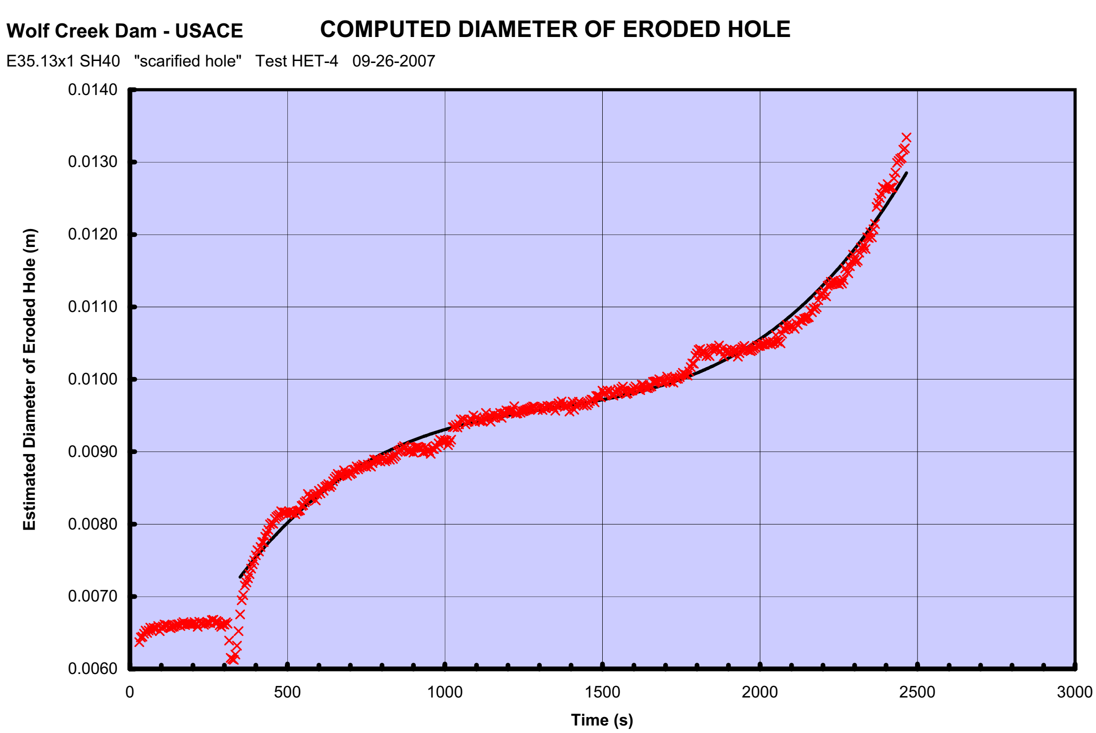
E35-62x Test HET-3 12-07-2007

HET Test Record

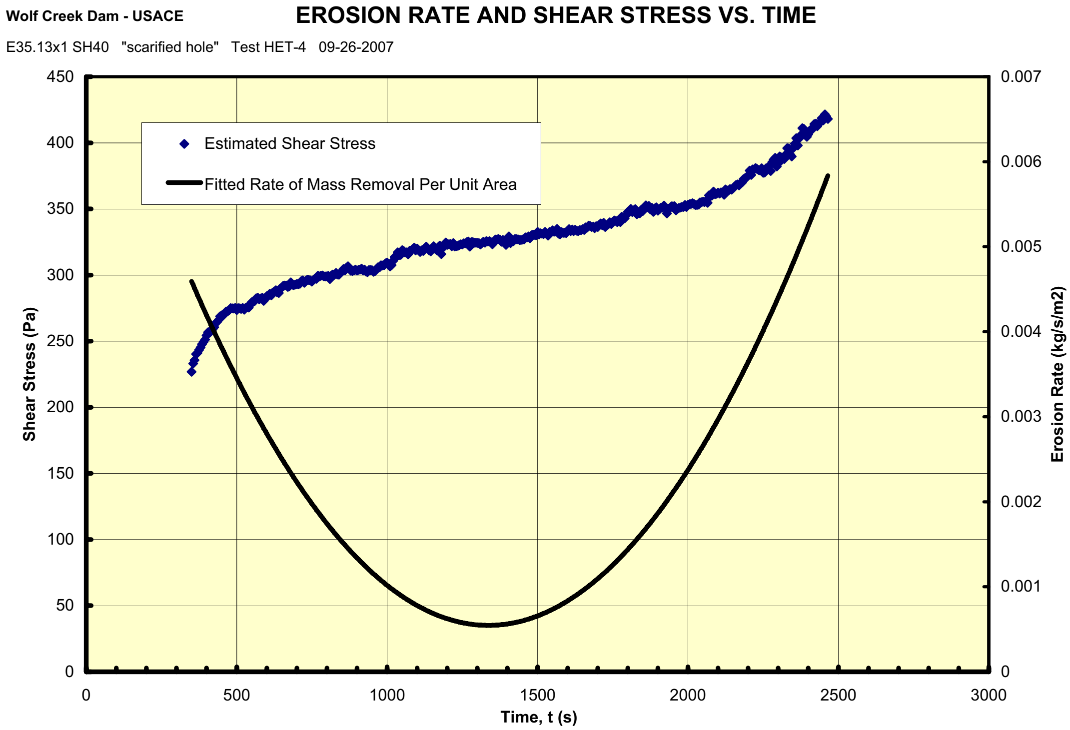


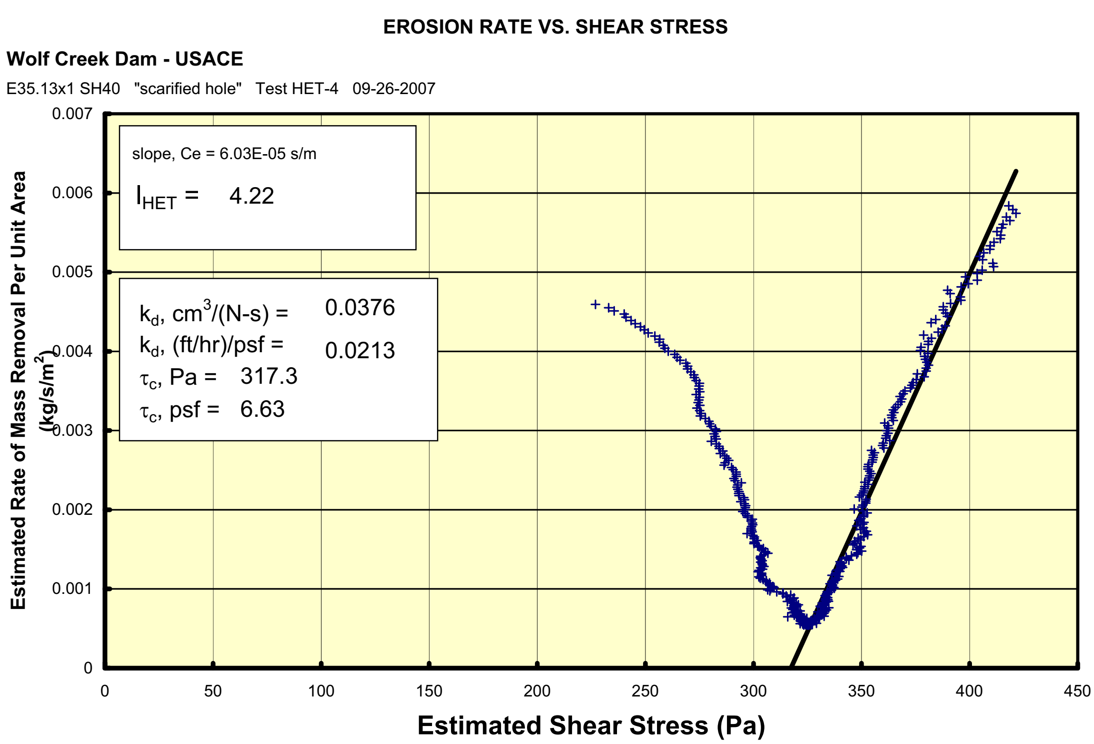


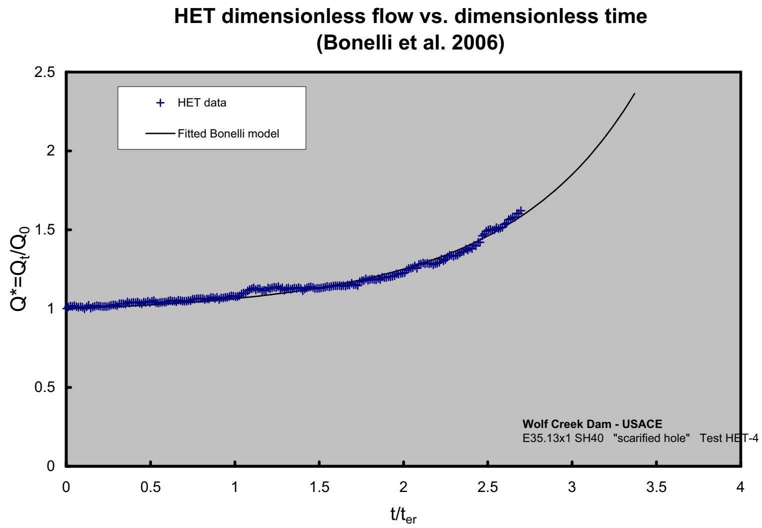
HET Test Record
Wolf Creek Dam - USACE
E35.13x1 SH40 "scarified hole" Test HET-4 09-26-2007
Test Head, mm
Flow Rate, liters/minute
Test Head, mm
Flow Rate, L/min
Time, minutes
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25
30
35
40
45



Wolf Creek Dam - USACE
COMPUTED DIAMETER OF ERODED HOLE
E35.13x1 SH40 "scarified hole" Test HET-4 09-26-2007
Estimated Diameter of Eroded Hole (m)
Time (s)
0.0060
0.0070
0.0080
0.0090
0.0100
0.0110
0.0120
0.0130
0.0140
0
500
1000
1500
2000
2500
3000


Wolf Creek Dam - USACE
ERROSION RATE AND SHEAR STRESS VS. TIME
E35.13x1 SH40 "scarified hole" Test HET-4 09-26-2007
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
50
100
150
200
250
300
350
400
450
0.001
0.002
0.003
0.004
0.005
0.006
0.007
500
1000
1500
2000
2500
3000


EROSION RATE VS. SHEAR STRESS
Wolf Creek Dam - USACE
E35.13x1 SH40 "scarified hole" Test HET-4 09-26-2007
slope, Ce = 6.03E-05 s/m
I_HET = 4.22
k_d, cm^3/(N-s) = 0.0376
k_d, (ft/hr)/psf = 0.0213
τ_c, Pa = 317.3
τ_c, psf = 6.63
Estimated Rate of Mass Removal Per Unit Area (kg/s/m^2)
Estimated Shear Stress (Pa)
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
50
100
150
200
250
300
350
400
450



Project Wolf Creek Dam - USACE
Feature E35.13x1 SH40 "scarified hole"
Test HET-4
Date 12/11/2007

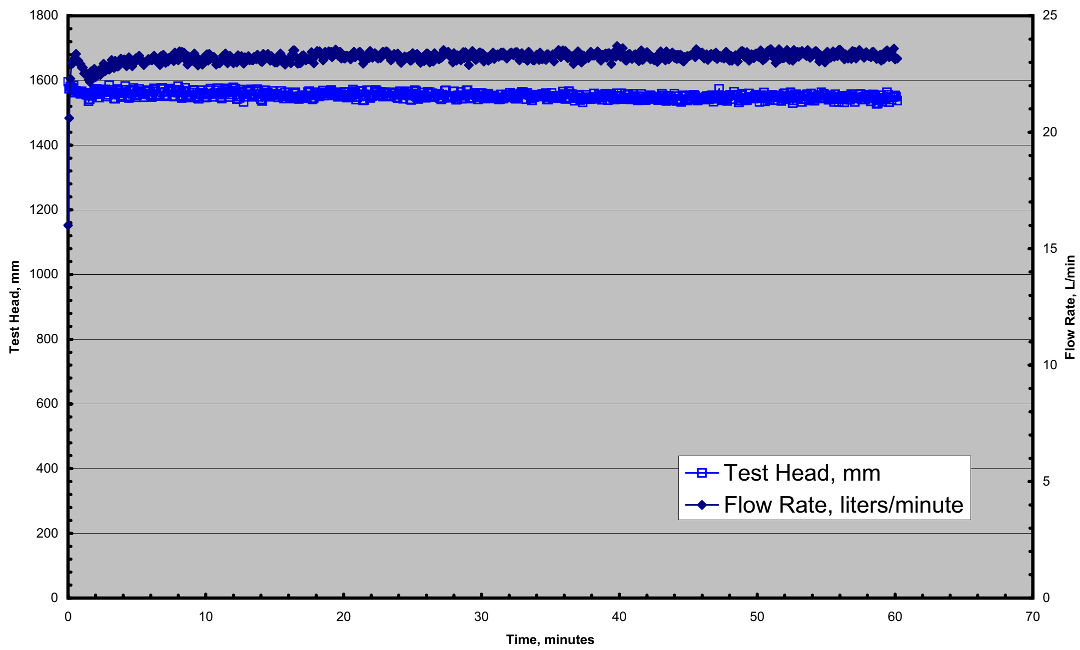
RESULTS SUMMARY

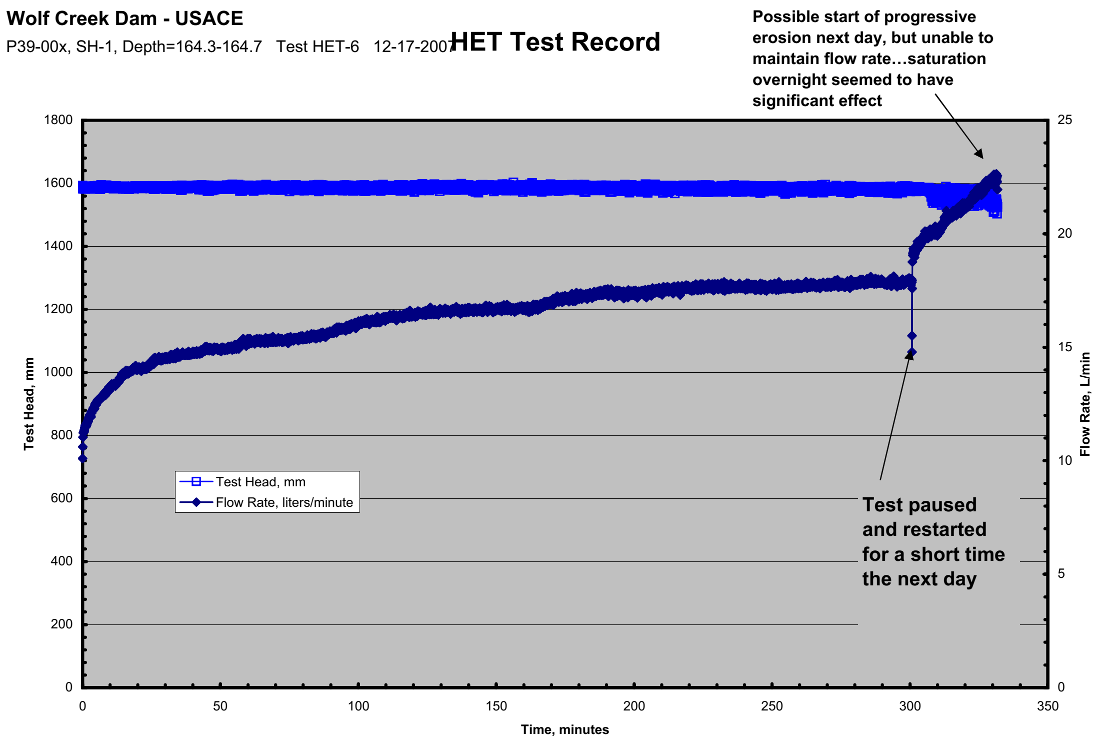
C_e	5.78E-05	((kg/s)/m^2)/Pa = s/m	
I_{HET}	4.24		**Group 4**
τ_c	316.1	Pa	
k_d	3.605E-08	m/s/Pa = m^3/(N-s)	
k_d	0.0361	cm^3/(N-s)	
k_d	0.0204	(ft/hr)/psf	
τ_c	6.60	psf	

Wolf Creek Dam - USACE

E35-48x SH16 221.8-222.2 Test HET-05 12-12-2007

HET Test Record

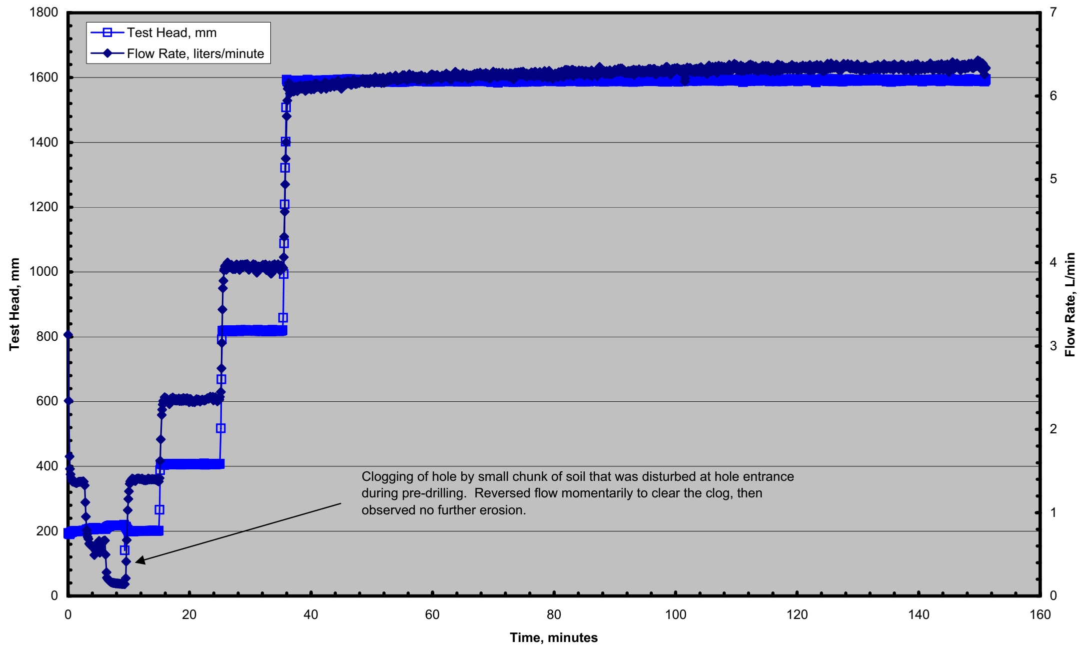



Wolf Creek Dam - USACE
P39-00x, SH-1, Depth=164.3-164.7 Test HET-6 12-17-200
HET Test Record
Possible start of progressive erosion next day, but unable to maintain flow rate…saturation overnight seemed to have significant effect
Test paused and restarted for a short time the next day
Test Head, mm
Flow Rate, liters/minute
Test Head, mm
Flow Rate, L/min
Time, minutes
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25
0
50
100
150
200
250
300
350

Wolf Creek Dam - USACE

E35.48x - SH12 Test HET-7 01-04-2008

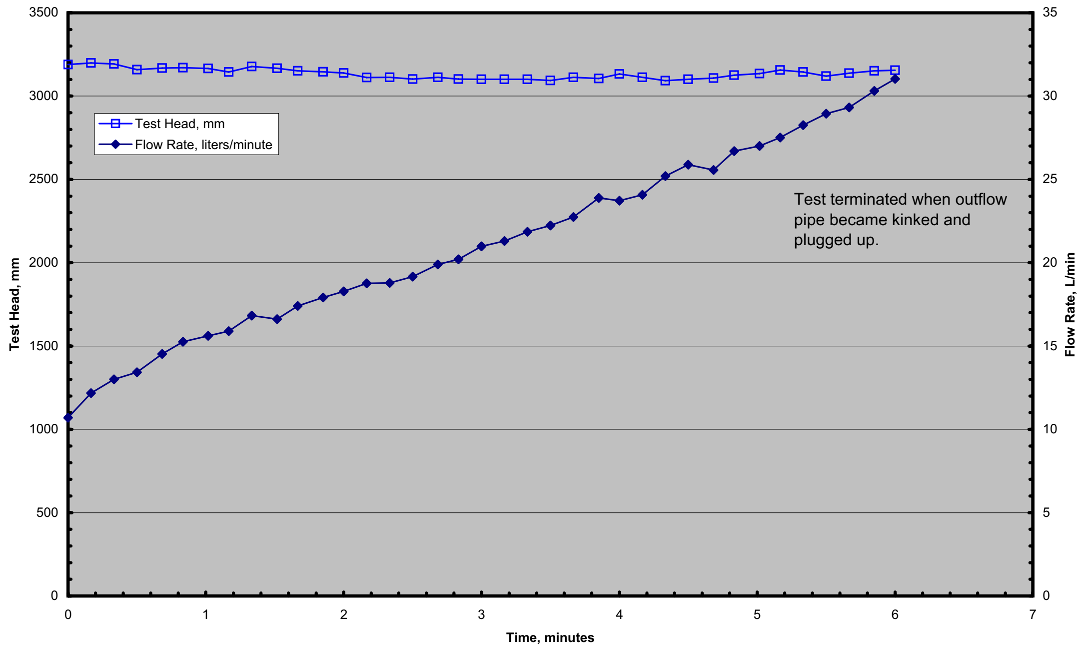
HET Test Record



Wolf Creek Dam - USACE

P39.00x SH-1 Test HET-8 02-01-2008

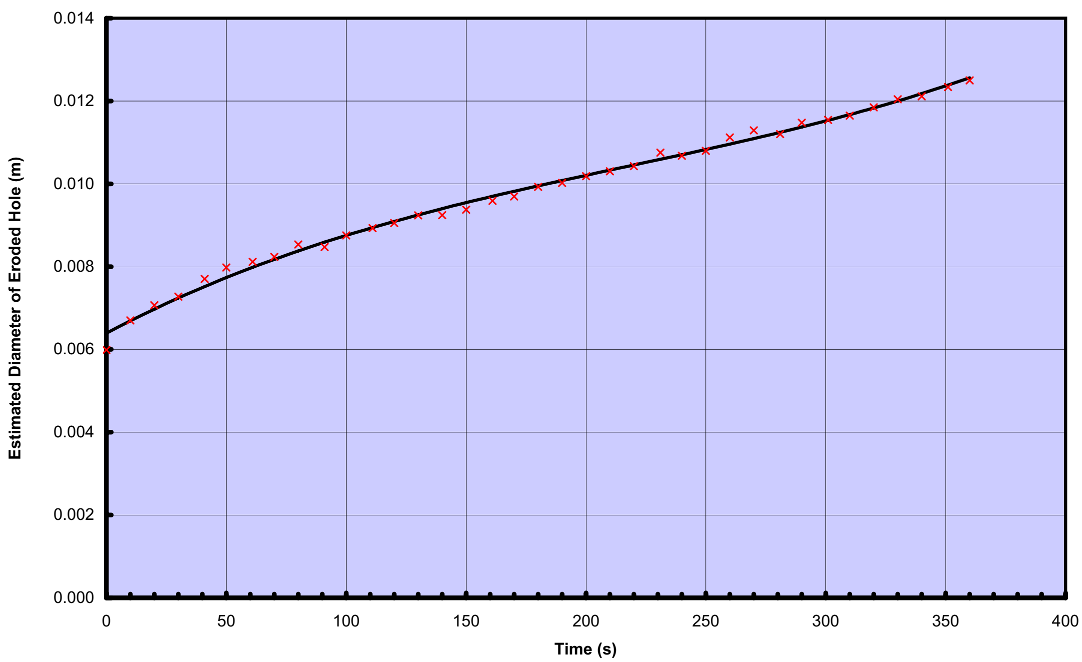
HET Test Record

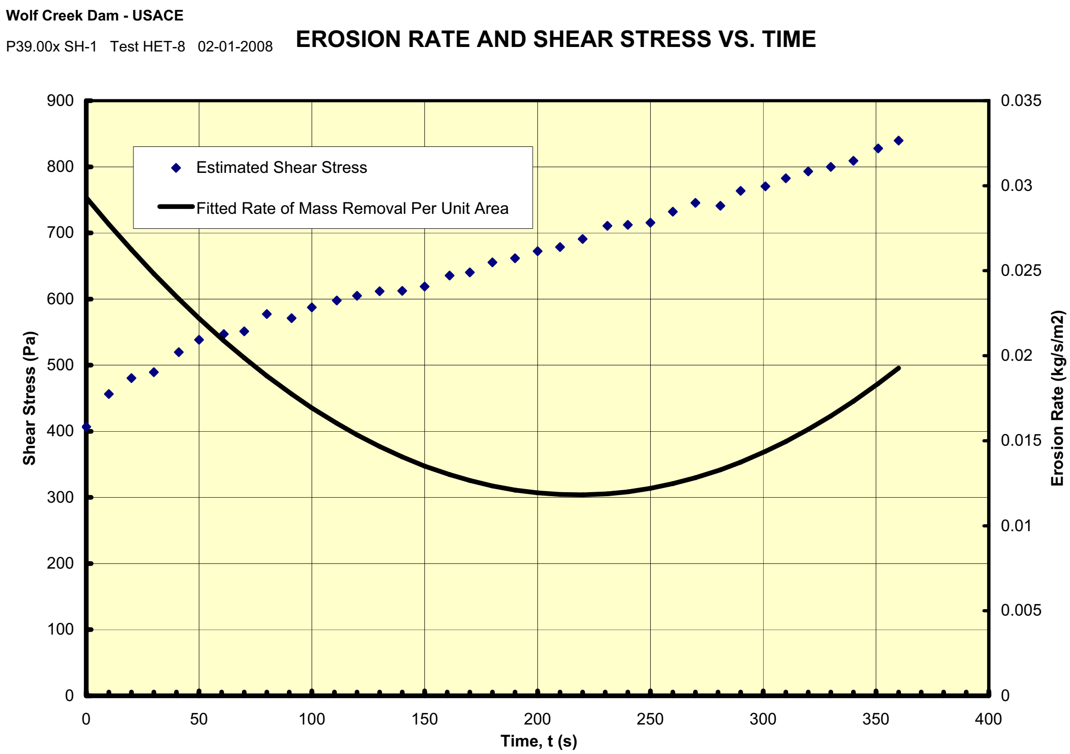


Wolf Creek Dam - USACE

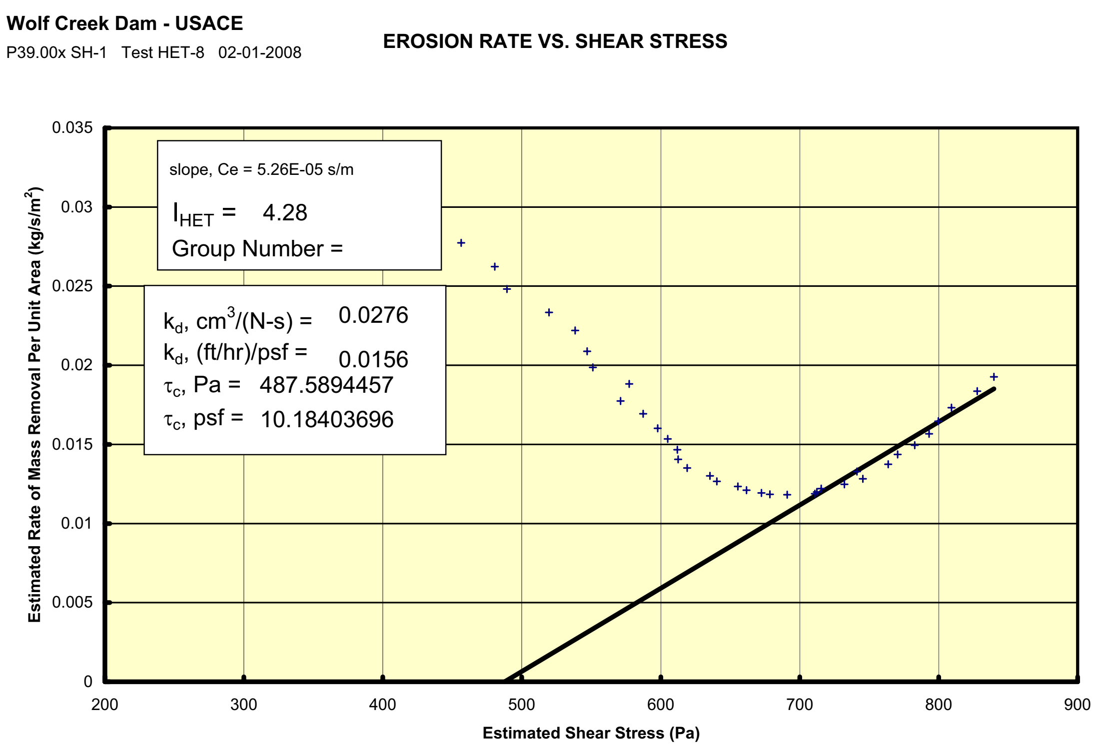
P39.00x SH-1 Test HET-8 02-01-2008

COMPUTED DIAMETER OF ERODED HOLE



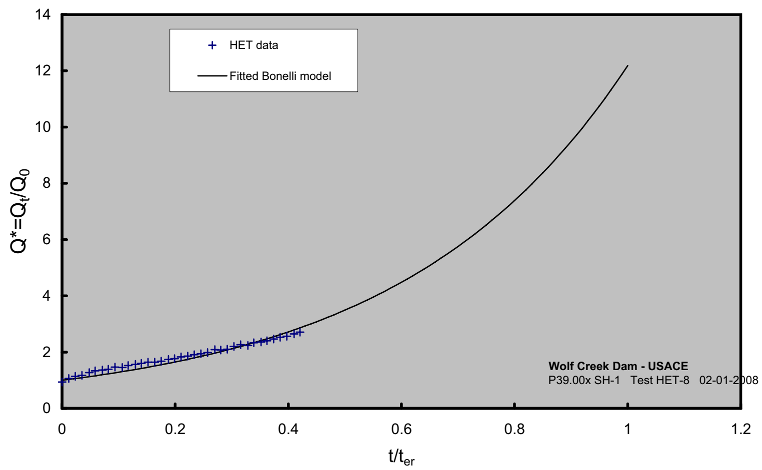


Wolf Creek Dam - USACE
P39.00x SH-1 Test HET-8 02-01-2008
EROSION RATE AND SHEAR STRESS VS. TIME
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
100
200
300
400
500
600
700
800
900
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0
50
100
150
200
250
300
350
400



Wolf Creek Dam - USACE
P39.00x SH-1 Test HET-8 02-01-2008
EROSION RATE VS. SHEAR STRESS
slope, Ce = 5.26E-05 s/m
I_HET = 4.28
Group Number =
k_d, cm³/(N-s) = 0.0276
k_d, (ft/hr)/psf = 0.0156
τ_c, Pa = 487.5894457
τ_c, psf = 10.18403696
Estimated Rate of Mass Removal Per Unit Area (kg/s/m²)
Estimated Shear Stress (Pa)
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
200
300
400
500
600
700
800
900

HET dimensionless flow vs. dimensionless time (Bonelli et al. 2006)



Project Wolf Creek Dam - USACE
Feature P39.00x SH-1
Test HET-8
Date 2/1/2008

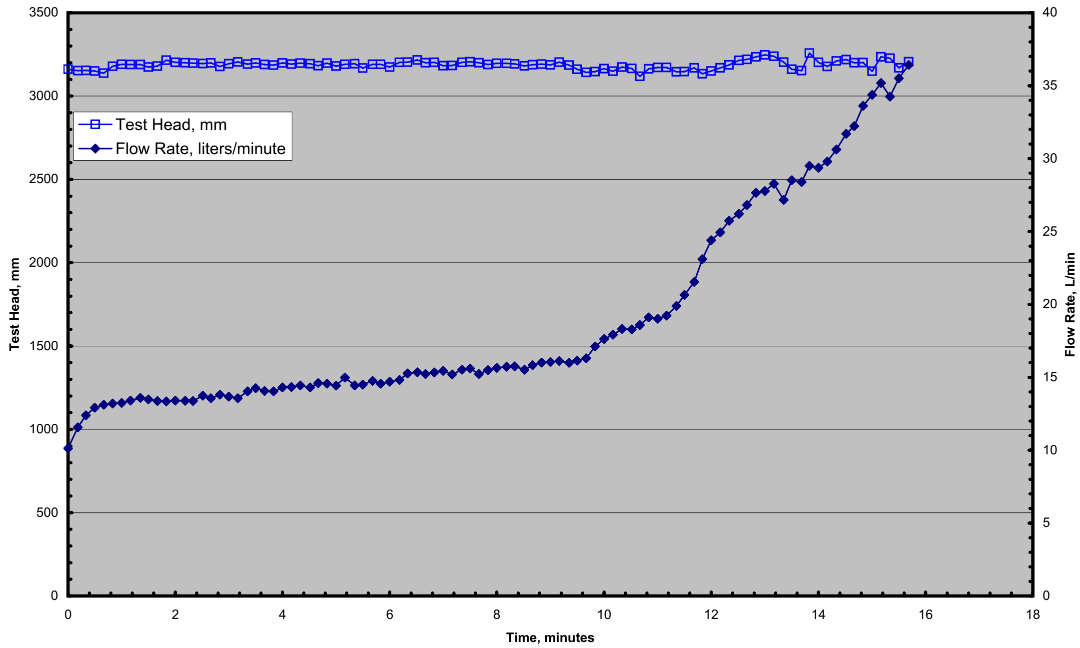
RESULTS SUMMARY

C_e	1.67E-05	((kg/s)/m^2)/Pa = s/m	
I_{HET}	4.78		**Group 4**
τ_c	0.0	Pa	
k_d	8.755E-09	m/s/Pa = m^3/(N-s)	
k_d	0.0088	cm^3/(N-s)	
k_d	0.0050	(ft/hr)/psf	
τ_c	0.00	psf	

Wolf Creek Dam - USACE

E35.48x SH-16 @221.8-222.2 Test HET-9 02-02-2008

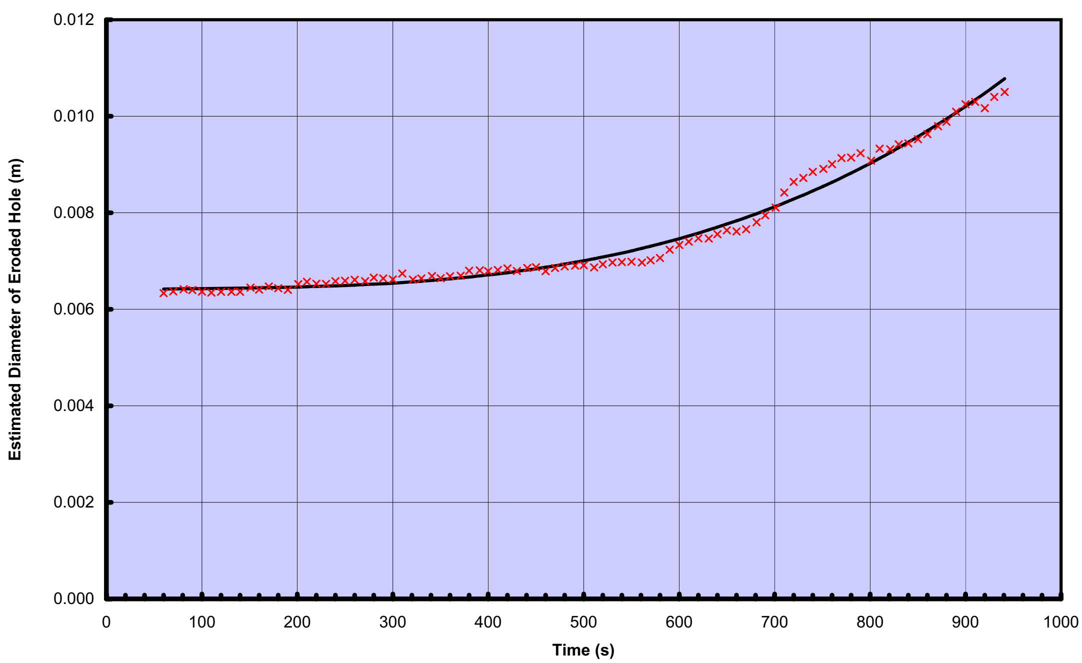
HET Test Record

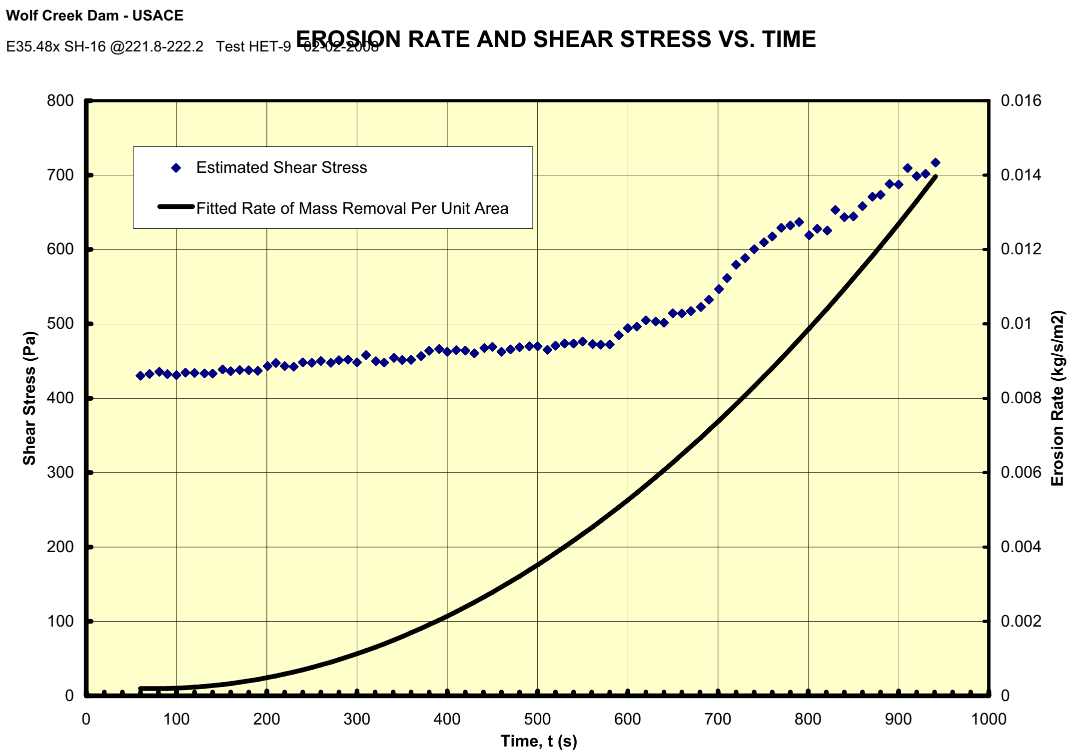


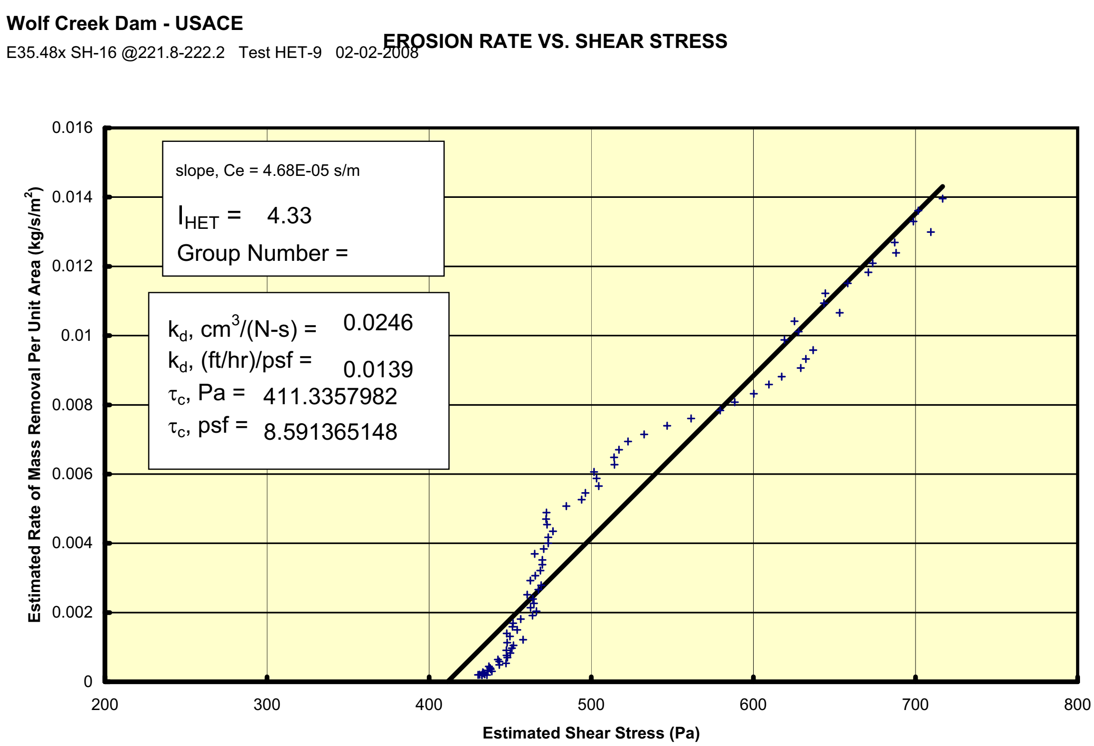
Wolf Creek Dam - USACE

E35.48x SH-16 @221.8-222.2 Test HET-9 02-02-2008

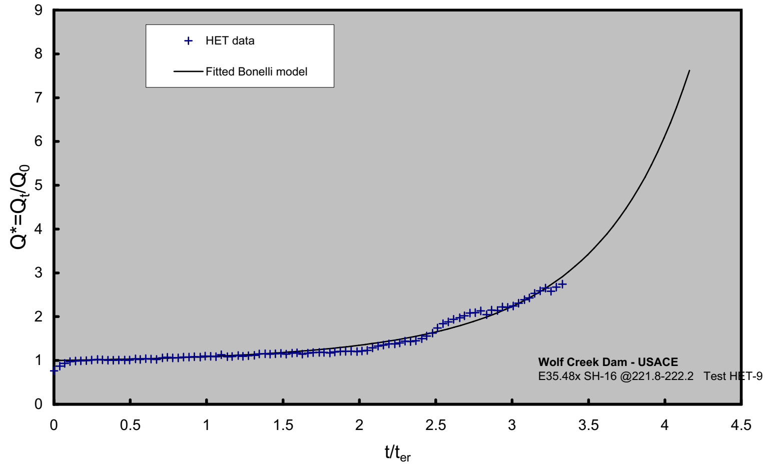
COMPUTED DIAMETER OF ERODED HOLE




Wolf Creek Dam - USACE
E35.48x SH-16 @221.8-222.2 Test HET-9 02-02-2008
EROSION RATE AND SHEAR STRESS VS. TIME
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
100
200
300
400
500
600
700
800
900
1000
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016


Wolf Creek Dam - USACE
E35.48x SH-16 @221.8-222.2 Test HET-9 02-02-2008
EROSION RATE VS. SHEAR STRESS
slope, Ce = 4.68E-05 s/m
I_HET = 4.33
Group Number =
k_d, cm^3/(N-s) = 0.0246
k_d, (ft/hr)/psf = 0.0139
τ_c, Pa = 411.3357982
τ_c, psf = 8.591365148
Estimated Rate of Mass Removal Per Unit Area (kg/s/m^2)
Estimated Shear Stress (Pa)
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
200
300
400
500
600
700
800

HET dimensionless flow vs. dimensionless time (Bonelli et al. 2006)

