RECLAMATION

Managing Water in the West

Measuring Erodibility of Gravelly Fine-Grained Soils

Research and Development Office
Science and Technology Program
Final Report 2014-4104

Hydraulic Laboratory Report HL-2014-05

Tony L. Wahl, P.E.

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2014

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
1. REPORT DATE September 2014	**2. REPORT TYPE** Research	**3. DATES COVERED** **October 2013 – July 2014**

4. TITLE AND SUBTITLE Measuring Erodibility of Gravelly Fine-Grained Soils	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Tony L. Wahl, P.E.	**5d. PROJECT NUMBER** 4104
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER 85-846000
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Bureau of Reclamation Hydraulic Investigations and Laboratory Services Group, 85-846000 Denver, CO 80225-0007	**8. PERFORMING ORGANIZATION REPORT NUMBER** HL-2014-05
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007	**10. SPONSOR/MONITOR'S ACRONYM(S)** R&D: Research and Development Office BOR/USBR: Bureau of Reclamation DOI: Department of the Interior
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 2014-4104

12. DISTRIBUTION / AVAILABILITY STATEMENT

This report can be downloaded from Reclamation's website: https://www.usbr.gov/research/

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 words)*

Test procedures were proposed for determining erodibility of gravelly fine-grained soils using the submerged jet erosion test method. The procedures overcome difficulties with performing the test on soils containing significant quantities of gravel or coarse sand. The study hypothesized that erodibility of a gravelly fine-grained soil can be determined by measuring the erodibility of a control fraction in which coarse particles have been removed. Tests were performed on a gravelly soil and two control fractions of that soil obtained by screening with No. 4 and No. 40 sieves. Oversize corrections were applied to adjust the compaction water content and target dry density of erosion test specimens of the control fraction soils in order to produce similar compaction states for the control fractions of each soil. Comparison of erosion test results validated the hypothesis. Although there was significant scatter among individual results, averages of multiple tests of the parent and control fraction soils were in reasonable agreement. Results were inconclusive on the question of whether it was preferable to remove coarse particles with the No. 4 or No. 40 sieve; screening at either size threshold appeared to yield reasonable results. For practicality, screening at the No. 4 sieve would be adequate and easiest to accomplish in most cases.

15. SUBJECT TERMS

Erosion, erodibility, submerged jet erosion test, embankments, dams, dam breach.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Tony L. Wahl
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	U	19	**19b. TELEPHONE NUMBER** 303-445-2155

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

Hydraulic Laboratory Report HL-2014-05

Measuring Erodibility of Gravelly Fine-Grained Soils

Digitally signed by TONY WAHL
DN: c=US, o=U.S. Government, ou=Department of the Interior, ou=Bureau of Reclamation, cn=TONY WAHL, 0.9.2342.19200300.100.1.1=14001000107789
Date: 2014.09.15 09:50:53 -06'00'

Prepared: Tony L. Wahl, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 85-846000

ROBERT EINHELLIG

Digitally signed by ROBERT EINHELLIG
DN: c=US, o=U.S. Government, ou=Department of the Interior, ou=Bureau of Reclamation, cn=ROBERT EINHELLIG, 0.9.2342.19200300.100.1.1=14001000107692
Date: 2014.09.18 09:08:53 -06'00'

Technical Approval: Robert F. Einhellig, P.E.
Manager, Hydraulic Investigations and Laboratory Services Group, 85-846000

Digitally signed by ROBERT RINEHART
DN: c=US, o=U.S. Government, ou=Department of the Interior, ou=Bureau of Reclamation, cn=ROBERT RINEHART, 0.9.2342.19200300.100.1.1=14001001522728
Date: 2014.09.15 09:56:38 -06'00'

Peer Review: Robert Rinehart, Ph. D., P.E.
Hydraulic Engineer, Flood Hydrology and Consequences Group, 85-825000

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

September 2014

Mission Statements

Disclaimer

Acknowledgments

Robert Rinehart and Bethany Jackson in the Materials Engineering Research Laboratory created the soil used for this research, performed soil properties analysis and compaction testing, computed oversize corrections, and prepared all soil erosion test specimens.

