RECLAMATION
Managing Water in the West

Hydraulic Laboratory Technical Memorandum
PAP-1045

Starvation Dam Issue Evaluation – Erosion Tests of Zone 1 Core Samples and Index Testing of Zone 3 Shell Sample

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

December 2011

BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Hydraulic Investigations and Laboratory Services, 86-68460

Technical Memorandum PAP-1045

Starvation Dam Issue Evaluation – Erosion Tests of Zone 1 Core Samples and Index Testing of Zone 3 Shell Sample

Central Utah Project – Bonneville Unit - Utah
Upper Colorado Region

Prepared: Tony L. Wahl, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services, 86-68460

Technical Approval: Robert F. Einhellig, P.E.
Manager, Hydraulic Investigations and Laboratory Services, 86-68460

Peer Review: Tom Strauss
Civil Engineer, Materials Engineering Research Laboratory, 86-68180

12-21-2011
Date

REVISIONS					
Date	Description	Prepared	Checked	Technical Approval	Peer Review

Introduction

Erosion and index properties tests were performed in November and December 2011on soil samples of zone 1 core and zone 3 shell materials from Starvation Dam, Utah. Index properties tests were performed in the Denver soil mechanics laboratory by the Materials Engineering Research Laboratory (MERL) group. Hole erosion and jet erosion tests (HET and JET) were performed in the hydraulics laboratory using a jet test apparatus constructed by Reclamation in accordance with ASTM D-5852, *Standard Test Method for Erodibility Determination of Soil in the Field or in the Laboratory by the Jet Index Method* and a hole erosion test facility modeled after the facility developed by Wan and Fell (2004). Both of these facilities and their use are described in detail in Wahl et al. (2008).

The Hole Erosion Test simulates internal erosion through a ¼"-diameter pre-drilled hole under a situation of incrementally increasing constant head. When the threshold for erosion is reached, head is held constant and the change in flow rate through the hole is measured as the hole erodes and enlarges. This enables the calculation of the erosion rate and applied stress, which can be used to determine the critical shear stress needed to initiation erosion and the detachment rate coefficient relating the change in erosion rate to the change in applied excess stress.

The submerged jet test simulates scour of a soil surface due to a perpendicular impinging jet. The test is run with a constant jet pressure. The depth of scour beneath the jet is measured over time and is used to estimate the critical shear stress and detachment rate coefficient. Procedures for analyzing the test data have been improved since the publication of ASTM D-5852; the data were analyzed using the method described in Hanson and Cook (2004).

Soil samples were originally obtained in June and July 2009, and were stored since that time in the 75% humidity storage facility of the MERL. The erosion samples were contained in 5-inch diameter acrylic tubes. At the time of testing the water content of the zone 1 core material samples was 6.0%. Significant drying of these samples may have occurred during storage.

Index Properties – Zone 3

Soil gradation analysis and Atterberg limits were determined for a bagged sample of zone 3 shell material recovered from drill hole DH-09-02 at depth 29.0 to 30.1 ft (37Q-181). The material was classified as GC-Clayey Gravel with Sand. The Particle Size Distribution Report and Summary are included in Appendix A.

Erosion Testing

Table 1 identifies the samples initially selected for erosion testing. From each tube we attempted to cut two samples, one for HET testing and the other for JET testing.

Table 1. — Soil samples selected for erosion testing.

Sample Number	Sampling Location	Depth, ft	Description
37Q-159	DH-09-01	15.0 – 17.5	Zone 1 core
37Q-160	DH-09-01	17.5 – 20.0	Zone 1 core
37Q-171	DH-09-01	45.0 – 47.5	Zone 1 core
37Q-174	DH-09-02	2.5 – 5.0	Zone 3 shell

The sample of zone 3 material (37Q-174) could not be tested due to the presence of nearly 40 percent coarse sand to medium gravel. This prevented the cutting of the sample into appropriate lengths for testing and would have also prevented the drilling of the initial erosion hole needed for the hole erosion test.

Paired samples were obtained from the three samples of zone 1 core material. Samples at approximate depths of 17.0, 19.5, and 47.0 ft were obtained for HET testing, and adjacent samples from the ends of the sample tube were used for JET testing. HET samples were approximately 4.5 inches in length, and JET samples were approximately 5 inches in length, except the sample at depth 17 ft which was only about 3.5 inches long. All water used for erosion testing was obtained from the hydraulics laboratory sump. This water originates from the Denver municipal water system. Water temperature at the time of the tests was about 18.5°C (65°F).

Hole Erosion Tests

Three hole erosion tests were performed. Sample 37Q-160 from depth 19.5 ft was tested first. The initial test head for this sample was set to about 180 mm, which caused immediate progressive erosion and enlargement of the pre-drilled ¼” diameter hole in the soil specimen. The test was stopped after 26 minutes when the flow rate had increased from about 1 L/min to nearly 21 L/min. Figure 1 shows a post-test photo of the eroded hole through the test specimen. Final diameter of the hole was estimated to be 23 mm from direct measurement of the specimen immediately after the test. Figure 2 shows graphical analysis of the test data leading to the determination of the I_{HET} index value of 3.4 for this sample. This index value indicates moderately rapid erosion on the descriptive scale developed by Wan and Fell (2004).