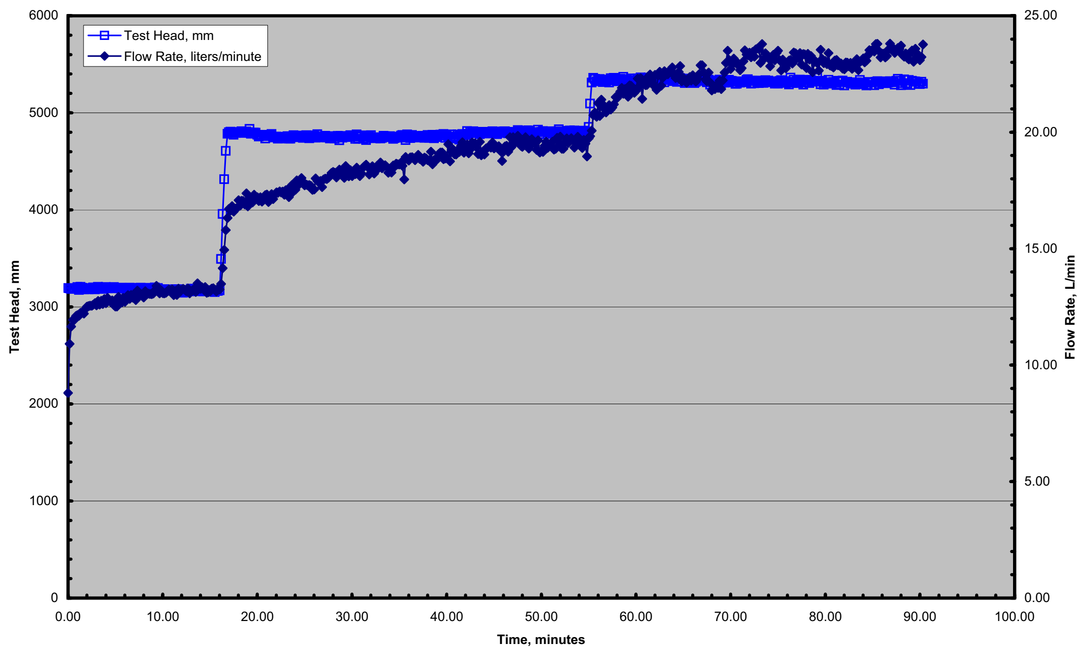


Project	Wolf Creek Dam - USACE
Feature	E35.48x SH-16 @221.8-222.2
Test	HET-9
Date	2/2/2008

RESULTS SUMMARY

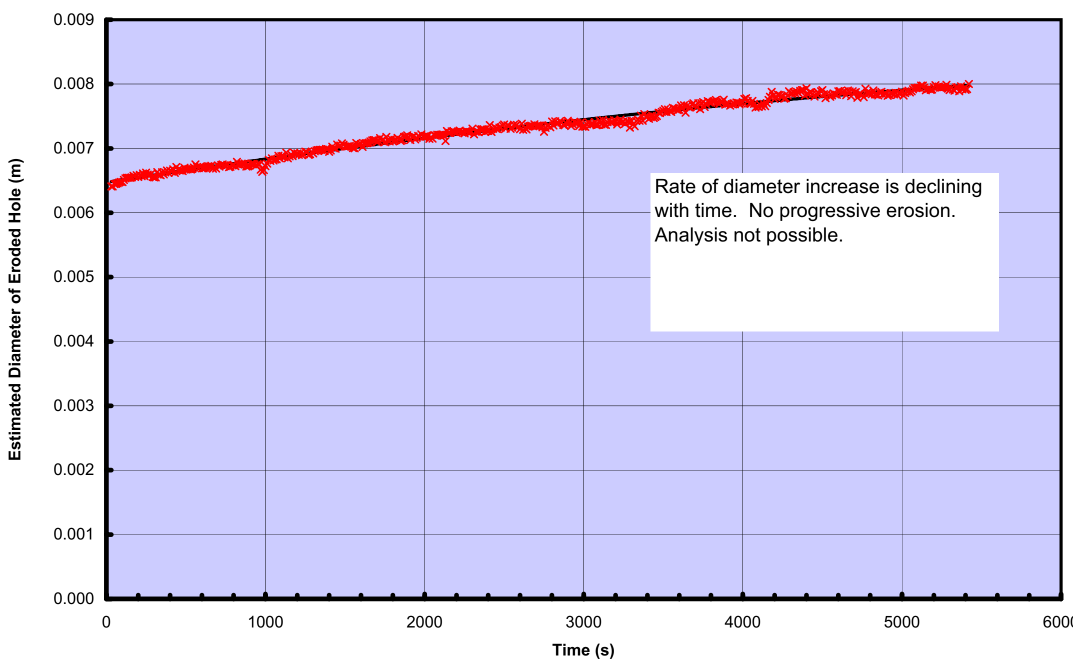
C_e	4.97E-05	$((kg/s)/m^2)/Pa = s/m$	
I_{HET}	4.30		**Group 4**
τ_c	422.3	Pa	
k_d	2.607E-08	$m/s/Pa = m^3/(N\text{-}s)$	
k_d	0.0261	$cm^3/(N\text{-}s)$	
k_d	0.0147	(ft/hr)/psf	
τ_c	8.82	psf	

Wolf Creek Dam - USACE
E35.48x SH-12 at 211.6 - 212.0   Test HET-10   02-08-2008 **HET Test Record**



Wolf Creek Dam - USACE
E35.48x SH-12 at 211.6 - 212.0   Test HET-10   02-08-2008

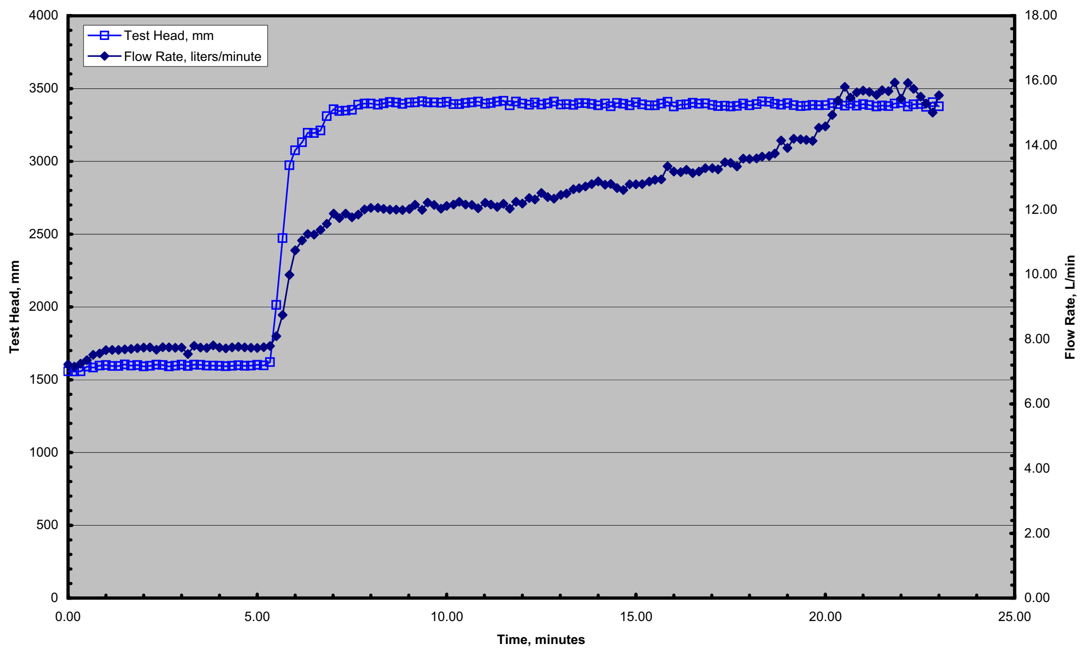
COMPUTED DIAMETER OF ERODED HOLE



Wolf Creek Dam - USACE

E3562x, SH15 Test Wolf Creek HET-11 02-22-2008

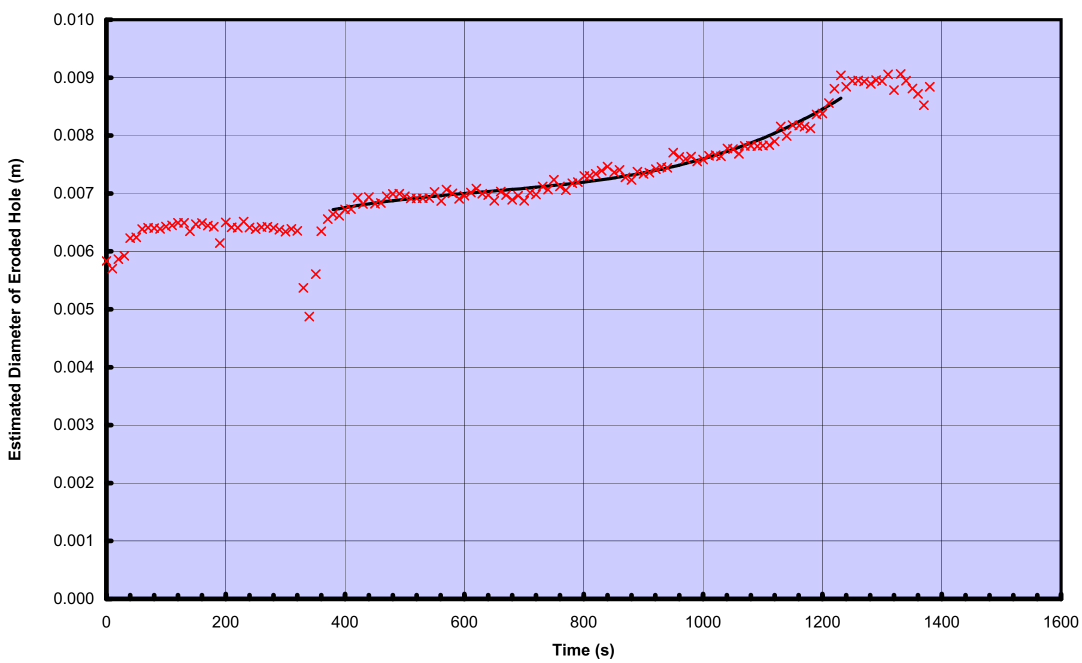
HET Test Record

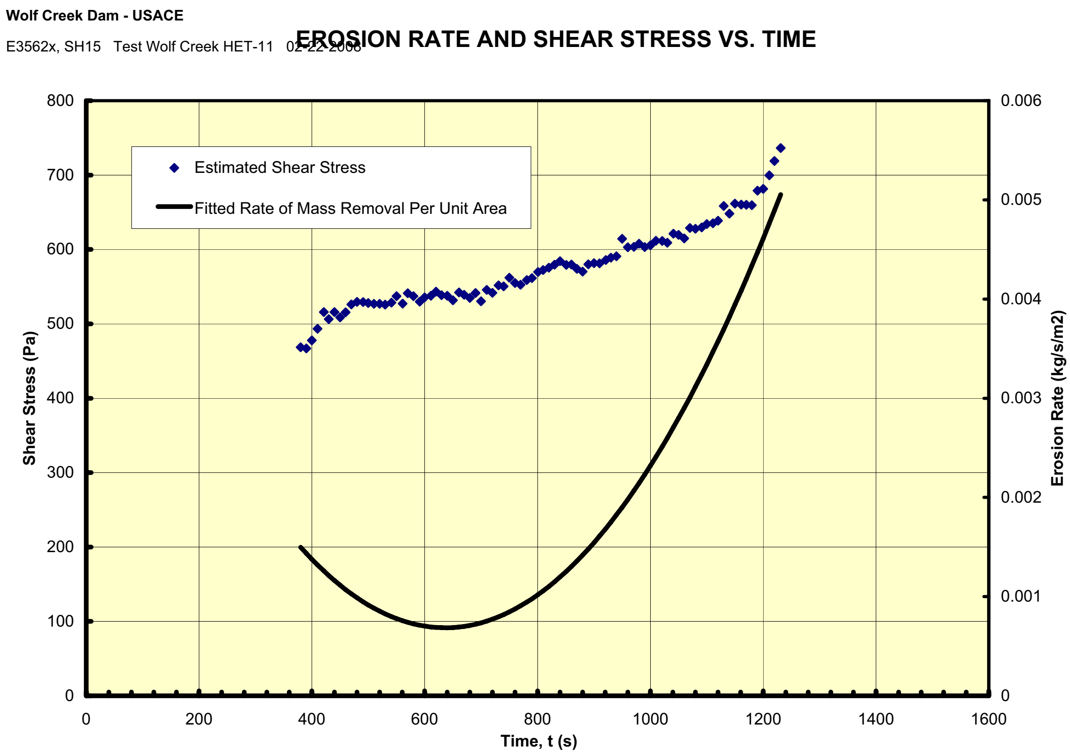


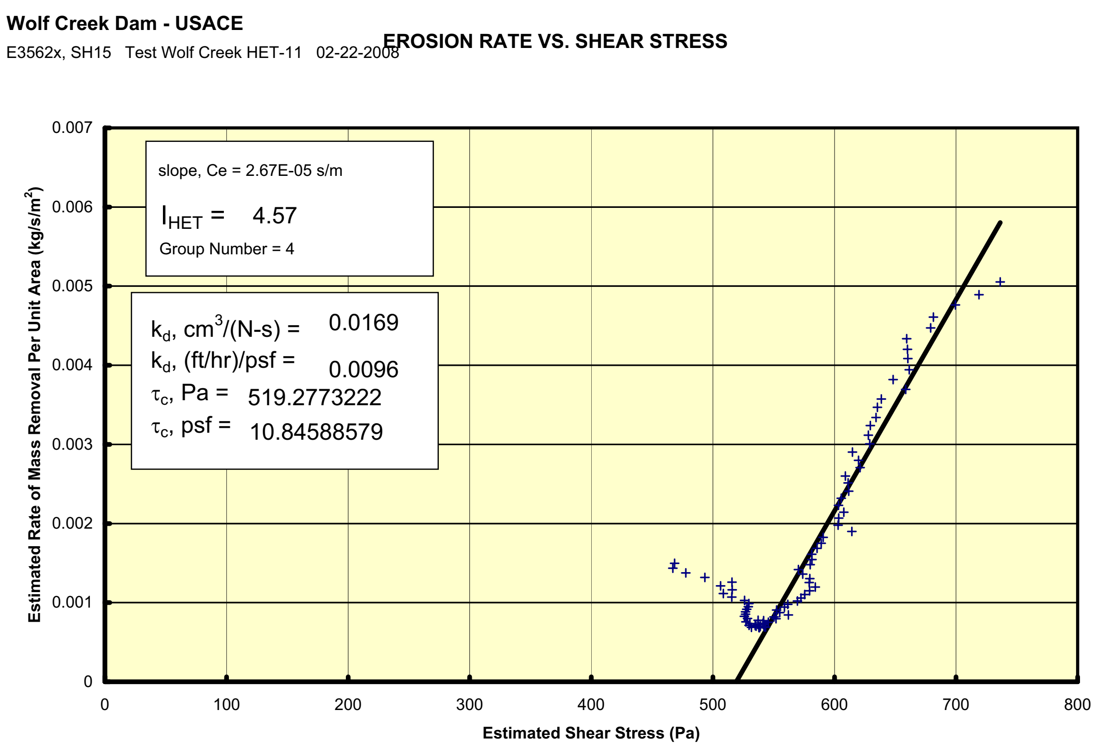
Wolf Creek Dam - USACE

E3562x, SH15 Test Wolf Creek HET-11 02-22-2008

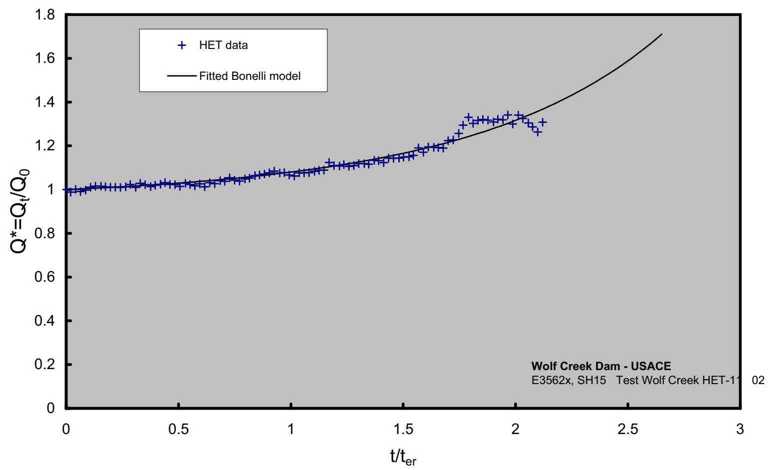
COMPUTED DIAMETER OF ERODED HOLE




Wolf Creek Dam - USACE
E3562x, SH15 Test Wolf Creek HET-11 02-22-2008
EROSION RATE AND SHEAR STRESS VS. TIME
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
100
200
300
400
500
600
700
800
0.001
0.002
0.003
0.004
0.005
0.006
200
400
600
800
1000
1200
1400
1600


Wolf Creek Dam - USACE
E3562x, SH15 Test Wolf Creek HET-11 02-22-2008
EROSION RATE VS. SHEAR STRESS
slope, Ce = 2.67E-05 s/m
I_HET = 4.57
Group Number = 4
k_d, cm^3/(N-s) = 0.0169
k_d, (ft/hr)/psf = 0.0096
τ_c, Pa = 519.2773222
τ_c, psf = 10.84588579
Estimated Rate of Mass Removal Per Unit Area (kg/s/m^2)
Estimated Shear Stress (Pa)
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
100
200
300
400
500
600
700
800

HET dimensionless flow vs. dimensionless time
(Bonelli et al. 2006)



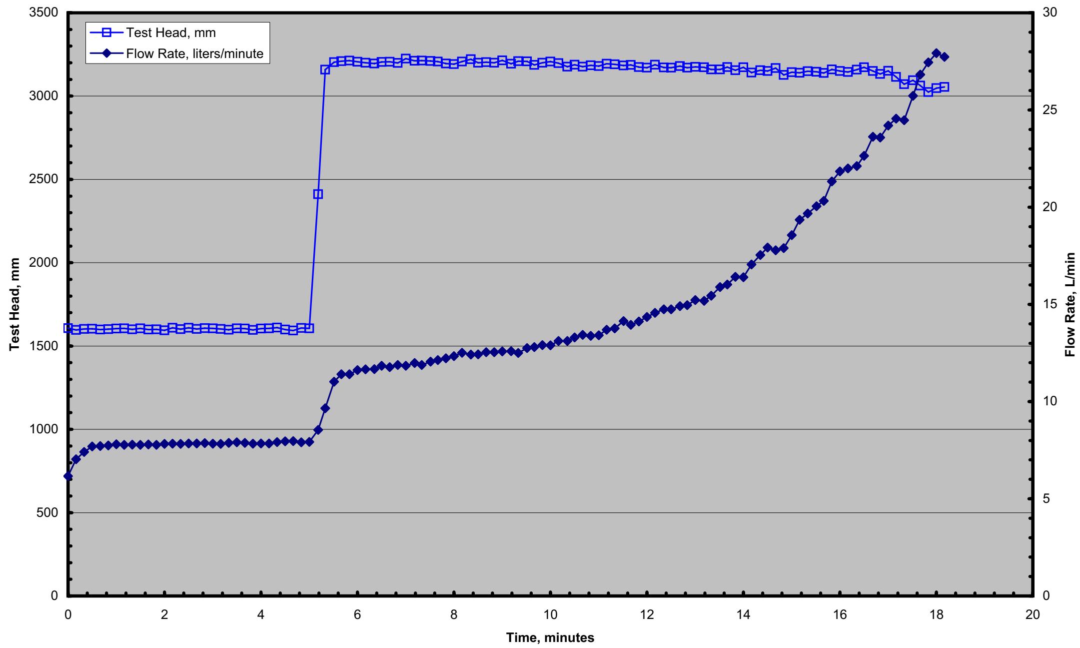
Project Wolf Creek Dam - USACE
Feature E3562x, SH15
Test Wolf Creek HET-11
Date 2/22/2008

RESULTS SUMMARY

C_e	2.26E-05	((kg/s)/m^2)/Pa = s/m	
I_{HET}	4.65		**Group 4**
τ_c	517.3	Pa	
k_d	1.431E-08	m/s/Pa = m^3/(N-s)	
k_d	0.0143	cm^3/(N-s)	
k_d	0.0081	(ft/hr)/psf	
τ_c	10.81	psf	

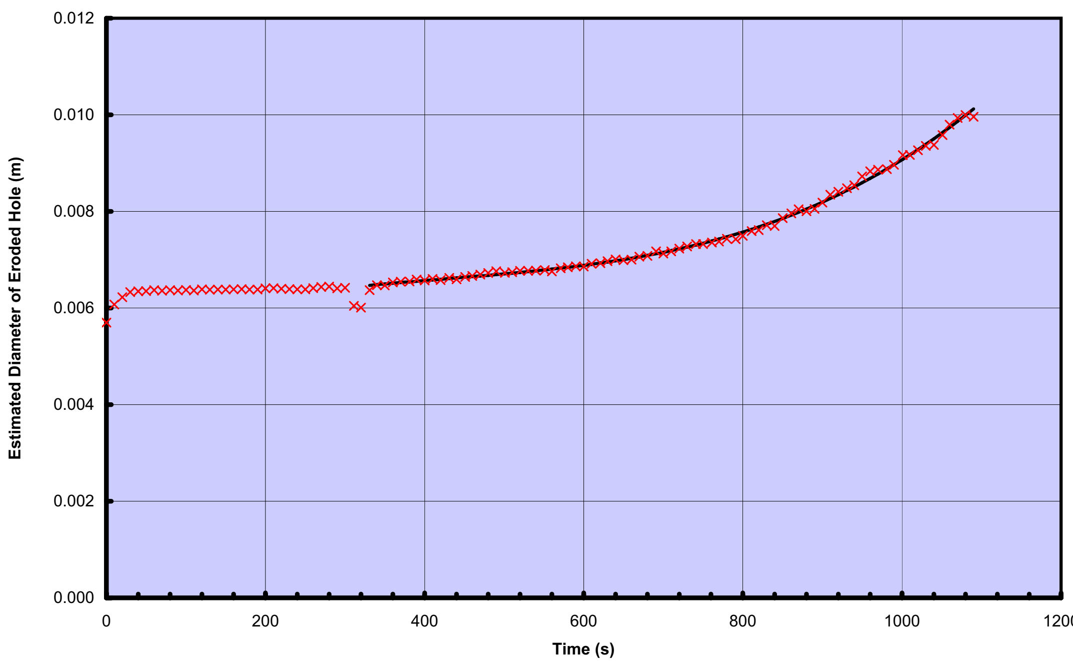
Wolf Creek Dam - USACE
E3562x, SH-12 Test HET-12 02-22-2008

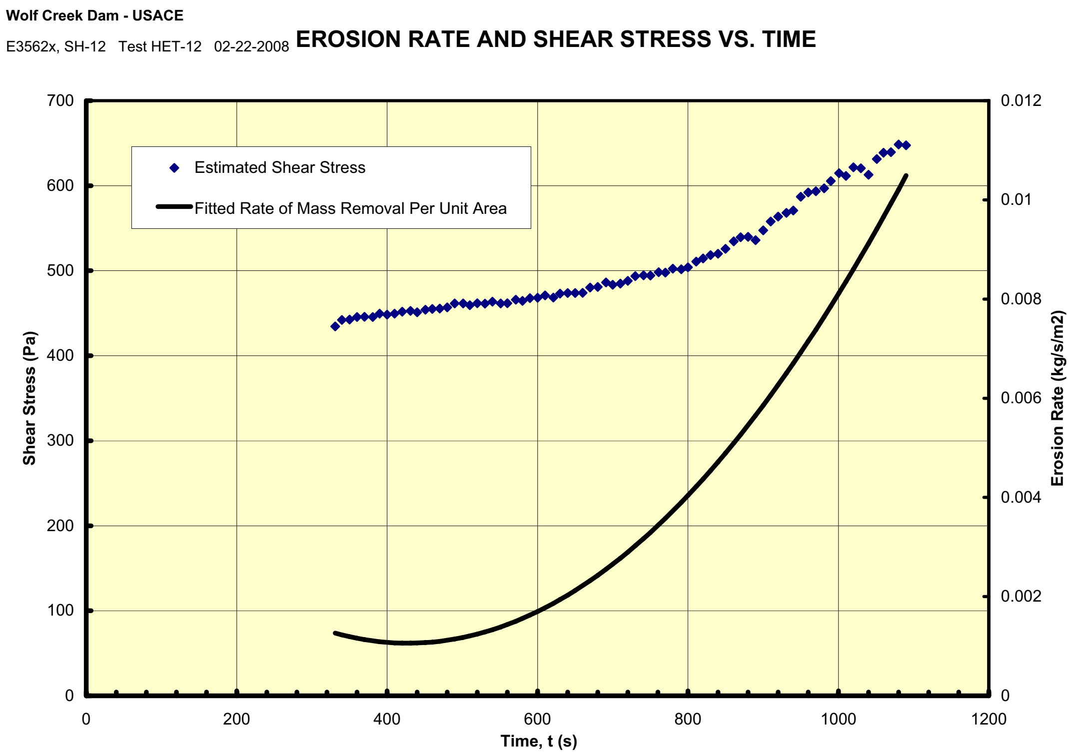
HET Test Record

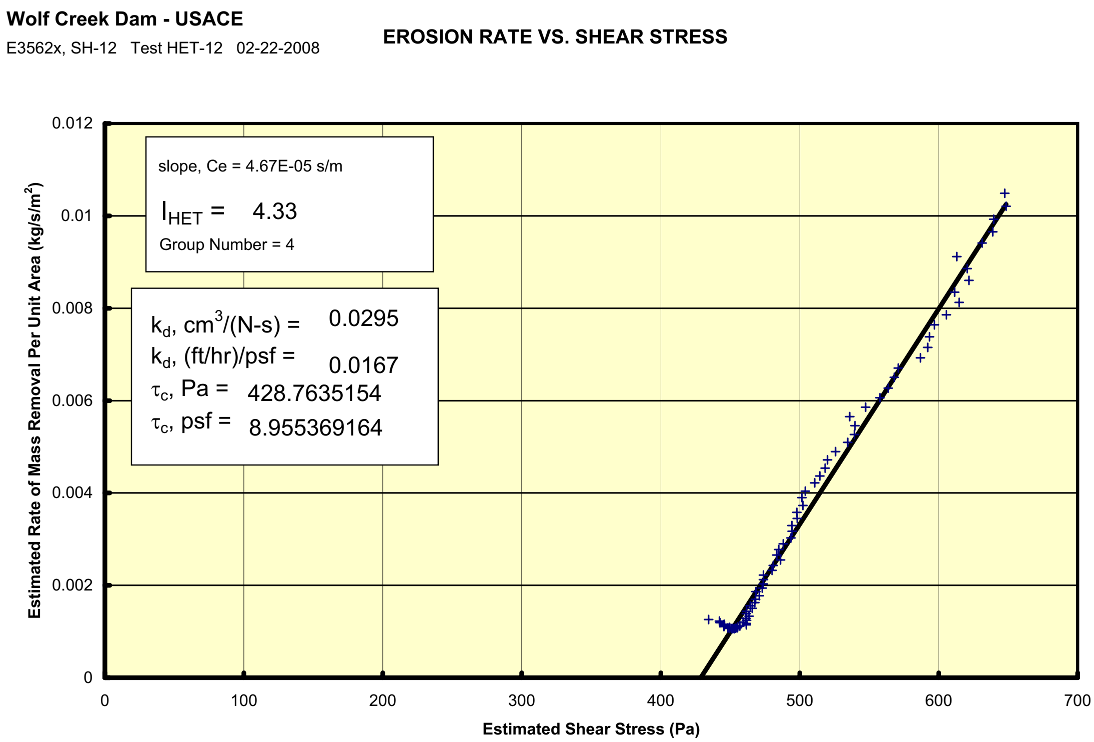


Wolf Creek Dam - USACE
E3562x, SH-12 Test HET-12 02-22-2008

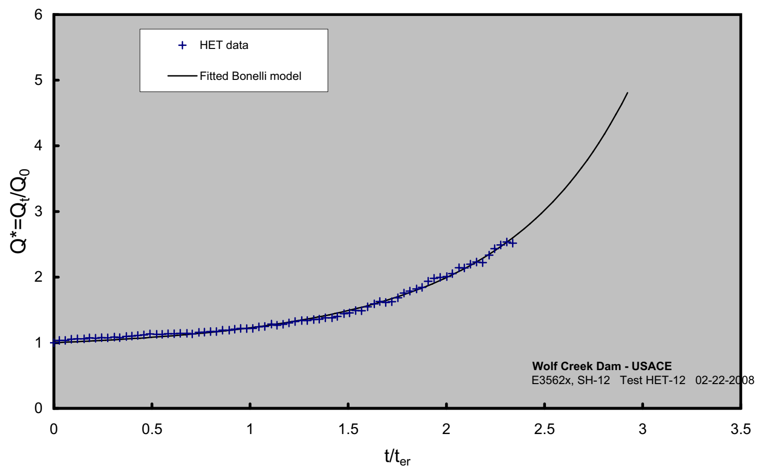
COMPUTED DIAMETER OF ERODED HOLE




Wolf Creek Dam - USACE
E3562x, SH-12 Test HET-12 02-22-2008
EROSION RATE AND SHEAR STRESS VS. TIME
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
100
200
300
400
500
600
700
0.002
0.004
0.006
0.008
0.01
0.012
0
200
400
600
800
1000
1200


Wolf Creek Dam - USACE
E3562x, SH-12 Test HET-12 02-22-2008
EROSION RATE VS. SHEAR STRESS
slope, Ce = 4.67E-05 s/m
I_HET = 4.33
Group Number = 4
k_d, cm^3/(N-s) = 0.0295
k_d, (ft/hr)/psf = 0.0167
τ_c, Pa = 428.7635154
τ_c, psf = 8.955369164
Estimated Rate of Mass Removal Per Unit Area (kg/s/m^2)
Estimated Shear Stress (Pa)
0
0.002
0.004
0.006
0.008
0.01
0.012
100
200
300
400
500
600
700

HET dimensionless flow vs. dimensionless time
(Bonelli et al. 2006)



Project Wolf Creek Dam - USACE
Feature E3562x, SH-12
Test HET-12
Date 2/22/2008

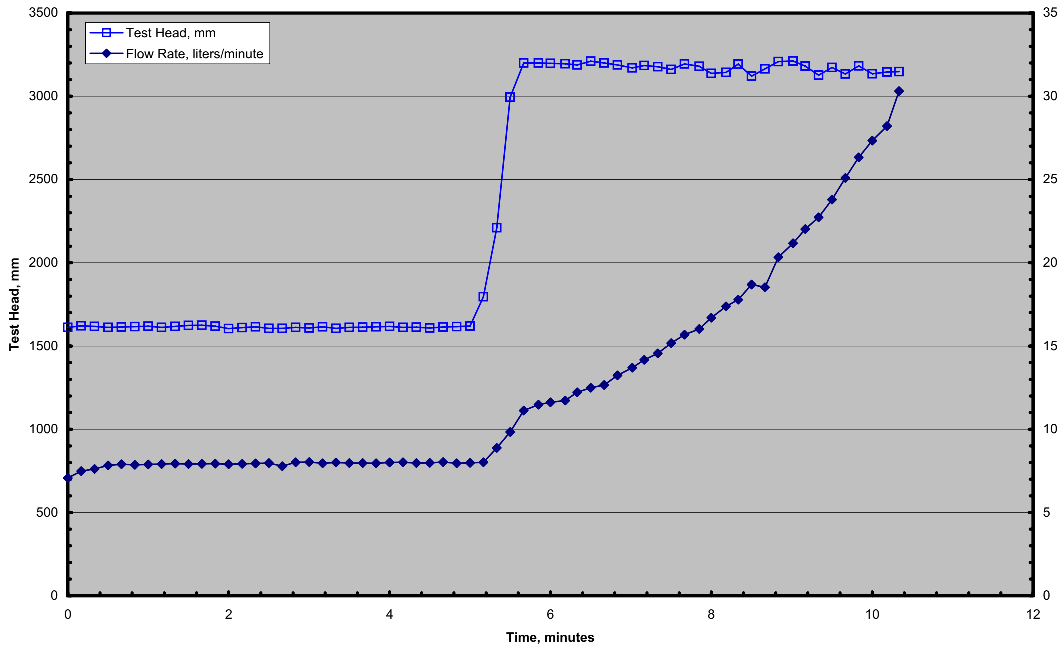
RESULTS SUMMARY

C_e	3.62E-05	$((kg/s)/m^2)/Pa = s/m$	
I_{HET}	4.44		**Group 4**
τ_c	408.6	Pa	
k_d	2.282E-08	$m/s/Pa = m^3/(N\text{-}s)$	
k_d	0.0228	$cm^3/(N\text{-}s)$	
k_d	0.0129	(ft/hr)/psf	
τ_c	8.54	psf	

Wolf Creek Dam - USACE

E3513x1, S-36 Test HET-13 02-22-2008

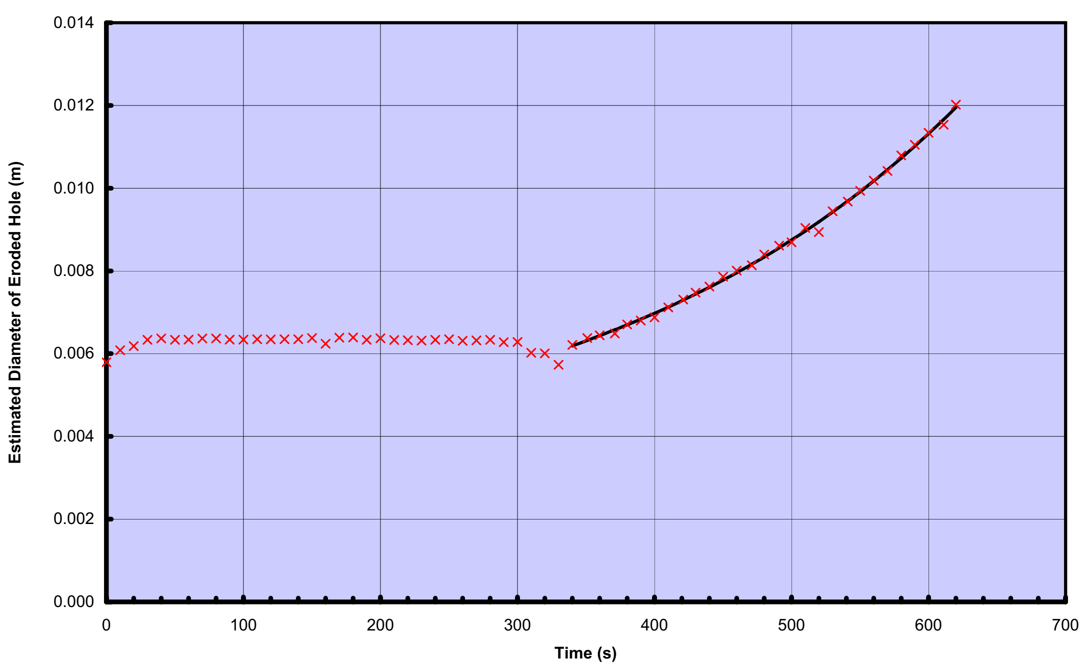
HET Test Record



Wolf Creek Dam - USACE

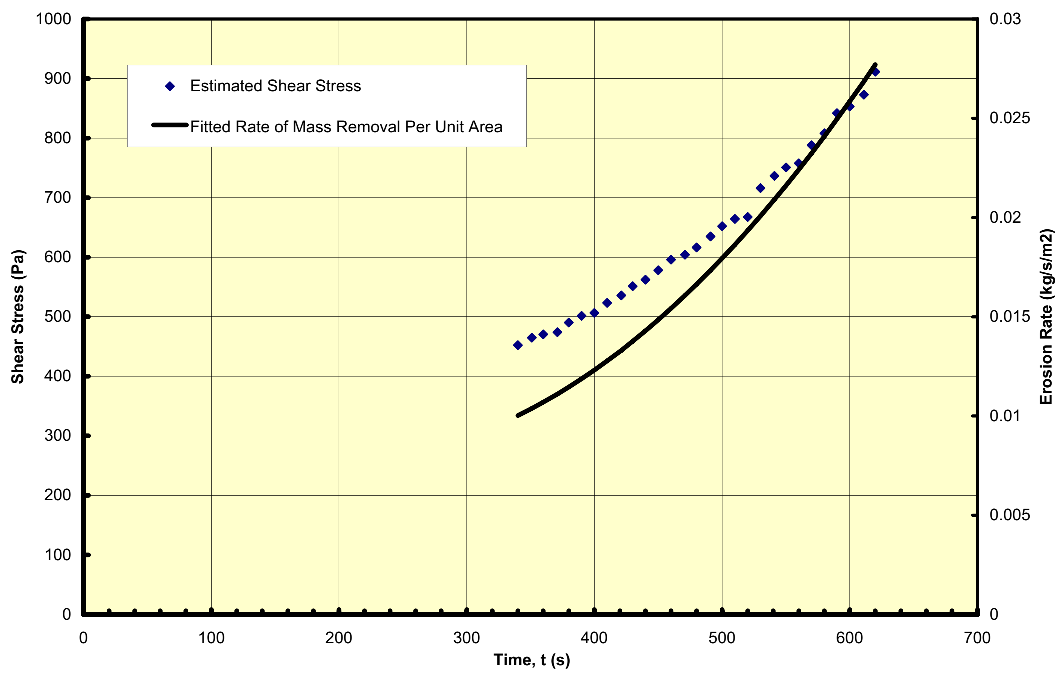
E3513x1, S-36 Test HET-13 02-22-2008

COMPUTED DIAMETER OF ERODED HOLE



Wolf Creek Dam - USACE

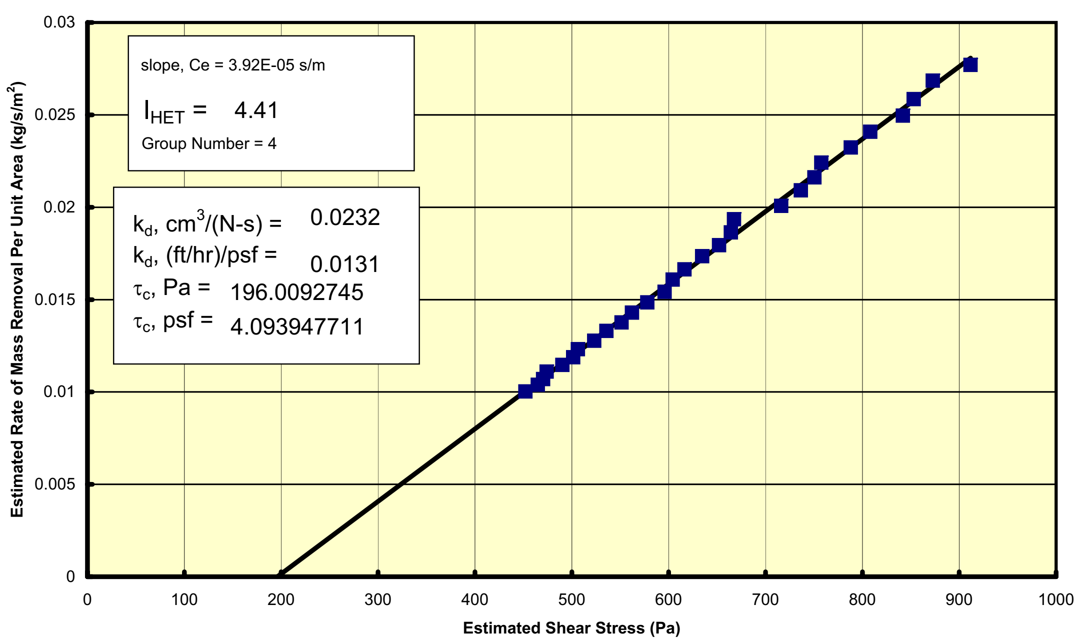
E3513x1, S-36 Test HET-13 02-22-2008 **EROSION RATE AND SHEAR STRESS VS. TIME**



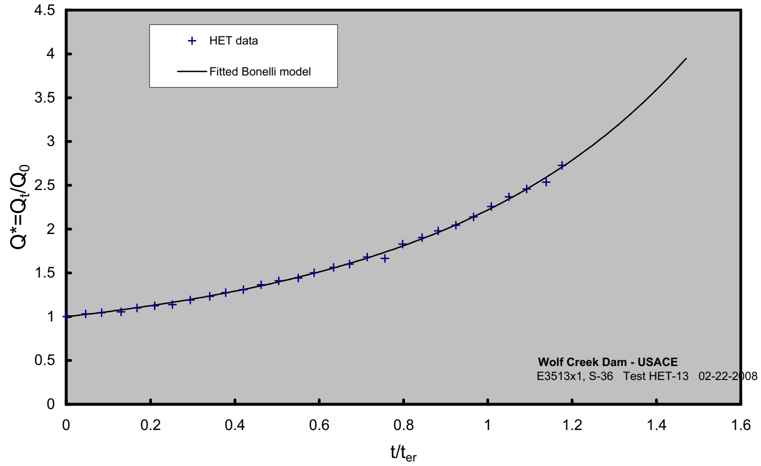
Wolf Creek Dam - USACE

E3513x1, S-36 Test HET-13 02-22-2008

EROSION RATE VS. SHEAR STRESS



**HET dimensionless flow vs. dimensionless time
(Bonelli et al. 2006)**



Project Wolf Creek Dam - USACE
Feature E3513x1, S-36
Test HET-13
Date 2/22/2008

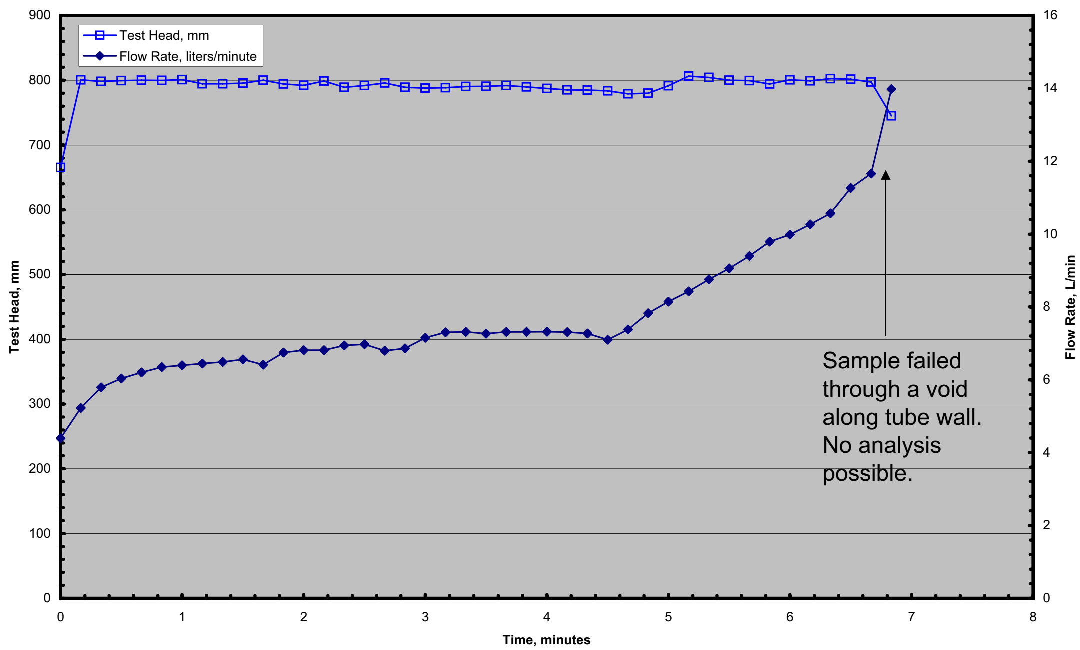
RESULTS SUMMARY

C_e	4.94E-05	((kg/s)/m^2)/Pa = s/m	
I_{HET}	4.31		**Group 4**
τ_c	356.1	Pa	
k_d	2.927E-08	m/s/Pa = m^3/(N-s)	
k_d	0.0293	cm^3/(N-s)	
k_d	0.0166	(ft/hr)/psf	
τ_c	7.44	psf	