Contents

Tables

Figures

Executive Summary

Measurements of soil erodibility are important for modeling erosion that affects embankment dams, levees, canal embankments, natural streams, and earthen spillway channels. The submerged jet erosion test has proven to be very useful in this regard, but can be difficult to apply to soils containing large percentages of gravel or coarse sand. Gravel particles may be large enough to interfere with the erosion process on the scale of the ¼-inch diameter jet and in sufficient quantity can armor the scour hole during the test. A potential work-around is to conduct the test with the jet apparatus tipped on its side so that the jet is in a nearly horizontal orientation. This allows coarse particles to fall out of the scour hole immediately after they are detached, but in both lab and field environments this creates significant logistical challenges for performing the tests.

To overcome this problem, this study hypothesized that erodibility of a gravelly fine-grained soil can be determined by measuring the erodibility of a control fraction in which coarse particles that hinder the test process are removed. To test the concept, a gravelly fine-grained soil was created and the proposed test procedures were applied for evaluation. Erodibility of the parent soil (containing gravel) was evaluated with jet tests performed in the non-standard orientation. The soil was then screened to remove coarse particles, and jet tests were performed in standard orientation on specimens of the control fraction compacted in an adjusted manner to reproduce the original compaction state of the control fraction of the parent soil. The study considered whether to use either the No.4 or No. 40 sieve for removal of coarse particles.

The results validated the hypothesis. Although there was significant scatter among individual test results, averages of multiple tests of the parent and modified soils were in reasonable agreement. Results were inconclusive on the question of whether coarse particles should be removed with the No. 4 or No. 40 sieve; it appears that screening at either size threshold would yield reasonable results. For practicality, screening at the No. 4 sieve would be adequate and easiest to accomplish in most cases.

Based on this study, erodibility of a gravelly fine-grained soil encountered in the field can be determined from submerged jet erosion tests performed in the laboratory on the control fraction of that soil. To accomplish this, the in situ dry density and moisture content of the soil would be measured in the field so that laboratory compaction could be performed with the soil in a comparable moisture-density state. A sample of the soil retrieved for laboratory testing would be sieved to remove +No.4 particles. The absorption ratio of the gravel particles and the specific gravity of the coarse and fine fractions would be determined through laboratory testing, and the remaining soil would be compacted at an adjusted water content to an adjusted dry density; both adjustments would be calculated using equations provided in ASTM D4718. Submerged jet erosion tests would then be conducted on these specimens in the typical vertical jet orientation. Tests should be conducted at an applied shear stress level that is comparable to the stress that is expected to be applied to the soil in the situation of interest.

Introduction and Purpose

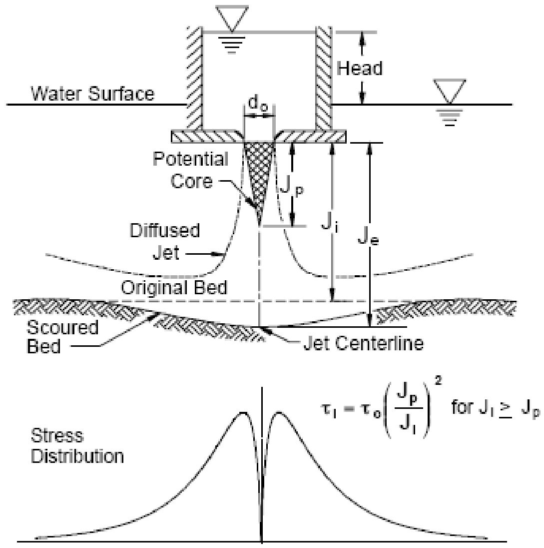
Determining erodibility of fine-grained soils enables modeling of erosion processes affecting embankment dams, levees, canal embankments, natural streams, and earthen spillway channels. A favored method in recent years has been the submerged jet erosion test (JET) developed by the Agricultural Research Service (ARS) at their Hydraulic Engineering Research Unit (HERU) in Stillwater, Oklahoma (Hanson and Cook 2004). The test is described in ASTM standard D5852, *Standard Test Method for Erodibility Determination of Soil in the Field or in the Laboratory by the Jet Index Method*. The Bureau of Reclamation hydraulics laboratory in Denver, Colorado has used a device of this type for several years (Wahl et al. 2008).