Figure 1. — Post-test photo of HET specimen from sample 37Q-160, DH-09-01, depth 19.5 ft.

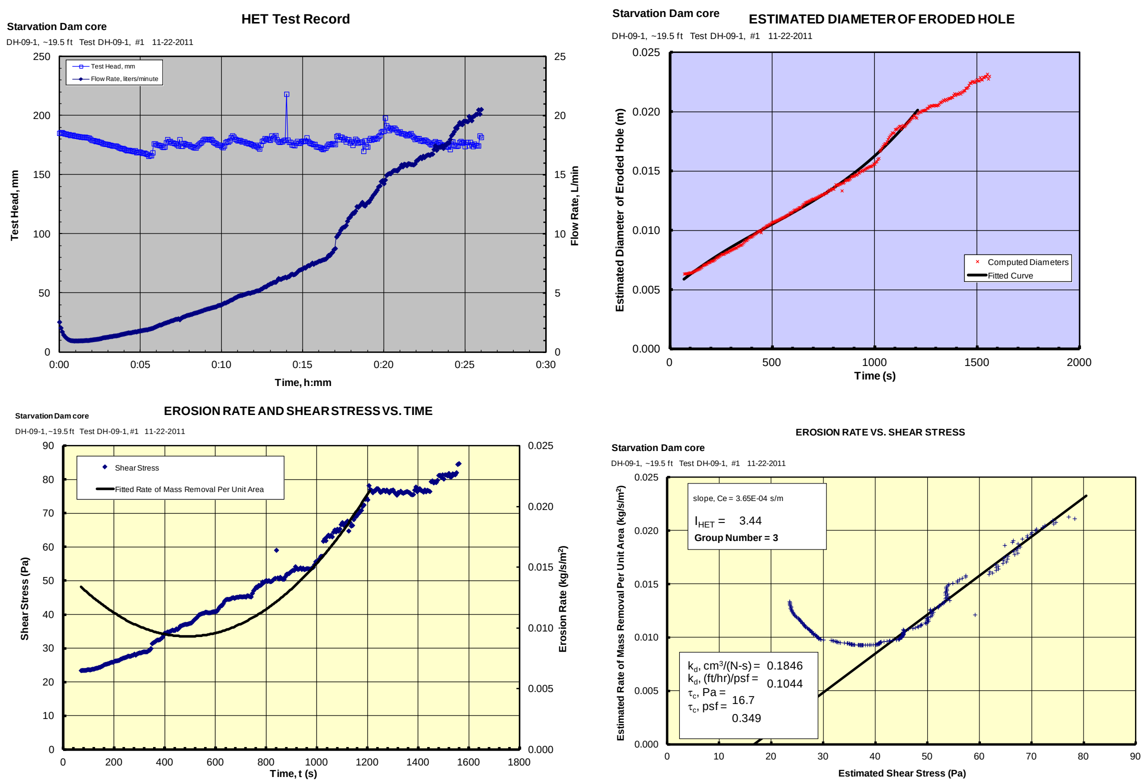


Figure 2. — Analysis of HET test data for sample 37Q-160.

Sample 37Q-159 from depth 17 ft was tested next. This test was started at a slightly higher head, about 300 mm of water. This caused immediate erosion of the sample, both via enlargement of the pre-drilled hole and due to flow around the top edge of the sample in the annular space between the soil and the acrylic tube. This flow around and over the sample quickly initiated a headcut at the exit of the sample. The test was stopped after 2½ minutes as the sample was rapidly disintegrating at the exit. The flow had increased from about 2 L/min to over 24 L/min. The final diameter of enlarged hole was estimated to be 12 mm (see Figure 3). Upon review, the first 35 seconds of recorded data from this test appeared to precede the headcut development and were suitable for analysis, and these data indicated an I_{HET} value of 1.8 for this sample, which indicates extremely rapid erosion. This is consistent with the observed behavior of the soil sample during the test. This value should be regarded as only an estimate, since the observed erosion was not confined to just hole enlargement, and significant judgment was applied in analyzing the data.

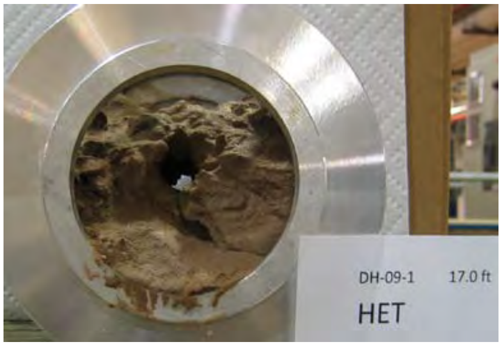


Figure 3. — Post-test photograph of the downstream end of HET specimen from sample tube 37Q-159.