Wolf Creek Dam - USACE

P4340x, ST-5 Test HET-14 02-27-2008

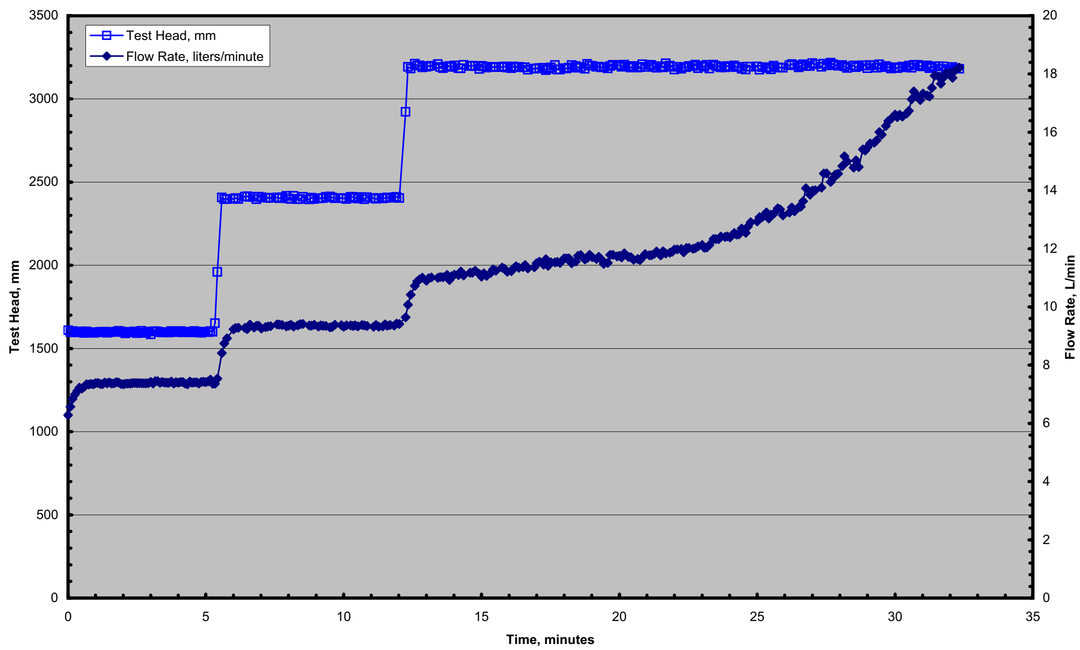
HET Test Record



Wolf Creek Dam - USACE

E3548x, SH-14 Test HET-15 02-27-2008

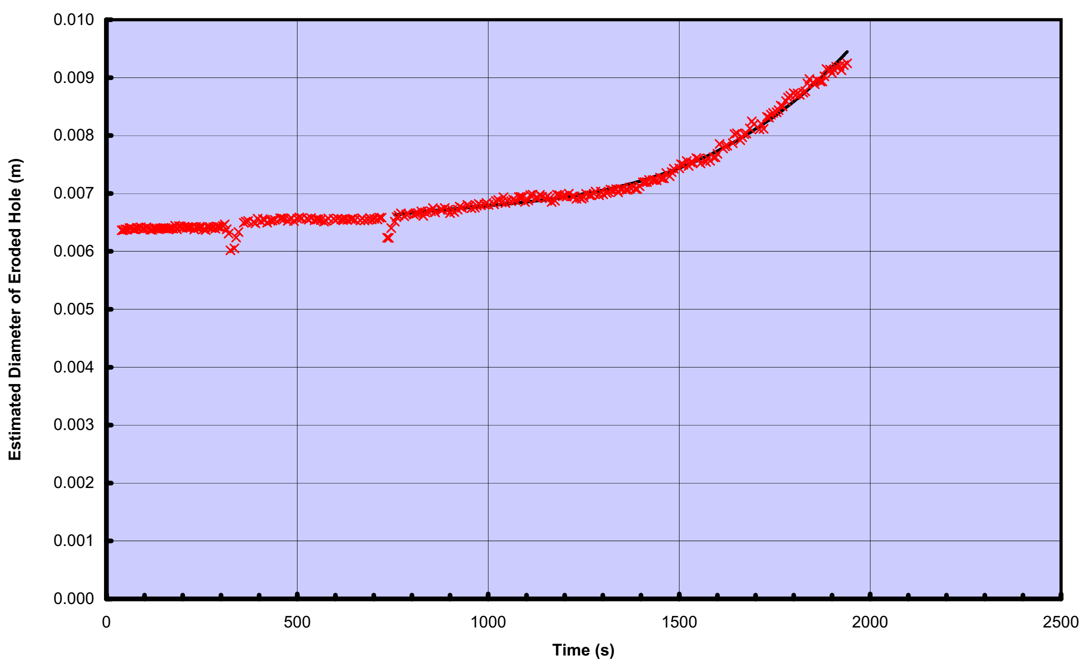
HET Test Record



Wolf Creek Dam - USACE

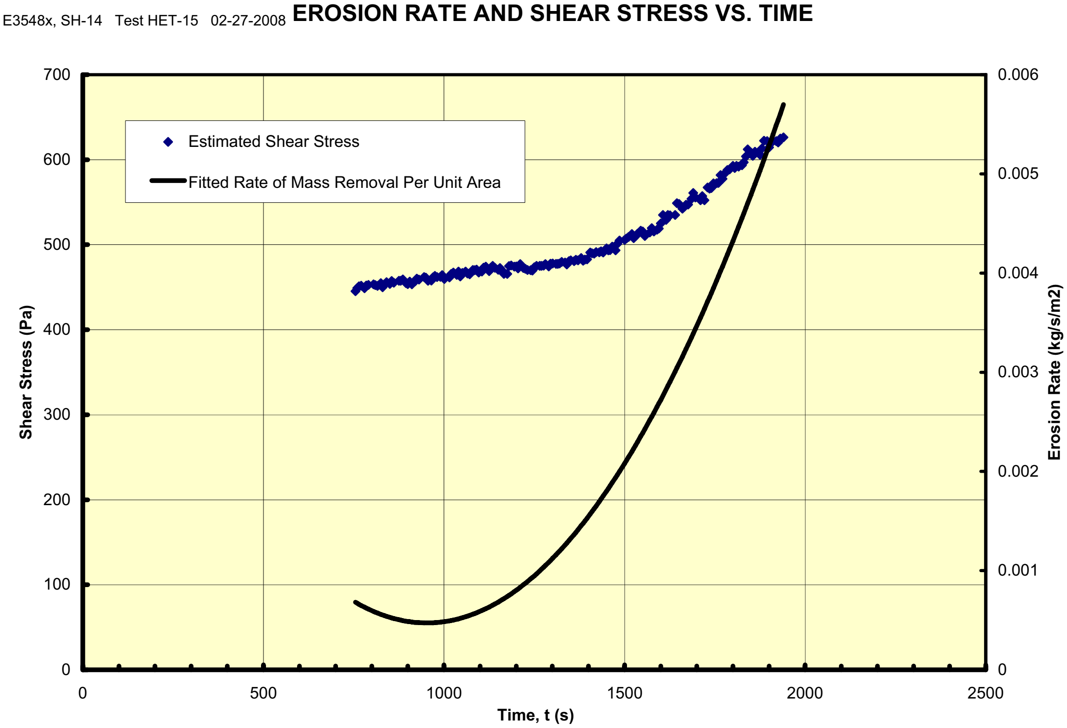
E3548x, SH-14 Test HET-15 02-27-2008

COMPUTED DIAMETER OF ERODED HOLE



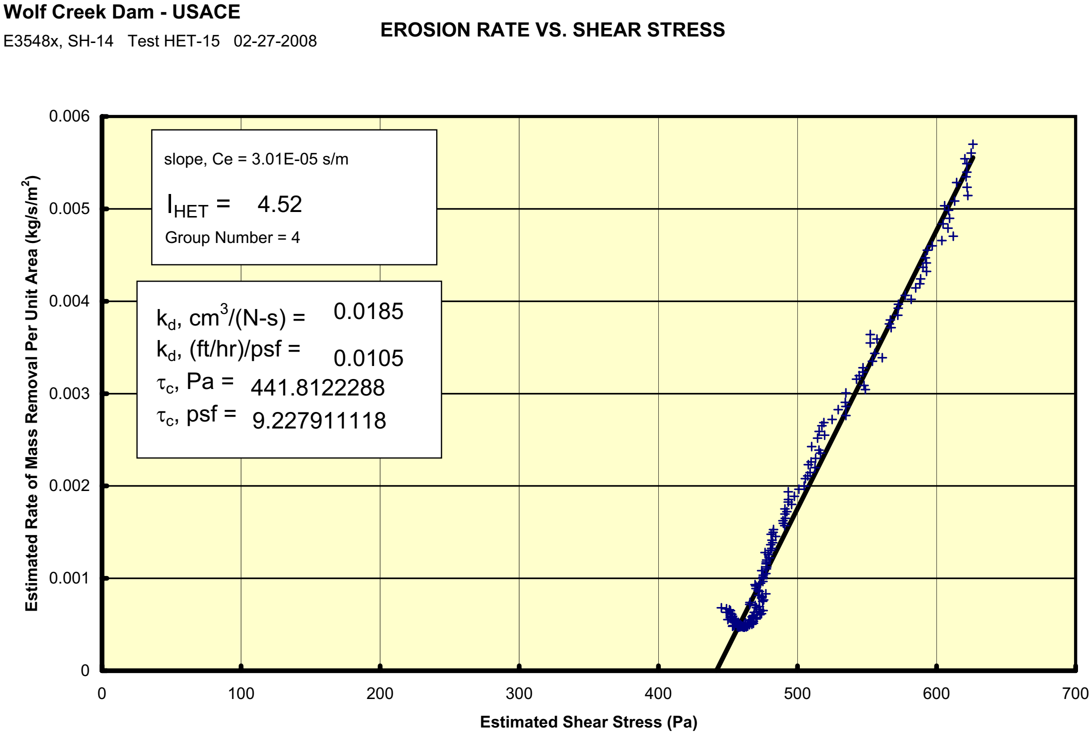
Wolf Creek Dam - USACE

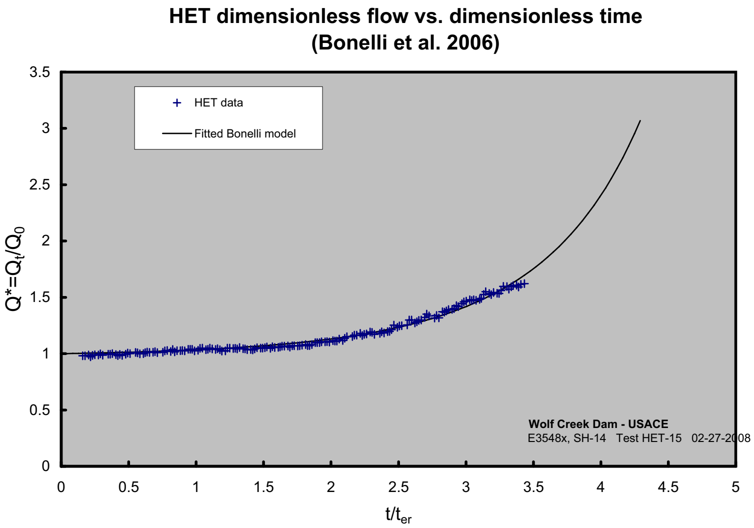
E3548x, SH-14 Test HET-15 02-27-2008



Wolf Creek Dam - USACE

E3548x, SH-14 Test HET-15 02-27-2008





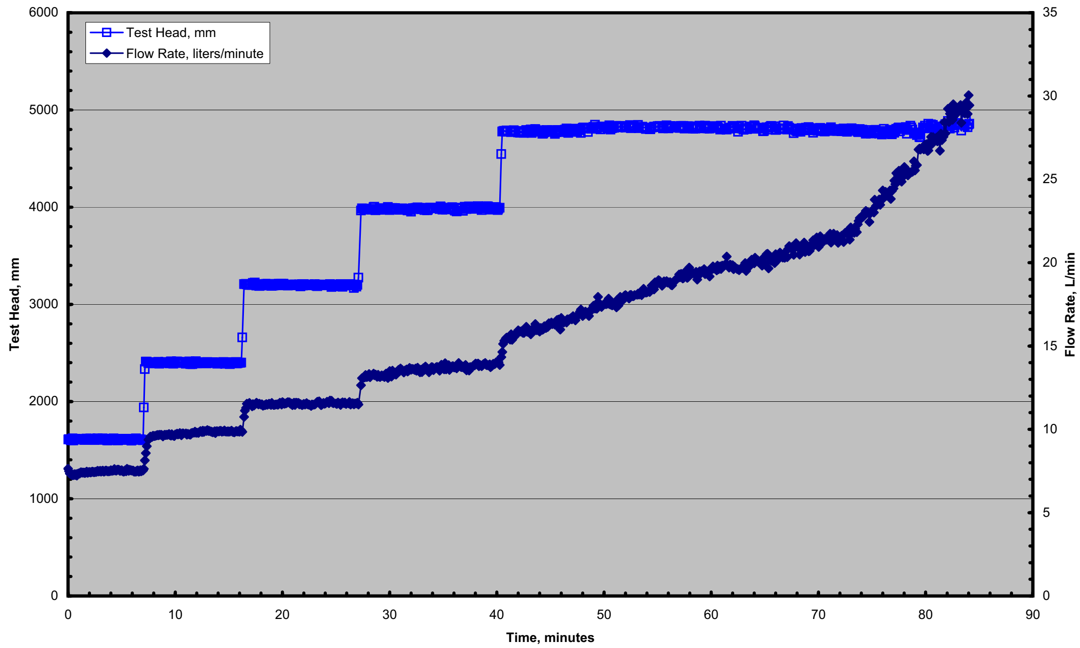
Project Wolf Creek Dam - USACE
Feature E3548x, SH-14
Test HET-15
Date 2/27/2008

RESULTS SUMMARY

C_e	3.47E-05	((kg/s)/m^2)/Pa = s/m	
I_{HET}	4.46		**Group 4**
τ_c	455.5	Pa	
k_d	2.131E-08	m/s/Pa = m^3/(N-s)	
k_d	0.0213	cm^3/(N-s)	
k_d	0.0121	(ft/hr)/psf	
τ_c	9.51	psf	

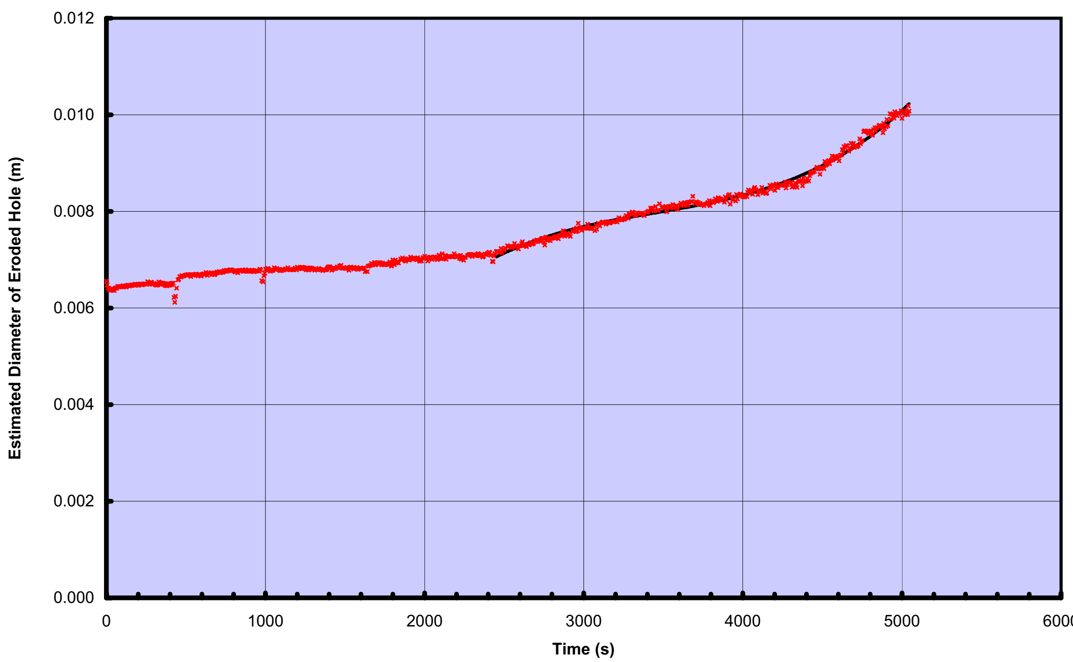
Wolf Creek Dam - USACE
E3560x, SH-2 Test HET-16 02-27-2008

HET Test Record



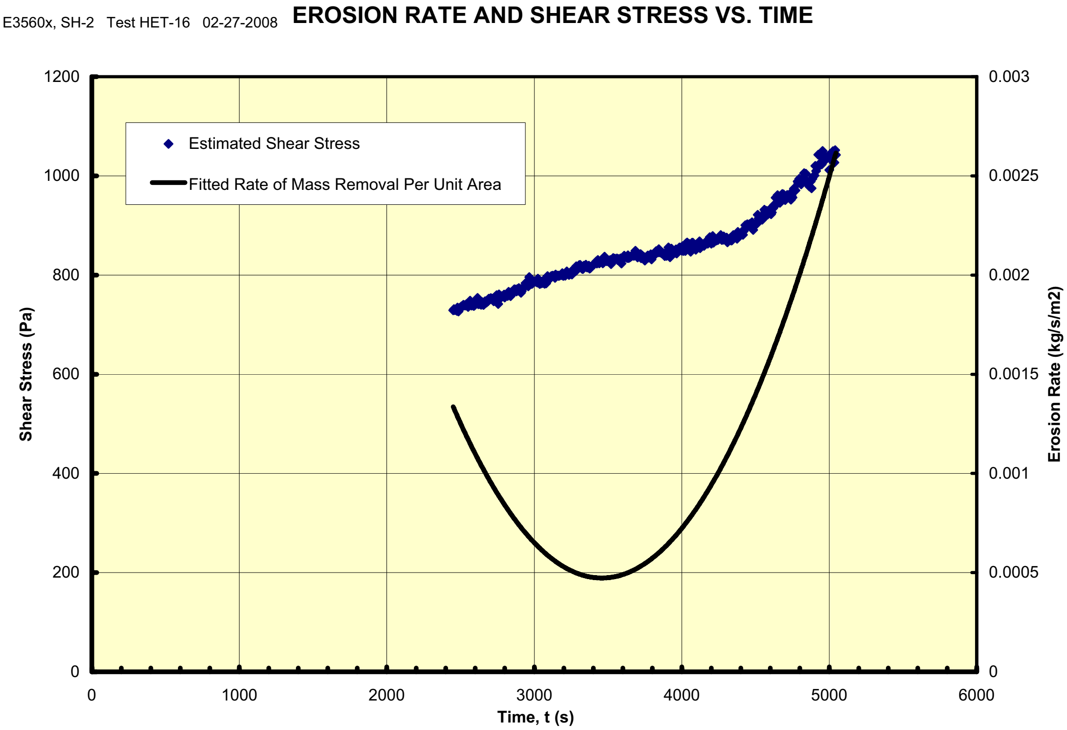
Wolf Creek Dam - USACE
E3560x, SH-2 Test HET-16 02-27-2008

COMPUTED DIAMETER OF ERODED HOLE



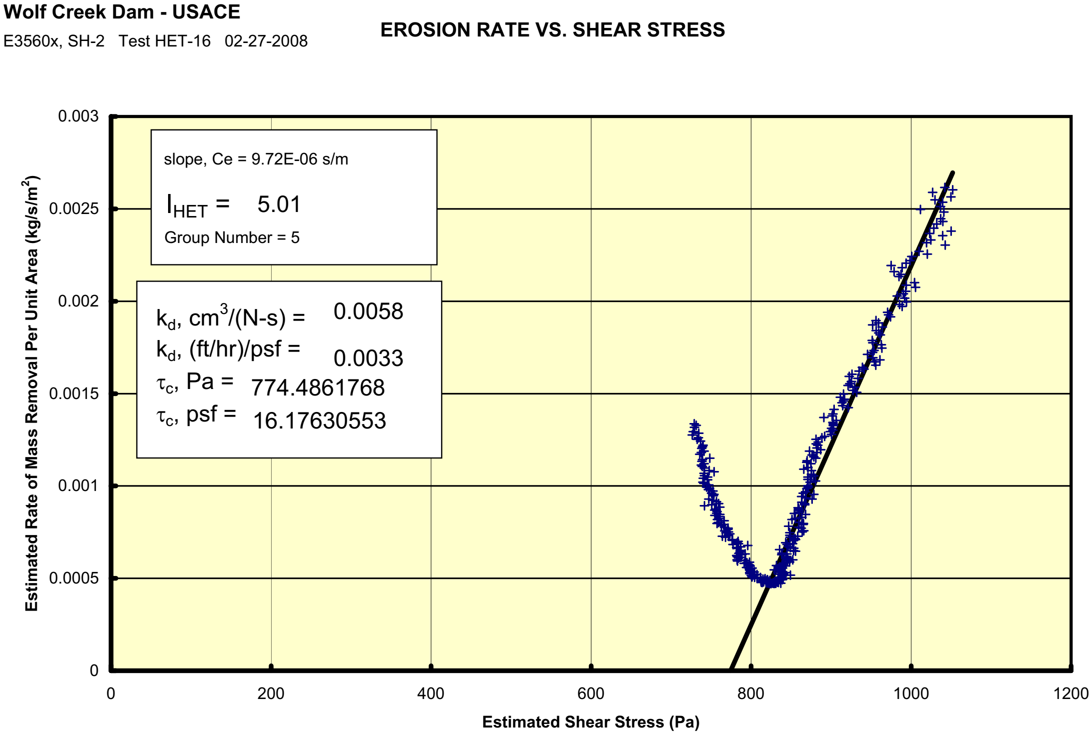
Wolf Creek Dam - USACE

E3560x, SH-2 Test HET-16 02-27-2008

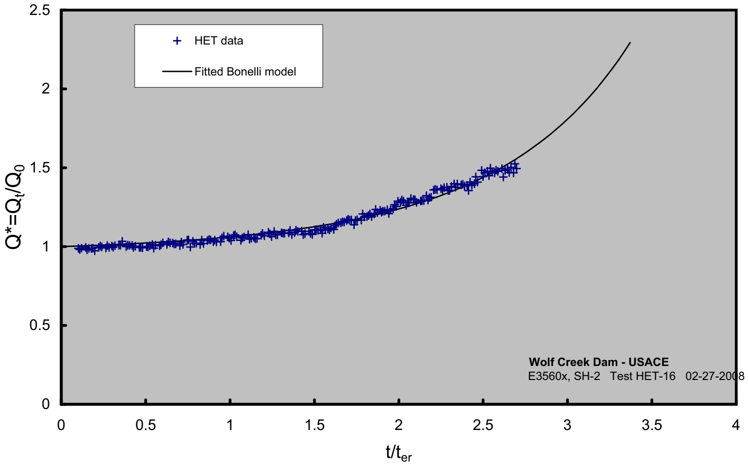


Wolf Creek Dam - USACE

E3560x, SH-2 Test HET-16 02-27-2008



HET dimensionless flow vs. dimensionless time
(Bonelli et al. 2006)



Project Wolf Creek Dam - USACE
Feature E3560x, SH-2
Test HET-16
Date 2/27/2008

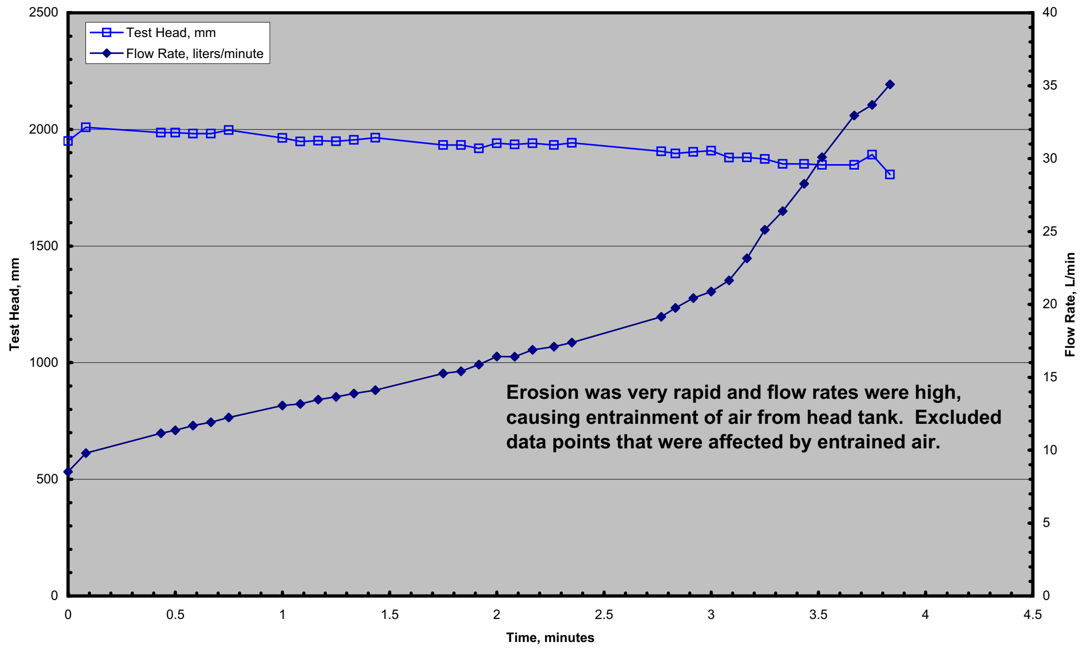
RESULTS SUMMARY

C_e	1.41E-05	((kg/s)/m^2)/Pa = s/m
I_{HET}	4.85	**Group 4**
τ_c	822.6	Pa
k_d	8.405E-09	m/s/Pa = m^3/(N-s)
k_d	0.0084	cm^3/(N-s)
k_d	0.0048	(ft/hr)/psf
τ_c	17.18	psf

Wolf Creek Dam - USACE

P4340x, ST-5   Test HET-17   02-28-2008

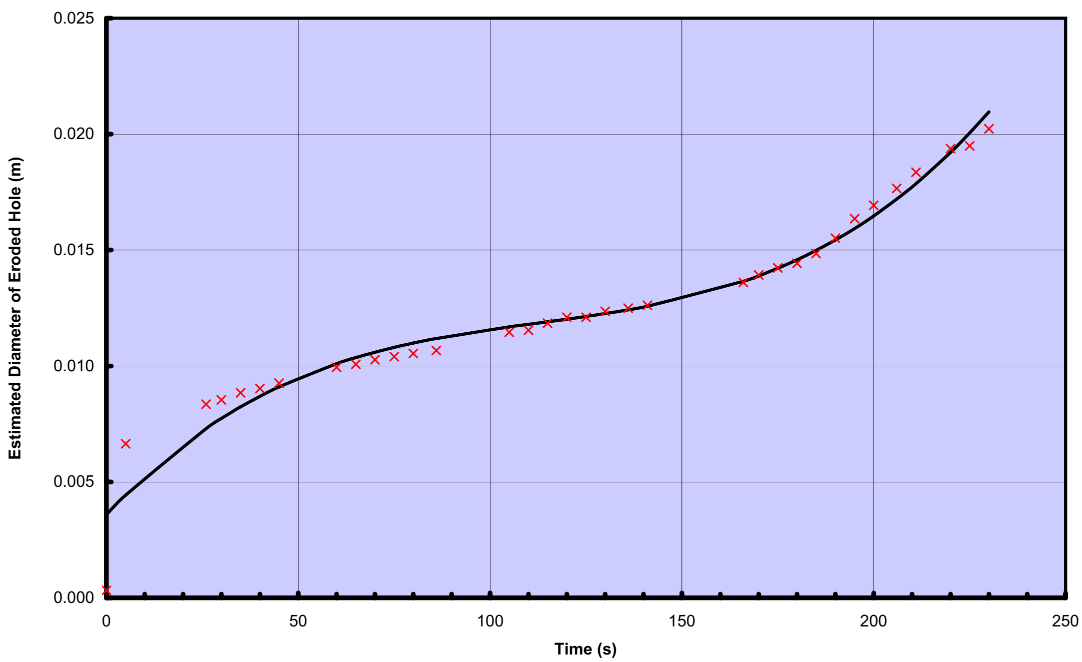
HET Test Record

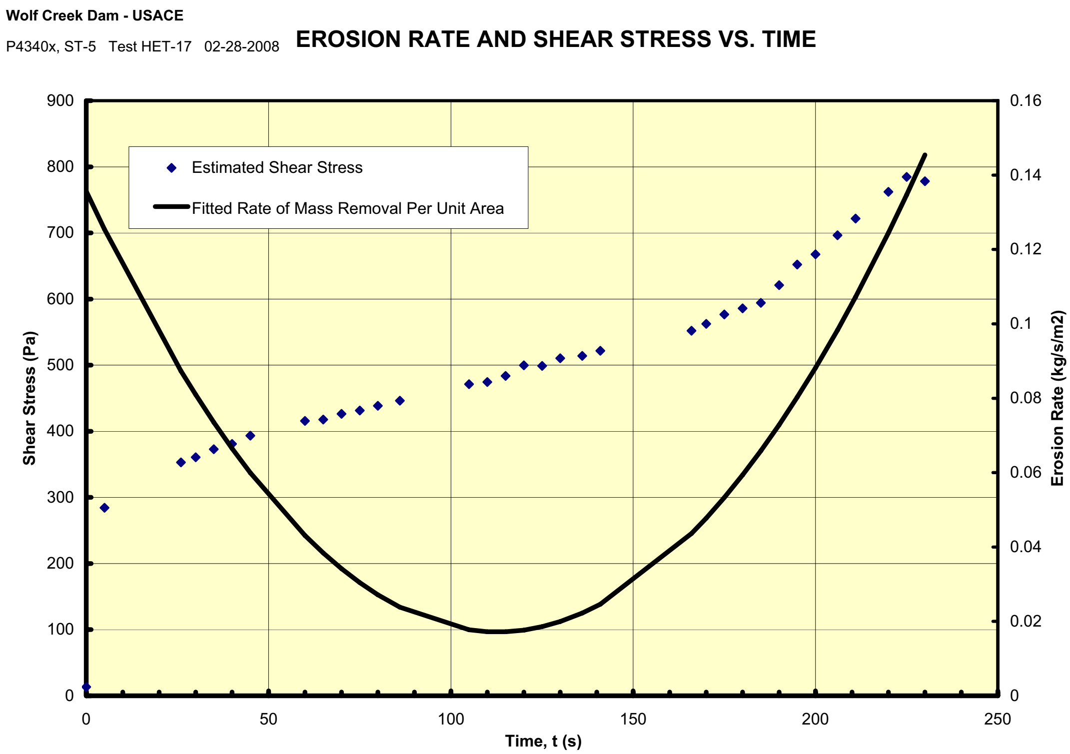


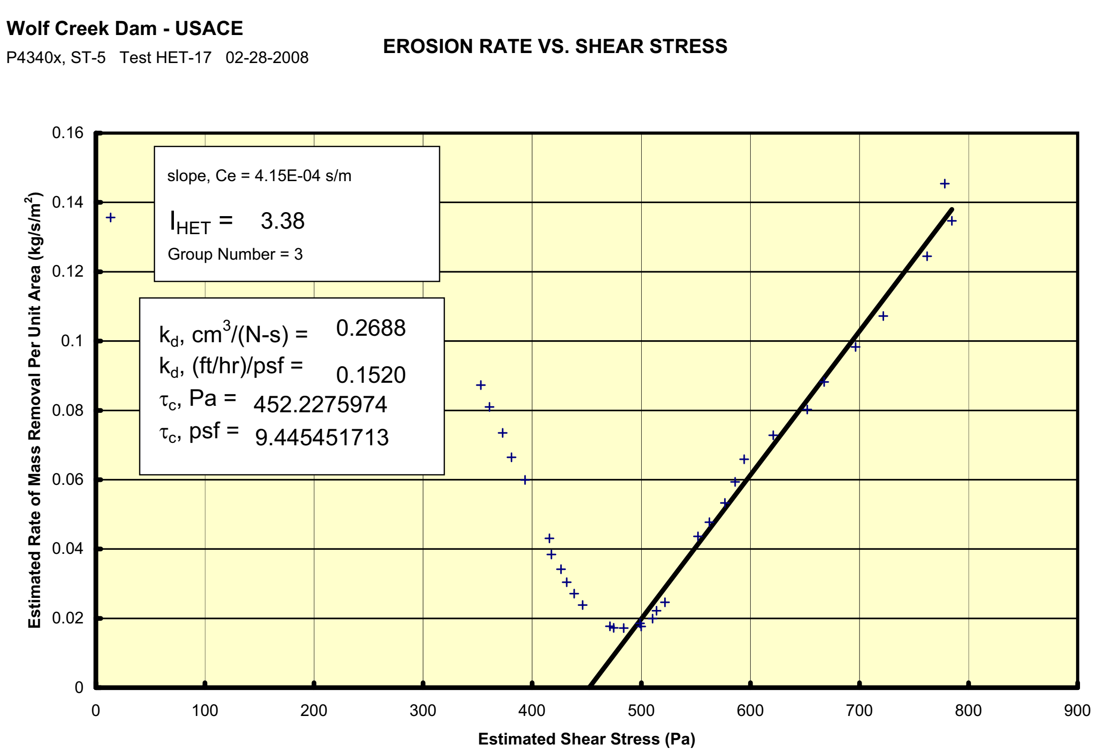
Wolf Creek Dam - USACE

P4340x, ST-5   Test HET-17   02-28-2008

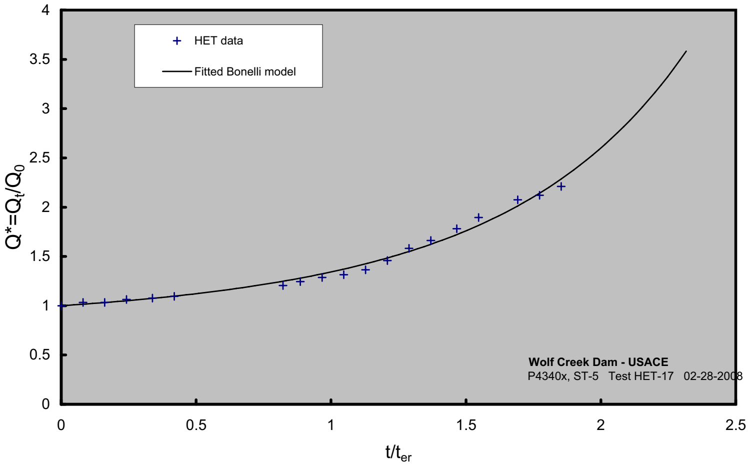
COMPUTED DIAMETER OF ERODED HOLE




Wolf Creek Dam - USACE
P4340x, ST-5 Test HET-17 02-28-2008
EROSION RATE AND SHEAR STRESS VS. TIME
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
100
200
300
400
500
600
700
800
900
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0
50
100
150
200
250


Wolf Creek Dam - USACE
P4340x, ST-5 Test HET-17 02-28-2008
EROSION RATE VS. SHEAR STRESS
slope, Ce = 4.15E-04 s/m
I_HET = 3.38
Group Number = 3
k_d, cm^3/(N-s) = 0.2688
k_d, (ft/hr)/psf = 0.1520
τ_c, Pa = 452.2275974
τ_c, psf = 9.445451713
Estimated Rate of Mass Removal Per Unit Area (kg/s/m^2)
Estimated Shear Stress (Pa)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0
100
200
300
400
500
600
700
800
900

HET dimensionless flow vs. dimensionless time (Bonelli et al. 2006)



Project Wolf Creek Dam - USACE
Feature P4340x, ST-5
Test HET-17
Date 2/28/2008

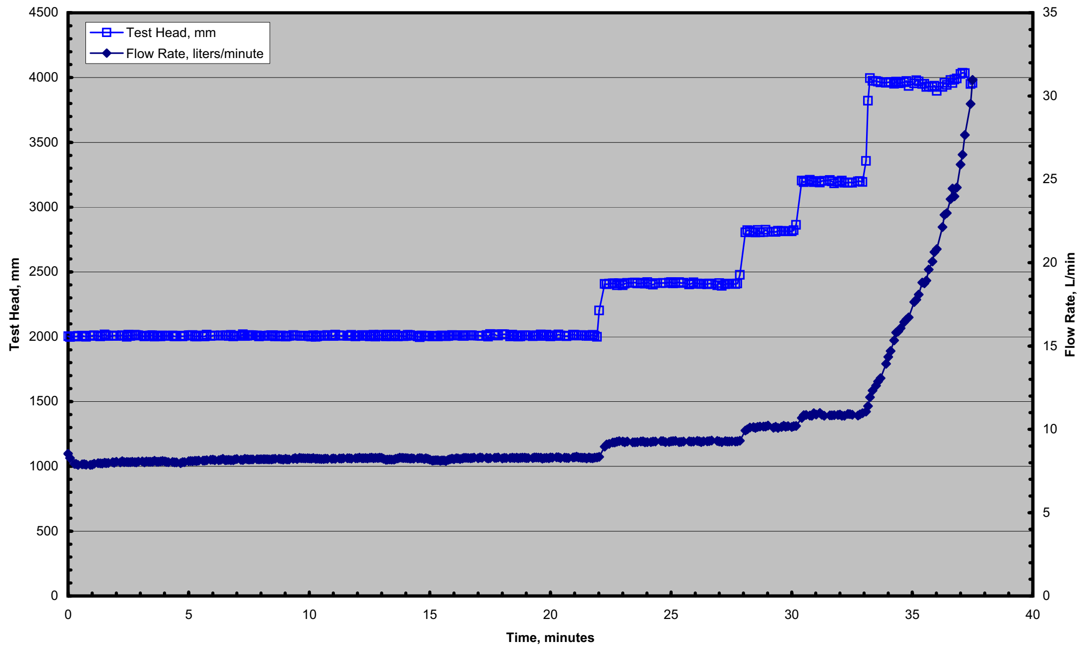
RESULTS SUMMARY

C_e	3.09E-04	((kg/s)/m^2)/Pa = s/m
I_{HET}	3.51	**Group 3**
τ_c	442.3	Pa
k_d	2.000E-07	m/s/Pa = m^3/(N-s)
k_d	0.2000	cm^3/(N-s)
k_d	0.1131	(ft/hr)/psf
τ_c	9.24	psf

Wolf Creek Dam - USACE

E3513x1, S36 Test HET-18 02-28-2008

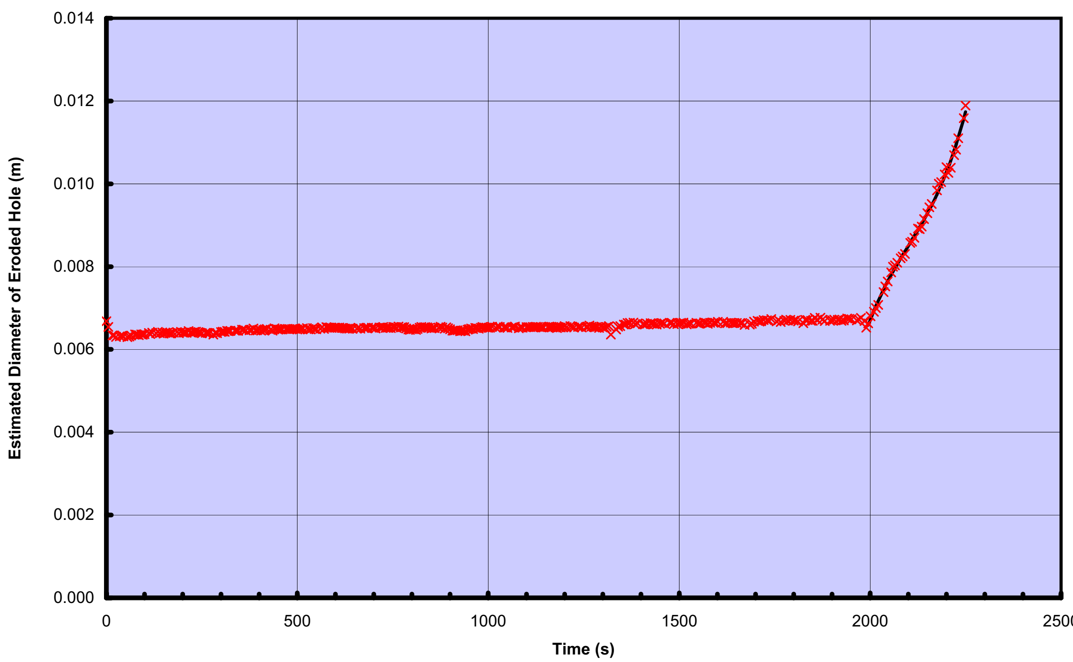
HET Test Record

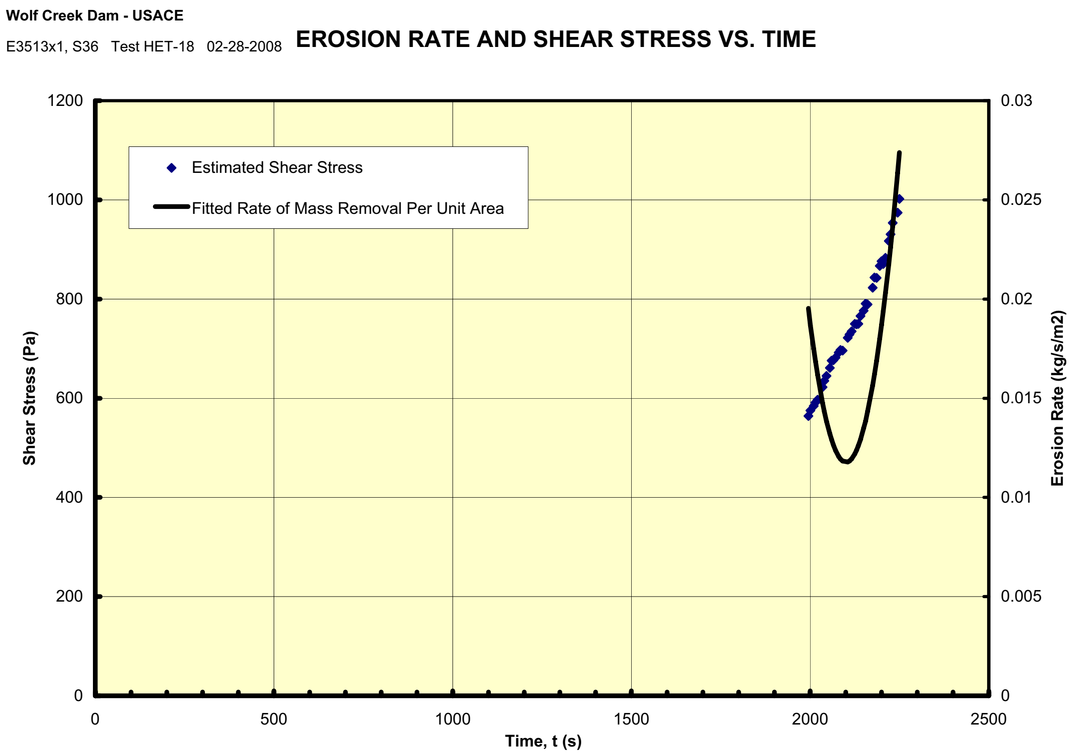


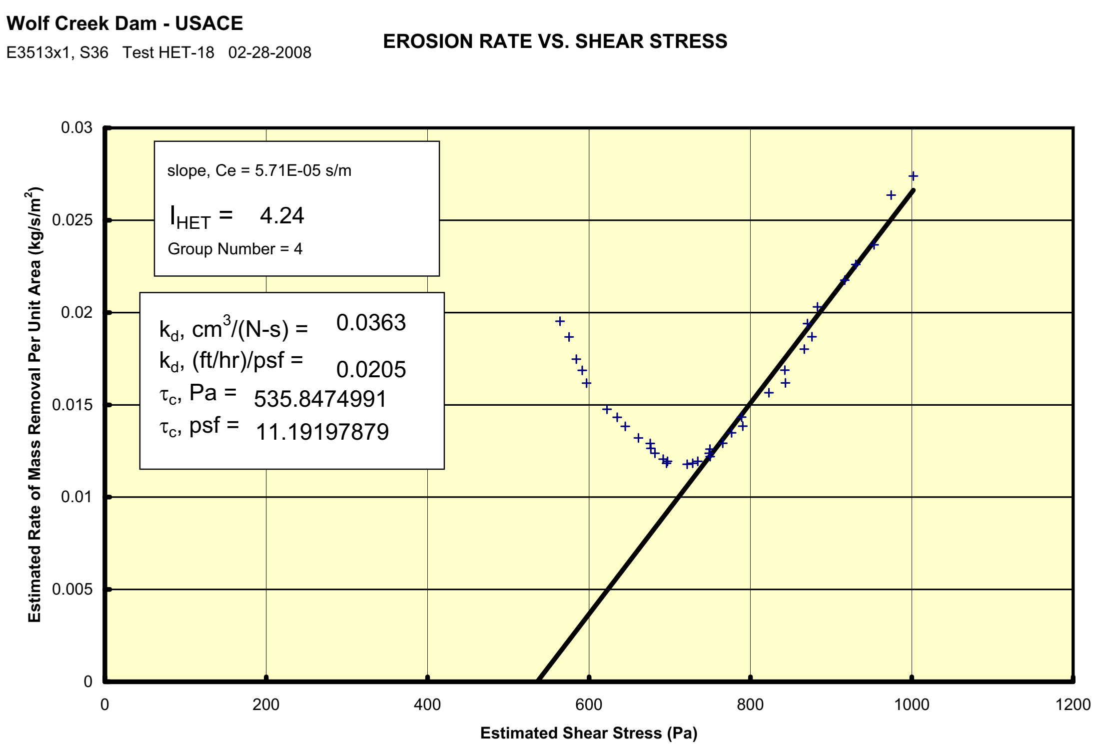
Wolf Creek Dam - USACE

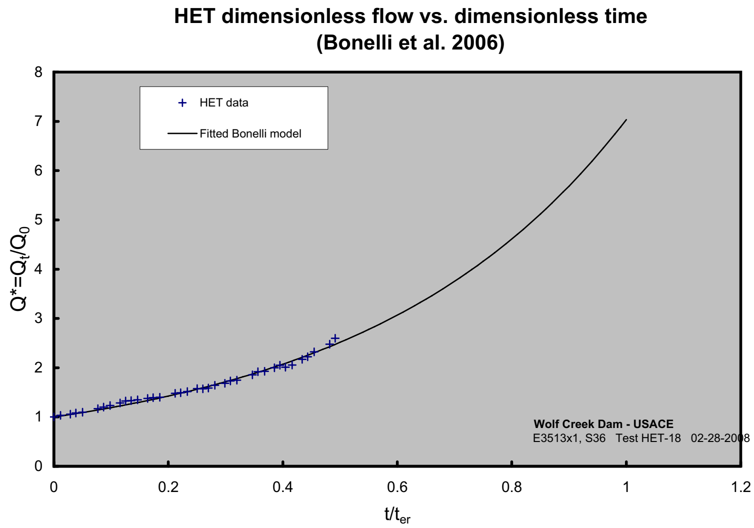
E3513x1, S36 Test HET-18 02-28-2008

COMPUTED DIAMETER OF ERODED HOLE




Wolf Creek Dam - USACE
E3513x1, S36 Test HET-18 02-28-2008
EROSION RATE AND SHEAR STRESS VS. TIME
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
200
400
600
800
1000
1200
0.005
0.01
0.015
0.02
0.025
0.03
500
1000
1500
2000
2500