The submerged jet test simulates scour of a soil surface due to a perpendicular impinging jet. The jet is positioned above the soil surface of interest, and the depth of scour produced by the jet is recorded over time. The jet is typically produced from a ¼-inch diameter nozzle operating under a pressure of about 1 to 8 ft of head. When the test is applied to predominately fine-grained soils that include a significant fraction of coarse sand or gravel, the strength of the jet is often too low to either detach the coarse particles or transport them out of the scour hole. This can lead to armoring of the scour hole by coarse particles. The threshold amount of coarse particles needed to create this problem is not well defined. One potential solution to the problem is to run the test with the entire apparatus tipped up on its side so that the jet is in a nearly horizontal orientation. This allows the coarse particles to fall out of the scour hole immediately after they are detached, but in both lab and field environments it creates significant logistical challenges for performing the tests.

This report presents research performed to evaluate an alternative approach to determining erodibility of fine-grained soils containing significant amounts of gravel or coarse sand (referred to hereafter as gravelly fine-grained soils). The hypothesis for this study is that the erodibility of a gravelly fine-grained soil will be primarily controlled by the erodibility of a finer-grained control fraction (i.e., the fraction of the soil that passes a pre-determined sieve size), so soil specimens could potentially be screened to eliminate the coarse fraction and jet tests could then be carried out on specimens with the modified gradation, compacted in an adjusted manner to reproduce the original compaction state of the finer-grained fraction of the parent soil. This research study tested the validity of this hypothesis and attempted to define the best methods for screening to eliminate the coarse material that impedes testing of the parent soil.

Background

Figure 1 shows a schematic diagram of the submerged jet erosion test and an accompanying photo of the laboratory apparatus constructed by the Bureau of Reclamation from plans provided by Greg Hanson, USDA-ARS (retired). ASTM standard D5852 describes the test, although data analysis methods have evolved since publication of the standard. Data from the tests described in this report were analyzed using the methods described in Hanson and Cook (2004). Recently, other analysis procedures have also been proposed (e.g., Daley, et al. 2013).



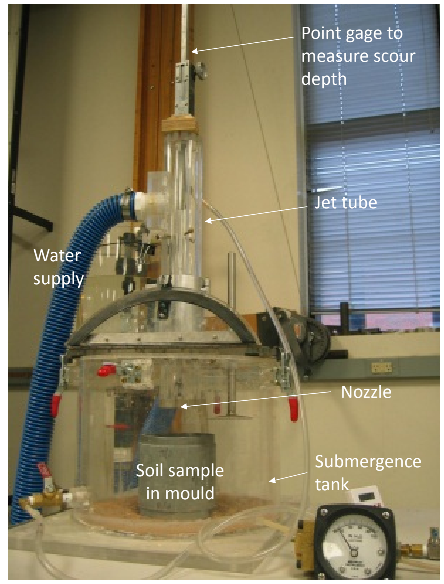


Figure 1. — Jet test schematic diagram and photo of laboratory test apparatus.

The test is typically run with a constant jet pressure that can be adjusted prior to each test. The jet is positioned over the soil surface of interest, and the initial elevation of the jet and the jet pressure are selected to apply a desired shear stress to the soil specimen. The depth of scour beneath the jet is measured over time and the recorded data are used to estimate the critical shear stress needed to initiate erosion and the detachment rate coefficient relating the rate of erosion to the applied stress in excess of the critical value. The analysis is based on a volumetric form of the excess stress erosion model:

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

where $\dot{\varepsilon}$ is the volume of material removed per unit surface area per unit time ($m^3/s/m^2$, or m/s), k_d is a detachment rate coefficient, τ is the applied stress (N/m^2=Pa), and τ_c is the critical shear stress (N/m^2=Pa). Typical units for k_d are $m^3/(N{\cdot}s)$ or $cm^3/(N{\cdot}s)$, or in U.S. customary units, $ft/hr/lb/ft^2$ [$1\ cm^3/(N{\cdot}s) = 0.5655\ ft/hr/lb/ft^2 = 10^{-6}\ m^3/(N{\cdot}s)$].