The last HET specimen came from sample tube 37Q-171 at a depth of about 47 ft (Figure 4). This sample was tested beginning at about 160 mm of head. The sample exhibited no significant erosion of the hole, as indicated by steady flow rates through the hole under a fixed head. The head was repeatedly increased to 250, 400, 800, 1600, and 3200 mm. At the last two head settings, it became apparent that the middle of the sample tube contained an erosion resistant clay lens about ¾" thick that was preventing any enlargement of the hole. Upstream and downstream from this layer, the upper half of the specimen was largely eroded away. When the flow was stopped and the specimen removed from the test apparatus, the original pre-drilled ¼" diameter hole was found unaffected as it passed through the clay lens. Figure 5 shows several views of the specimen after the completion of the test. The material in the clay lens was very solid, while the soil on the upstream and downstream side of the lens was fully saturated and very soft. Because the hole did not enlarge, quantitative analysis of this test was not possible. Flow rate at each head setting was essentially constant, except for slight flow increases associated with the shortening of the hole due to erosion of the areas upstream and downstream from the clay lens.

Figure 4. — Photograph of HET specimen from sample tube 37Q-171 prior to erosion test.

Figure 5. — Several views of HET specimen from sample tube 37Q-171, following erosion test. Clockwise from top-left: top view through specimen tube showing clay lens left of center (flow right to left); upstream end of specimen; and downstream end of specimen.

Jet Erosion Tests

Three submerged jet erosion tests were performed on soil samples cut from the sample tubes adjacent to the HET samples. The jet erosion test is performed in the apparatus shown in Figure 6. The jet is produced through a ¼" diameter orifice. The flow impinges on the soil surface causing scour of the surface that is measured as a function of test time. The jet pressure is held constant during the test. The data are analyzed to estimate the critical shear stress needed to initiate detachment of soil particles and the detachment rate coefficient expressing the change in erosion rate per unit of additional excess stress. Results of the three tests are plotted in Figure 7, relative to erodibility classifications proposed by Hanson and Simon (2001). Two of the samples (depths 19.5 and 47.0 ft) plot very close to one another, on the margin between erodible and very erodible. The third sample (17.0 ft) plots in the very erodible range. Figure 8 shows the post-test condition of the jet test samples.

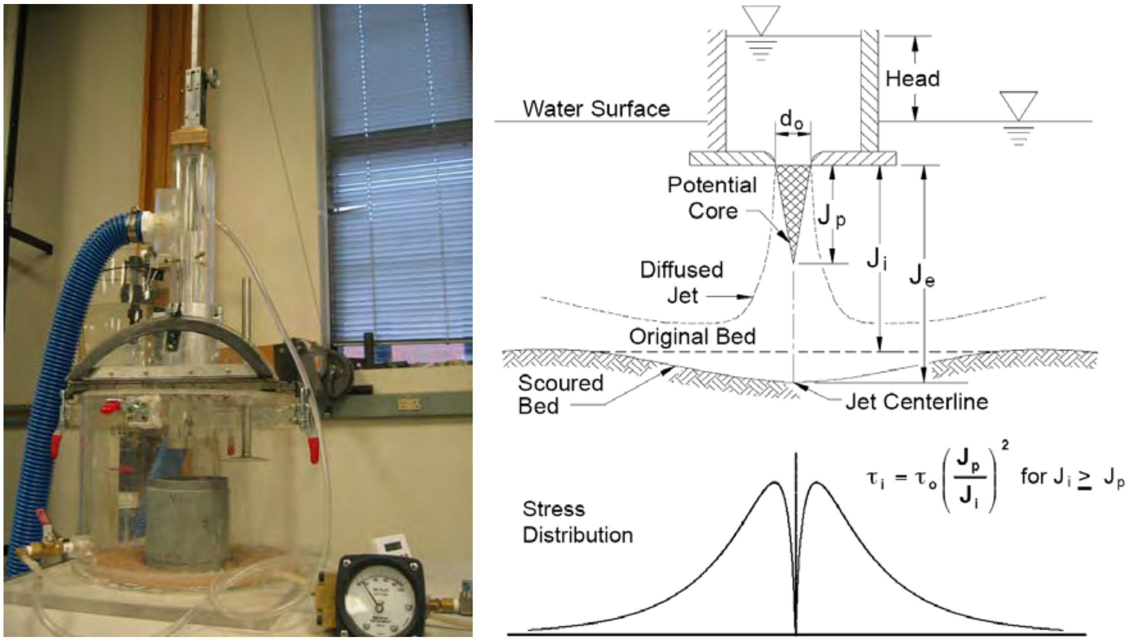


Figure 6. — Submerged jet erosion test apparatus.