Wolf Creek Dam - USACE
E3513x1, S36 Test HET-18 02-28-2008
EROSION RATE VS. SHEAR STRESS
slope, Ce = 5.71E-05 s/m
I_HET = 4.24
Group Number = 4
kd, cm3/(N-s) = 0.0363
kd, (ft/hr)/psf = 0.0205
τc, Pa = 535.8474991
τc, psf = 11.19197879
Estimated Rate of Mass Removal Per Unit Area (kg/s/m2)
Estimated Shear Stress (Pa)
0
0.005
0.01
0.015
0.02
0.025
0.03
200
400
600
800
1000
1200



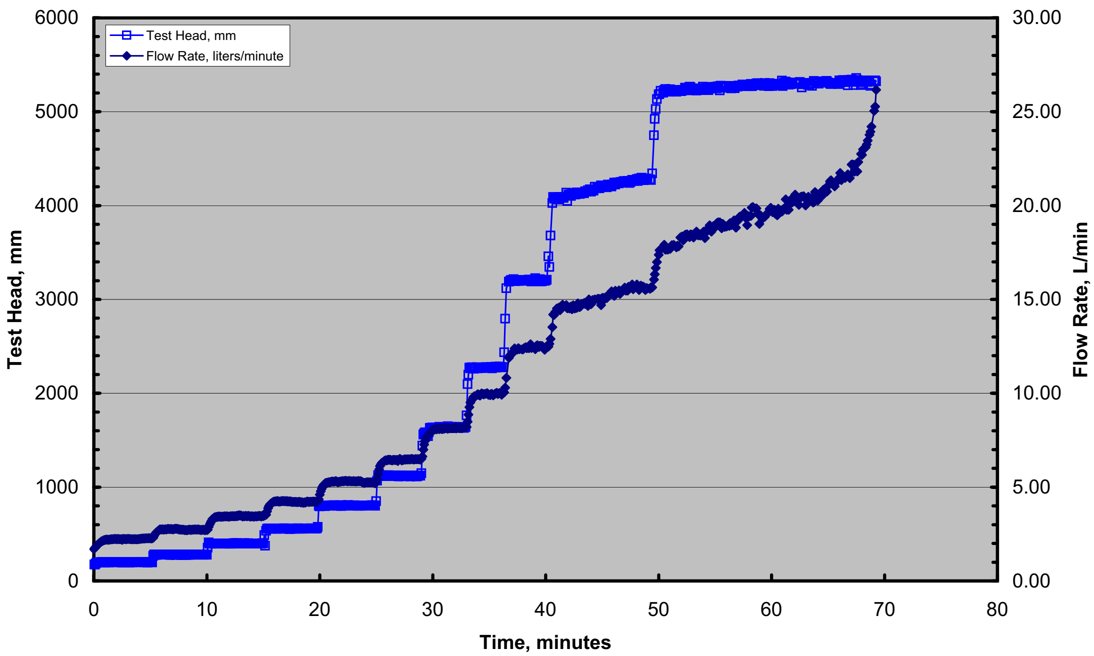
Project Wolf Creek Dam - USACE
Feature E3513x1, S36
Test HET-18
Date 2/28/2008

RESULTS SUMMARY

C_e	1.80E-05	((kg/s)/m^2)/Pa = s/m
I_{HET}	4.75	**Group 4**
τ_c	174.5	Pa
k_d	1.142E-08	m/s/Pa = m^3/(N-s)
k_d	0.0114	cm^3/(N-s)
k_d	0.0065	(ft/hr)/psf
τ_c	3.64	psf

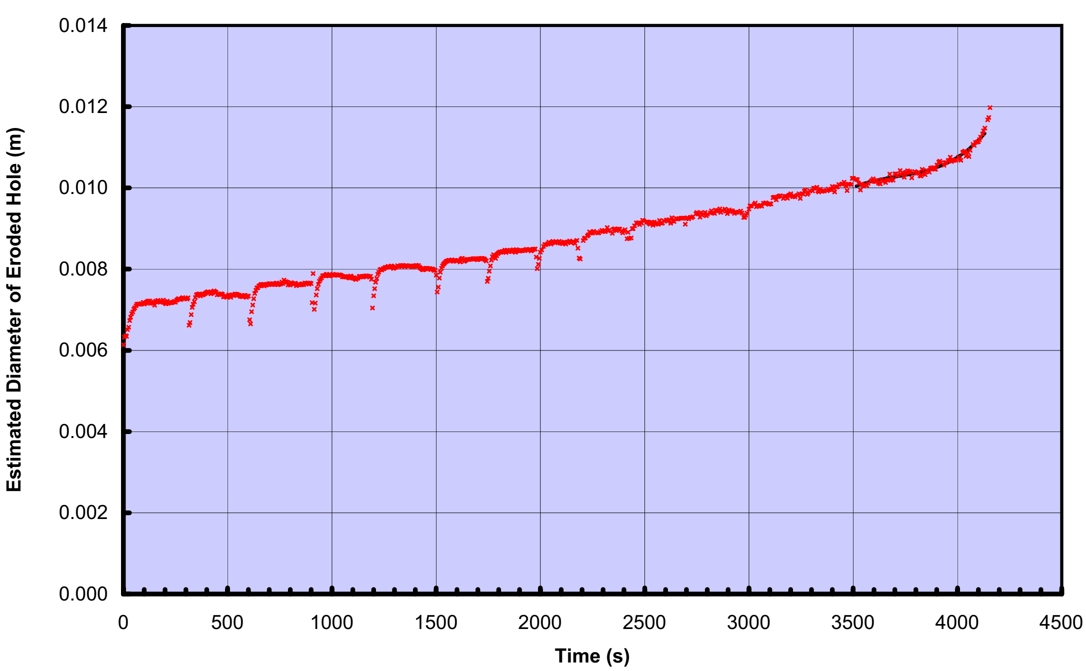
Wolf Creek Dam - USACE
P4340x, ST-5 Test HET-19 03-04-2008

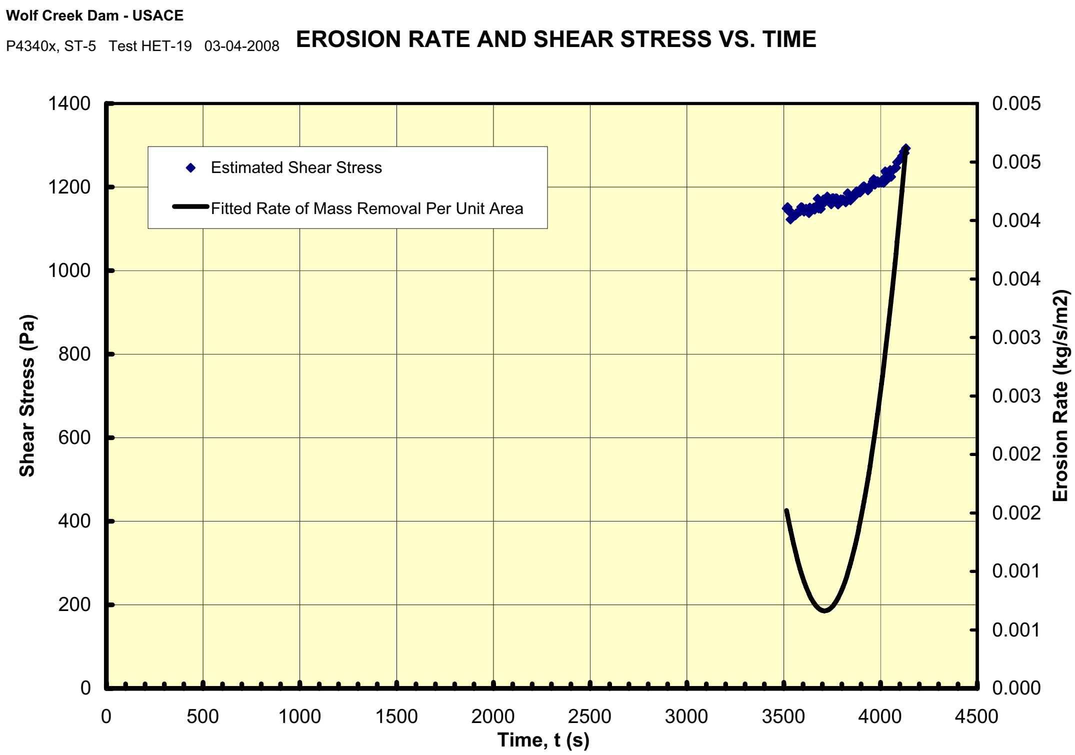
HET Test Record

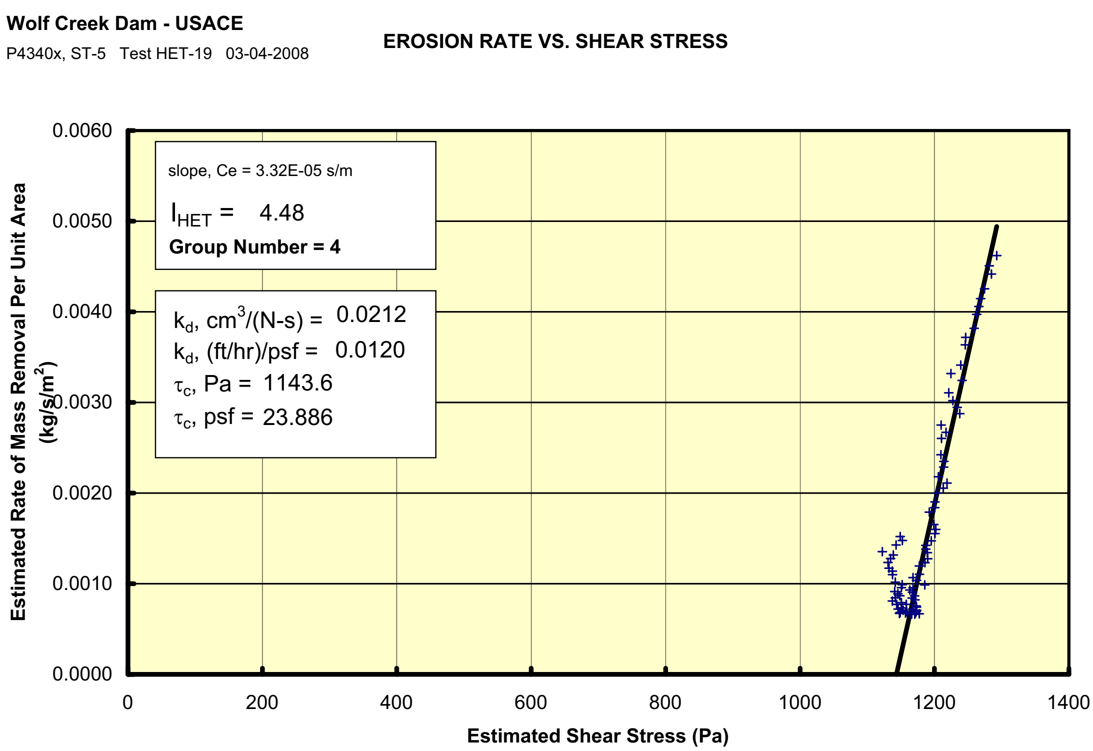


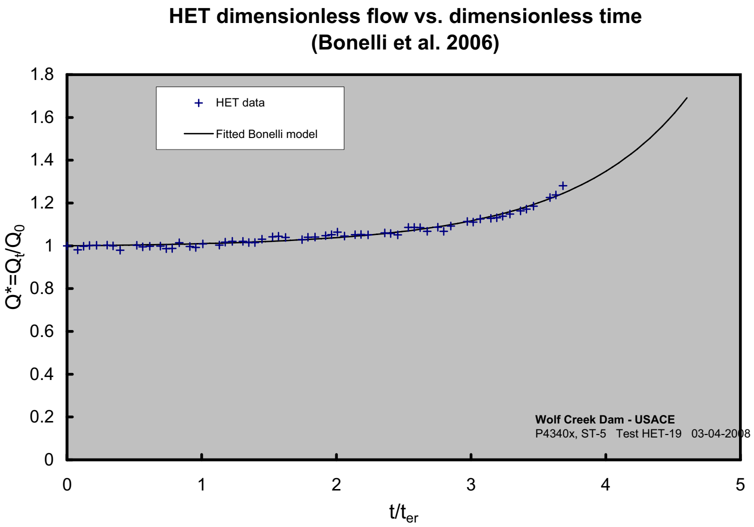
Wolf Creek Dam - USACE
P4340x, ST-5 Test HET-19 03-04-2008

COMPUTED DIAMETER OF ERODED HOLE




Wolf Creek Dam - USACE
P4340x, ST-5 Test HET-19 03-04-2008
EROSION RATE AND SHEAR STRESS VS. TIME
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
1400
1200
1000
800
600
400
200
0
0.005
0.004
0.003
0.002
0.001
0.000
0
500
1000
1500
2000
2500
3000
3500
4000
4500


Wolf Creek Dam - USACE
P4340x, ST-5 Test HET-19 03-04-2008
EROSION RATE VS. SHEAR STRESS
slope, Ce = 3.32E-05 s/m
I_HET = 4.48
Group Number = 4
k_d, cm^3/(N-s) = 0.0212
k_d, (ft/hr)/psf = 0.0120
τ_c, Pa = 1143.6
τ_c, psf = 23.886
Estimated Rate of Mass Removal Per Unit Area (kg/s/m^2)
Estimated Shear Stress (Pa)
0.0060
0.0050
0.0040
0.0030
0.0020
0.0010
0.0000
0
200
400
600
800
1000
1200
1400



Project Wolf Creek Dam - USACE
Feature P4340x, ST-5
Test HET-19
Date 3/4/2008

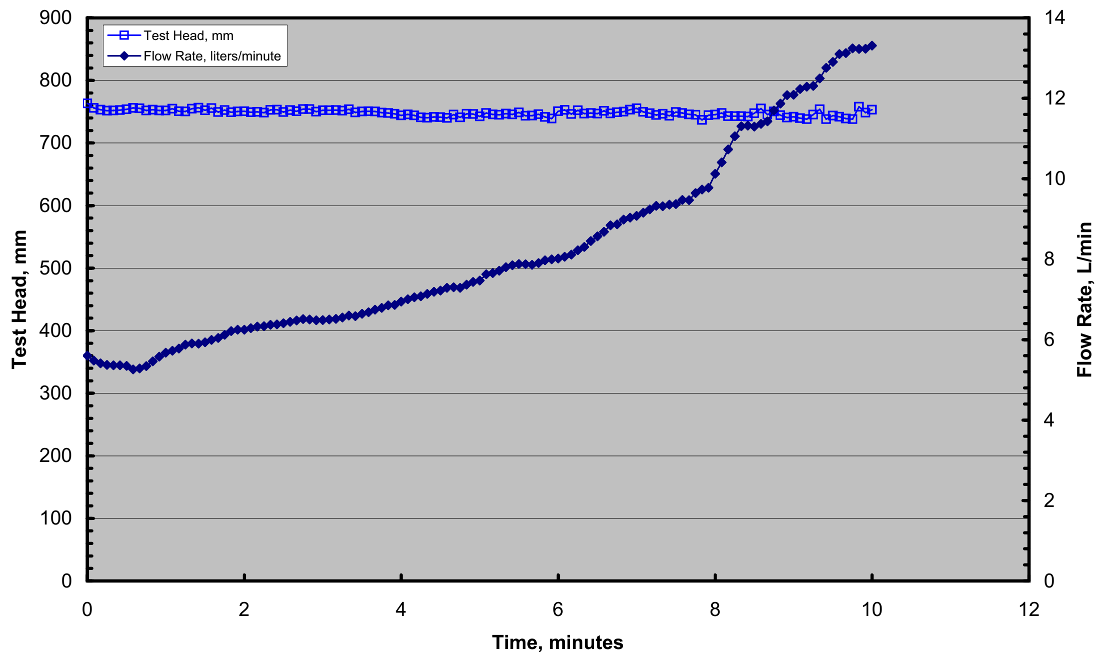
RESULTS SUMMARY

C_e	6.07E-05	$((kg/s)/m^2)/Pa = s/m$	
I_{HET}	4.22		**Group 4**
τ_c	1171.8	Pa	
k_d	3.875E-08	$m/s/Pa = m^3/(N\text{-}s)$	
k_d	0.0387	$cm^3/(N\text{-}s)$	
k_d	0.0219	(ft/hr)/psf	
τ_c	24.47	psf	

Wolf Creek Dam - USACE

E35.62X SH-7 Test HET-20 03-06-2008

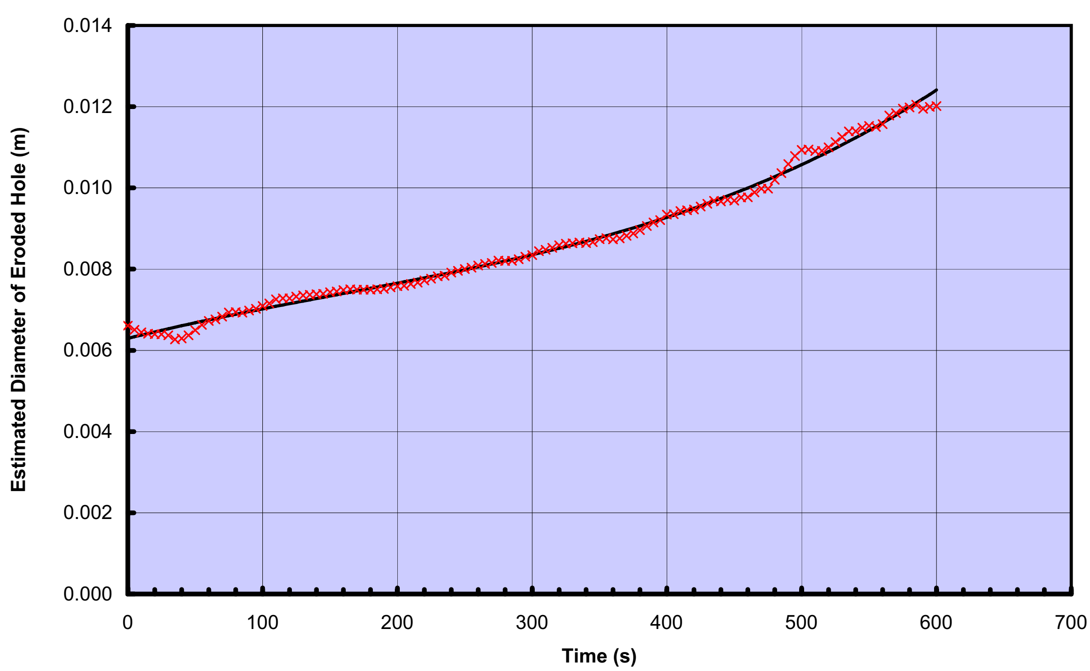
HET Test Record



Wolf Creek Dam - USACE

E35.62X SH-7 Test HET-20 03-06-2008

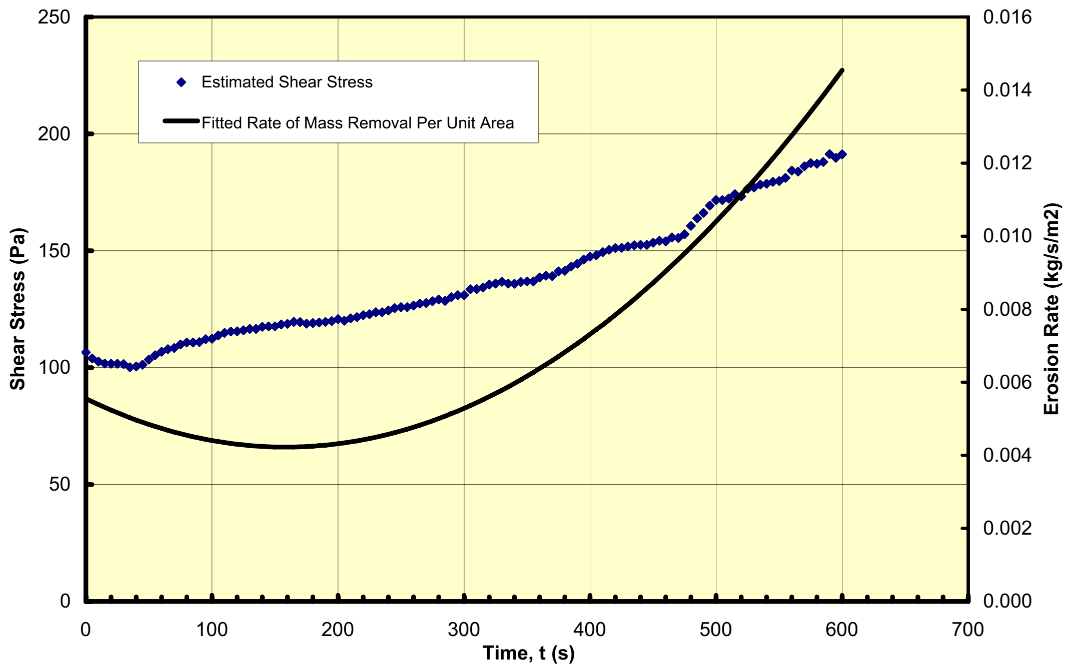
COMPUTED DIAMETER OF ERODED HOLE



Wolf Creek Dam - USACE

E35.62X SH-7 Test HET-20 03-06-2008

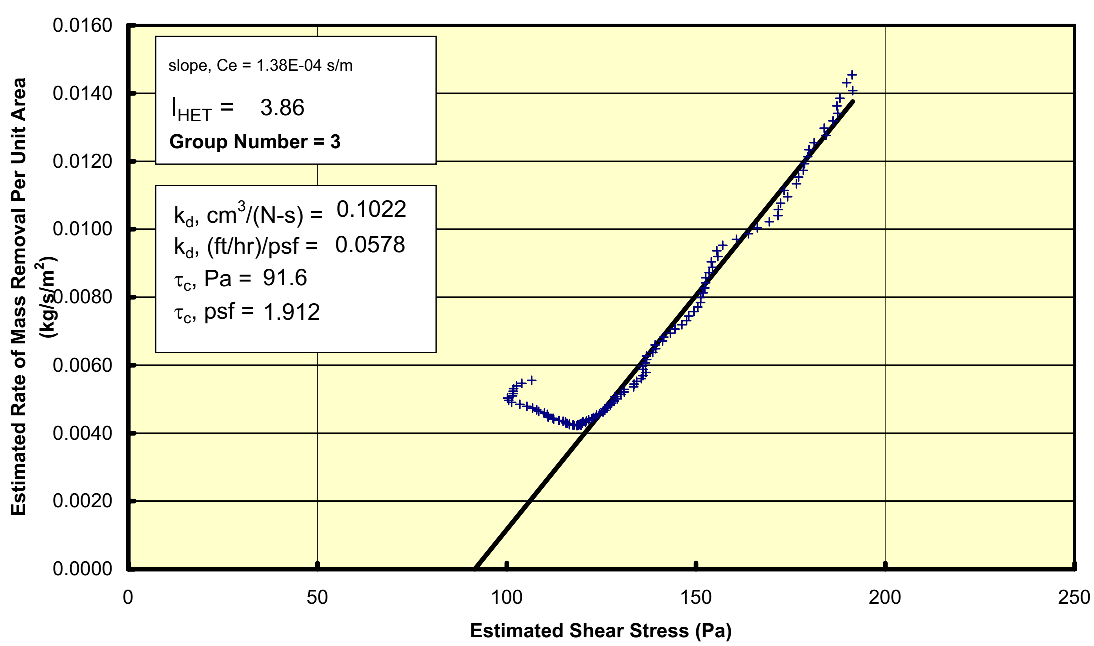
EROSION RATE AND SHEAR STRESS VS. TIME



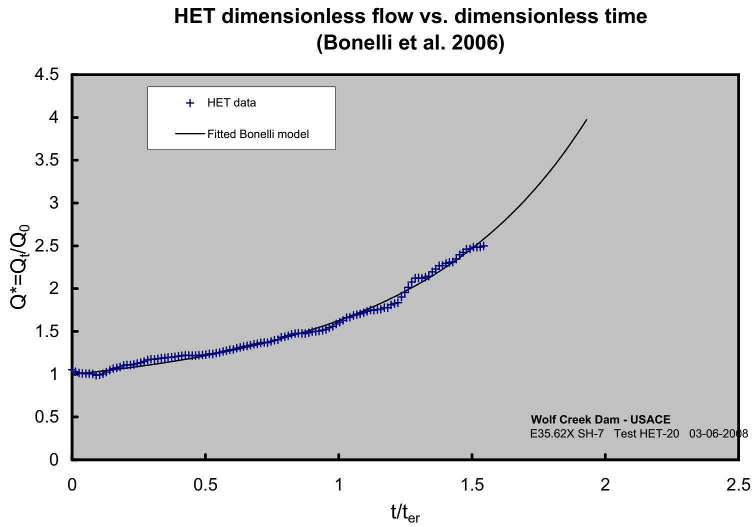
Wolf Creek Dam - USACE

E35.62X SH-7 Test HET-20 03-06-2008

EROSION RATE VS. SHEAR STRESS



HET dimensionless flow vs. dimensionless time (Bonelli et al. 2006)



Project Wolf Creek Dam - USACE
Feature E35.62X SH-7
Test HET-20
Date 3/6/2008

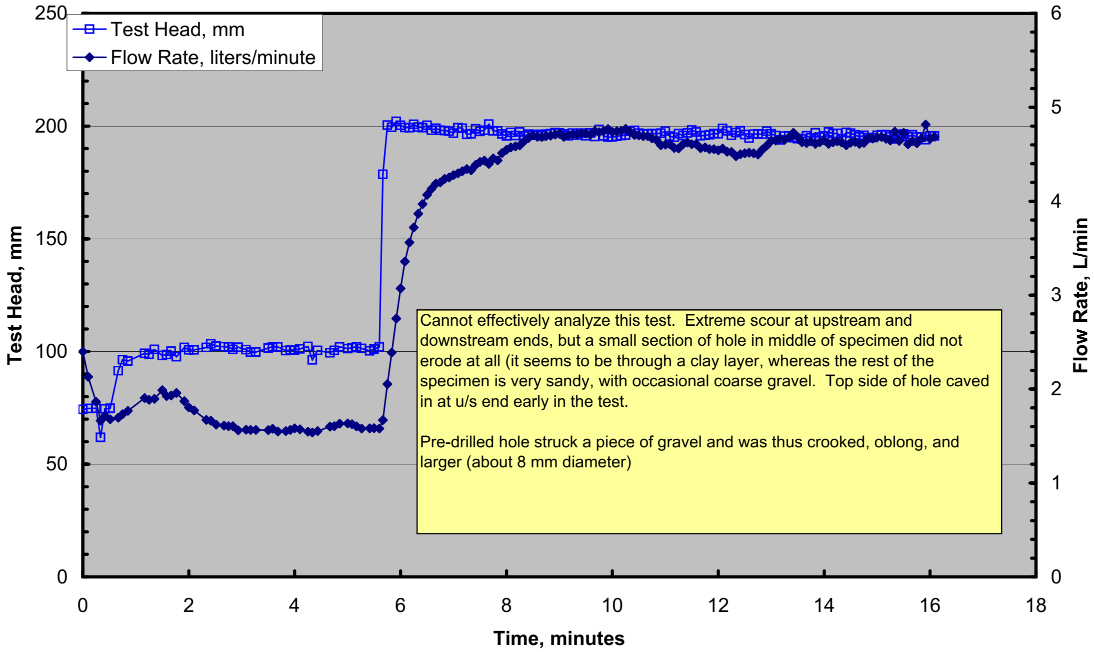
RESULTS SUMMARY

C_e	1.10E-04	((kg/s)/m^2)/Pa = s/m	
I_{HET}	3.96		**Group 3**
τ_c	87.9	Pa	
k_d	8.136E-08	m/s/Pa = m^3/(N-s)	
k_d	0.0814	cm^3/(N-s)	
k_d	0.0460	(ft/hr)/psf	
τ_c	1.83	psf	

Wolf Creek Dam - USACE

E3513x, ST-2 Test HET-21 03-07-2008

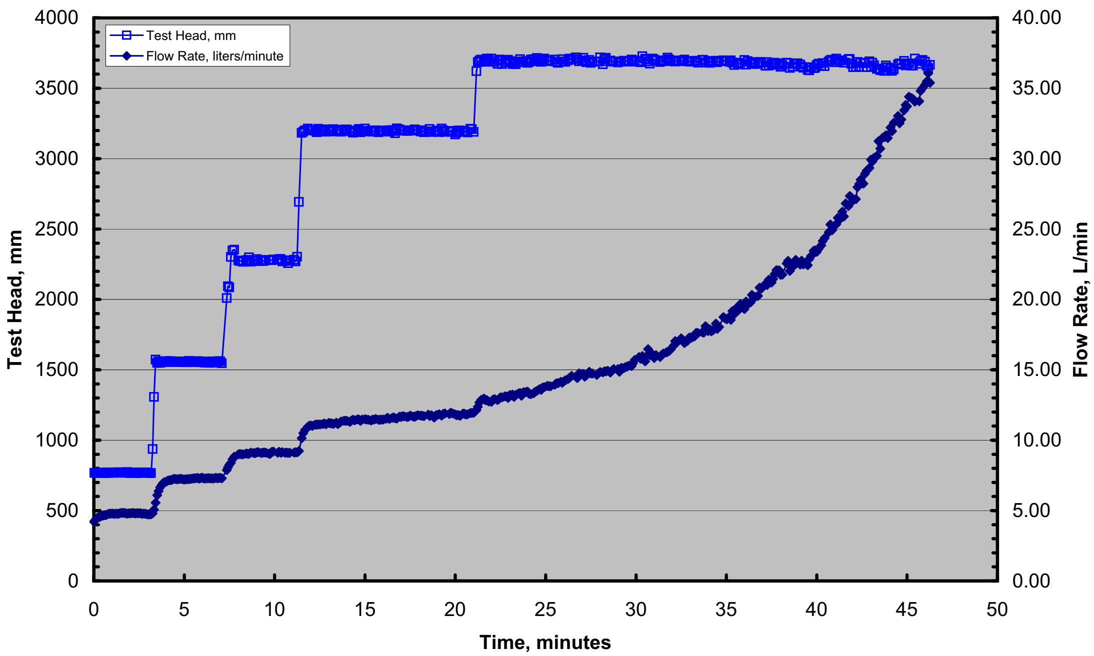
HET Test Record



Wolf Creek Dam - USACE

E3513x1 S-31 204.4-204.8 Test HET-22 03-07-2008

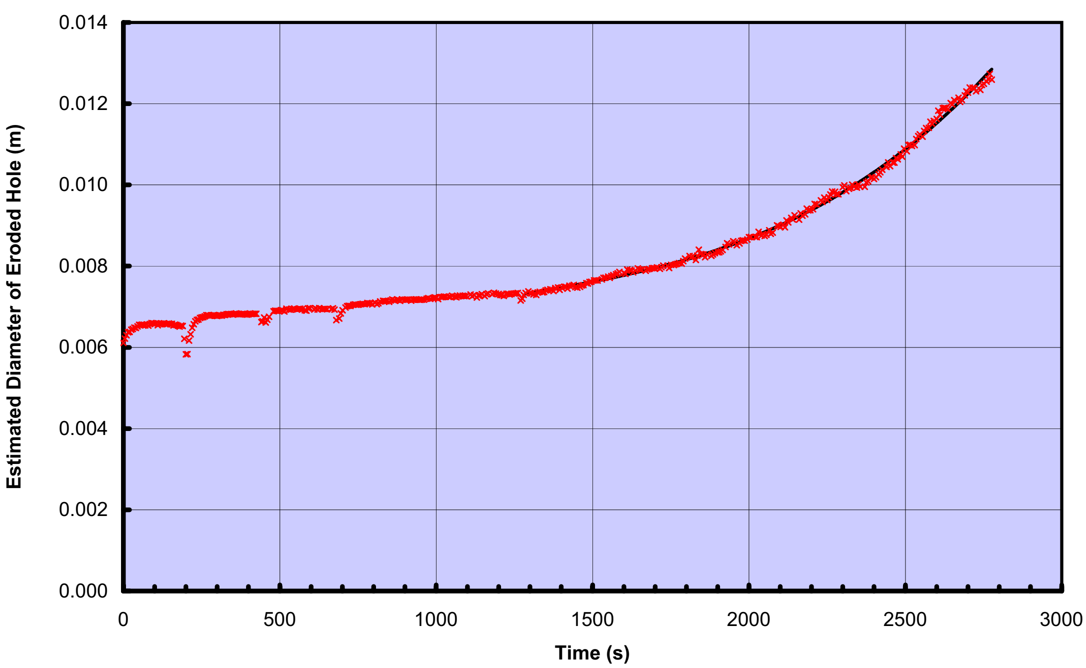
HET Test Record



Wolf Creek Dam - USACE

E3513x1 S-31 204.4-204.8 Test HET-22 03-07-2008

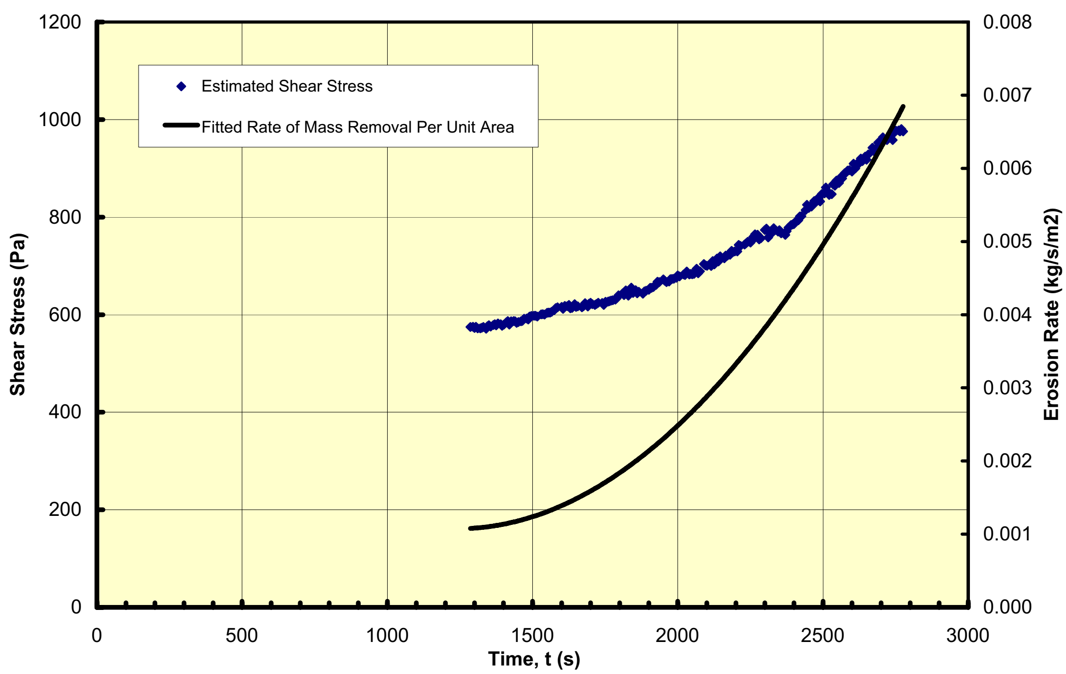
COMPUTED DIAMETER OF ERODED HOLE



Wolf Creek Dam - USACE

E3513x1 S-31 204.4-204.8 Test HET-22 03-07-2008

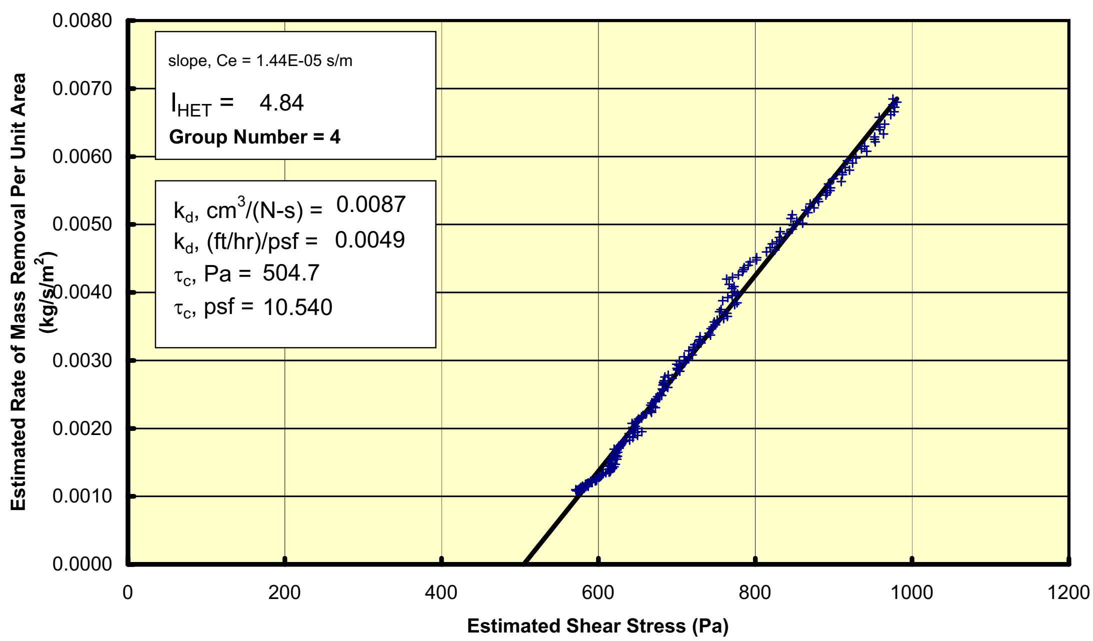
EROSION RATE AND SHEAR STRESS VS. TIME

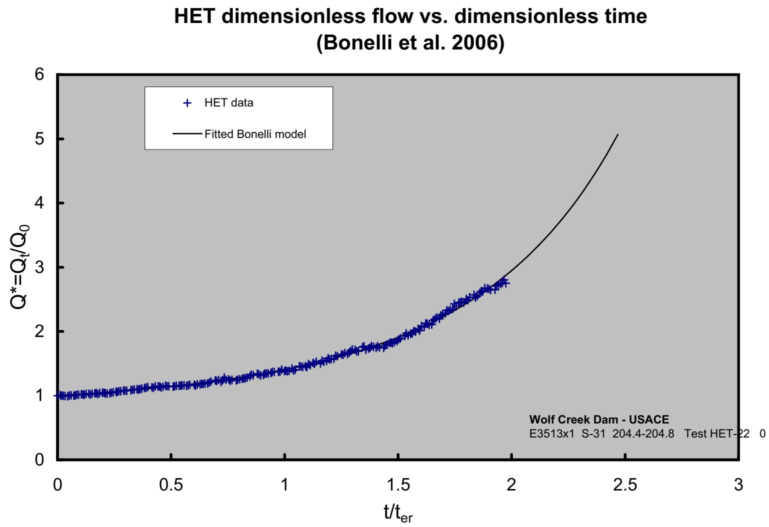


Wolf Creek Dam - USACE

E3513x1 S-31 204.4-204.8 Test HET-22 03-07-2008

EROSION RATE VS. SHEAR STRESS





Project Wolf Creek Dam - USACE
Feature E3513x1 S-31 204.4-204.8
Test HET-22
Date 3/7/2008

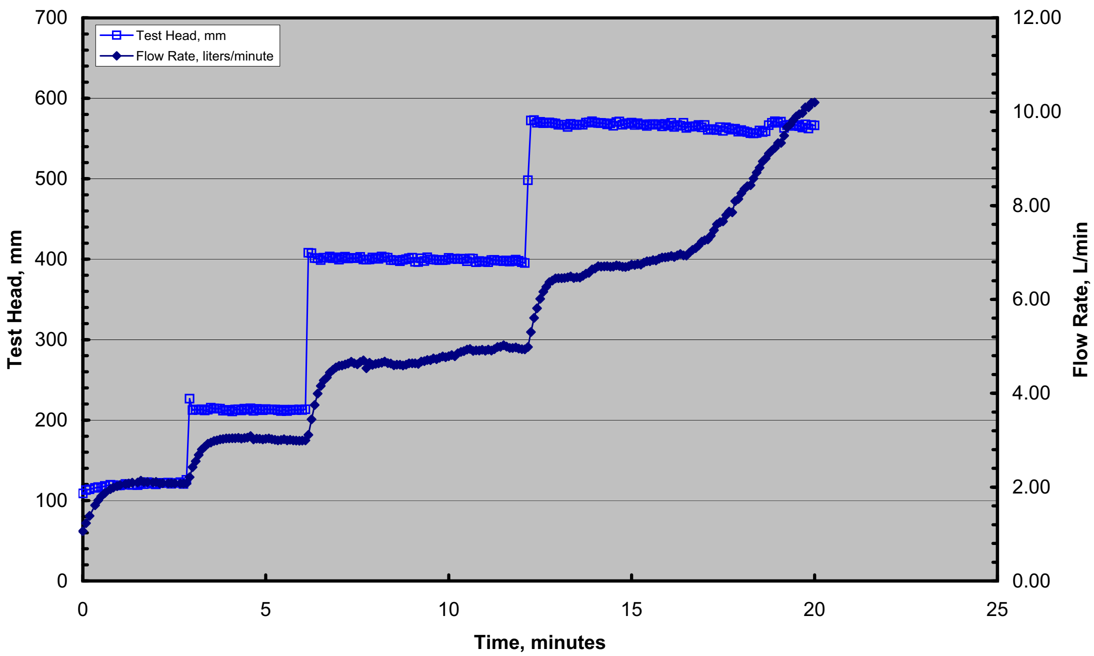
RESULTS SUMMARY

C_e	1.40E-05	$((kg/s)/m^2)/Pa = s/m$	
I_{HET}	4.85		**Group 4**
τ_c	523.1	Pa	
k_d	8.510E-09	$m/s/Pa = m^3/(N\text{-}s)$	
k_d	0.0085	$cm^3/(N\text{-}s)$	
k_d	0.0048	(ft/hr)/psf	
τ_c	10.93	psf	