The excess stress erosion model presumes that the relation between erosion rate and excess stress is linear, but this may not always be the case. For this reason, it is always desirable to perform tests at an applied shear stress level that is comparable to the stress that is expected to be applied to the soil in the situation of interest. This can be accomplished by adjusting the jet pressure and the initial distance between the nozzle and the soil surface.

Theory

The hypothesis for this study is that the erodibility of a gravelly fine-grained soil will be controlled by the erodibility of the finer portion of the soil, which will be described as a control fraction, primarily made up of sand, silt and clay particles. To determine the erodibility of a gravelly soil, it is proposed to separate the specimen into finer and coarser fractions and to then perform submerged erosion jet testing on compacted specimens of the finer control fraction. Compaction of the finer-grained material should be adjusted so that the compaction state of the specimen is similar to the compaction state of the finer-grained material contained in the original gravelly soil specimen.

The ideal break point for separating the coarse and fine soil fractions is not obvious. Two potential options are the No. 4 and No. 40 U.S. Standard sieve sizes (4.76 mm and 0.42 mm, respectively). The No. 4 sieve removes all gravel-sized particles and would yield a sample containing only sand-size particles, silt, and clay. Samples passing the No. 4 sieve are typically used for compaction testing (ASTM D698, ASTM D1557). The No. 40 sieve removes all gravel, coarse and medium sand, yielding a sample that contains only fine sand, silt and clay. Samples finer than the No. 40 sieve are used for determination of the Atterberg limits that indicate soil plasticity properties (ASTM D4318). Previous work (Hanson et al. 2010) has related soil erodibility parameters to clay content, so it could be expected that erodibility parameters might correlate well with plasticity characteristics. Thus, a sample based on the minus No. 40 fraction might provide the most useful indication of erodibility characteristics. A practical consideration is that separating with the No. 40 sieve cannot readily be accomplished with moist soil and requires significantly greater effort to break down the soil specimen prior to sieving, particularly for the large specimen size required for the JET test.

Soil and Test Specimen Preparation

A test soil was created for the research by combining two soils already present in the laboratory to create soil 36B-X91. The coarse gravel fraction (larger than ¾" sieve) was then removed, producing soil 36B-X92. According to the Unified Soil Classification System (USCS), the soil type was SC – Clayey Sand. The makeup of the soil was 47 percent fines, 39 percent sand, and 14 percent fine gravel. Atterberg limits were also determined, and the soil was plastic with liquid limit LL=39, plastic limit PL=17, and plasticity index PI=22. Specific gravities for the minus No. 40 and minus No. 4 fractions were determined, as well as the bulk specific gravity of the No. 4 to ¾" fraction in a saturated surface dry (SSD) condition. The absorption ratio for the gravel was determined to be 2.9% and the absorption ratio of the medium and coarse sand particles (+ No. 40 material) was assumed to be the same. Detailed test results are presented in the Appendix.

A standard Proctor compaction test (ASTM D698, Method C) was performed on soil 36B-X92, which will hereafter be described as the *parent soil*. Optimum water content was determined to be 12.2%, and the maximum dry unit weight was 115.6 lb/ft^3. A submerged jet erosion test was performed on each of the five compaction test specimens (in 6-inch diameter moulds), with the test apparatus oriented so that the jet was approximately horizontal and the soil surface was approximately vertical (Figure 2). Test results are shown in Table 1. These tests are somewhat more difficult to conduct than tests in the more typical orientation (vertical jet) because the sample must be securely fastened into the submergence tank, drainage from the test is difficult to confine, and the deflector plate that blocks the jet while scour depths are being measured was not designed to operate well in this orientation. For relatively erosion resistant soils the pattern of scour caused by the jet is similar in this orientation to the vertical jet, but for very erodible soils, accelerated erosion of the top side of the scour hole can occur because gravity contributes to instability of the soil above the impinging jet. This can lead to an asymmetric scour hole shape that may contribute to accelerated erosion at the jet centerline where scour depth measurements are made (Figure 3).