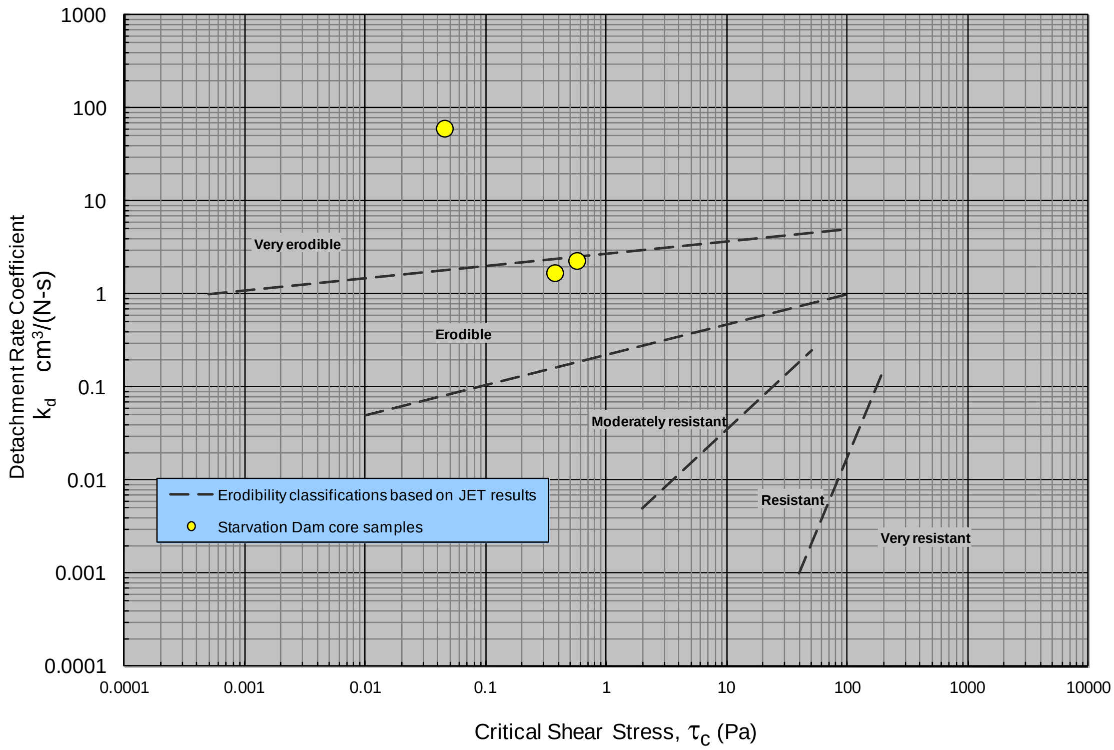


Figure 7. — JET erosion test results. Erodibility classifications are those proposed by Hanson and Simon (2001). Note unit conversions: 1 $cm^3/(N\text{-}s)$ = 0.5655 ft/hr/psf; 1 Pa = 0.0209 psf.

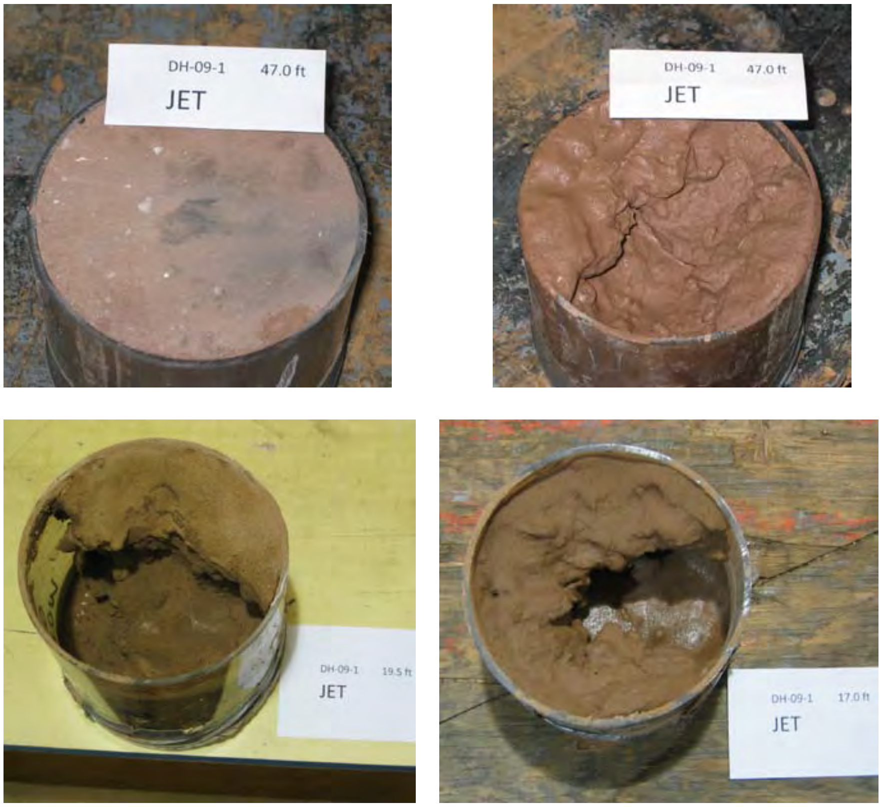


Figure 8. — Photographs of JET specimens of Starvation Dam zone 1 core material (DH-09-01), clockwise from top-left: from depth 47.0 ft, pre-test; depth 47.0 ft, post-test; depth 17.0 ft, post-test; and depth 19.5 ft, post-test.

Comparison of Erosion Test Results

Table 2 presents a summary of the erosion tests. To compare the HET and JET results, the values of the detachment rate coefficient for each test are shown. Wahl et al. (2008) showed that the hole erosion test tends to produce detachment rate coefficient values that are about 1 order of magnitude lower than values obtained from the submerged jet test. The results from the 17.0 and 19.5 ft depths are very consistent with this finding.