Wolf Creek Dam - USACE

E3513x, ST-2 Test HET-23 03-07-2008

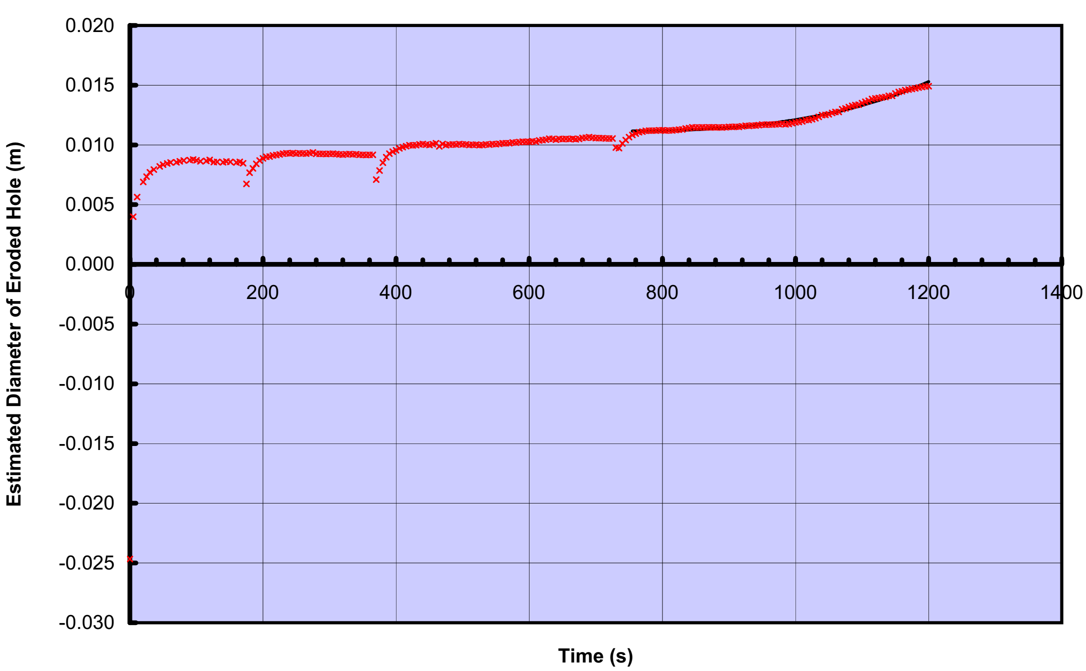
HET Test Record



Wolf Creek Dam - USACE

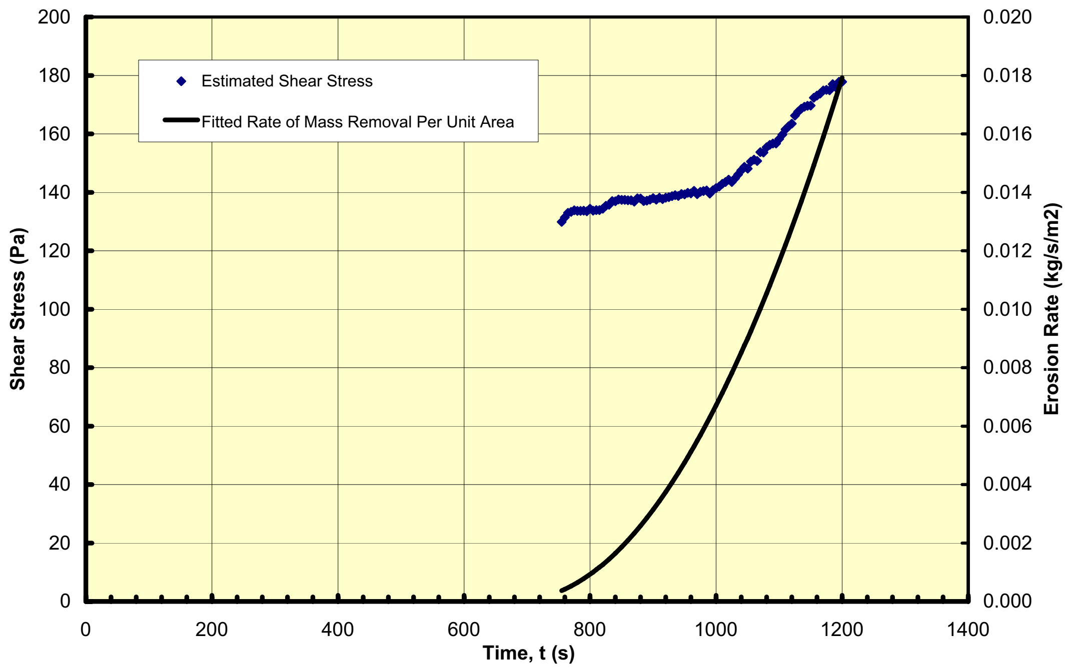
E3513x, ST-2 Test HET-23 03-07-2008

COMPUTED DIAMETER OF ERODED HOLE



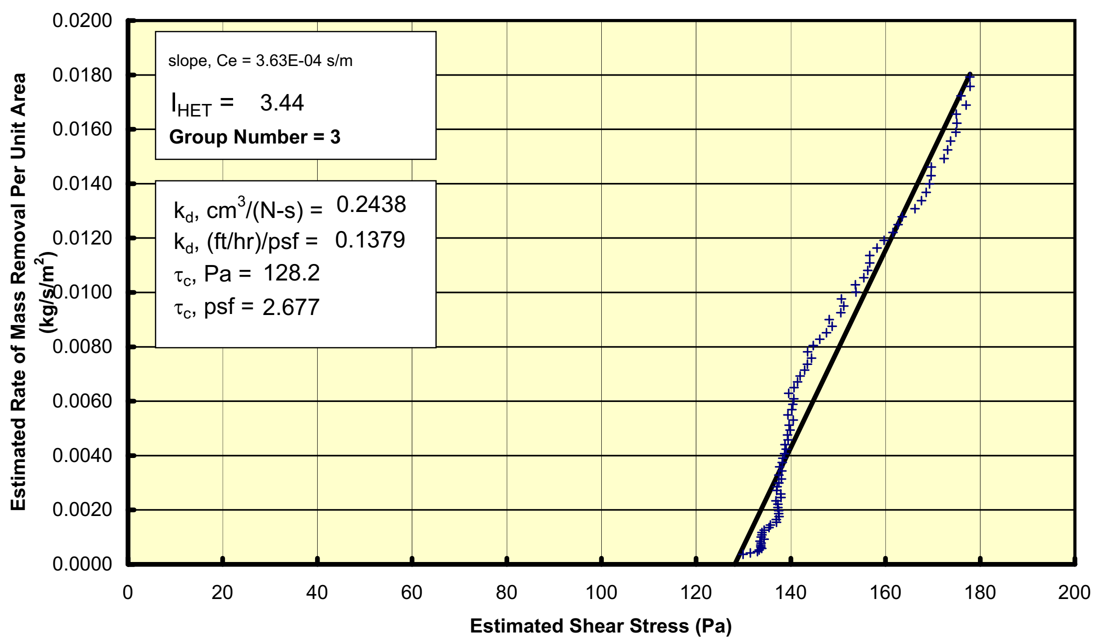
Wolf Creek Dam - USACE
E3513x, ST-2 Test HET-23 03-07-2008

EROSION RATE AND SHEAR STRESS VS. TIME

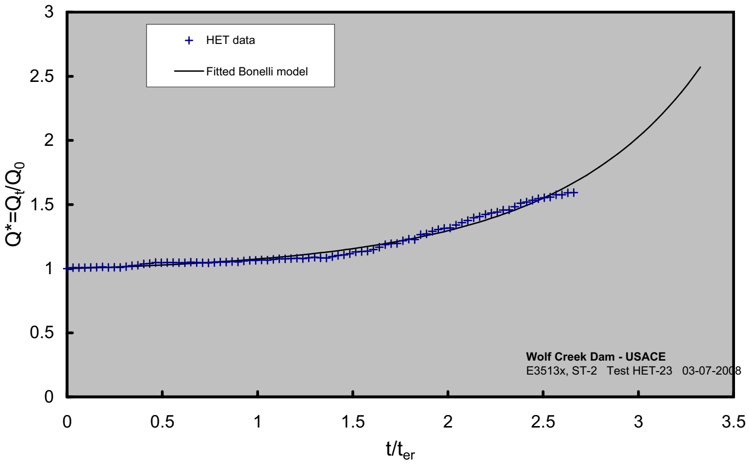


Wolf Creek Dam - USACE
E3513x, ST-2 Test HET-23 03-07-2008

EROSION RATE VS. SHEAR STRESS



HET dimensionless flow vs. dimensionless time
(Bonelli et al. 2006)



Project Wolf Creek Dam - USACE
Feature E3513x, ST-2
Test HET-23
Date 3/7/2008

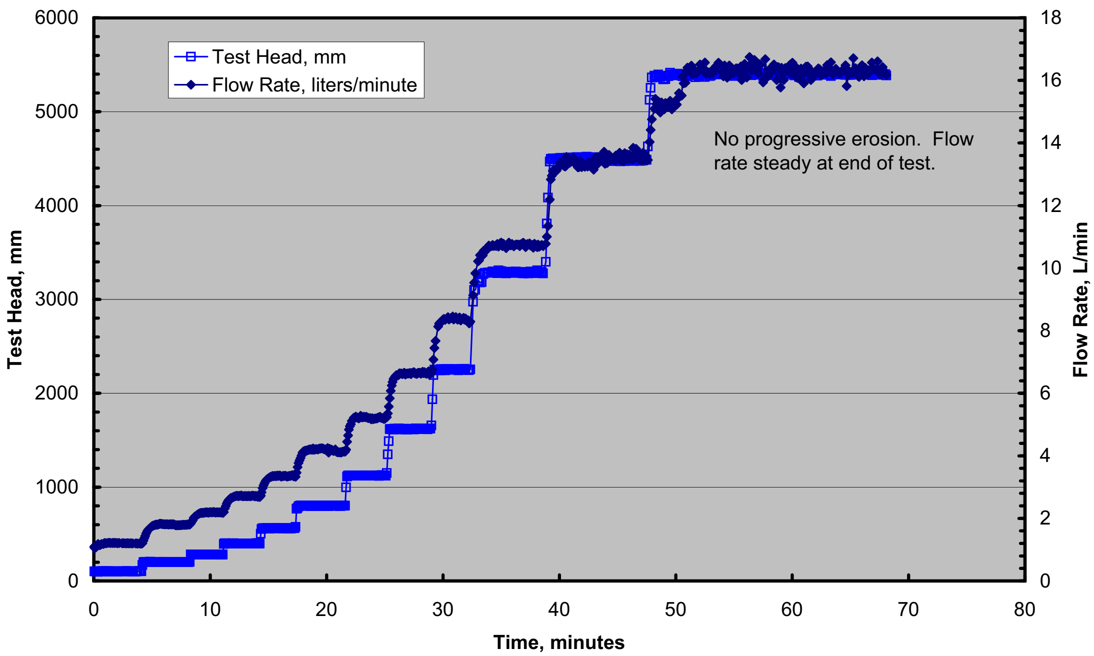
RESULTS SUMMARY

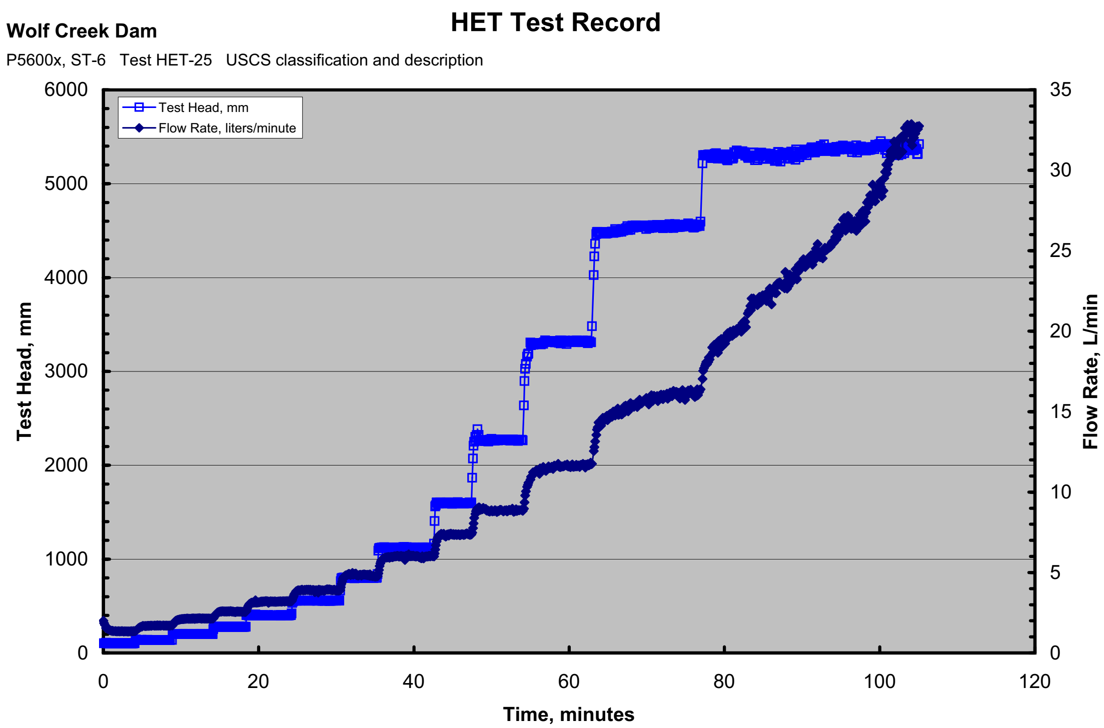
C_e	3.86E-04	((kg/s)/m^2)/Pa = s/m	
I_{HET}	3.41		**Group 3**
τ_c	130.2	Pa	
k_d	2.596E-07	m/s/Pa = m^3/(N-s)	
k_d	0.2596	cm^3/(N-s)	
k_d	0.1468	(ft/hr)/psf	
τ_c	2.72	psf	

USACE - Wolf Creek Dam

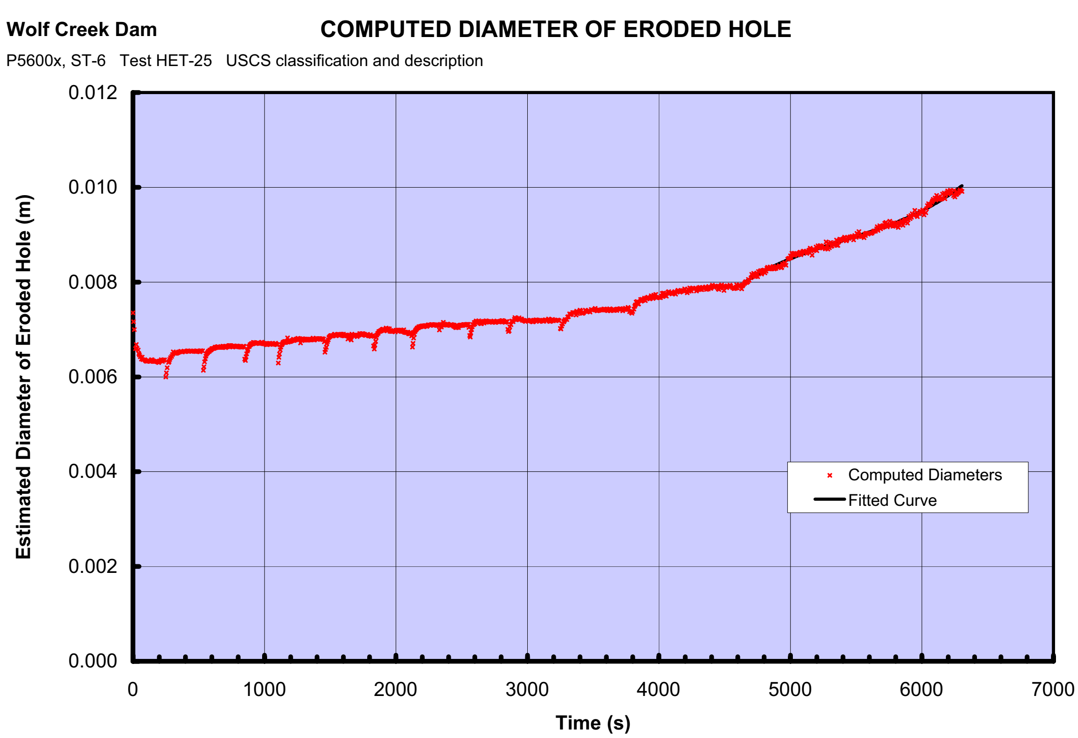
P5600x, ST-1 Test HET-24 unknown

HET Test Record

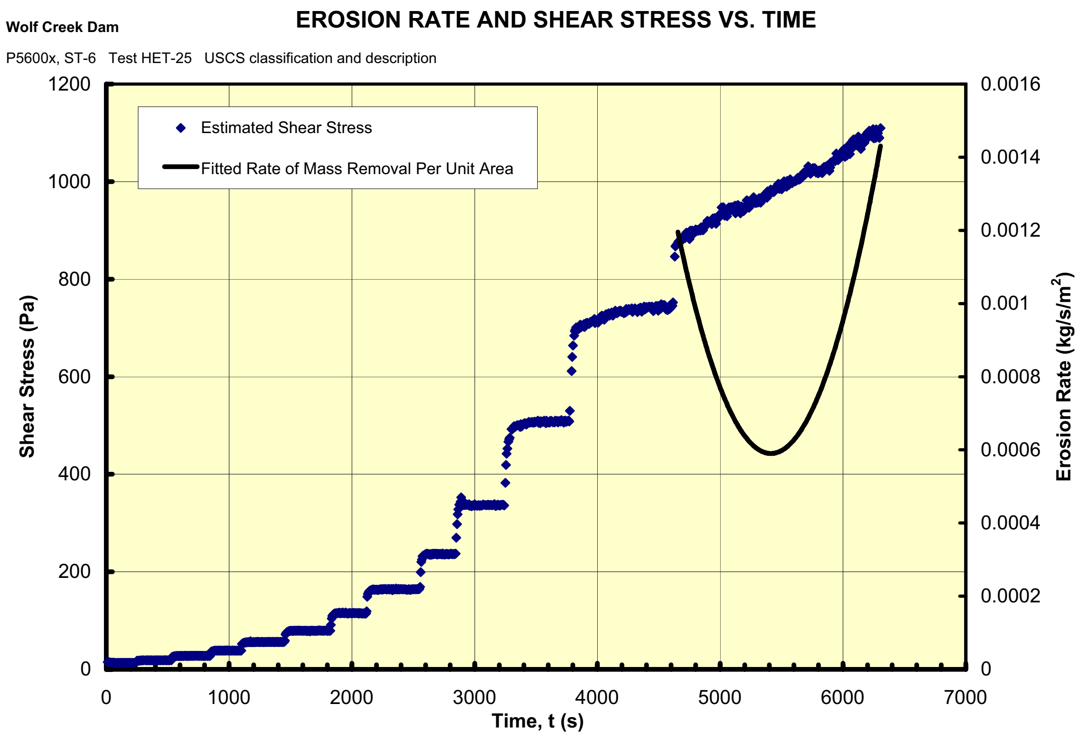


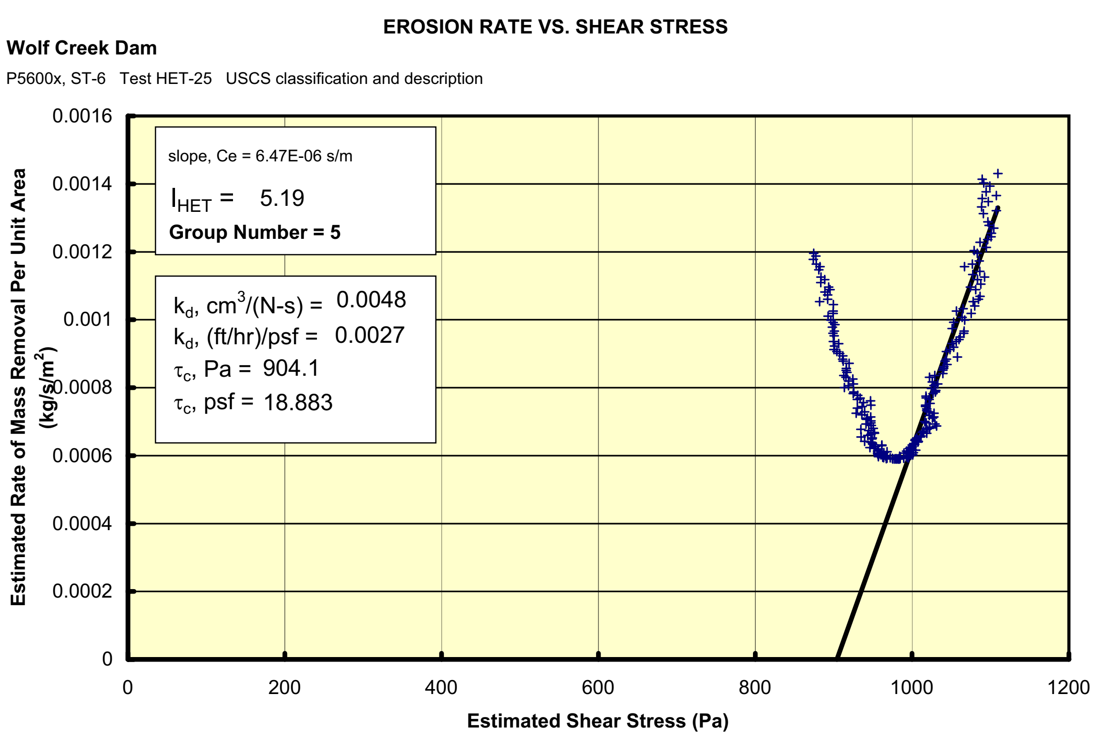


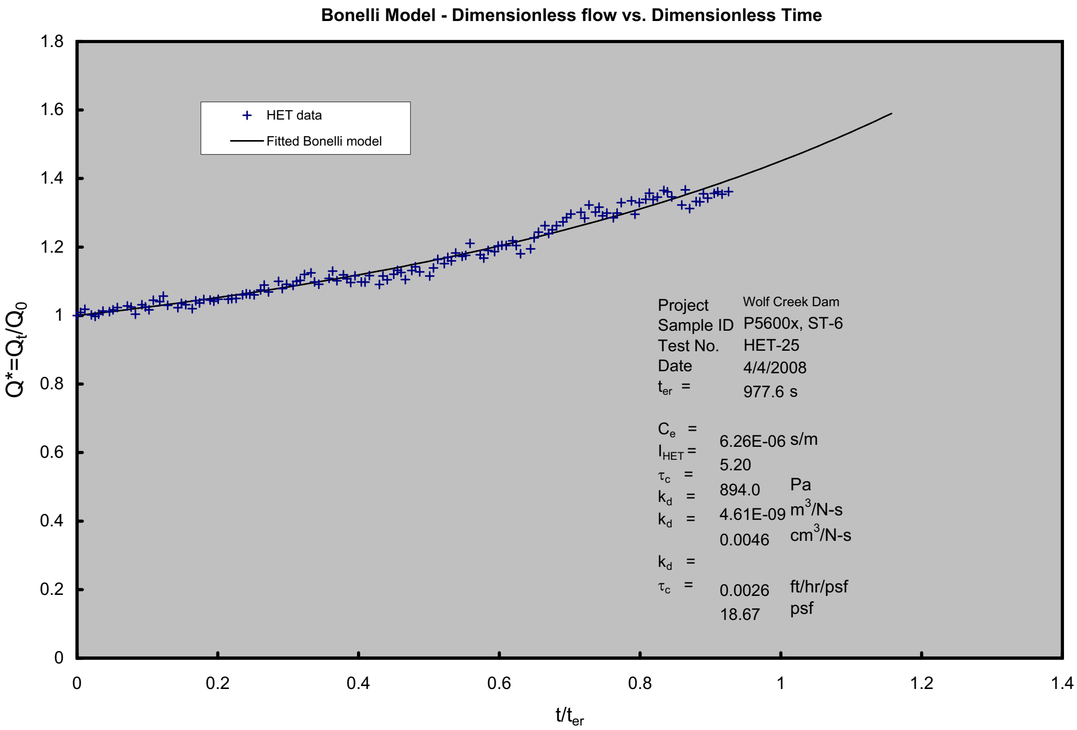
Wolf Creek Dam
HET Test Record
P5600x, ST-6 Test HET-25 USCS classification and description
Test Head, mm
Flow Rate, liters/minute
Test Head, mm
Flow Rate, L/min
Time, minutes
0
1000
2000
3000
4000
5000
6000
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120



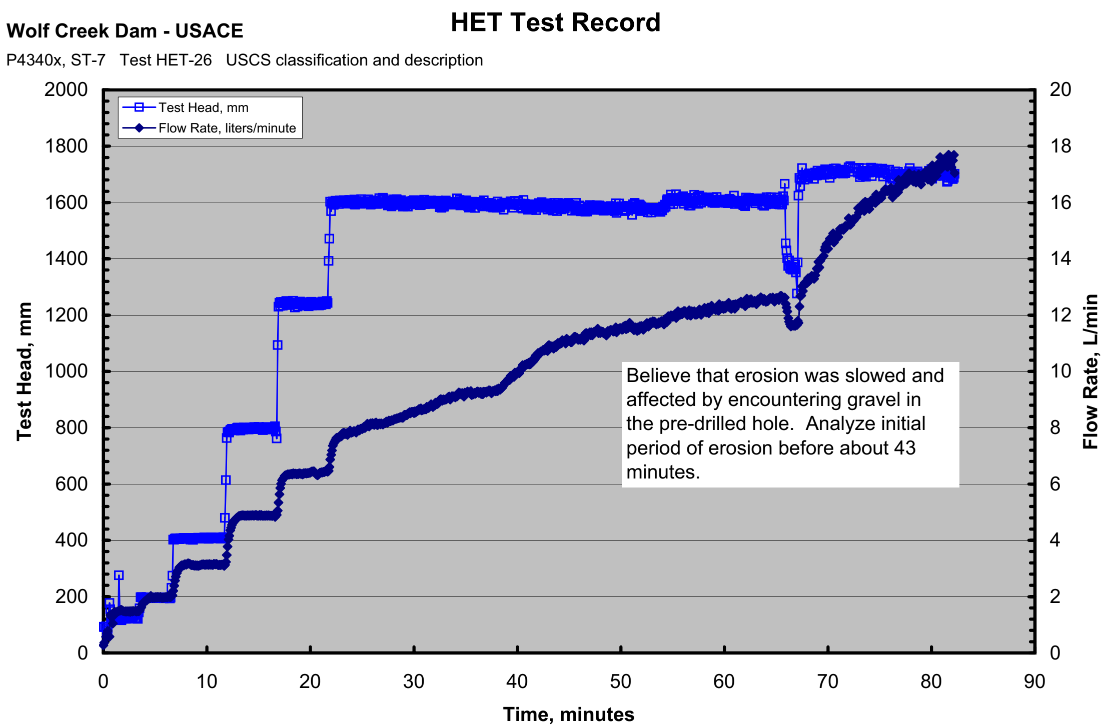
Wolf Creek Dam
COMPUTED DIAMETER OF ERODED HOLE
P5600x, ST-6 Test HET-25 USCS classification and description
Computed Diameters
Fitted Curve
Estimated Diameter of Eroded Hole (m)
Time (s)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0
1000
2000
3000
4000
5000
6000
7000


Wolf Creek Dam
EROSION RATE AND SHEAR STRESS VS. TIME
P5600x, ST-6 Test HET-25 USCS classification and description
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
200
400
600
800
1000
1200
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
0.0014
0.0016
1000
2000
3000
4000
5000
6000
7000

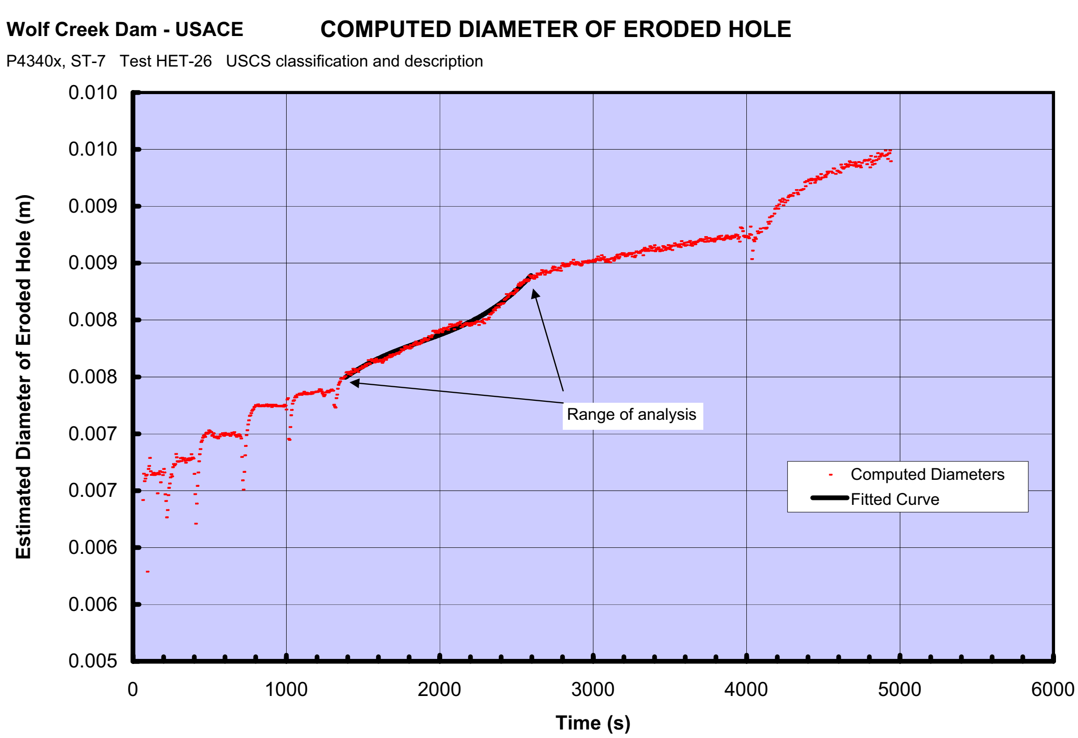

EROSION RATE VS. SHEAR STRESS
Wolf Creek Dam
P5600x, ST-6 Test HET-25 USCS classification and description
slope, Ce = 6.47E-06 s/m
IHET = 5.19
Group Number = 5
kd, cm3/(N-s) = 0.0048
kd, (ft/hr)/psf = 0.0027
τc, Pa = 904.1
τc, psf = 18.883
Estimated Rate of Mass Removal Per Unit Area (kg/s/m2)
Estimated Shear Stress (Pa)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
0.0014
0.0016
200
400
600
800
1000
1200



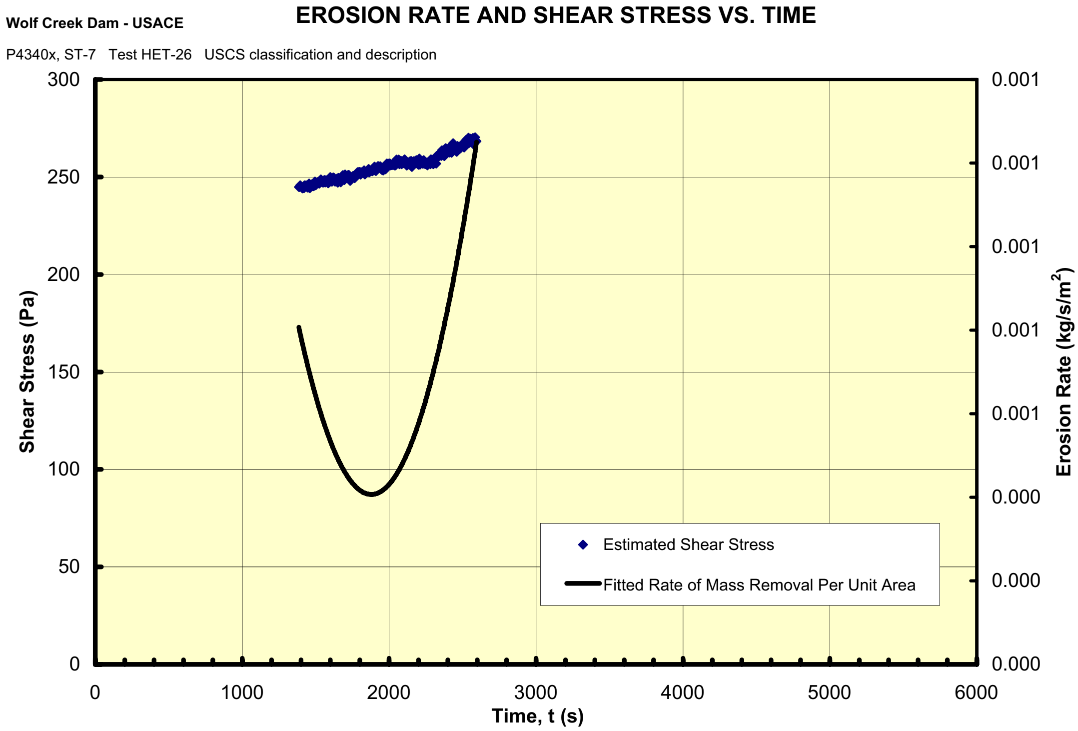
Bonelli Model - Dimensionless flow vs. Dimensionless Time
HET data
Fitted Bonelli model
Project Wolf Creek Dam
Sample ID P5600x, ST-6
Test No. HET-25
Date 4/4/2008
t_{er} = 977.6 s
C_e = 6.26E-06 s/m
I_{HET} = 5.20
τ_c = 894.0 Pa
k_d = 4.61E-09 m^3/N-s
k_d = 0.0046 cm^3/N-s
k_d = 0.0026 ft/hr/psf
τ_c = 18.67 psf
$Q^*=Q_t/Q_0$
t/t_{er}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

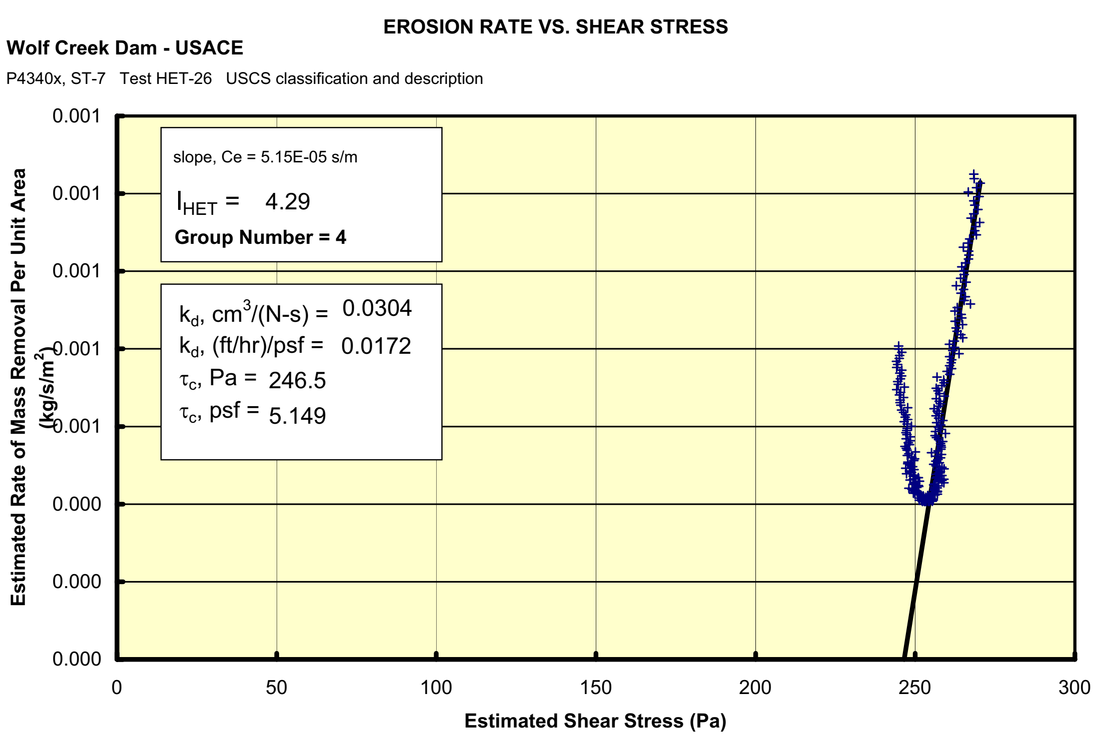


Wolf Creek Dam - USACE
HET Test Record
P4340x, ST-7 Test HET-26 USCS classification and description
Test Head, mm
Flow Rate, liters/minute
Believe that erosion was slowed and affected by encountering gravel in the pre-drilled hole. Analyze initial period of erosion before about 43 minutes.
Test Head, mm
Flow Rate, L/min
Time, minutes

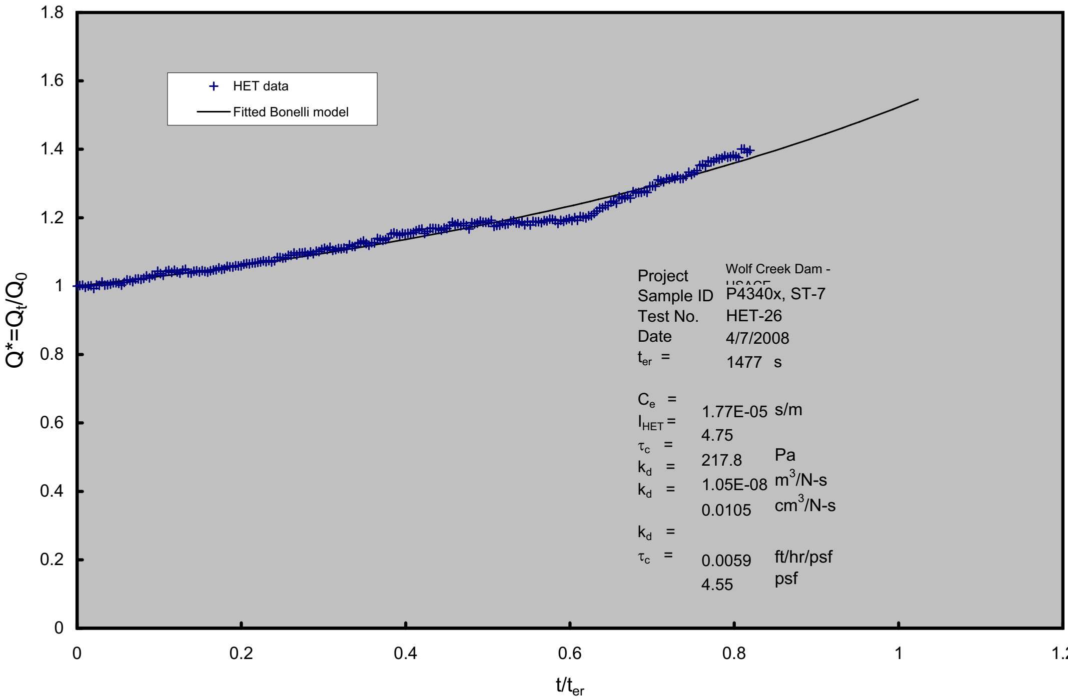


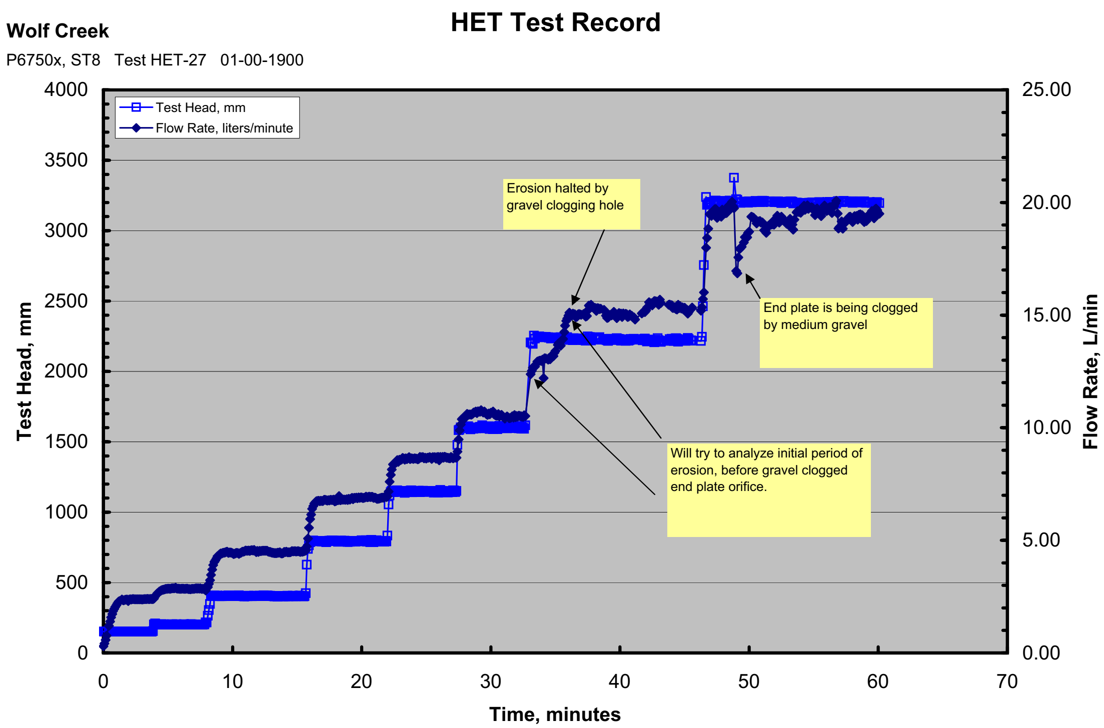
Wolf Creek Dam - USACE
COMPUTED DIAMETER OF ERODED HOLE
P4340x, ST-7 Test HET-26 USCS classification and description
Range of analysis
Computed Diameters
Fitted Curve
Estimated Diameter of Eroded Hole (m)
Time (s)


Wolf Creek Dam - USACE
EROSION RATE AND SHEAR STRESS VS. TIME
P4340x, ST-7 Test HET-26 USCS classification and description
Shear Stress (Pa)
Erosion Rate (kg/s/m^2)
Time, t (s)
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
300
250
200
150
100
50
0
0.001
0.000
0
1000
2000
3000
4000
5000
6000

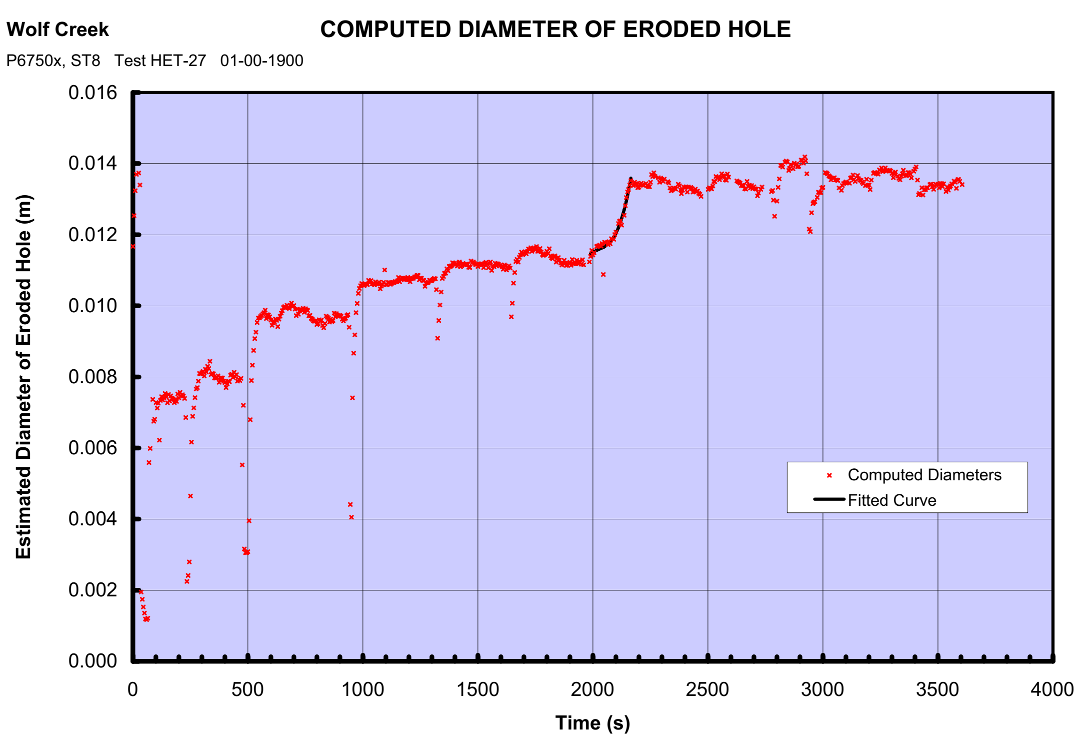

EROSION RATE VS. SHEAR STRESS
Wolf Creek Dam - USACE
P4340x, ST-7 Test HET-26 USCS classification and description
slope, Ce = 5.15E-05 s/m
I_HET = 4.29
Group Number = 4
k_d, cm^3/(N-s) = 0.0304
k_d, (ft/hr)/psf = 0.0172
τ_c, Pa = 246.5
τ_c, psf = 5.149
Estimated Rate of Mass Removal Per Unit Area (kg/s/m^2)
Estimated Shear Stress (Pa)
0.001
0.000
0
50
100
150
200
250
300