Figure 2. — Submerged jet erosion test performed with the jet in a horizontal orientation.

Table 1. — Submerged jet erosion test results from compaction test specimens.

Compaction state		**Erodibility**	
Dry density lb/ft^3	**Water content %**	**k_d ft/hr/lb/ft^2**	**τ_c lb/ft^2**
109.4	7.2	30.1	0.000953
113.4	8.9	7.38	0.00269
115.5	10.4	0.295	0.0594
114.5	12.9	0.17	0.1043
113.8	15.3	0.069	0.604

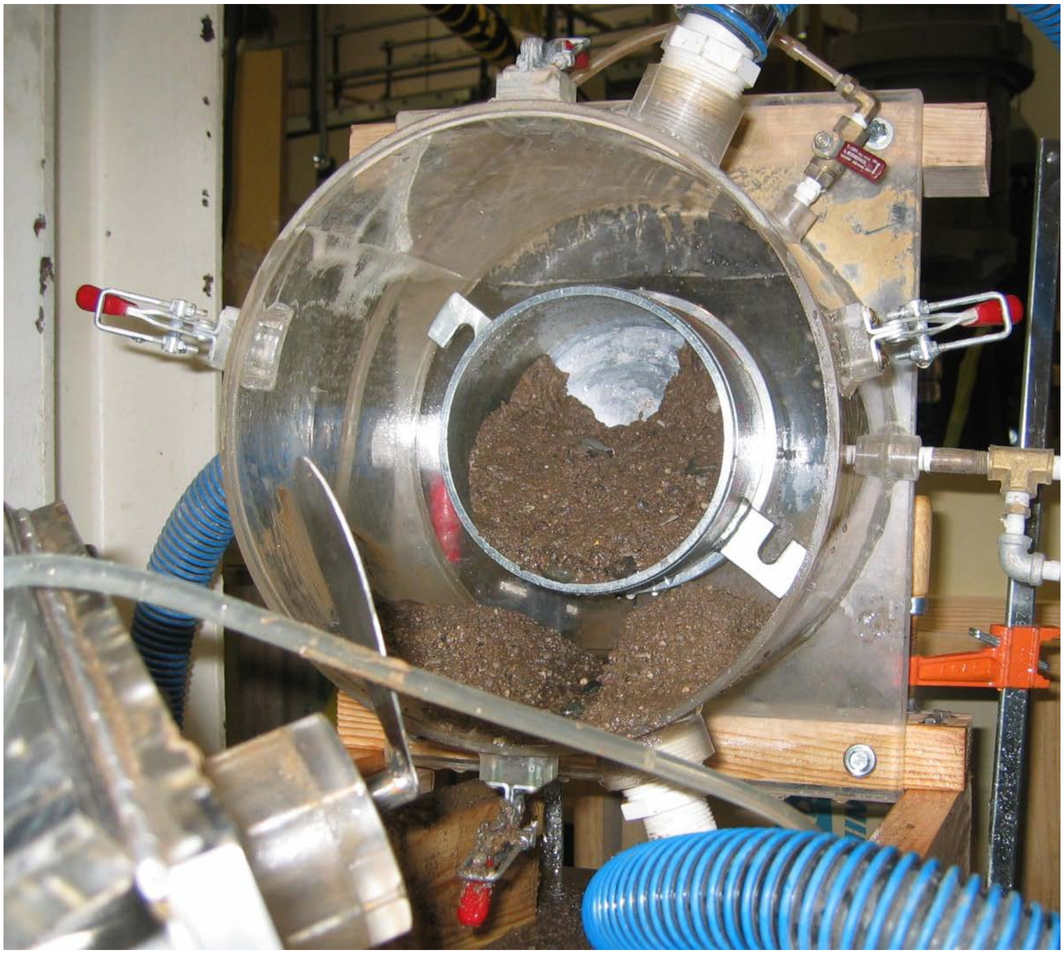


Figure 3. — Asymmetric development of the scour hole in a test of a weak soil with horizontal jet orientation.