Table 2. — Summary of erosion test results.

Sample	I_{HET} Index*	HET k_d (ft/hr/psf)	JET k_d (ft/hr/psf)	JET category**
37Q-159, DH-09-01, depth=17.0 ft	1.8-extremely rapid	4.9	35	Very Erodible
37Q-160, DH-09-01, depth=19.5 ft	3.4-moderately rapid	0.1	0.97	Erodible to Very Erodible
37Q-171, DH-09-01, depth=47.0 ft	Did not erode due to resistant clay lens		1.3	Erodible to Very Erodible

* I_{HET} indices are: 1-extremely rapid, 2-very rapid, 3-moderately rapid, 4-moderately slow, 5-slow, 6-very slow.
** JET categories are: Very Erodible, Erodible, Moderately Resistant, Resistant, Very Resistant.

Post-Test Analysis of Zone 1 Core Sample from Depth 19.5 ft

After the erosion tests were complete, to verify similarity of the tested samples and previous analyses of the zone 1 core material, remnants of the HET and JET samples from depth range 19.0 to 20.0 ft (sample tube 37Q-160) were combined and analyzed to determine particle gradation. These particular samples were selected because their HET and JET results were in the middle of the range of the several samples tested and were believed to be most representative of the erodibility of the zone 1 core material.

The combined sample contained 51 percent sand, 49 percent fines, and was non-plastic. Based on these results, the soil classification would be SM-Silty Sand, the same as all previously tested zone 1 core samples. The gradation of this sample was very similar to the previously tested zone 1 core sample at depth 27.5 ft. Results of these gradation analysis tests are included in Appendix A.

Summary and Conclusions

Erosion tests of zone 1 core material from Starvation Dam indicated that the soil has the potential for moderately rapid to extremely rapid development of internal erosion and is erodible to very erodible under the scouring action of an impinging jet. Erosion resistant clay was present in small quantities in one sample, but is not representative of the bulk of the core. The sample of zone 3 shell material was classified as GC-Clayey Gravel with Sand. The zone 3 material could not be tested for erodibility due to the significant amount of gravel in the sample tube.

References

ASTM, 2007. Standard D-5852. Standard test method for erodibility determination of soil in the field or in the laboratory by the jet index method. *Annual Book of ASTM Standards*, Section 4: Construction, Vol. 04.08. Philadelphia, Penn.: American Society for Testing and Materials.

Bureau of Reclamation, *Earth Manual*, Part 2, 3rd Edition, Denver, CO, 1990.

Hanson, G.J., and Simon, A., 2001. Erodibility of cohesive streambeds in the loess area of the midwestern USA. *Hydrological Processes*, Vol. 15, pp. 23-38.

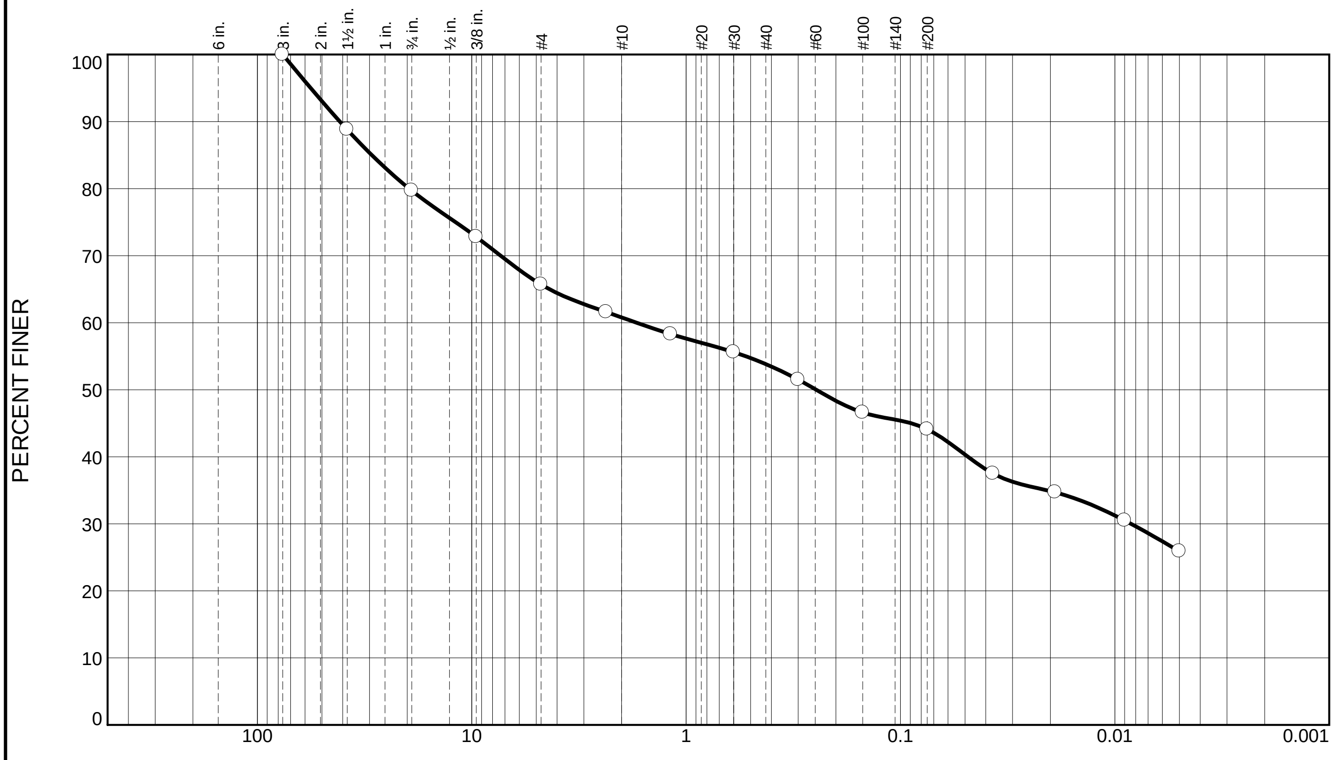
Hanson, G.J., and Cook, K.R., 2004. Apparatus, test procedures, and analytical methods to measure soil erodibility in situ. *Applied Engineering in Agriculture*, 20(4):455-462.