Bonelli Model - Dimensionless flow vs. Dimensionless Time

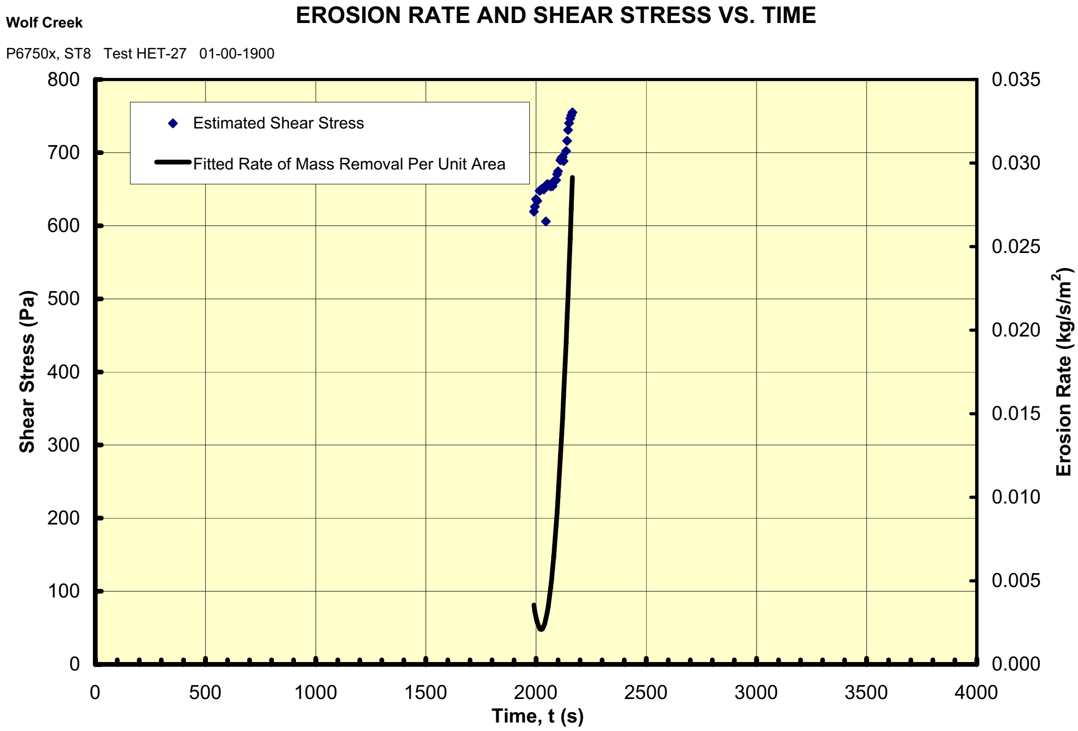


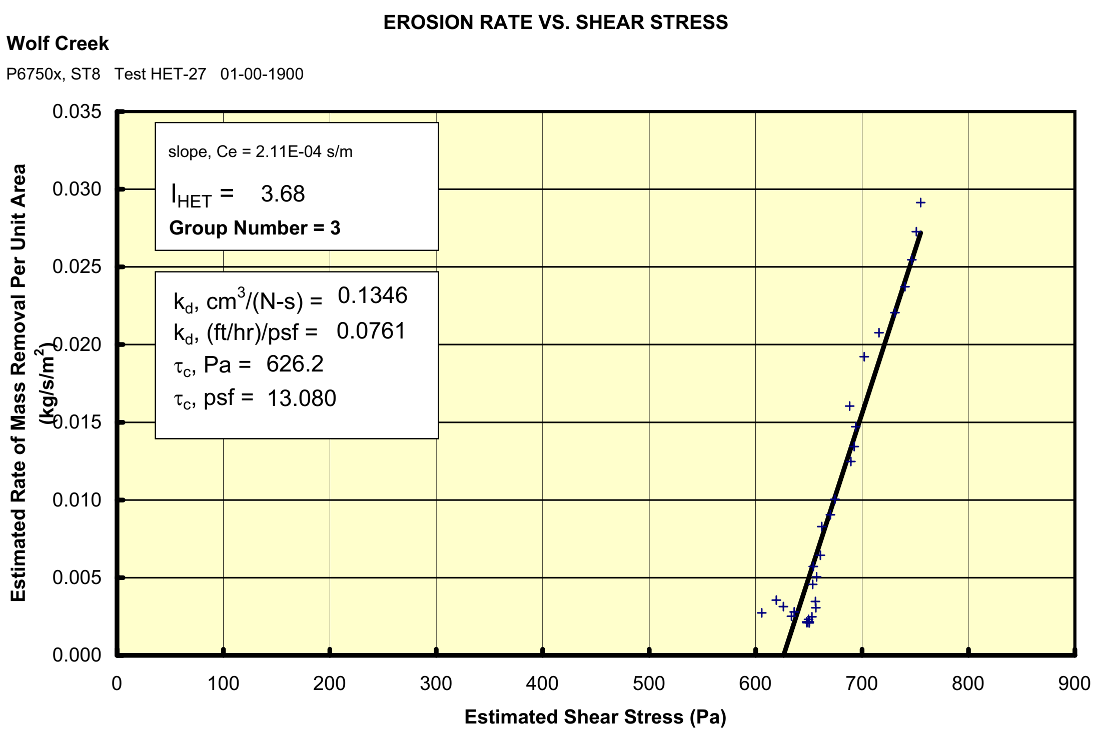


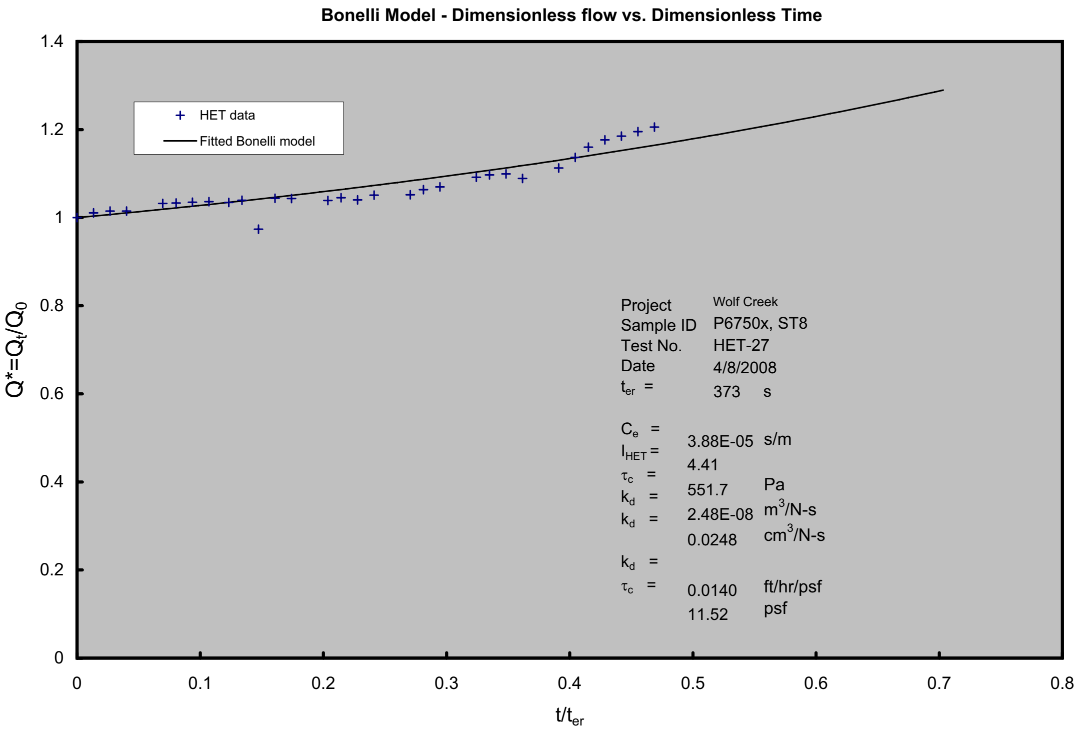
Wolf Creek
HET Test Record
P6750x, ST8 Test HET-27 01-00-1900
Test Head, mm
Flow Rate, liters/minute
Erosion halted by gravel clogging hole
End plate is being clogged by medium gravel
Will try to analyze initial period of erosion, before gravel clogged end plate orifice.
Test Head, mm
Flow Rate, L/min
Time, minutes

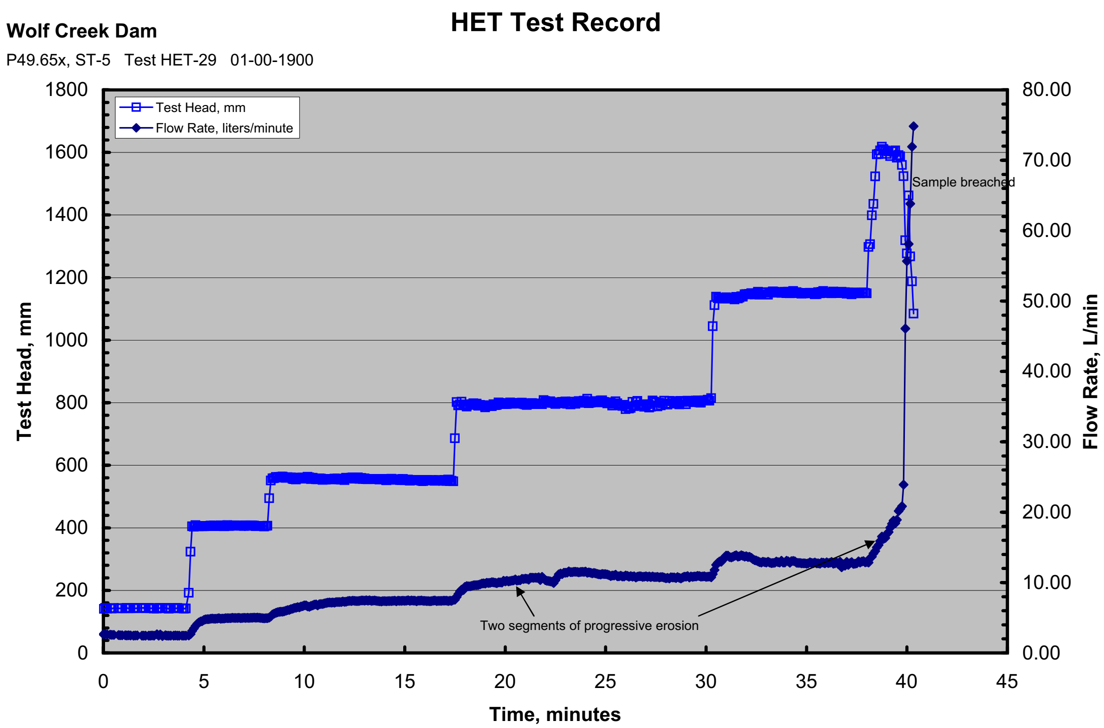


Wolf Creek
COMPUTED DIAMETER OF ERODED HOLE
P6750x, ST8 Test HET-27 01-00-1900
Computed Diameters
Fitted Curve
Estimated Diameter of Eroded Hole (m)
Time (s)

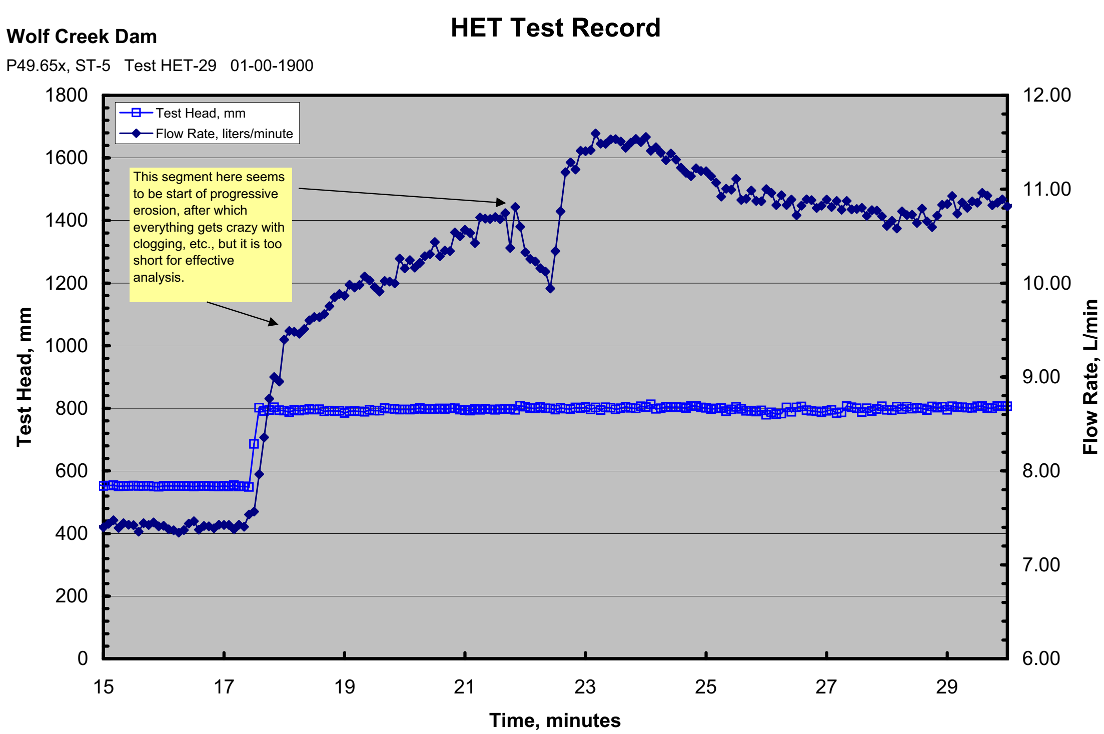

Wolf Creek
EROSION RATE AND SHEAR STRESS VS. TIME
P6750x, ST8 Test HET-27 01-00-1900
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
500
1000
1500
2000
2500
3000
3500
4000
100
200
300
400
600
700
800
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035


EROSION RATE VS. SHEAR STRESS
Wolf Creek
P6750x, ST8 Test HET-27 01-00-1900
slope, Ce = 2.11E-04 s/m
IHET = 3.68
Group Number = 3
kd, cm3/(N-s) = 0.1346
kd, (ft/hr)/psf = 0.0761
τc, Pa = 626.2
τc, psf = 13.080
Estimated Rate of Mass Removal Per Unit Area (kg/s/m2)
Estimated Shear Stress (Pa)
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0
100
200
300
400
500
600
700
800
900

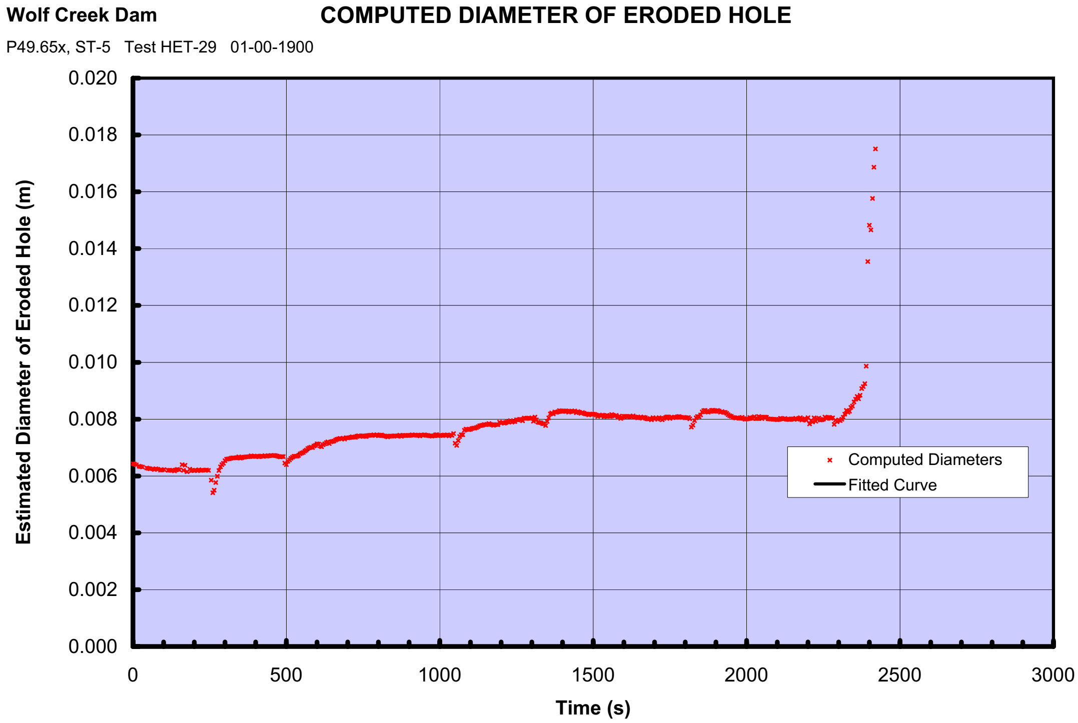

Bonelli Model - Dimensionless flow vs. Dimensionless Time
Q*=Qt/Q0
t/ter
HET data
Fitted Bonelli model
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Project Wolf Creek
Sample ID P6750x, ST8
Test No. HET-27
Date 4/8/2008
ter = 373 s
Ce = 3.88E-05 s/m
IHET = 4.41
τc = 551.7 Pa
kd = 2.48E-08 m3/N-s
kd = 0.0248 cm3/N-s
kd = 0.0140 ft/hr/psf
τc = 11.52 psf



HET Test Record
Wolf Creek Dam
P49.65x, ST-5 Test HET-29 01-00-1900
Test Head, mm
Flow Rate, liters/minute
Sample breached
Two segments of progressive erosion
Test Head, mm
Flow Rate, L/min
Time, minutes
1800
1600
1400
1200
1000
800
600
400
200
0
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
5
10
15
20
25
30
35
40
45

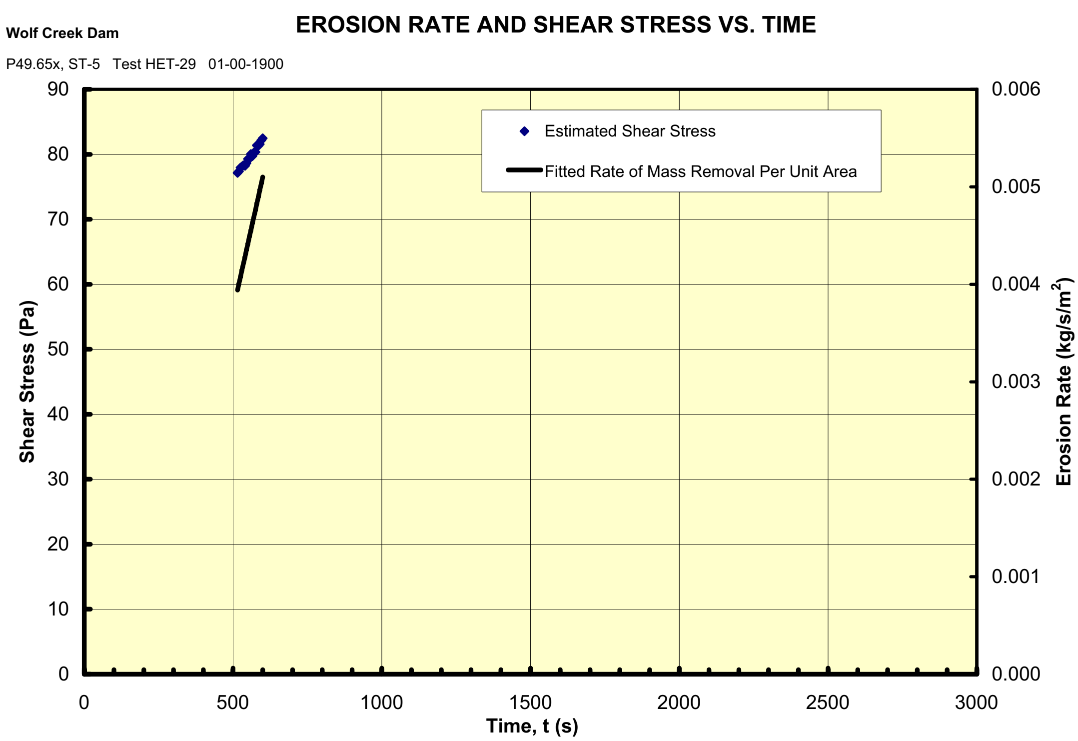


HET Test Record
Wolf Creek Dam
P49.65x, ST-5 Test HET-29 01-00-1900
Test Head, mm
Flow Rate, liters/minute
This segment here seems to be start of progressive erosion, after which everything gets crazy with clogging, etc., but it is too short for effective analysis.
Test Head, mm
Flow Rate, L/min
Time, minutes
1800
1600
1400
1200
1000
800
600
400
200
0
12.00
11.00
10.00
9.00
8.00
7.00
6.00
15
17
19
21
23
25
27
29

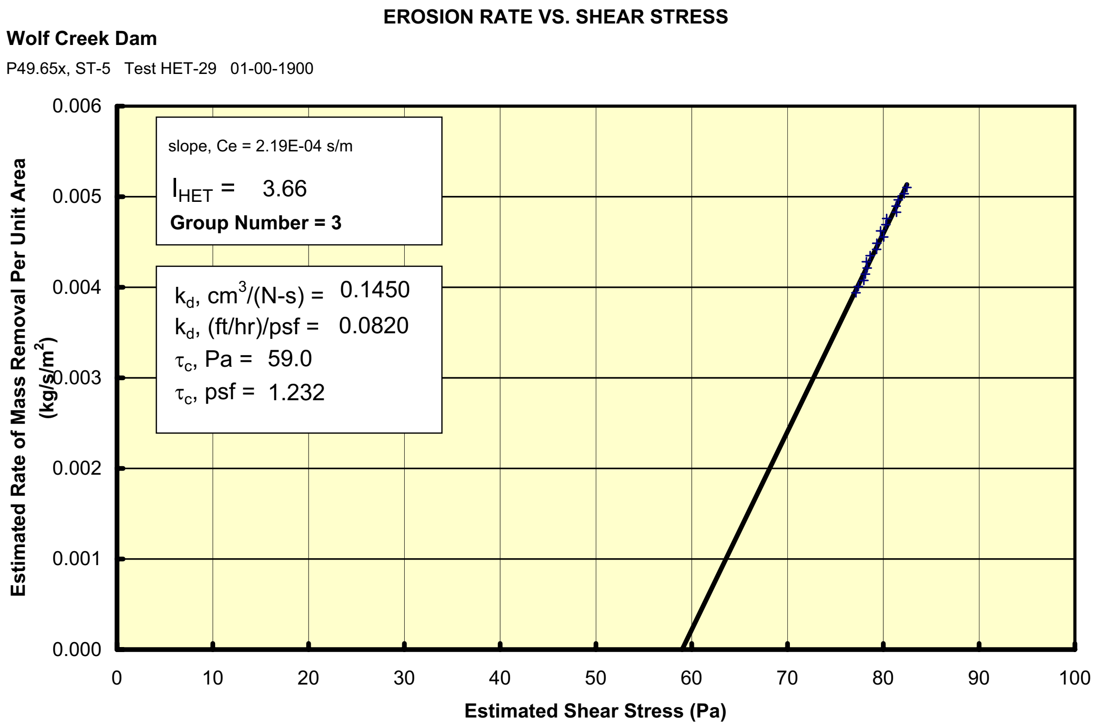


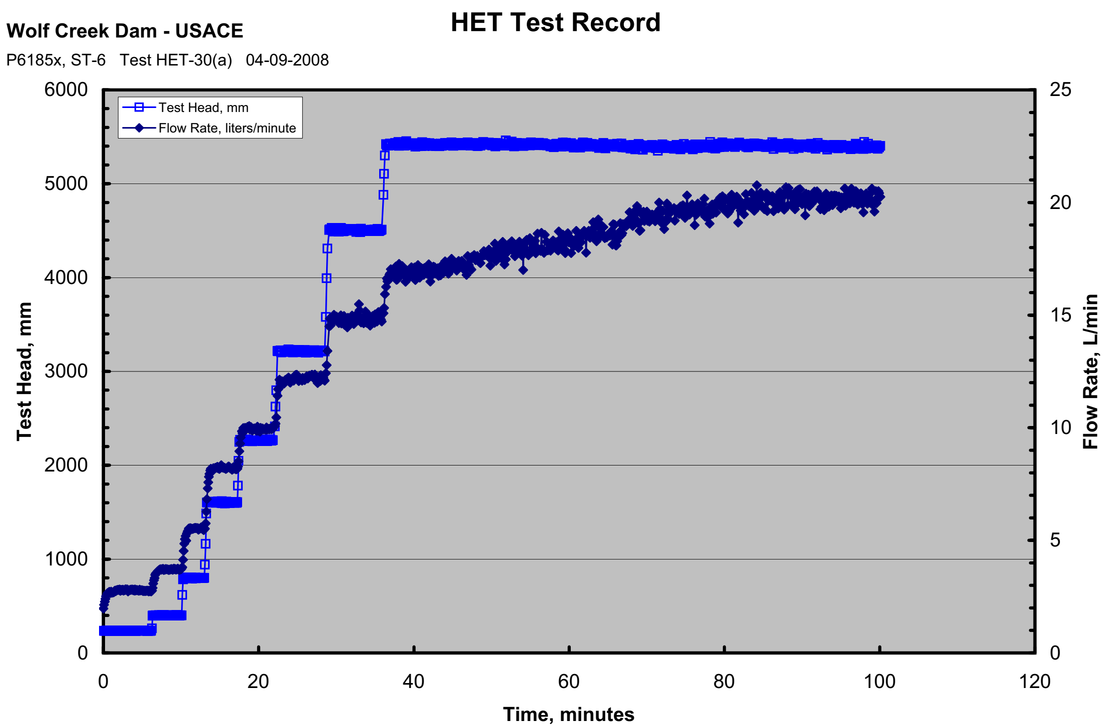
Wolf Creek Dam
COMPUTED DIAMETER OF ERODED HOLE
P49.65x, ST-5 Test HET-29 01-00-1900
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Estimated Diameter of Eroded Hole (m)
0
500
1000
1500
2000
2500
3000
Time (s)
Computed Diameters
Fitted Curve

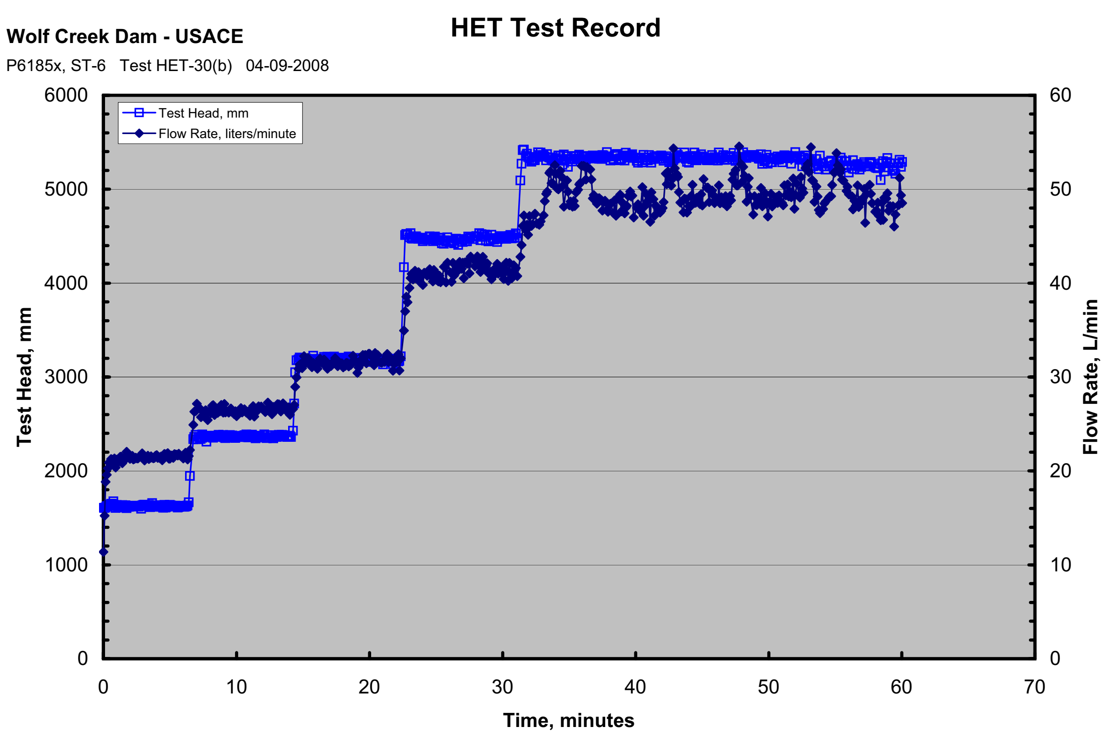
e,T



Wolf Creek Dam
EROSION RATE AND SHEAR STRESS VS. TIME
P49.65x, ST-5 Test HET-29 01-00-1900
90
80
70
60
50
40
30
20
10
0
Shear Stress (Pa)
0.006
0.005
0.004
0.003
0.002
0.001
0.000
Erosion Rate (kg/s/m2)
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
0
500
1000
1500
2000
2500
3000
Time, t (s)


EROSION RATE VS. SHEAR STRESS
Wolf Creek Dam
P49.65x, ST-5 Test HET-29 01-00-1900
slope, Ce = 2.19E-04 s/m
I_{HET} = 3.66
Group Number = 3
k_d, $cm^3/(N\text{-}s)$ = 0.1450
k_d, (ft/hr)/psf = 0.0820
τ_c, Pa = 59.0
τ_c, psf = 1.232
Estimated Rate of Mass Removal Per Unit Area ($kg/s/m^2$)
Estimated Shear Stress (Pa)
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0
10
20
30
40
50
60
70
80
90
100

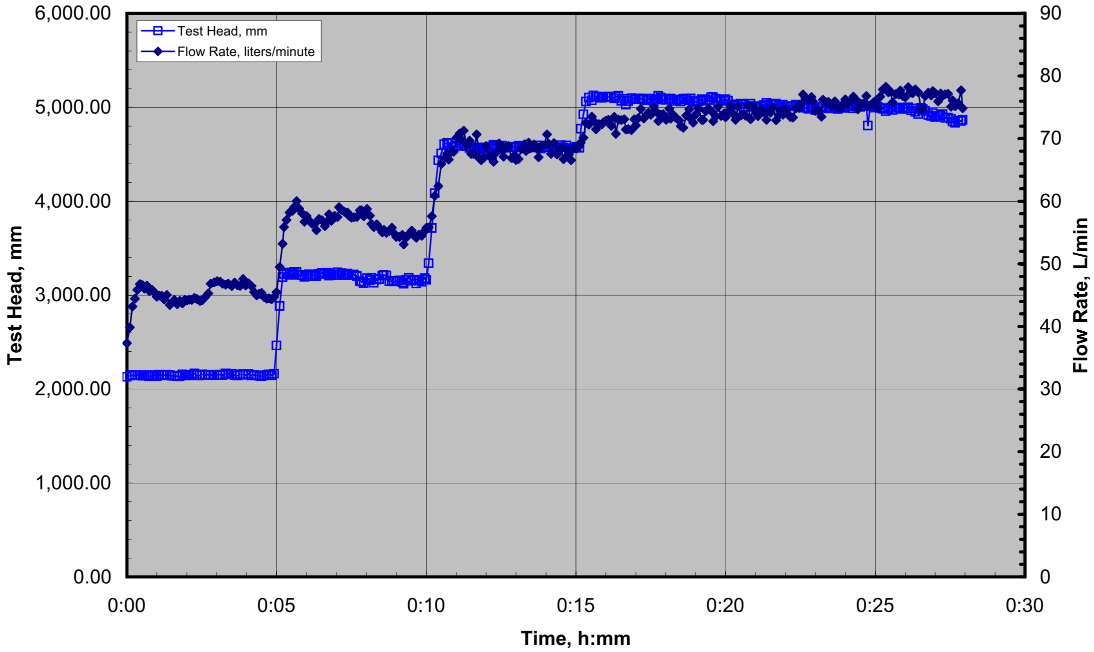

HET Test Record
Wolf Creek Dam - USACE
P6185x, ST-6 Test HET-30(a) 04-09-2008
Test Head, mm
Flow Rate, liters/minute
Test Head, mm
Flow Rate, L/min
Time, minutes
0
1000
2000
3000
4000
5000
6000
0
5
10
15
20
25
0
20
40
60
80
100
120

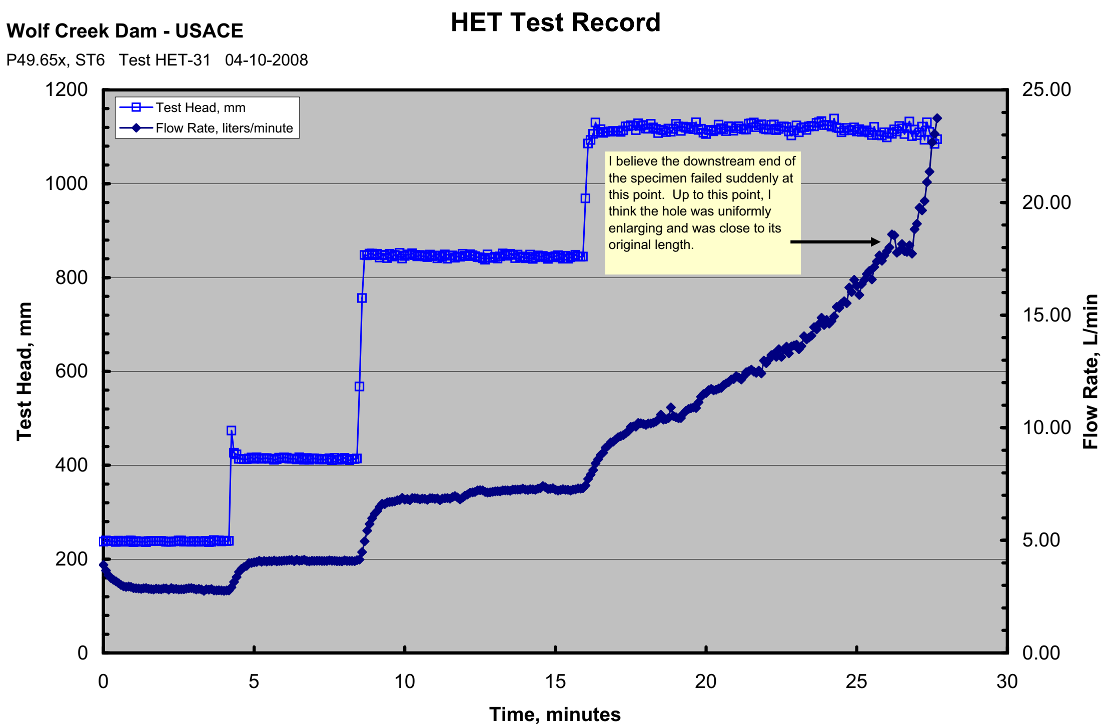

HET Test Record
Wolf Creek Dam - USACE
P6185x, ST-6 Test HET-30(b) 04-09-2008
Test Head, mm
Flow Rate, liters/minute
Test Head, mm
Flow Rate, L/min
Time, minutes
0
1000
2000
3000
4000
5000
6000
0
10
20
30
40
50
60
0
10
20
30
40
50
60
70

Wolf Creek Dam

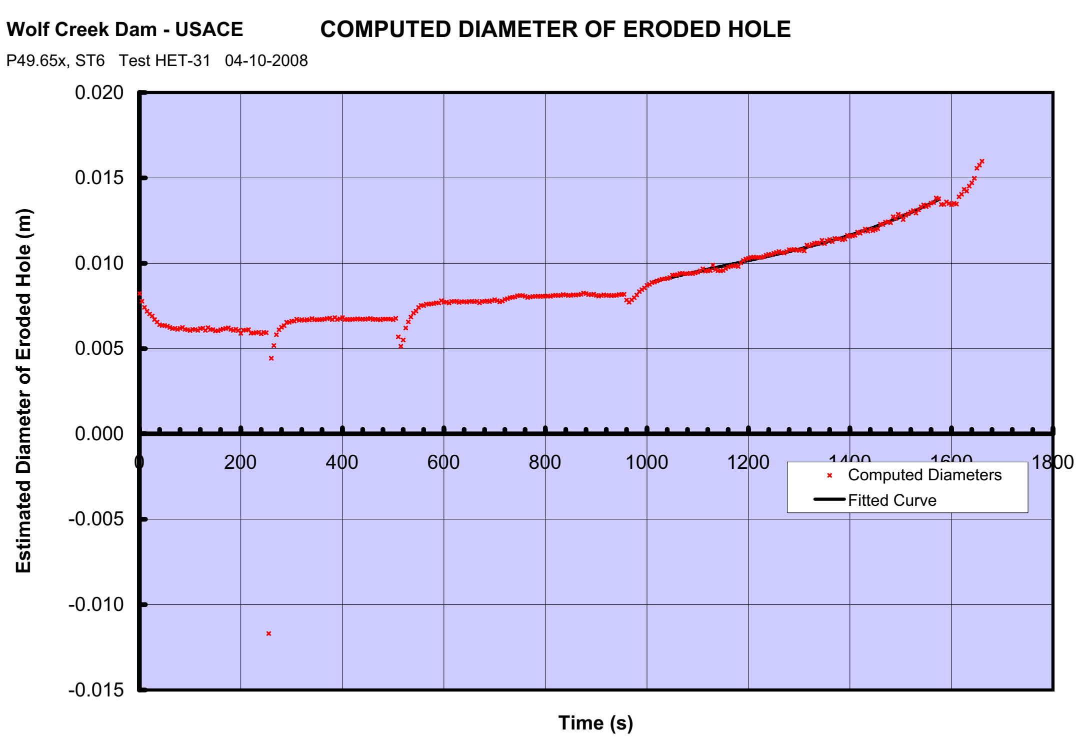
P6185x, ST-6   Test HET-30c   04-17-2008

HET Test Record

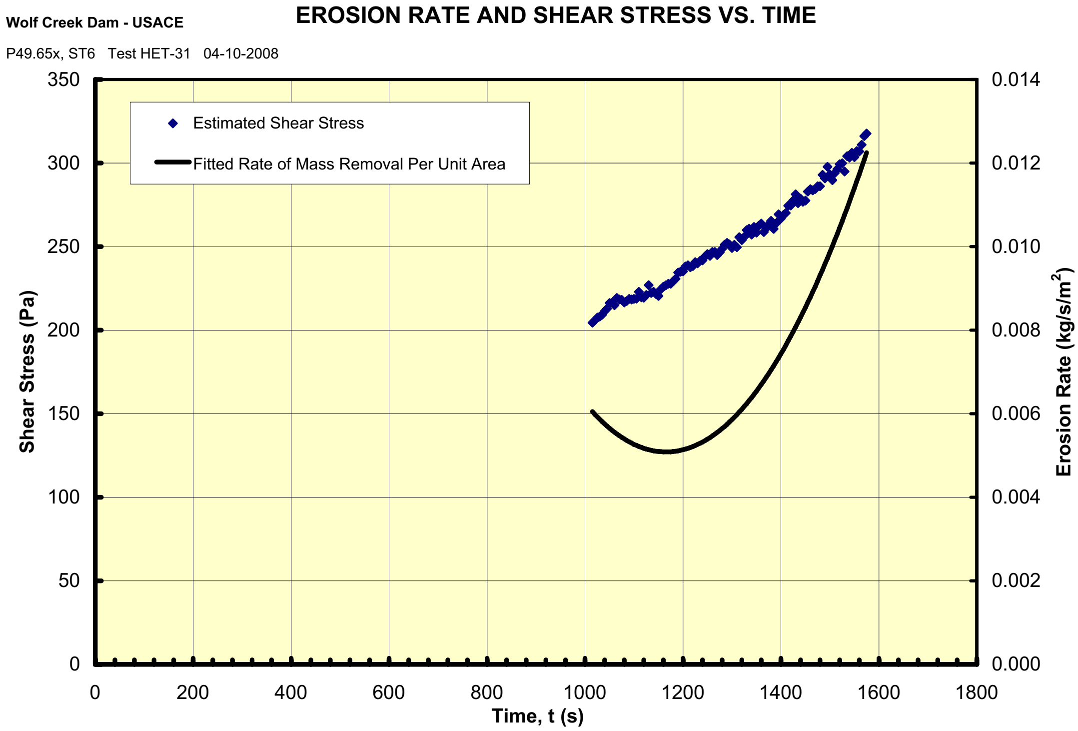


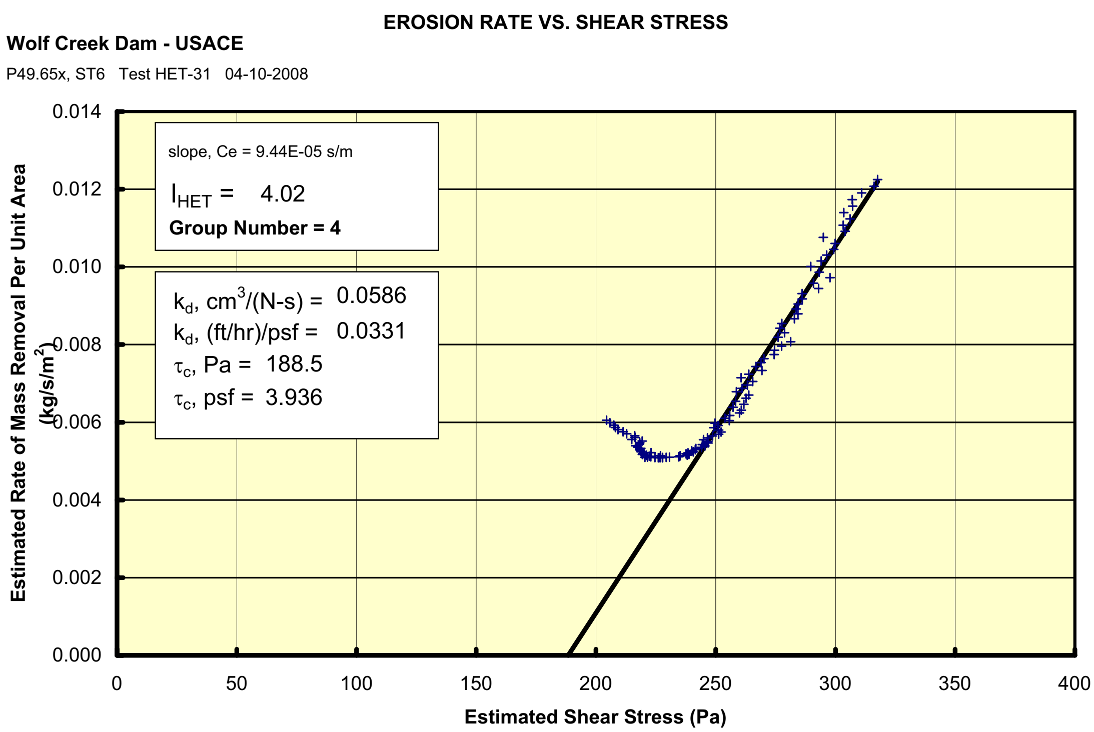


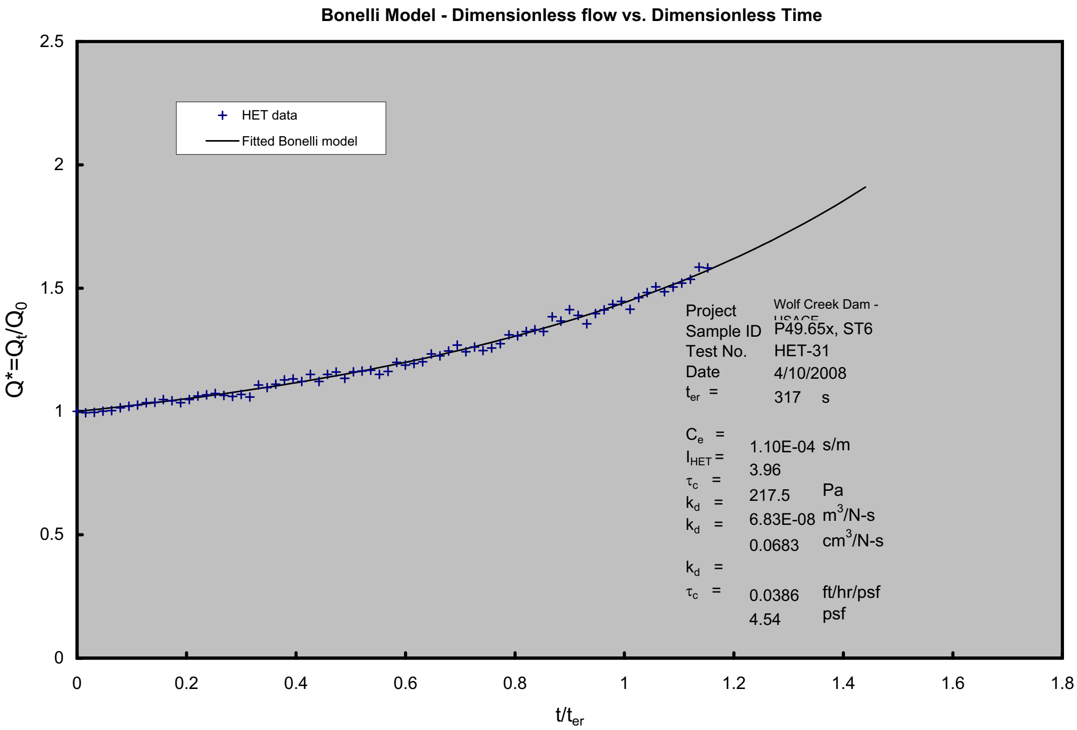
Wolf Creek Dam - USACE
HET Test Record
P49.65x, ST6 Test HET-31 04-10-2008
Test Head, mm
Flow Rate, liters/minute
I believe the downstream end of the specimen failed suddenly at this point. Up to this point, I think the hole was uniformly enlarging and was close to its original length.
Test Head, mm
Flow Rate, L/min
Time, minutes
0
200
400
600
800
1000
1200
0.00
5.00
10.00
15.00
20.00
25.00
0
5
10
15
20
25
30