Wahl, Tony L.**,** Regazzoni, Pierre-Louis, and Erdogan, Zeynep, 2008. *Determining Erosion Indices of Cohesive Soils with the Hole Erosion Test and Jet Erosion Test*, Dam Safety Technology Development Report DSO-08-05, U.S. Dept. of the Interior, Bureau of Reclamation, Denver, Colorado, 45 pp. http://www.usbr.gov/pmts/hydraulics_lab/pubs/DSO/DSO-08-05.pdf

Wan, C.F., and Fell, R., 2004. Investigation of rate of erosion of soils in embankment dams. *Journal of Geotechnical and Geoenvironmental Engineering*, 130(4):373-380.

Appendix A – Soils Laboratory Reports

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	20.3	14.0	4.9	7.0	9.7	18.2	25.9

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
3	100.0		
1.5	88.8		
.75	79.7		
.375	72.8		
#4	65.7		
#8	61.6		
#16	58.3		
#30	55.6		
#50	51.5		
#100	46.6		
#200	44.1		
.037mm	37.5		
.019mm	34.7		
.009mm	30.5		
.005mm	25.9		

* (no specification provided)

Material Description

clayey gravel with sand

Atterberg Limits

PL= 14 LL= 34 PI= 20

Coefficients

D_{90}= 41.2244 D_{85}= 29.2462 D_{60}= 1.7046
D_{50}= 0.2476 D_{30}= 0.0084 D_{15}=
D_{10}= C_u= C_c=

Classification

USCS= GC AASHTO= A-6(4)

Remarks

Location: DH-09-02
Sample Number: 37Q-181 **Depth:** 29.0-30.10 **Date:** 11/16/2011

BUREAU OF RECLAMATION

Client:
Project: Cnetral Valley Project
Project No: 37Q **Figure**

Tested By: Baca **Checked By:** Strauss

GRAIN SIZE DISTRIBUTION TEST DATA

11/21/2011

Project: Cnetral Valley Project
Project Number: 37Q
Location: DH-09-02
Depth: 29.0-30.10 **Sample Number:** 37Q-181
Material Description: clayey gravel with sand
Date: 11/16/2011 **PL:** 14 **LL:** 34 **PI:** 20
USCS Classification: GC **AASHTO Classification:** A-6(4)
Tested by: Baca **Checked by:** Strauss

Sieve Test Data

Sieve Opening Size	Percent Finer
3	100.0
1.5	88.8
.75	79.7
.375	72.8
#4	65.7
#8	61.6
#16	58.3
#30	55.6
#50	51.5
#100	46.6
#200	44.1
.037mm	37.5
.019mm	34.7
.009mm	30.5
.005mm	25.9
.002MM	
.001mm	

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	20.3	14.0	34.3	4.9	7.0	9.7	21.6	18.2	25.9	44.1

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0084	0.2476	1.7046	19.5734	29.2462	41.2244	56.3935

Fineness Modulus
3.19

BUREAU OF RECLAMATION

7-1415 (10-86)
Bureau of Reclamation

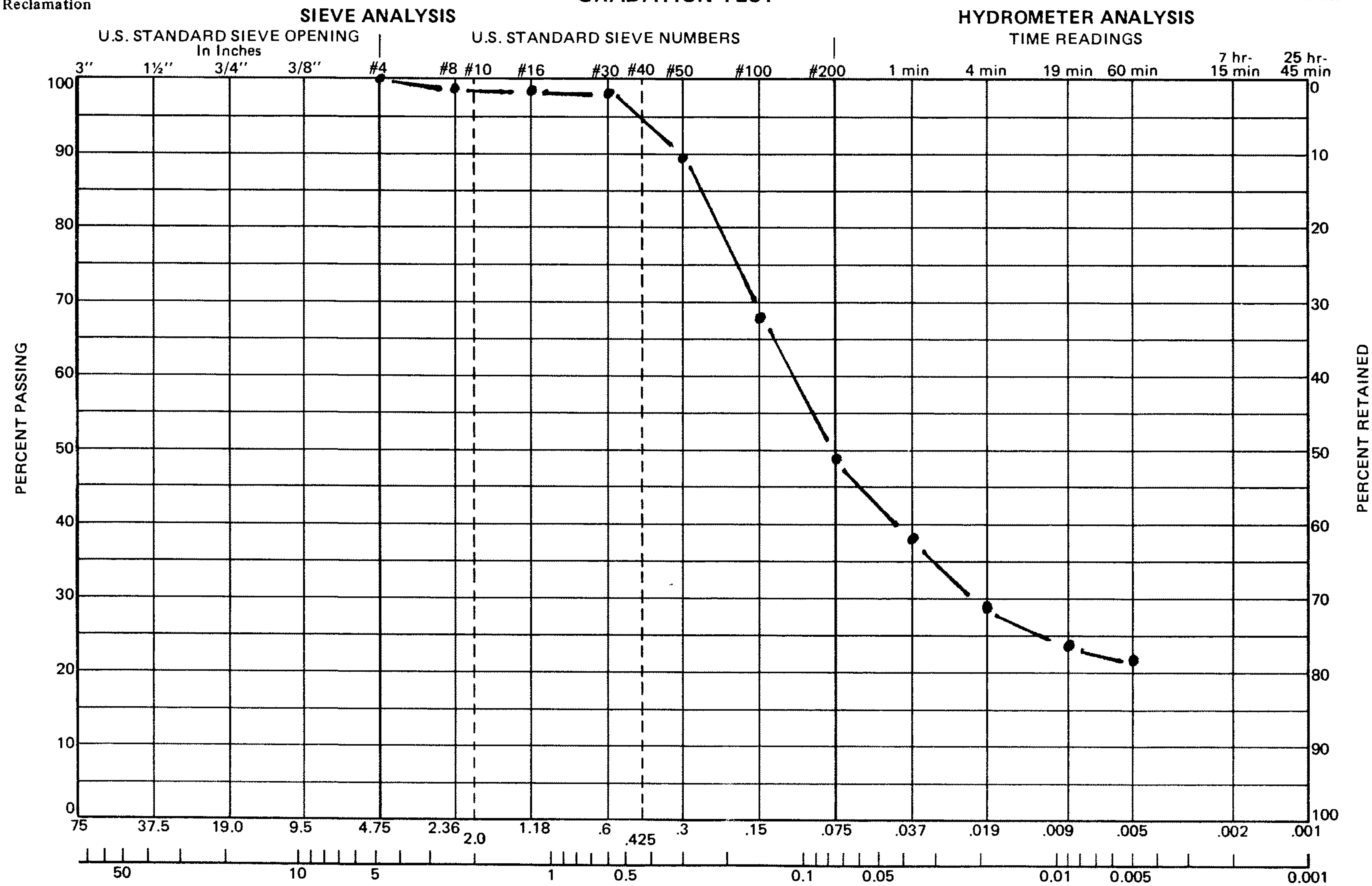
GRADATION TEST

Designation USBR ________ __ __

PREPARED BY BACA

CHECKED BY [illegible signature]

FIGURE ____



GRAVEL		SAND			FINES
COARSE	FINE	COARSE	MEDIUM	FINE	

SAMPLE NO.	HOLE NO.	ELEV. OR DEPTH ☑ft ☐m	UNIFIED SOIL CLASSIFICATION GROUP SYMBOL	% GRAVEL	% SAND	% FINES	ATTERBERG LIMITS LL (%)	PI (%)	SL (%)	SPECIFIC GRAVITY MINUS NO. 4	OTHER	NOTES
37Q-160	DH-09-01	19.0-20.0		0	51	49	N/P	N/P				Specimen from HET/JET, both Samples were combined for Gradation + Atterberg.

GPO 852-232

7-1461 (9-86)
Bureau of Reclamation

GRADATION ANALYSIS

Designation USBR 5325-___
Designation USBR 5330-___
Designation USBR 5335-___

SAMPLE NO. 37Q-160	PROJECT	FEATURE Starvation Dam
AREA HET/JET Spec's	EXC. NO. DH-09-01	DEPTH 19-20 ft Combined

GRADATION OF GRAVEL SIZES

TESTED AND COMPUTED BY	DATE	% MOISTURE CONTENT OF + NO. 4	WET MASS OF TOTAL SPECIMEN
B. Baca	12/10/11		
CHECKED BY	DATE	% MOISTURE CONTENT OF - NO. 4	TOTAL DRY MASS OF SPECIMEN 4990.8

SIEVE SIZE		3" (75 mm)	1-1/2" (37.5 mm)	3/4" (19.0 mm)	3/8" (9.5 mm)	NO. 4 (4.75 mm)	PAN
MASS OF CONTAINER AND RETAINED MATERIAL							
MASS OF CONTAINER							
WET MASS RETAINED							
DRY MASS RETAINED						0.0	
DRY MASS PASSING						4990.8	☐ lbm ☐ kg ☒ g
% OF TOTAL PASSING						100.0	