Wolf Creek Dam - USACE
COMPUTED DIAMETER OF ERODED HOLE
P49.65x, ST6 Test HET-31 04-10-2008
Estimated Diameter of Eroded Hole (m)
0.020
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
0
200
400
600
800
1000
1200
1800
Computed Diameters
Fitted Curve
Time (s)


Wolf Creek Dam - USACE
EROSION RATE AND SHEAR STRESS VS. TIME
P49.65x, ST6 Test HET-31 04-10-2008
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
50
100
150
200
250
300
350
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0
200
400
600
800
1000
1200
1400
1600
1800


EROSION RATE VS. SHEAR STRESS
Wolf Creek Dam - USACE
P49.65x, ST6 Test HET-31 04-10-2008
slope, Ce = 9.44E-05 s/m
IHET = 4.02
Group Number = 4
kd, cm3/(N-s) = 0.0586
kd, (ft/hr)/psf = 0.0331
τc, Pa = 188.5
τc, psf = 3.936
Estimated Rate of Mass Removal Per Unit Area (kg/s/m2)
Estimated Shear Stress (Pa)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0
50
100
150
200
250
300
350
400

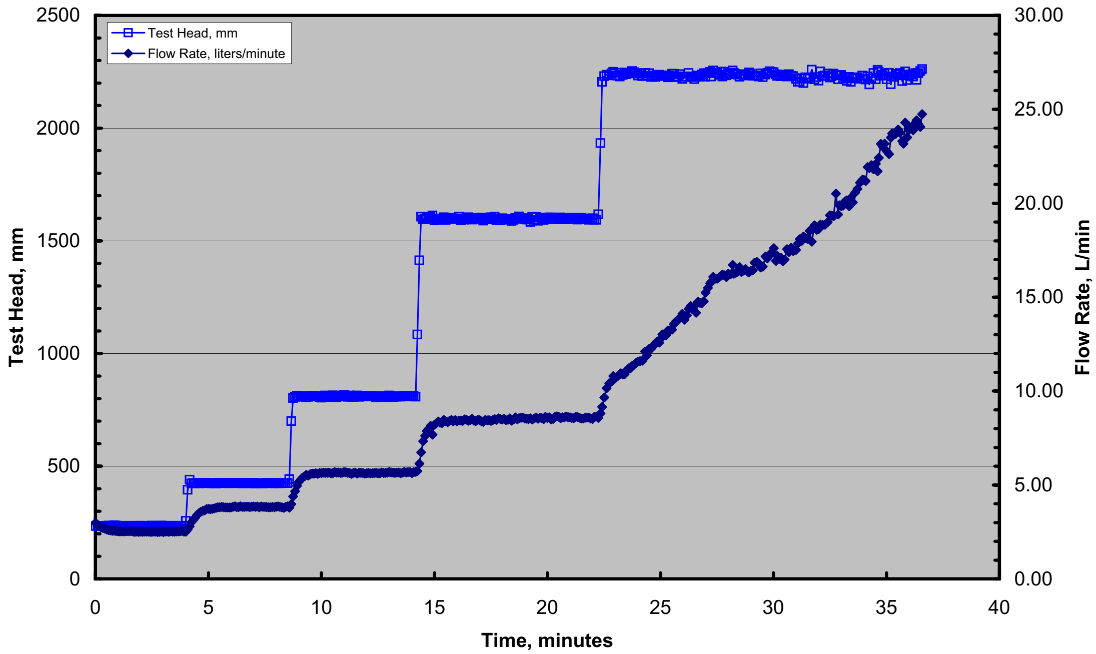


Bonelli Model - Dimensionless flow vs. Dimensionless Time
HET data
Fitted Bonelli model
Q*=Qt/Q0
t/ter
0
0.5
1
1.5
2
2.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Project
Wolf Creek Dam - USACE
Sample ID
P49.65x, ST6
Test No.
HET-31
Date
4/10/2008
ter = 317 s
Ce = 1.10E-04 s/m
IHET = 3.96
τc = 217.5 Pa
kd = 6.83E-08 m3/N-s
kd = 0.0683 cm3/N-s
kd = 0.0386 ft/hr/psf
τc = 4.54 psf

Wolf Creek Dam - USACE

HET Test Record

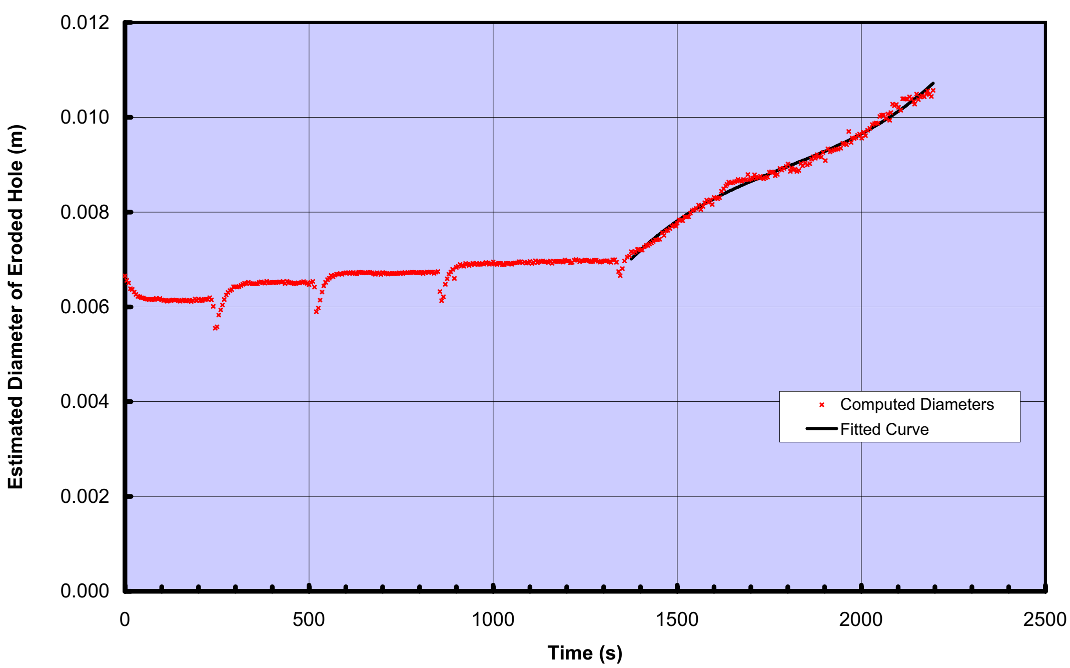
P4340x, ST-7   Test HET-32   04-10-2008

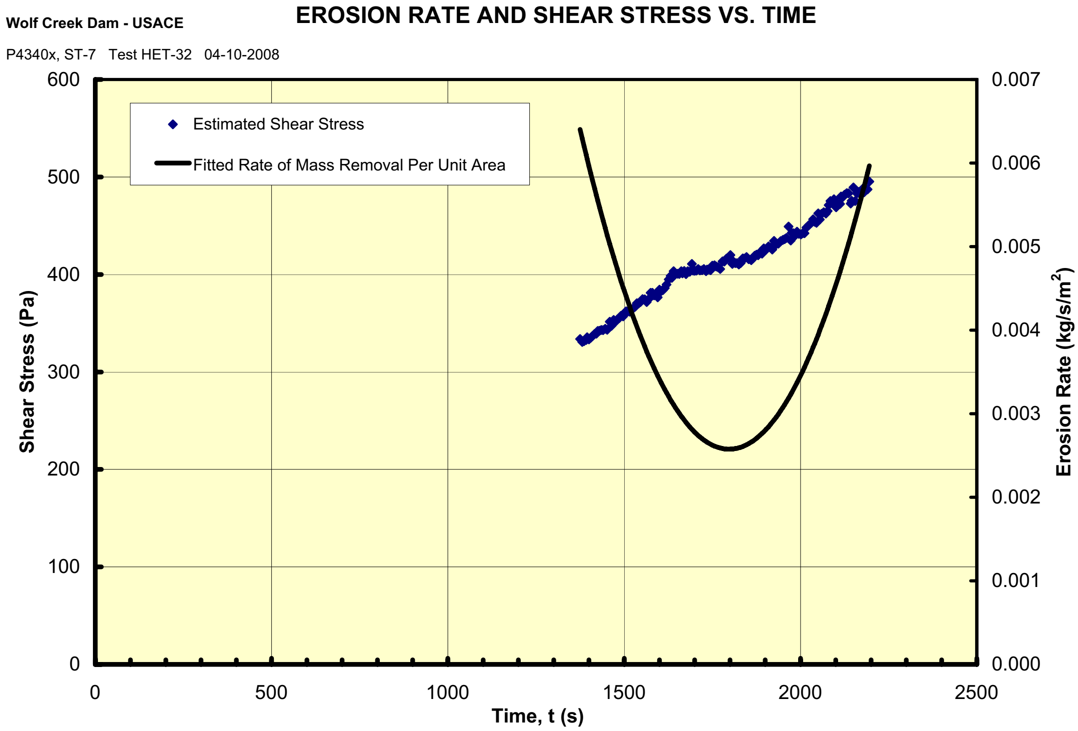


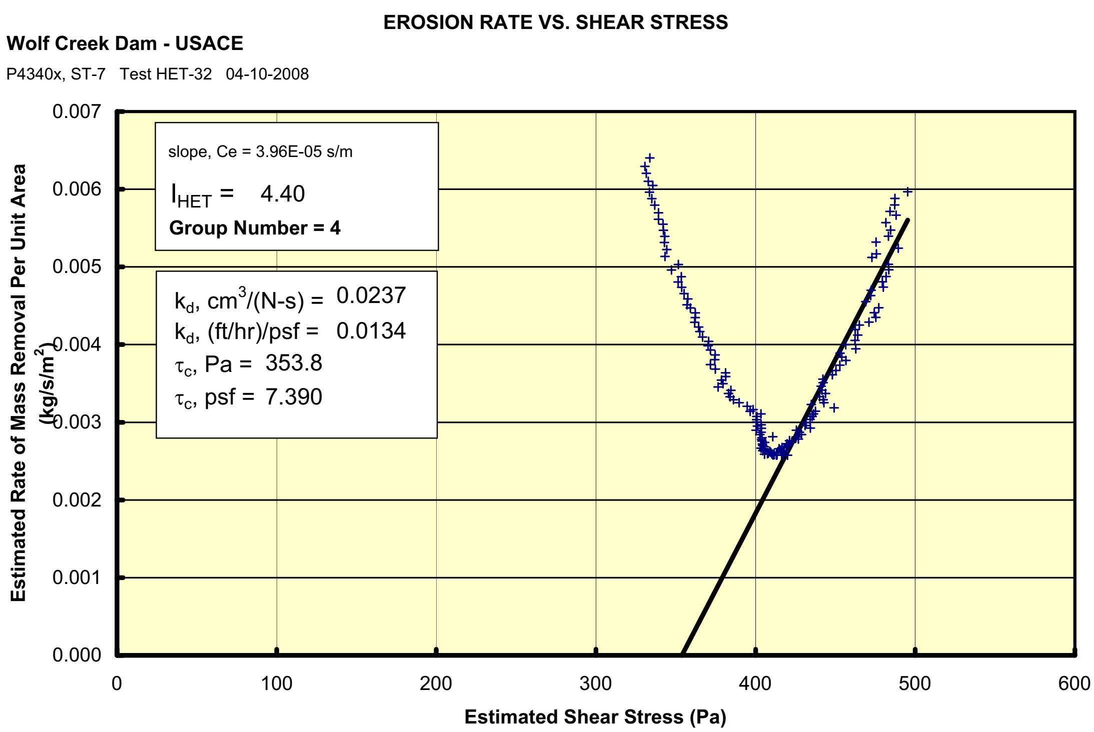
Wolf Creek Dam - USACE

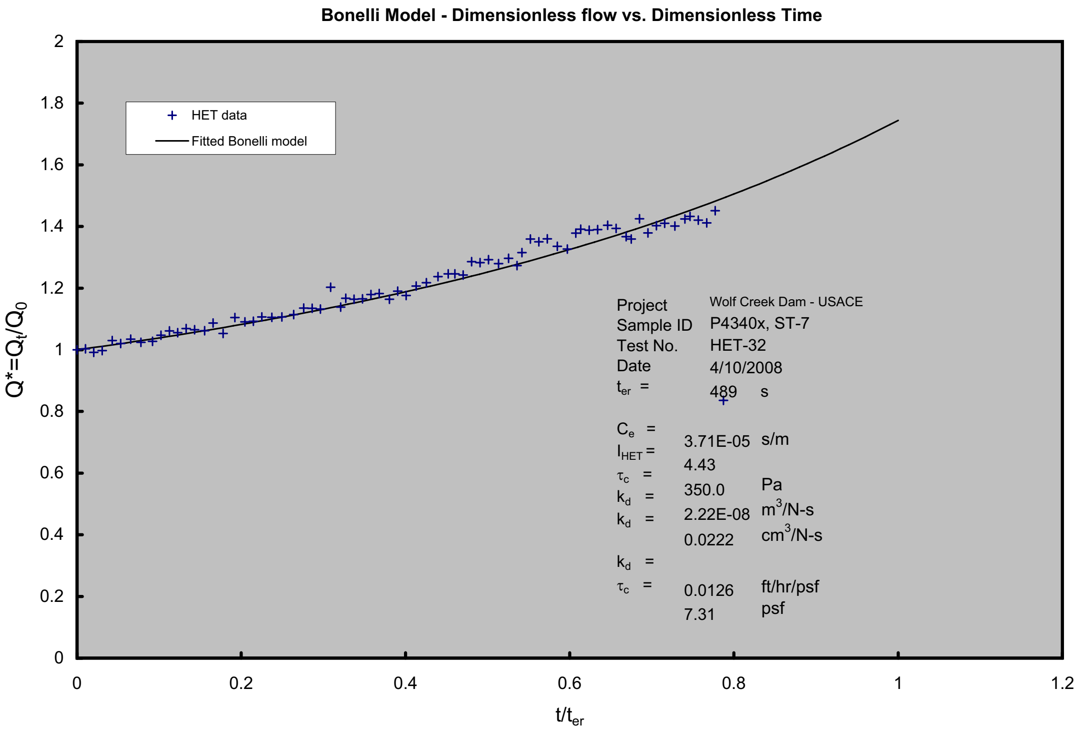
COMPUTED DIAMETER OF ERODED HOLE

P4340x, ST-7   Test HET-32   04-10-2008

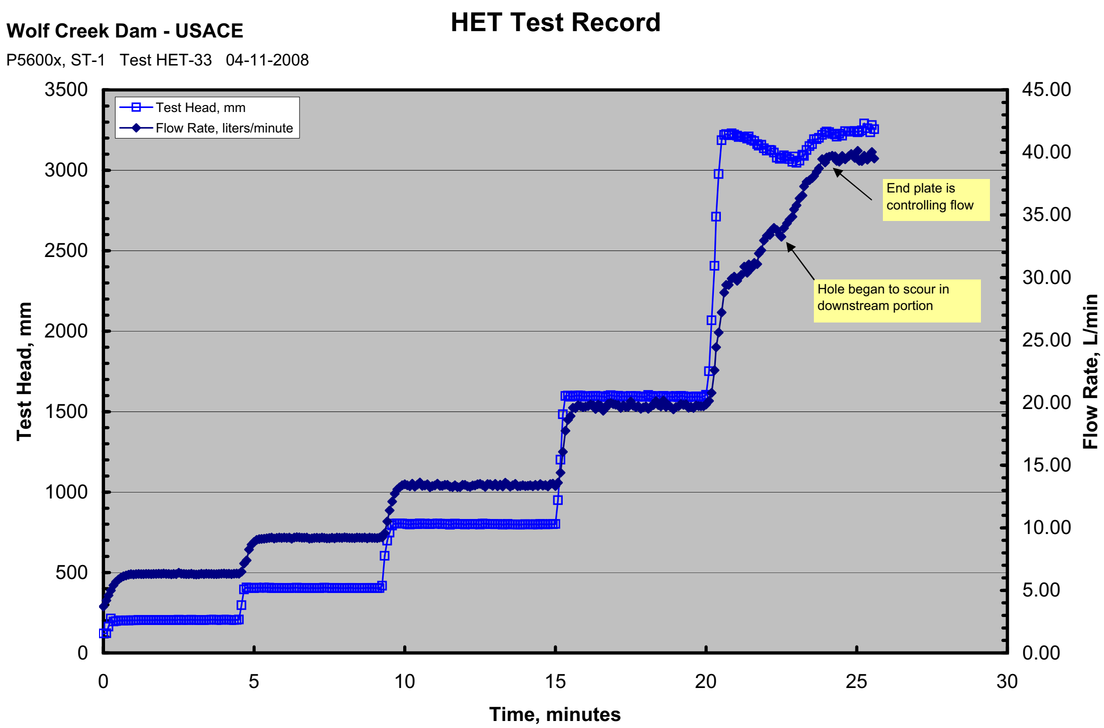


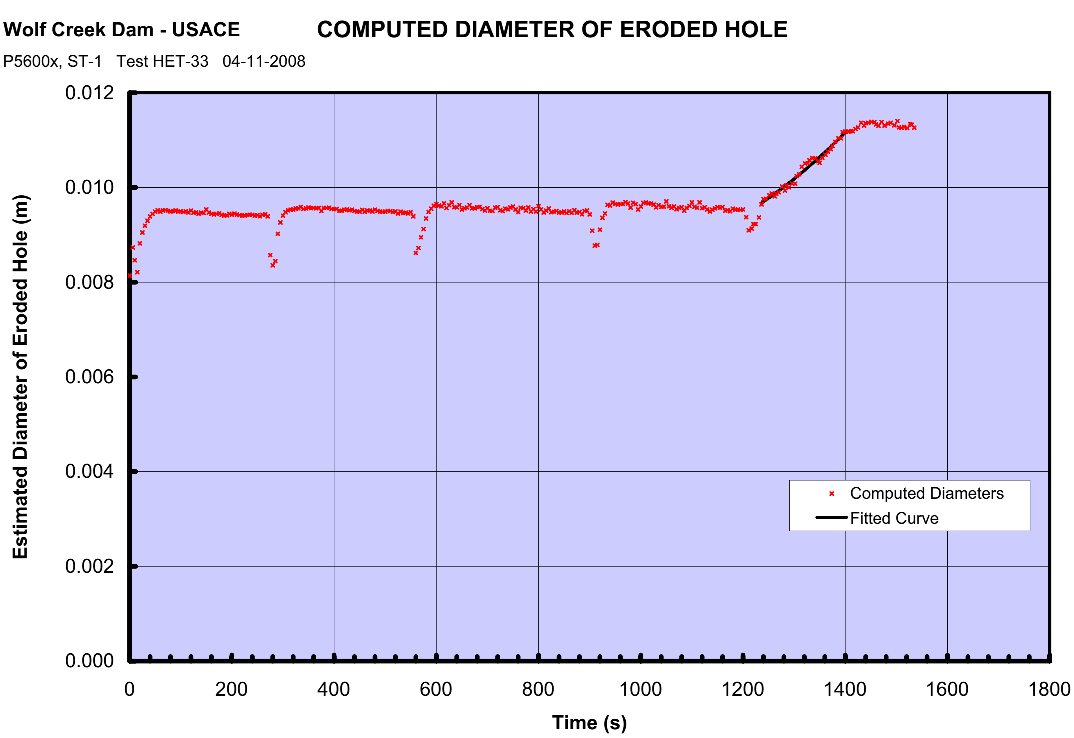

Wolf Creek Dam - USACE
EROSION RATE AND SHEAR STRESS VS. TIME
P4340x, ST-7 Test HET-32 04-10-2008
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
100
200
300
400
500
600
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
500
1000
1500
2000
2500

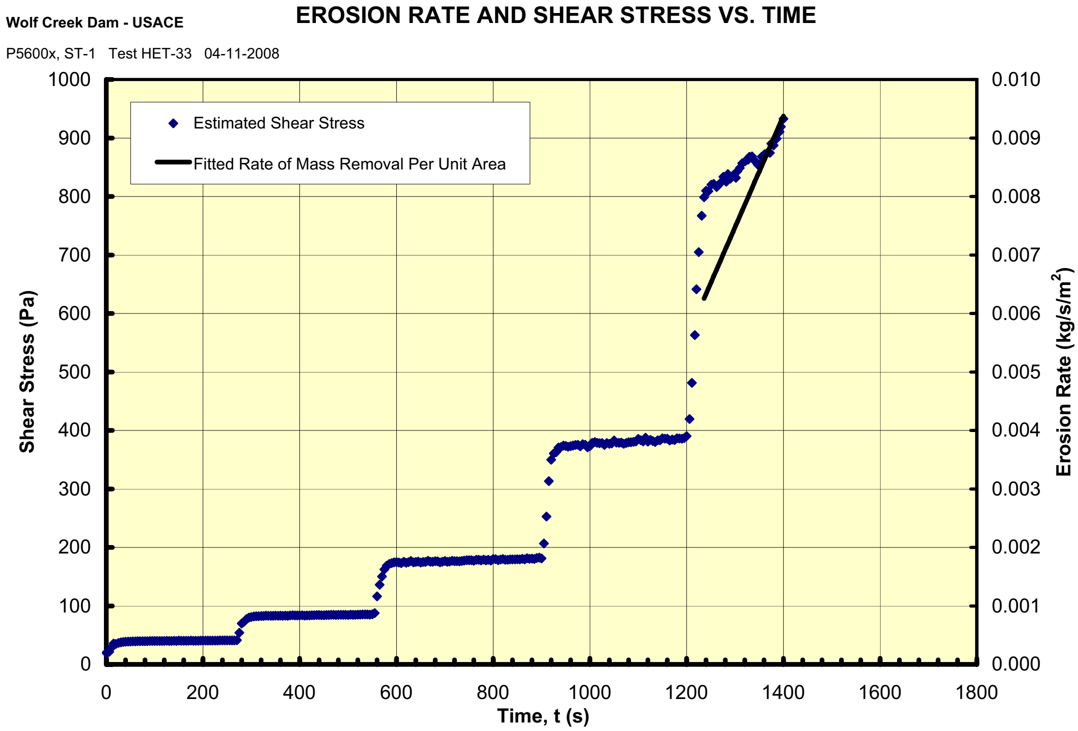

EROSION RATE VS. SHEAR STRESS
Wolf Creek Dam - USACE
P4340x, ST-7 Test HET-32 04-10-2008
slope, Ce = 3.96E-05 s/m
IHET = 4.40
Group Number = 4
kd, cm3/(N-s) = 0.0237
kd, (ft/hr)/psf = 0.0134
τc, Pa = 353.8
τc, psf = 7.390
Estimated Rate of Mass Removal Per Unit Area (kg/s/m2)
Estimated Shear Stress (Pa)
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0
100
200
300
400
500
600



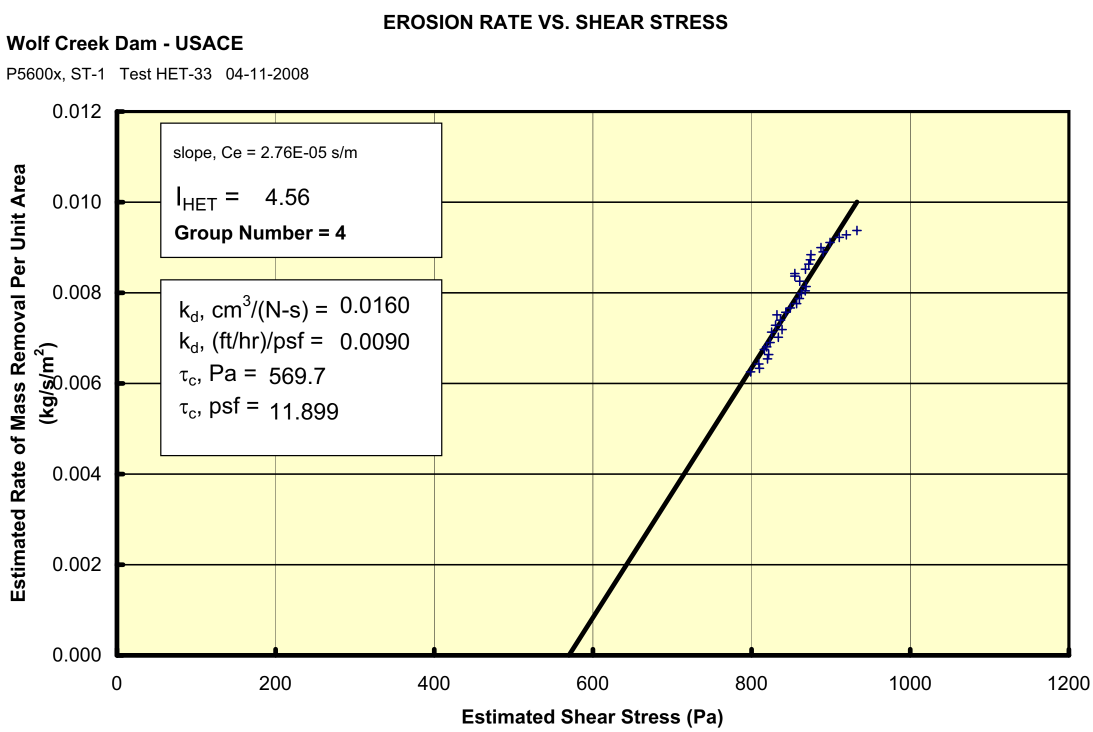
Bonelli Model - Dimensionless flow vs. Dimensionless Time
HET data
Fitted Bonelli model
Project Wolf Creek Dam - USACE
Sample ID P4340x, ST-7
Test No. HET-32
Date 4/10/2008
t_{er} = 489 s
C_e = 3.71E-05 s/m
I_{HET} = 4.43
τ_c = 350.0 Pa
k_d = 2.22E-08 m^3/N-s
k_d = 0.0222 cm^3/N-s
k_d = 0.0126 ft/hr/psf
τ_c = 7.31 psf
$Q^*=Q_t/Q_0$
t/t_{er}


Wolf Creek Dam - USACE
HET Test Record
P5600x, ST-1 Test HET-33 04-11-2008
Test Head, mm
Flow Rate, liters/minute
End plate is controlling flow
Hole began to scour in downstream portion
Test Head, mm
Flow Rate, L/min
Time, minutes
0
500
1000
1500
2000
2500
3000
3500
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
0
5
10
15
20
25
30

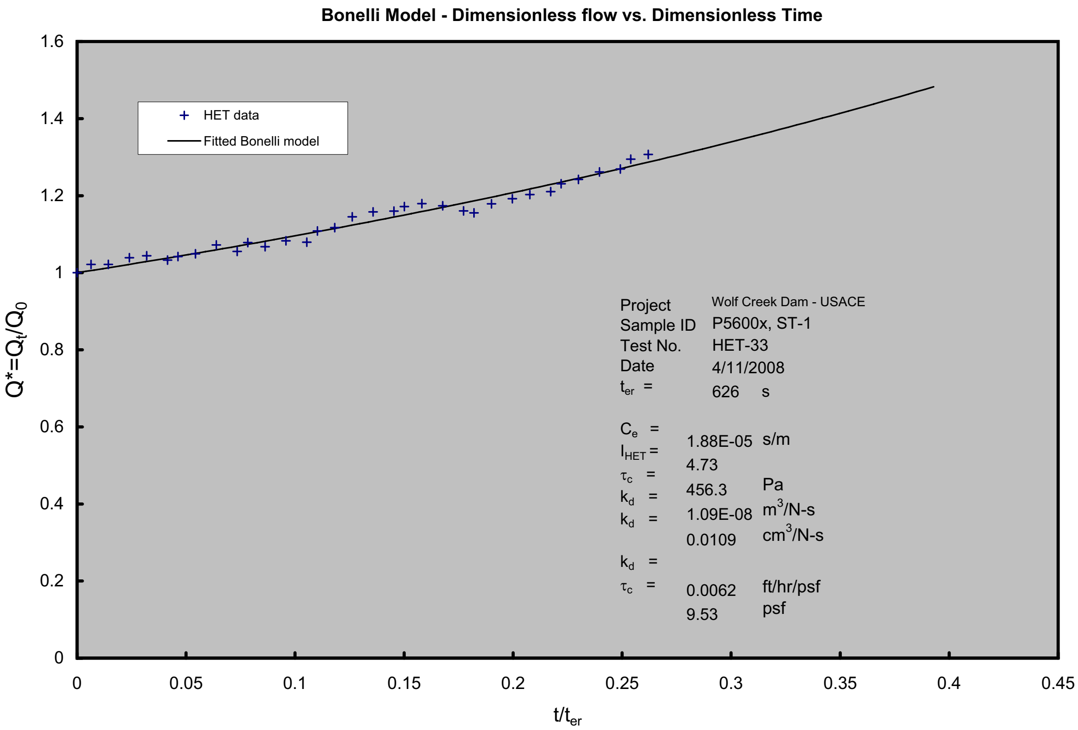

Wolf Creek Dam - USACE
COMPUTED DIAMETER OF ERODED HOLE
P5600x, ST-1 Test HET-33 04-11-2008
Estimated Diameter of Eroded Hole (m)
Time (s)
Computed Diameters
Fitted Curve
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0
200
400
600
800
1000
1200
1400
1600
1800



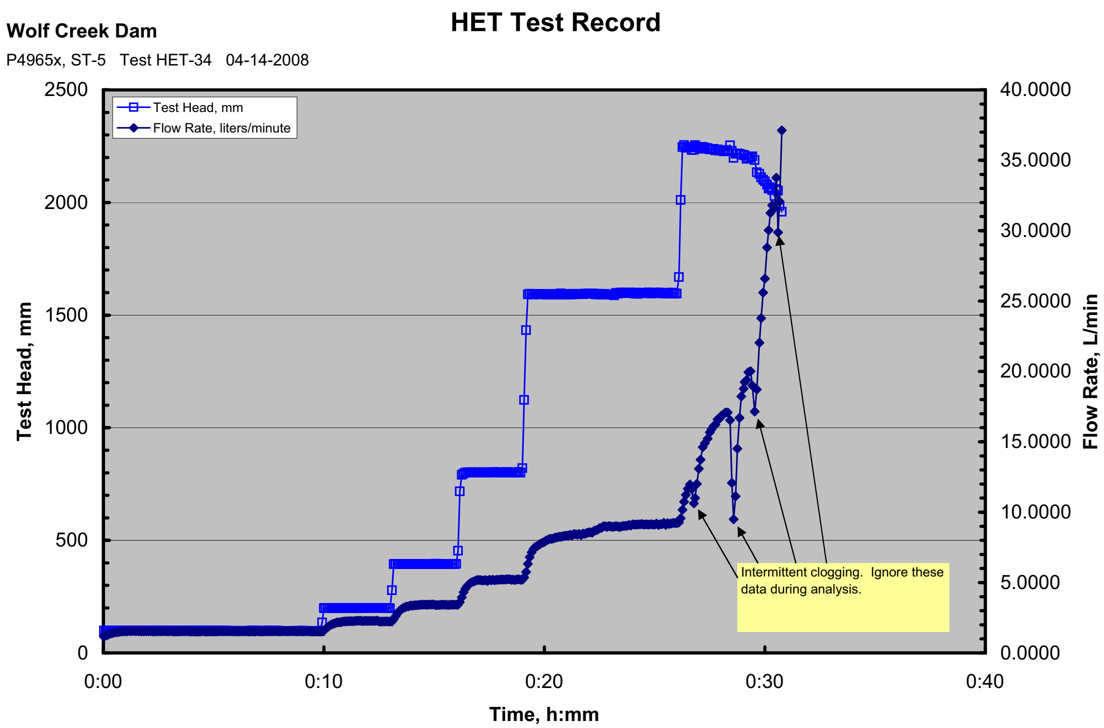
Wolf Creek Dam - USACE
EROSION RATE AND SHEAR STRESS VS. TIME
P5600x, ST-1 Test HET-33 04-11-2008
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m^2)
Time, t (s)
0
100
200
300
400
500
600
700
800
900
1000
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.010
0
200
400
600
800
1000
1200
1400
1600
1800



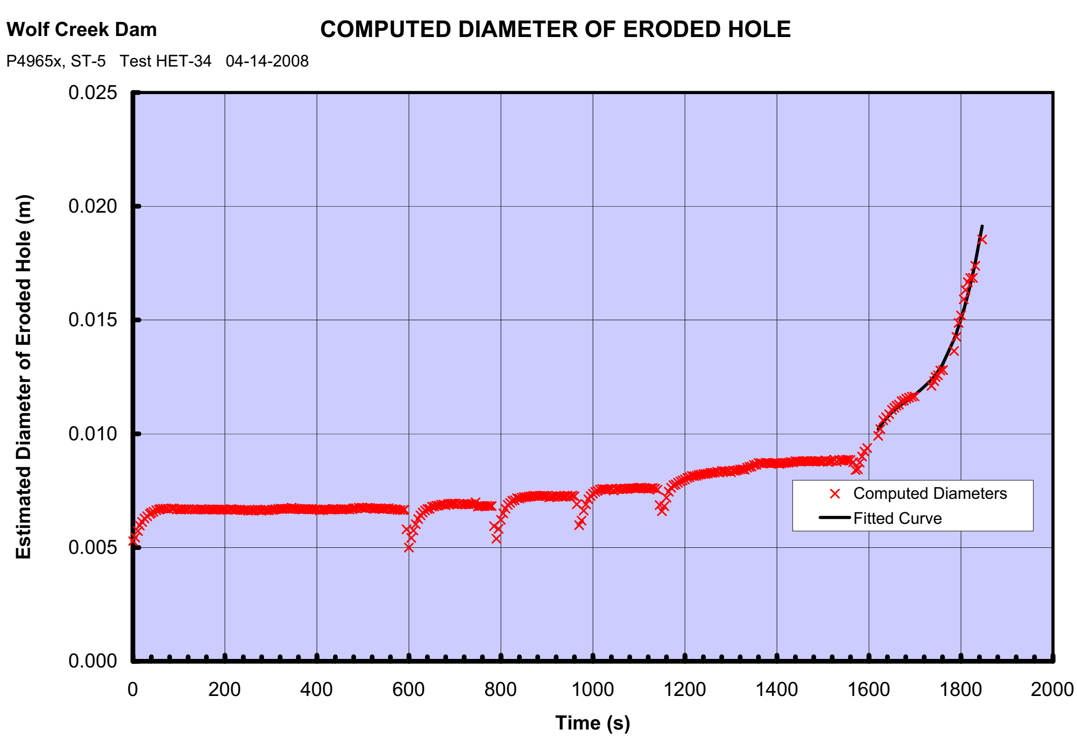
EROSION RATE VS. SHEAR STRESS
Wolf Creek Dam - USACE
P5600x, ST-1 Test HET-33 04-11-2008
slope, Ce = 2.76E-05 s/m
I_HET = 4.56
Group Number = 4
k_d, cm^3/(N-s) = 0.0160
k_d, (ft/hr)/psf = 0.0090
τ_c, Pa = 569.7
τ_c, psf = 11.899
Estimated Rate of Mass Removal Per Unit Area (kg/s/m^2)
Estimated Shear Stress (Pa)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0
200
400
600
800
1000
1200



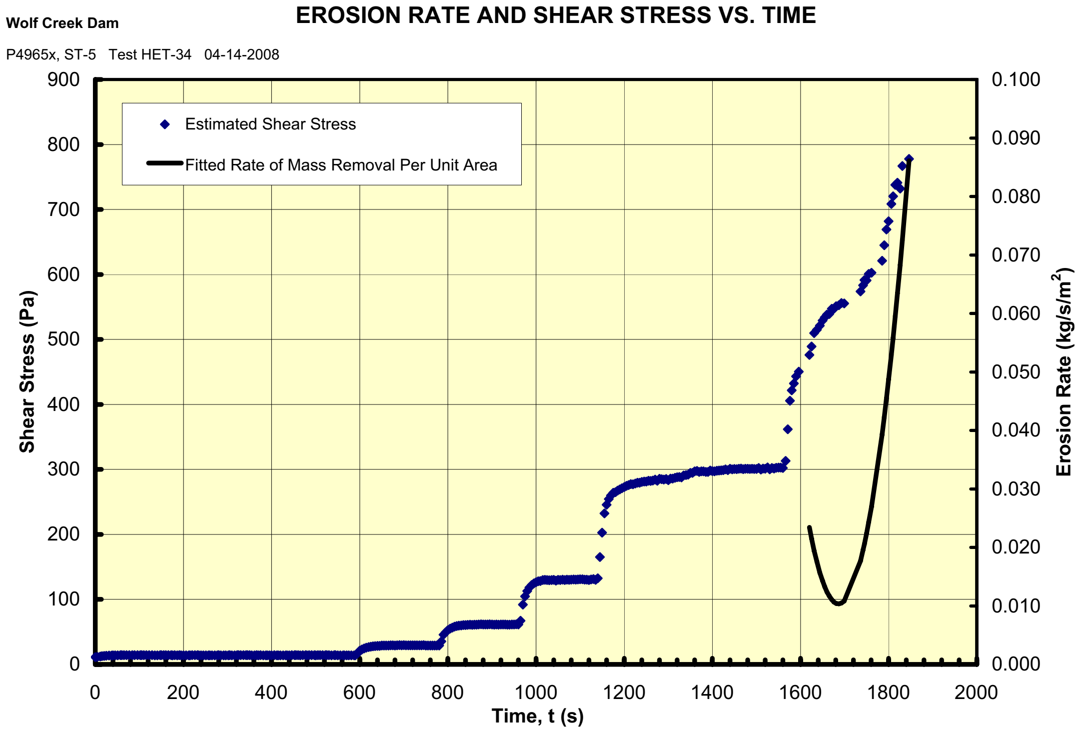
Bonelli Model - Dimensionless flow vs. Dimensionless Time
HET data
Fitted Bonelli model
Project Wolf Creek Dam - USACE
Sample ID P5600x, ST-1
Test No. HET-33
Date 4/11/2008
t_{er} = 626 s
C_e = 1.88E-05 s/m
I_{HET} = 4.73
τ_c = 456.3 Pa
k_d = 1.09E-08 m^3/N-s
k_d = 0.0109 cm^3/N-s
k_d = 0.0062 ft/hr/psf
τ_c = 9.53 psf
$Q^*=Q_t/Q_0$
t/t_{er}

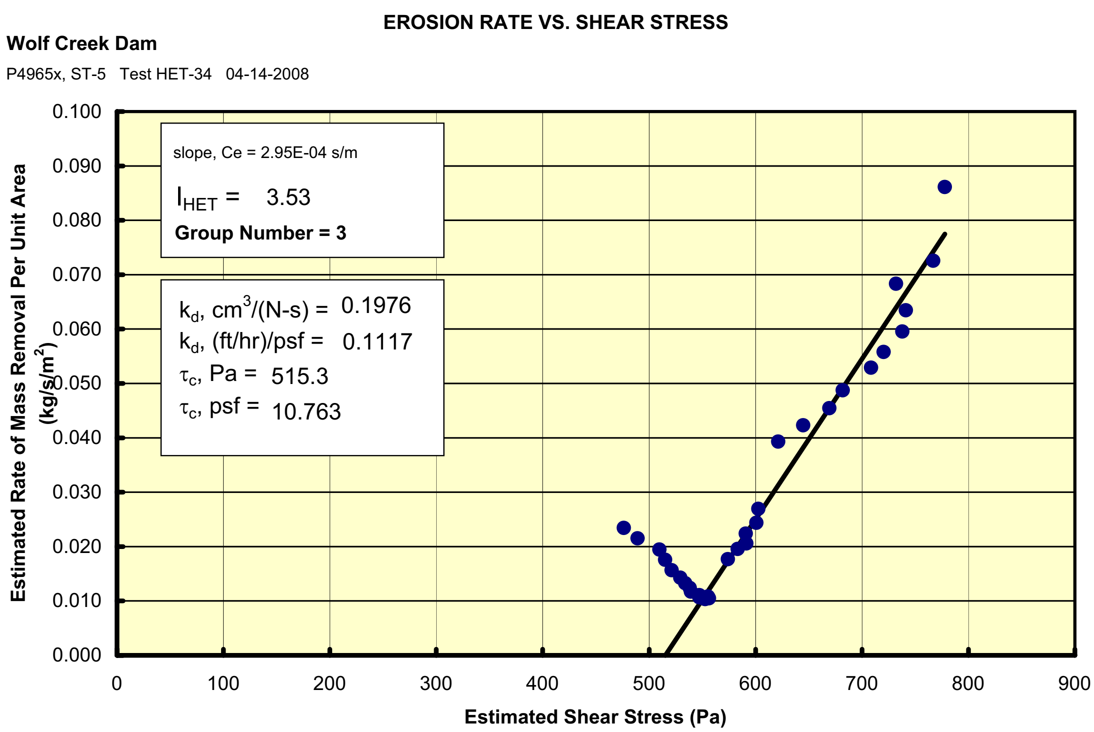


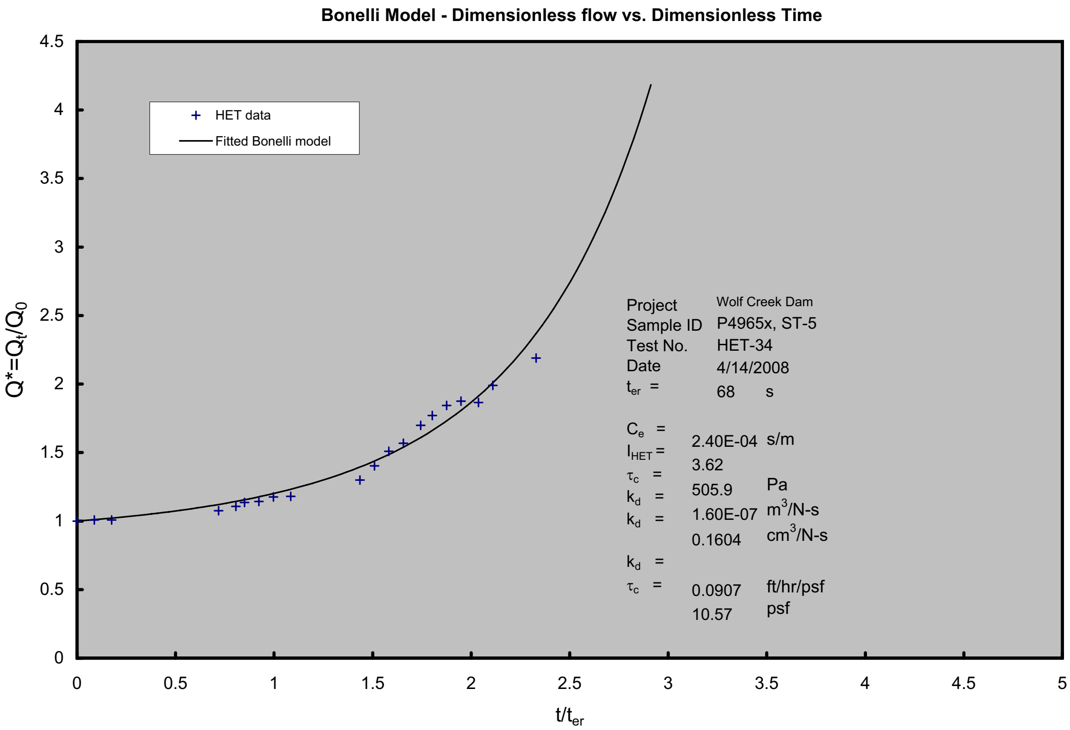
Wolf Creek Dam
HET Test Record
P4965x, ST-5 Test HET-34 04-14-2008
Test Head, mm
Flow Rate, liters/minute
Test Head, mm
Flow Rate, L/min
Time, h:mm
0:00
0:10
0:20
0:30
0:40
0
500
1000
1500
2000
2500
0.0000
5.0000
10.0000
15.0000
20.0000
25.0000
30.0000
35.0000
40.0000
Intermittent clogging. Ignore these data during analysis.



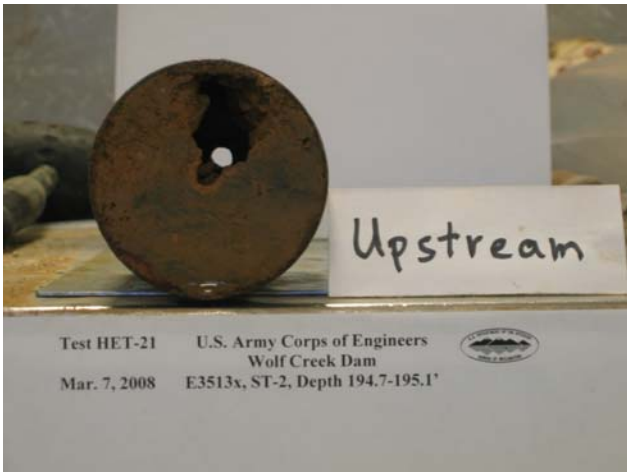
Wolf Creek Dam
COMPUTED DIAMETER OF ERODED HOLE
P4965x, ST-5 Test HET-34 04-14-2008
Estimated Diameter of Eroded Hole (m)
Time (s)
0.000
0.005
0.010
0.015
0.020
0.025
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Computed Diameters
Fitted Curve


Wolf Creek Dam
EROSION RATE AND SHEAR STRESS VS. TIME
P4965x, ST-5 Test HET-34 04-14-2008
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)
0
100
200
300
400
500
600
700
800
900
0.000
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.100
0
200
400
600
800
1000
1200
1400
1600
1800
2000


EROSION RATE VS. SHEAR STRESS
Wolf Creek Dam
P4965x, ST-5 Test HET-34 04-14-2008
slope, Ce = 2.95E-04 s/m
IHET = 3.53
Group Number = 3
kd, cm3/(N-s) = 0.1976
kd, (ft/hr)/psf = 0.1117
τc, Pa = 515.3
τc, psf = 10.763
Estimated Rate of Mass Removal Per Unit Area (kg/s/m2)
Estimated Shear Stress (Pa)
0.000
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.100
0
100
200
300
400
500
600
700
800
900


Bonelli Model - Dimensionless flow vs. Dimensionless Time
HET data
Fitted Bonelli model
Q*=Qt/Q0
t/ter
Project Wolf Creek Dam
Sample ID P4965x, ST-5
Test No. HET-34
Date 4/14/2008
ter = 68 s
Ce = 2.40E-04 s/m
IHET = 3.62
τc = 505.9 Pa
kd = 1.60E-07 m3/N-s
kd = 0.1604 cm3/N-s
kd =
τc = 0.0907 ft/hr/psf
10.57 psf
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

Appendix C: Hole Erosion Test Photographs



(a)

(b)

(c)

(d)

Figure C1- Specimen E3513x, ST2 at 194.7-195.1 ft, applied heads: 100 and 200 mm. After high-head HET#21 (a), (b) Upstream end, and (c), (d) Downstream end. Unable to analyze this test.

(e)

(f)

(g)

Figure C1 (cont)- Specimen E3513x, ST2 at 195.1-195.5 ft, applied heads: 120, 210, 400, and 570 mm After high-head HET#23 (e) Upstream end, (f) Downstream end, and (g) Enlarged hole cast in hydrostone. Some gravel encountered during hole drilling.

(a)

(b)

(c)

Figure C2- Specimen E3513x1,S31 at 204.4-204.8 ft, applied heads: 770, 1560, 2280, 3200, and 3700 mm, good test. After high-head HET#22 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone.

(a)

(b)

(c)

Figure C3- Specimen E3513x1, S36 at 215.0-215.4 ft, applied heads: 1620 and 3180 mm, good test. After high-head HET#13 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone.

(d)

(e)

(f)

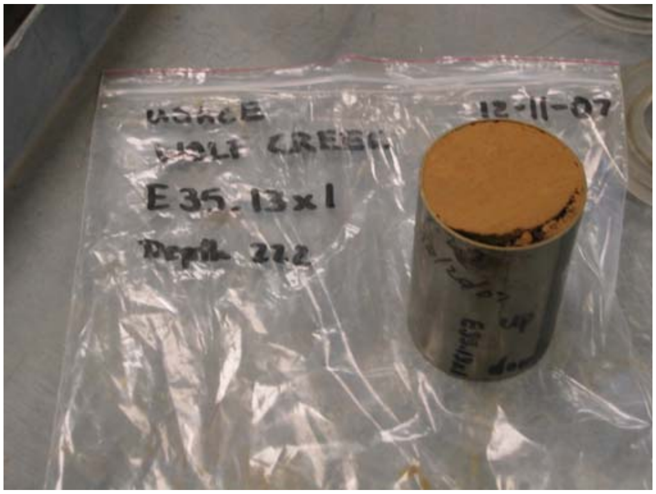
Figure C3 (cont)- Specimen E3513x1, S36 at 214.6-215.0 ft, applied heads: 2000, 2400, 2800, 3200, and 4000 mm. After high-head HET#18 (d) Upstream end, (e) Downstream end, and (f) Enlarged hole cast in hydrostone.

(a)

(b)

(c)

Figure C4- Specimen E3513x1, S40 at 222.8-223.2 ft, applied heads: 800 and 1600 mm, no erosion. After HET#2 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone.



(d)

(e)

(f)

(g)

Figure C4 (cont)- Specimen E3513x1, S40 at 223.3-223.7 ft, applied heads: 800 and 1600 mm HET#4 (d) Before test upstream end, (e) After test upstream end, (f) After test downstream end, and (g) Enlarged hole cast in hydrostone.

(a) (b)

Figure C5- Specimen E3548x, SH12 at 211.2-211.6 ft, applied heads: 200, 400, 820, 1590 mm No erosion was observed. After HET#7 (a) Downstream end, and (b) Final hole cast in hydrostone.

(c) (d)

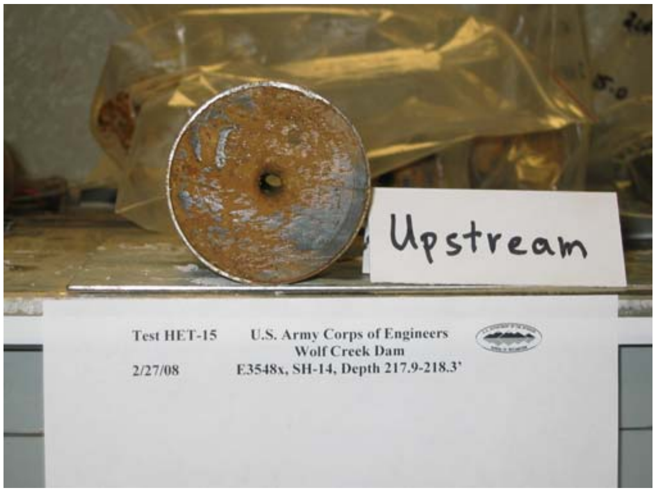
Figure C5 (cont)- Specimen E3548x, SH12 at 211.6-212.0 ft during high-head HET#10 (c) Head at 4753 mm at 36 min from beginning of test, (d) high-head HET apparatus.

(e)

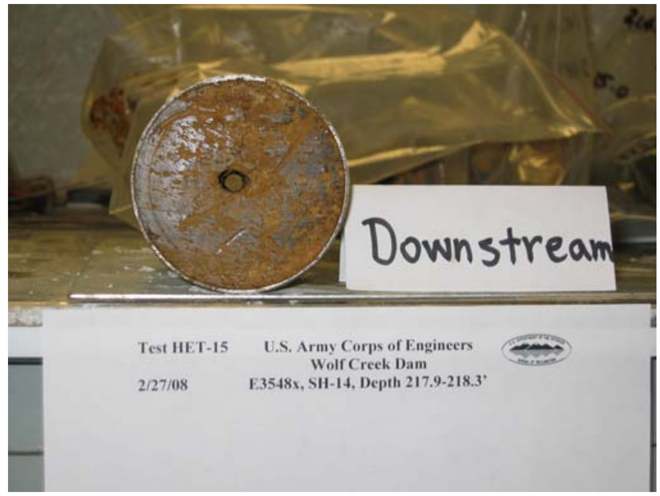
(f)

(g)

Figure C5 (cont)- Specimen E3548x, SH12 at 211.6-212.0 ft, applied heads: 3200, 4800, and 5300 mm. No progressive erosion. After high-head HET#10 (e) Upstream end, (f) Downstream end, and (g) Enlarged hole cast in hydrostone.



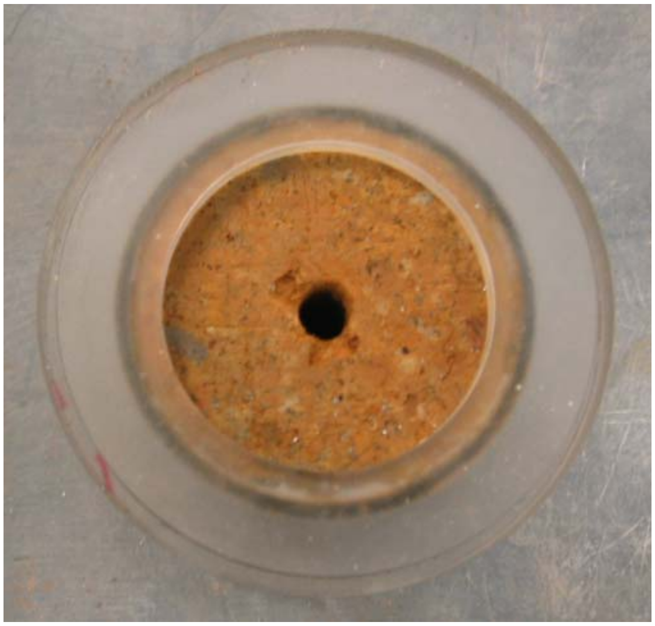
(a)



(b)

(c)

Figure C6- Specimen E3548x, SH14 at 217.9-218.3 ft, applied heads: 1600, 2400, and 3200 mm, good test. After high-head HET#15 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone.



(a)

(b)

(c)

Figure C7- Specimen E3548x, SH16 at 221.8-222.2 ft. Initial hole diameter=9.52 mm. Applied head: 1560 mm. No erosion was observed after 1 hr, and test was terminated. After HET#5 (a) Upstream end, (b) Downstream end, and (c) Final hole cast in hydrostone.

(d)

(e)

(f)

Figure C7 (cont)- Specimen E3548x, SH16 at 222.2-222.6 ft, applied head: 3200 mm. Good test. After high-head HET#9 (d) Upstream end, (e) Downstream end, and (f) Enlarged hole cast in hydrostone.

(a)

(b)

(c)

Figure C8- Specimen E3560x, SH2 at 209.9-210.3 ft, applied heads: 1600, 2400, 3200, and 4800 mm. Good test. After high-head HET#16 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone. While erosion was occurring, discharge was still extremely clear (no fines in suspension).

(a)

(b)

(c)

Figure C9- Specimen E3562x, SH7 at 195.3-195.7 ft, applied head: 750 mm. Good test. After high-head HET#20 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone. Photos (a) and (b) were taken after specimen was oven-dried.

(a)

(b)

(c)

Figure C10- Specimen E3562x, SH12 at 205.6-206.0 ft, applied heads: 1600 and 3200 mm. Good test. After high-head HET#12 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone.

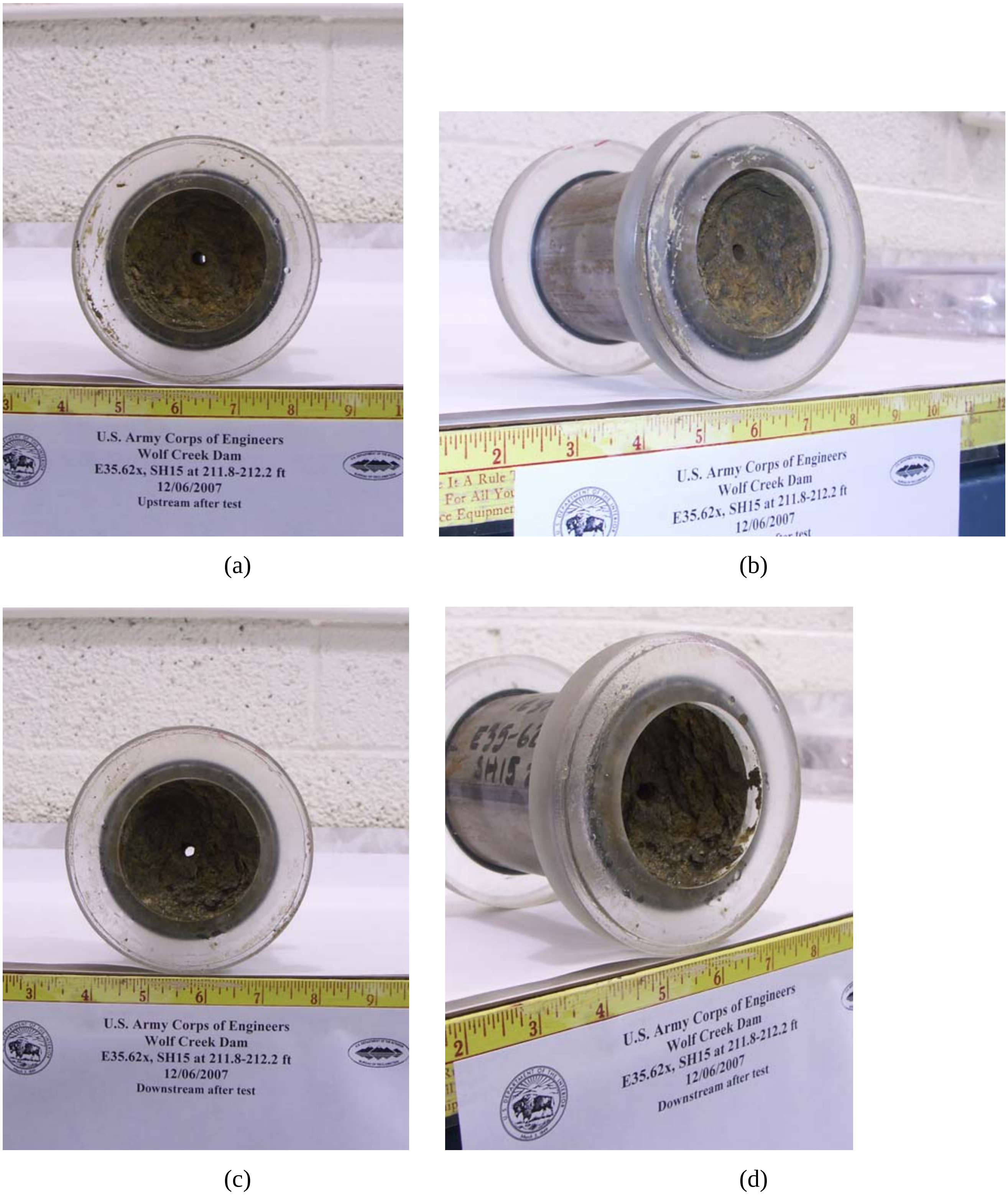


Figure C11- Specimen E3562x, SH15 at 211.8-212.2 ft, applied heads: 100, 200, 400, and 800 mm Progressive erosion not achieved. After HET#1 (a), (b) Upstream end, and (c), (d) Downstream end.

(e)

(f)

Figure C11 (cont)- Specimen E3562x, SH15 at 211.8-212.2 ft after HET#1
(e) Final hole cast in hydrostone, and (f) Crumb test after 20 hours.

(g)

(h)

(i)

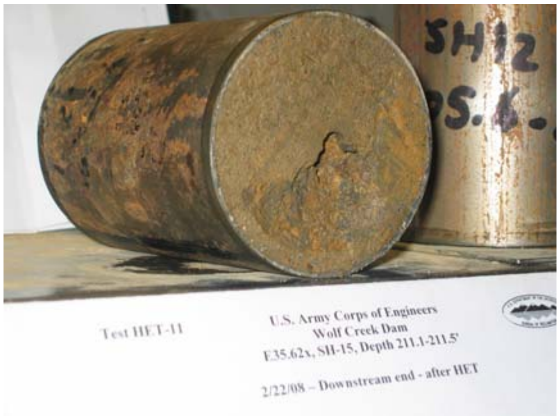
(j)

Figure C11 (cont)- Specimen E3562x, SH15 at 212.3-212.7 ft, applied heads: 800, 1400, and 1600 mm Progressive erosion not achieved. After HET#3 (g) Upstream end, (h), (i) Downstream end, and (j) Final hole cast in hydrostone.

(k)

(l)

(m)



(n)

(o)

Figure C11 (cont)- Specimen E3562x, SH15 at 211.1-211.5 ft, applied heads: 1600 and 3400 mm, good test.
After high-head HET#11 (k), (l) Upstream end, (m), (n) Downstream end, and (o) Enlarged hole cast in hydrostone.

(a)

(c)

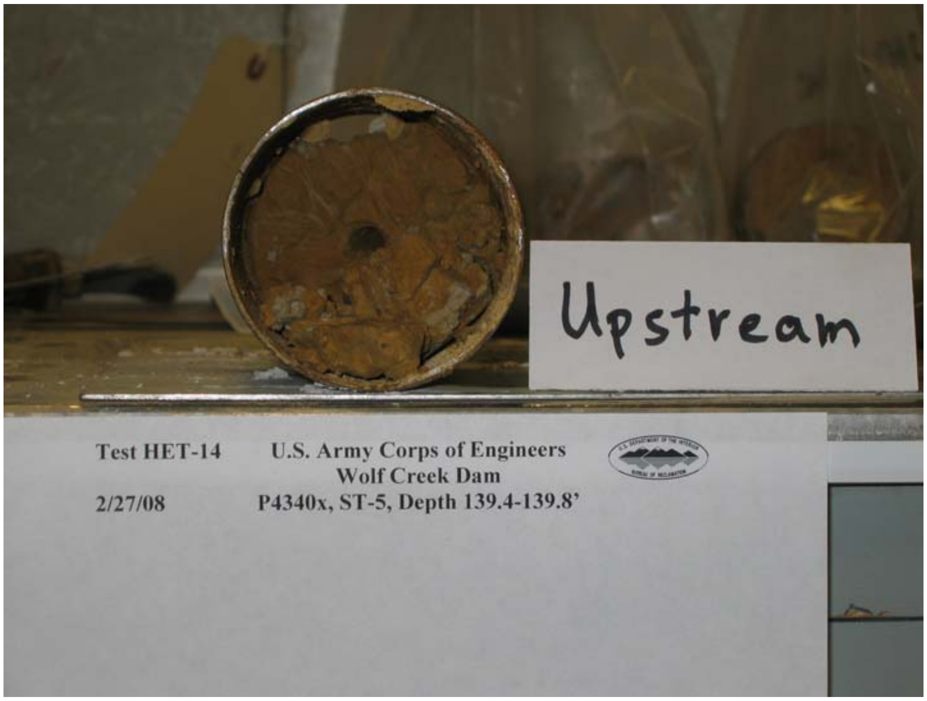
Figure C12- Specimen P3900x, SH1 at 164.3-164.7 ft, applied head: 1600 mm. Progressive erosion not achieved. After HET#6 (a) Upstream end, and (b) Downstream end.

(d)

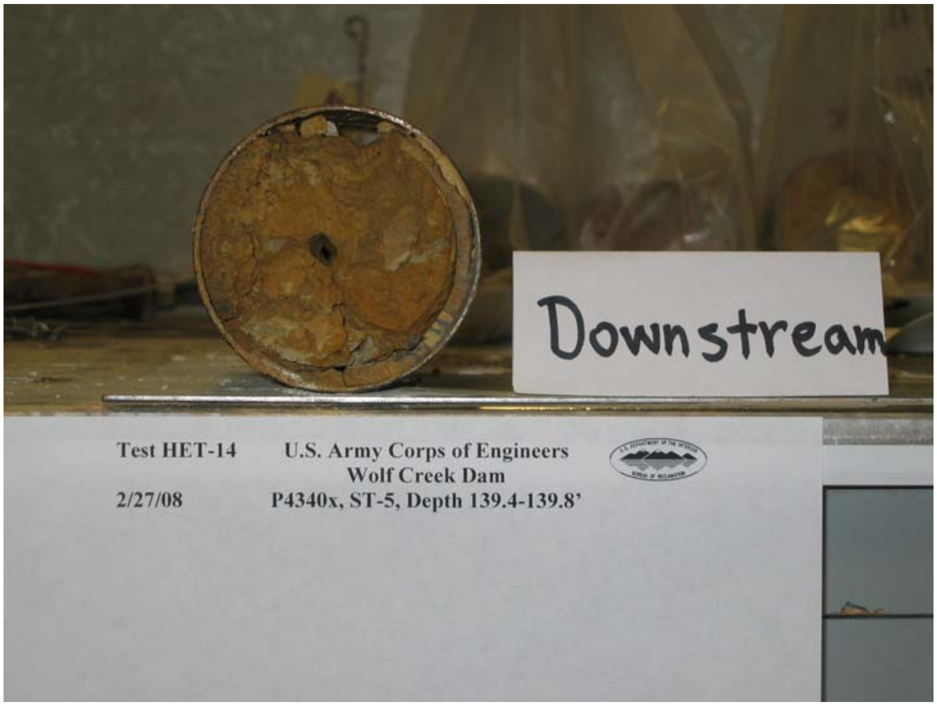
(e)

(f)

Figure C12 (cont)- Specimen P3900, SH1 at 163.9-164.3 ft, applied head: 3200 mm. Erosion progressed rapidly. Outflow pipe from HET apparatus became kinked and plugged, terminating test early. Photos after high-head HET#8 (c) Upstream end, (d) Downstream end, and (e) Enlarged hole cast in hydrostone.



(a)



(b)

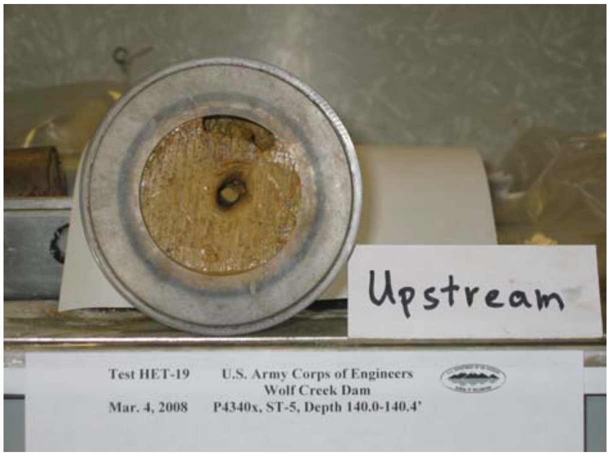
Figure C13- Specimen P4340, ST5 at 139.4-139.8 ft, applied head: 800 mm. Bad test. Specimen failed rapidly through a void along the tube wall. After high-head HET#14 (a) Upstream end, and (b) Downstream end.

(c)

(d)

(e)

Figure C13 (cont)- Specimen P4340x, ST5 at 139.0-139.4 ft, applied head: 2000 mm
Good test but initial head was probably higher than needed to initiate erosion. After high-head HET#17 (c) Upstream end, (d) Downstream end, and (e) Enlarged hole cast in hydrostone.



(f)

(g)

(h)

Figure C13 (cont)- Specimen P4340x, ST5 at 140.0-140.4 ft, applied heads: 200, 300, 400, 600, 800, 1100, 1600, 2300, 3200, 4200, and 5300 mm. Good test. After high-head HET#19 (f) Upstream end, (g) Downstream end, and (h) Enlarged hole cast in hydrostone.

(a)

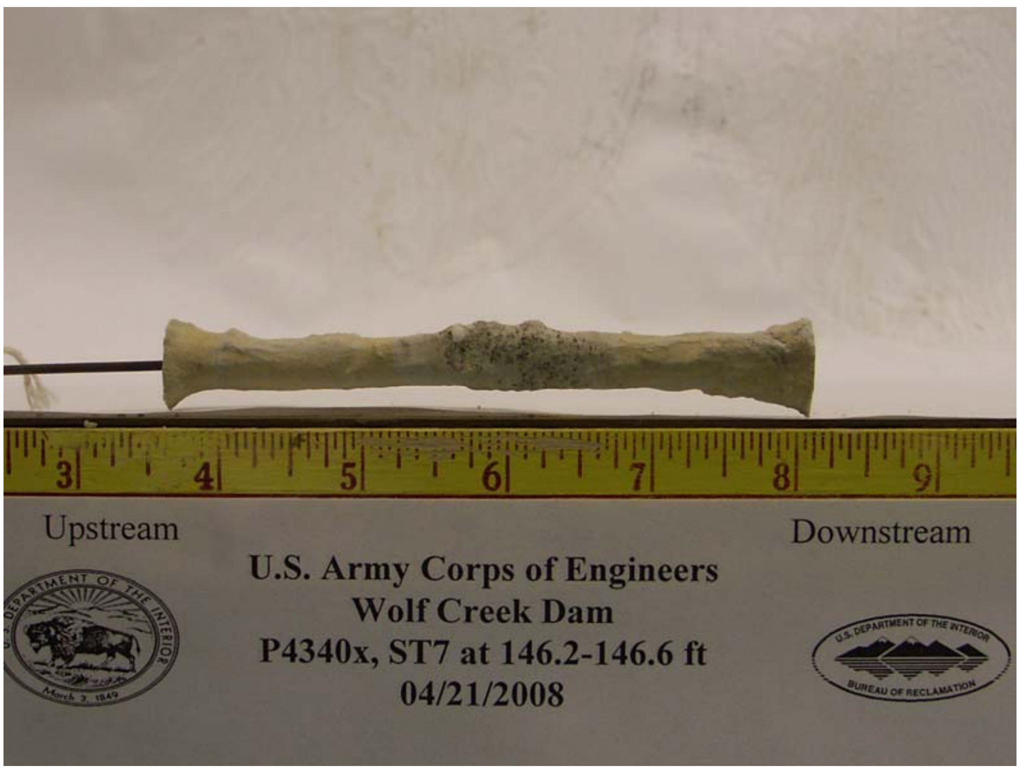
(b)

(c)

Figure C14- Specimen P4340x, ST7 at 145.8-146.2 ft, applied heads: 100, 200, 400, 800, and 1700 mm. Flow became erratic possibly due to some gravel particles. Analysis requires subjectivity. After high-head HET#26 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone.

(d)

(e)



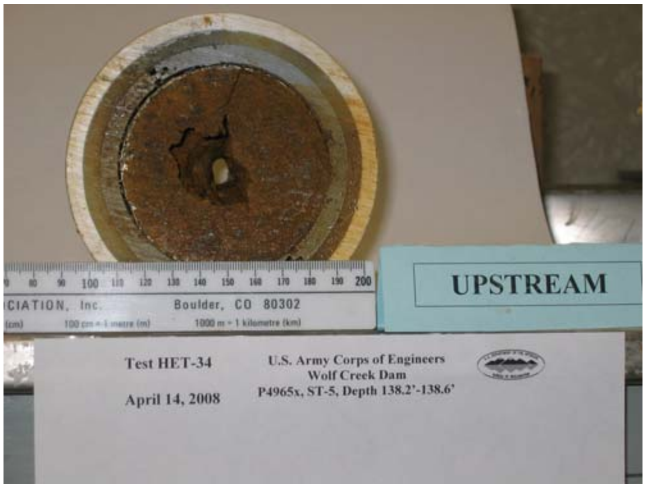
(f)

Figure C14 (cont)- Specimen P4340x, ST7 at 146.2-146.6 ft, applied heads: 200, 400, 800, 1600, and 2200 mm, good test. After high-head HET#32 (d) Upstream end, (e) Downstream end, and (f) Enlarged hole cast in hydrostone.

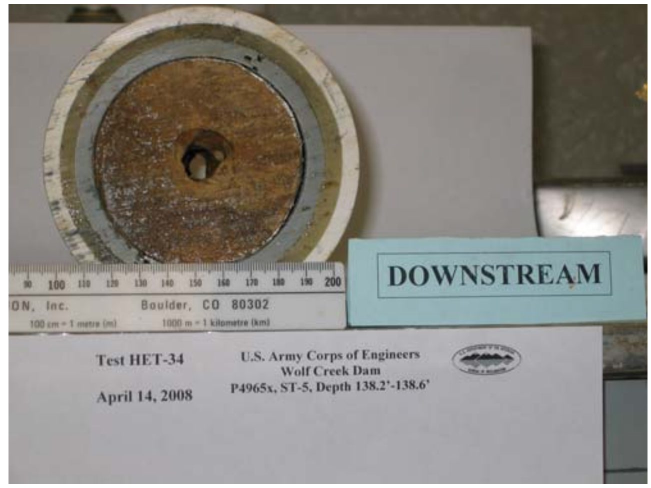
(a)

(b)

Figure C15- Specimen P4965x, ST5 at 137.3-137.7 ft, applied heads: 140, 400, 600, 800, 1100, and 1600 mm. Progressive erosion was just beginning at 1600 mm head when flow became erratic. Specimen breached along edge of tube. After high-head HET#29 (a) Upstream end, and (b) Downstream end.



(c)



(d)

(e)

Figure C15 (cont)- Specimen P4965x, ST5 at 138.2-138.6 ft, applied heads: 100, 200, 400, 800, 1600, and 2200 mm. Progressive erosion started at 2200 mm head, and there was intermittent hole clogging. After high-head HET#34 (c) Upstream end, (d) Downstream end, and (e) Enlarged hole cast in hydrostone. This sample was loose in the tube and cracked longitudinally during hole drilling [crack is visible at top of photo (c)].

(a)

(b)

(c)

Figure C16- Specimen P4965x, ST6 at 141.4-141.8 ft, applied heads: 240, 400, 850, and 1100 mm, good test. After high-head HET#31 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone. Photo (c) is retouched to fill an air void in the casting.

(a)

(b)

Figure C17- Specimen P5600x, ST1 at 100.7-101.1 ft, applied head: 100, 200, 300, 400, 600, 800, 1100, 1600, 2200, 3300, 4500, and 5400 mm. Geomesh (u/s) turbulence filter and 15 mm end plates (u/s and d/s) installed. No progressive erosion observed. After high-head HET#24 (a) Upstream end, and (b) Downstream end.

(c)

(d)

(e)

Figure C17 (cont)- Specimen P5600x, ST1 at 101.1-101.5 ft, applied heads: 200, 400, 800, 1600, and 3200 mm. Initial hole diameter was 9.5 mm. Progressive erosion occurred at 3200 mm head. After high-head HET#33 (c) Upstream end, (d) Downstream end, and (e) Enlarged hole cast in hydrostone

(a)

(b)

(c)

Figure C18- Specimen P5600x, ST6 at 110.3-110.7 ft, applied heads: 100, 200, 400, 550, 800, 1100, 1600, 2300, 3300, 4500, and 5400 mm, good test. After high-head HET#25 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone.

(a)

(b)

Figure C19- Specimen P6185x, ST6 at 100.3-100.7 ft, applied heads: 240, 400, 800, 1600, 2300, 3200, 4500, and 5400 mm, no erosion. End of first segment of three-part high-head HET#30 (a) Upstream end, and (b) Downstream end. Initial hole drilled to 6.35 mm, enlarged during test to 8 mm, but erosion was not progressive (erosion rate decelerating throughout test).

(c)

(d)

Figure C19 (cont)- Specimen P6185x, ST6 at 100.3-100.7 ft, applied heads: 1600, 2400, 3200, 4500, and 5400 mm, no erosion. End of second part of three-part high-head HET#30. Hole re-drilled to 9.52 mm, and enlarged during test to 11 mm, but erosion was not progressive (erosion rate decelerating throughout test). (c) Upstream end, and (d) Downstream end.

(d)

(f)

(g)

Figure C19 (cont)- Specimen P6185x, ST6 at 100.3-100.7 ft, applied heads: 2150, 4500, and 5100 mm, no progressive erosion. After high-head HET#30. Hole pre-drilled to 12.25 mm, and enlarged to 14 mm during test, but erosion was not progressive (erosion rate decelerating throughout test). (e) Upstream end, (f) Downstream end, and (g) Enlarged hole cast in hydrostone.

(a)

(b)

(c)

Figure C20- Specimen P6750x, ST8 at 87.3-87.7 ft, applied heads: 150, 200, 400, 800, 1150, 1600, 2250, and 3200 mm. A short period of erosion at 2250 mm. Initial hole was angled due to hitting gravel particles during hole drilling. After high-head HET#27 (a) Upstream end, (b) Downstream end, and (c) Enlarged hole cast in hydrostone.

Appendix D: Current Hole Erosion Test Procedures Used by the Bureau of Reclamation

The hole erosion test (Wan and Fell 2004) is one of several methods for evaluating the erodibility of cohesive soils. The HET utilizes an internal flow, similar to that occurring during piping erosion of embankment dams. A 6-mm or ¼-inch diameter hole is pre-drilled through a soil specimen and flow is passed through that hole under constant head. The head is increased incrementally until the threshold stress to initiate erosion is exceeded. Once erosion is initiated, the flow rate will accelerate over time, since enlargement of the hole leads to further increases in shear stress and higher rates of erosion. One must reach this "progressive erosion" condition in order to have a successful test.

An ASTM standard for the hole erosion test does not yet exist; in its absence, tests are performed and analyzed using methods consistent with those described by Wan and Fell (2004). Recently, the Bureau of Reclamation and others have also investigated other methods for analyzing the data collected during HETs, focusing on the use of a piping erosion model developed by Bonelli et al. (2006). The data reported here were analyzed using the Wan and Fell (2004) procedures, although they were also checked for consistency using the Bonelli method when applicable. The data analysis procedures are described below.

Test Facilities and Procedures

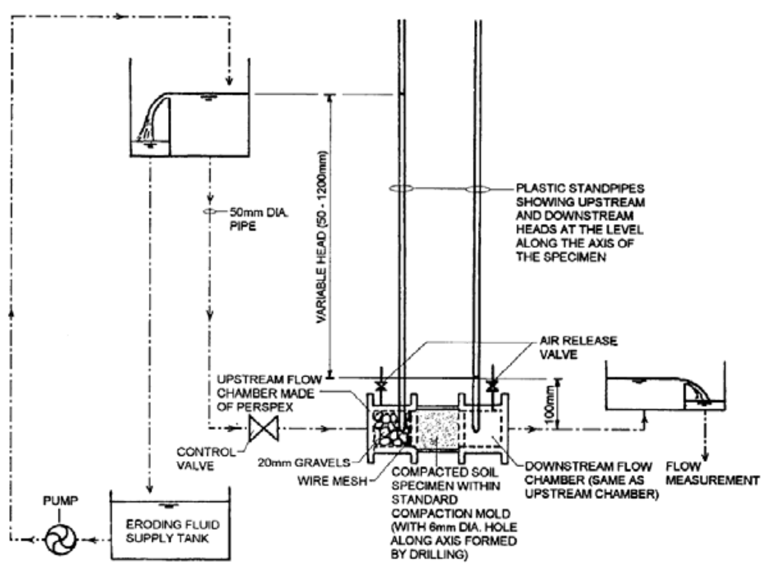


Figure A-1. Schematic diagram of hole erosion test facilities (Wan and Fell 2004).

The hole erosion test facilities at the Bureau of Reclamation are similar to those used by Wan and Fell (2004), except that the maximum head values in our two facilities are approximately 1600 mm and 5400 mm. Flow measurement is accomplished using 10° V-notch weirs, and data collection is automated using a computerized data acquisition system that records differential head and flow rate at 5 second intervals. The upstream and downstream chambers are similar to those shown in the schematic diagram. With erosion-resistant soils we have found no need for the 20 mm gravel in the upstream chamber. When testing very erosive soils we have found it helpful to place a plastic geotextile mesh fabric in the upstream chamber and protect the upstream and downstream faces of the compacted soil specimen with end plates. We have a range of end plates available, with orifice openings varying from 10 mm to 25 mm. The orifice size is selected based on the expected erodibility of the sample, with smaller orifices generally used to provide more protection to the faces of weaker specimens. The test operator must consider the orifice size and plan to end the test before the hole enlarges enough to allow the orifice openings to limit the flow rate.

The basic test procedure is as follows:

1. Following specimen preparation and compaction, specimens are sealed in plastic bags to prevent moisture loss and cured overnight before testing.
2. After curing, a ¼-inch diameter hole is drilled through the specimen using a drill press and wood auger bit to minimize compaction of the side walls of the hole. Drilling is performed at the slowest possible speed and the bit is advanced slowly and cleaned repeatedly during drilling.
3. The hole is cleaned using a 0.22-inch diameter rifle brush.
4. Specimens are installed into the apparatus with the original top surface (last compacted layer) upstream. If the soil is expected to be highly erodible or susceptible to scour of the upstream and downstream faces, protective end plates are also installed. A plastic geofabric mesh filter is also installed in the upstream chamber to reduce turbulence when specimens are expected to be highly erodible.
5. The test facility is filled slowly with water and all air is bled from piezometer tubes connected to pressure sensors.
6. The water supply head tank is positioned to the desired starting head level. For specimens of unknown erodibility, tests are usually started at 50 mm of head.
7. The downstream weir box tank is filled with water to the level of the horizontal weir that maintains nearly-constant downstream head, and some additional water is then added to produce flow through the V-notch weir at a rate that approximates the expected starting flow rate. This is done in an attempt to have the test start with the weir box system in a state of flow rate equilibrium.
8. The data acquisition system is started and the inlet valve upstream from the test specimen is opened.
9. The flow rate is monitored to determine whether it is increasing or becoming steady. If the flow rate stabilizes at a given head, then the head tank is raised to increase the head. We generally double the head each time, or if we feel that the erosion threshold is near, we will increase the head in somewhat smaller increments.

10. When the flow rate begins to accelerate, the test head is maintained until at least several minutes of accelerating flow is observed. The operator should be aware of the approximate maximum flow increase that can occur if end plates have been installed. For example, if 10 mm end plates have been installed, the ratio of flow rates with a 10 mm hole diameter to the flow through the original 6 mm diameter hole is approximately $(10/6)^2 \approx 3$. Thus, one should stop the test well before the flow rate has tripled from its value at the start of accelerating flow. If the test is allowed to continue too long, the orifice plate opening will begin to limit the flow rate, which will hinder the data analysis.
11. After the test is stopped, the upstream and downstream chambers are drained and the specimen is removed from the test facility. An initial visual estimate of the final hole diameter is made, and the specimen is weighed.
12. Specimens are oven-dried, weighed, and then a hydrostone casting is made of the erosion hole.
13. Hole diameters are determined from the casting, typically at 5 positions spaced approximately equally along the length. The length of the portion of the casting that is of relatively uniform diameter is also recorded. (Large scour holes at the upstream or downstream end are considered to reduce the effective length of the hole, which is taken into account in the data analysis.)

Wan and Fell analysis procedure

The deterministic data analysis method described by Wan and Fell (2004) attempts to compute the hole diameter at each time step at which data have been recorded. The computed time series of hole diameters can then be used to estimate the erosion rate and applied shear stress. Microsoft Excel spreadsheets are used to make the computations and present the data graphically.

The analysis begins by considering a cylinder of eroding fluid passing through the pre-drilled hole in a soil specimen. Assuming that over a short interval of time the flow is at steady state, the equation for force equilibrium is:

$$\tau \cdot P_w \cdot L = \rho_w \cdot g \cdot \Delta h \cdot \frac{\pi d^2}{4}$$

where:

τ = shear stress along the sides of the hole
P_w = perimeter of the hole
L = length of the hole
ρ_w = fluid density
g = acceleration due to gravity

Δh = head difference across the hole from upstream to downstream
d = diameter of the hole

For a laminar flow condition, the shear stress is expected to be proportional to the mean velocity of the flow

$$\tau = f_L \bar{v}$$

where

f_L = friction factor, S.I. units of kg/s/m
$\bar{v}$ = mean velocity of the flow, $Q/(\pi d^2/4)$
Q = flow rate

Combining these equations and solving for the friction factor yields:

$$f_L = \frac{\rho_w g}{Q} \frac{\Delta h}{L} \frac{\pi d^3}{16}$$

This equation can be used to solve for the friction factor at the start and end of the test, when the hole diameter, length, head differential and flow rate are all known. This research project has shown that the friction factor is best correlated with the hole diameter, but the hole diameters during the test are not known until the analysis is complete, so the friction factor is instead assumed to vary during the test in proportion to the value of $(Q/\Delta h)^{1/3}$ for laminar flow, and $(Q^2/\Delta h)^{1/5}$ for turbulent flow. These quantities are surrogates for the hole diameter. The length of the erosion hole is assumed to vary linearly with time during the test (although it stays constant in many tests). The quantity $(Q^2/\Delta h)^{1/5}$ is also plotted on the data acquisition computer during a test to help the operator know when accelerating enlargement of the hole diameter is occurring. Most tests take place with turbulent flow conditions. The onset of turbulence is assumed to occur when the Reynolds number of flow through the hole exceeds 2000 ($\mathrm{Re}=Vd/\nu$, where V is the flow velocity, d is the hole diameter, and ν is the kinematic viscosity).

Denoting friction factors and hole lengths at intermediate times during the test by the subscript t, the same equations can be solved for the hole diameter to allow it to be computed throughout the test from measured values of the flow rate.

$$d = \left(f_{L_t} \frac{Q_t}{\rho_w g} \frac{L_t}{\Delta h_t} \frac{16}{\pi} \right)^{1/3}$$

If the flow is turbulent, the shear stress is proportional the square of the mean velocity and the following equations apply:

$$\tau = f_T \bar{v}^2$$

$$f_T = \frac{\rho_w g}{Q^2}\frac{\Delta h}{L}\frac{\pi^2 d^5}{64}$$

$$d = \left(f_{T_t} \frac{Q_t^{\,2}}{\rho_w g}\frac{L_t}{\Delta h_t}\frac{64}{\pi^2} \right)^{1/5}$$

Bonelli analysis procedure

Bonelli et al. (2006) proposed a universal model for piping erosion, applicable to analysis of the hole erosion test. They showed that the change in dimensionless hole radius is an exponential function of the dimensionless test time and the initial and critical shear stresses

$$\frac{R(t)}{R_0} = 1 + \left(1 - \frac{\tau_c}{\tau_0}\right)\left(e^{t/t_{er}} - 1\right)$$

where $R(t)$=radius at any time t and R_0=the initial radius at time zero, τ_c=critical shear stress, τ_0=shear stress at time zero, t=test time, and t_{er}=a characteristic erosion time scale for each test

$$t_{er} = \frac{2L}{k_d \gamma_w \Delta h} = \frac{2L\gamma_d}{C_e \gamma_w \Delta h}$$

where L=length of the hole, γ_w=unit weight of water ($\rho_w g$), Δh=head differential across the hole, γ_d=dry unit weight of soil, C_e=erosion rate coefficient (mass/time/area/stress), and k_d is a volumetric detachment rate coefficient (volume/time/area/stress).

The model assumes turbulent flow conditions and neglects any variation of the friction factor, the test head, or the length of the eroded hole. The method also presumes that the test data are collected entirely during the period of accelerating erosion. Bonelli et al. (2006) showed that the proposed model fit the observed hole radius data computed from 17 HETs performed by Wan and Fell (2002) using 9 different soils. Bonelli and Brivois (2007) have offered further development of the model.

Recognizing that dimensionless discharge, Q^*, is proportional to the 2.5 power of the dimensionless radius (again neglecting effects of any change in the friction factor during a test), one can write

$$Q^* = \frac{Q(t)}{Q_0} = \left(\frac{R(t)}{R_0}\right)^{5/2} = \left[1 + \left(1 - \frac{\tau_c}{\tau_0}\right)\left(e^{t/t_{er}} - 1\right)\right]^{5/2}$$

Since flow rates are measured throughout a test and the initial shear stress is known from the starting hole diameter and flow rate, this model has only two unknown parameters, the erosion time scale, t_{er}, and the critical shear stress, τ_c. Using a non-linear optimization tool such as the Excel Solver, one can optimize these two parameters to obtain a best fit of the observed dimensionless values of discharge to predicted values computed for each dimensionless test time, t/t_{er}. The coefficient of soil erosion or the detachment rate coefficient can then be determined from the fitted value of the time scale factor, t_{er}. The significant advantages of this analysis method are the fact that the final hole diameter does not need to be measured, and the curve-fitting procedure minimizes the influence of short-term anomalies in erosion behavior during a test. A disadvantage of the method is that in some cases a distinct set of optimum parameters is difficult to identify; a wide range of critical shear stresses and corresponding time scales produce a reasonably good fit of the data, requiring one to resort back to the Wan and Fell analysis for a better indication of the critical shear stress.

It should be emphasized that the formulation of the Bonelli model requires the fitted value of the critical shear stress τ_c to be less than the initial stress, τ_0, otherwise the quantity $(1-\tau_c/\tau_0)$ is negative. This means that tests must be conducted at a stress level that exceeds the critical stress and produces immediate progressive erosion, or one must customize the analysis to only examine the portion of the test in which the shear stress exceeds τ_c. If a test begins at a stress level that is slightly lower than the value needed to initiate progressive erosion, but the stress then increases due to cleanout erosion of material disturbed during hole drilling, the only way to accurately determine the critical stress would be to estimate the increase in hole diameter and shear stress that takes place leading up to the progressive erosion phase, then start the Bonelli analysis at that point in time. This requires the combined use of both the Wan and Fell and Bonelli analysis procedures.

References

Bonelli, S., Brivois, O., Borghi, R., and Benahmed, N., 2006. On the modeling of piping erosion. *Comptes Rendus Mecanique* 334, Elsevier SAS, pp. 555-559.

Bonelli, S., and Brivois, O., 2007. The scaling law in the hole erosion test with a constant pressure drop. *International Journal for Numerical and Analytical Methods in Geomechanics*, 24 pp. Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/nag.683

Wan, C.F., and Fell, R., 2004. Investigation of rate of erosion of soils in embankment dams. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 4, pp. 373-380.