GRADATION OF SAND SIZES

DRY MASS OF SPECIMEN 89.9 g FACTOR = % TOTAL PASSING NO. 4 / DRY MASS OF SPECIMEN = 100.0 / 89.9 = 1.112 ✓

DISH NO. F1 DRY MASS OF SPECIMEN (SIEVED) 46.1

SIEVING TIME 15 min. DATE 12/13/11

SIEVE NO.	MASS RETAINED (g)	MASS PASSING (g)	FACTOR X MASS PASSING = % OF TOTAL PASSING	% OF TOTAL PASSING	PARTICLE DIAMETER	REMARKS
8	1.0	88.9		98.9	2.36 mm	Sample Dish – 133.6
16	1.5	88.4		98.3	1.18 mm	
30	2.3	87.6		97.4	600 µm	0% Gravel
50	9.6	80.3		89.3	300 µm	51% fine sand
100	29.0	60.9		67.7	150 µm	49% fines, non-plastic
200	45.8	44.1		49.0	75 µm	
PAN	46.1	TESTED AND COMPUTED BY		DATE	CHECKED BY	DATE
TOTAL	46.1	Baca		12/13/11		

HYDROMETER ANALYSIS

HYDROMETER NO. 168617 DISPERSING AGENT Sodium Hexametaphosphate

STARTING TIME 828 DATE 12/12/11 AMOUNT 4% 125 mL

TIME	TEMP °C	HYD READ	HYD CORR	CORR READ	FACTOR X CORRECT READ = % OF TOTAL PASSING	% OF TOTAL PASSING	PARTICLE DIAMETER	REMARKS
1 min	18.1	40.0	6.0	34.0		37.8	37 µm	
4 min	18.0	32.0	6.0	26.0		28.9	19 µm	
19 min	18.0	27.5	6.0	21.5		23.9	9 µm	
60 min	17.9	25.5	6.0	19.5		21.7	5 µm	AUXILIARY TESTS: USBR 5205-__ USBR 5300-__
7 h 15 min*							2 µm	
25 h 45 min*							1 µm	

TESTED AND COMPUTED BY	DATE	CHECKED BY	DATE
Baca	12/12/11	T. Wahl	12/19/11

*Not required for standard test.

GPO 853-659

7-1702 (11-85)
Bureau of Reclamation

SOIL CONSISTENCY TEST (ONE-POINT LIQUID LIMIT METHOD)

Designation USBR ______ - __ __

SAMPLE NO.	FEATURE	PROJECT
37Q-160	STARVation Dam	

Air dried ☒ Tested by Z Zacc Date 12/12/11
Oven dried ☐ Computed by ______ Date ______
Natural ☐ Checked by T Dahl Date 12/19/11

	PLASTIC LIMIT 1	PLASTIC LIMIT 2	LIQUID LIMIT 1	LIQUID LIMIT 2
Trial No.	1	2	1	2
Dish No.	108	152	S-59	
No. of blows (N)	—	—		
Mass of dish + wet soil (g)				
Mass of dish + dry soil (g)				
Mass of dish (g)	6.332	6.334	8.739	
Mass of water (g)				
Mass of dry soil (g)				
Moisture % / W_n =				
Average Plastic Limit / F_n =				
Liquid Limit				

SHRINKAGE LIMIT

1. Shrinkage Dish No.		
2. Mass of dish + wet soil (g)		
3. Mass of dish + dry soil (g)		
4. Mass of dish (g)		
5. Mass of water (2 - 3) (g)		
6. Mass of dry soil (W_o) (3 - 4) (g)		
7. % Moisture (5/6 x 100)		
8. Vol. Shrinkage Dish (V)		
9. Vol. Dry Soil (V_o)		
10. $V - V_o$ = (8 - 9)		
11. $\frac{V - V_o}{W_o} \times 100 = \left(\frac{10}{6} \times 100\right)$		
12. Shrinkage Limit (7 - 11)		
13. Shrinkage Ratio (6/9)		

$$LL = W_n \left(\frac{N}{25}\right)^{0.120}$$

$$F_n = \left(\frac{N}{25}\right)^{0.120}$$

$$LL = (F_n)(W_n)$$

N	F_n
20	0.974
21	0.979
22	0.985
23	0.990
24	0.995
25	1.000
26	1.005
27	1.009
28	1.014
29	1.018
30	1.022

PLASTICITY INDEX: PI = LL - PL

PI = ____ - ____ = ____

LIQUID LIMIT (LL) = ______
PLASTIC LIMIT (PL) = ______
PLASTICITY INDEX (PI) = ______
SHRINKAGE LIMIT (SL) = ______

This sample is non-plastic, could not Roll a Thread!

Auxiliary tests; USBR 5205 - __ __
USBR 5300 - __ __
USBR 5350 - __ __
USBR 5360 - __ __
USBR 5365 - __ __

Remarks: Specimen from composite of HET + JET Test, 19.0 - 20.0 ft.

GPO 849-227