After testing of the compaction specimens was complete, the remaining soil was then split into three portions to be used for erosion tests of the parent soil, the –No. 4 fraction, and the –No. 40 fraction. Three test cylinders for each soil fraction were hand-compacted with the objective of achieving compaction equivalent to 95% of standard Proctor maximum density. For the cylinders prepared from the finer soil fractions, water contents and target densities were adjusted so that compaction of the finer-grained soils would be equivalent to the computed dry densities of the matching finer-grained fraction when the parent soil was compacted to 95% of maximum density.

The adjusted water contents and dry densities were computed using equations given in ASTM D4718, *Standard Practice for Correction of Unit Weight and Water Content for Soils Containing Oversize Particles*. The adjustments are based upon three assumptions:

- the coarse-grained particles (oversize material) being excluded (either +No. 4 or +No. 40 material) are floating in a matrix of the finer particles, with all voids between the coarse particles filled by the finer soil, or stated in another way, there is no interference between the coarse-grained particles that affects the compacted unit weight of the finer fraction;

- the coarse-grained particles are internally saturated (saturated, surface dry = SSD) during compaction; and

- the coarse sand and medium sand particles in soil 36B-X92 have the same absorption ratio as the fine gravel particles.

ASTM D4718 states:

> "This practice is based on tests performed on soils and soil-rock mixtures in which the portion considered oversize is that fraction of the material retained on the No. 4 sieve. Based on these tests, this practice is applicable to soils and soil-rock mixtures in which up to 40% of the material is retained on the No. 4 sieve. The practice also is considered valid when the oversize fraction is that portion retained on some other sieve, such as the 3/4-in. sieve, but the limiting percentage of oversize particles for which the correction is valid may be lower. However, the practice is considered valid for materials having up to 30% oversize particles when the oversize fraction is that portion retained on the 3/4-in. sieve."

Since the limiting percentage of oversize particles is believed to decrease with an increase in the size of the oversize material, it can be inferred that when the oversize particle division point is finer than the No. 4 sieve, the maximum amount of oversize particles should increase to something greater than 40%. In the case of soil 36B-X92, the percentage of particles retained on the No. 4 sieve is only 14 percent and the percentage retained on the No. 40 sieve is 33 percent. Thus, the practice described in ASTM D4718 should be applicable when we choose either the No. 4 or No. 40 sieve to define oversize particles.

The equations used to compute the water content and dry unit weights are:

$$w_F = \frac{(100w - w_C P_C)}{P_F}$$

$$\gamma_{d,F} = \frac{\gamma_d G_C \gamma_w P_F}{100(G_C \gamma_w) - \gamma_d P_C}$$

where:

w_F = water content of control fraction, (F = finer fraction in this application)
w_C = water content of oversize (coarse) fraction, (C=coarse)
w = water content of total sample,
$\gamma_{d,F}$ = dry unit weight of control fraction,
γ_d = dry unit weight of total sample,
γ_w = unit weight of water,
G_C = bulk specific gravity of coarse fraction,
P_F = percent of control fraction by weight,
P_C = percent of coarse fraction by weight.

The equations above can be derived from relations that compute the water content and dry unit volume (volume per unit weight) of the total sample as the weighted average of the associated quantities for the fine and coarse fractions. To apply the equations to this soil, the water content of the coarse fraction was assumed to be the absorption ratio (2.9%), and the bulk specific gravity was calculated as a weighted average of the specific gravities determined for the gravel and sand fractions represented in the oversize component. Table 2 shows the computed target water contents and dry densities for each series of erosion test specimens. The objective was to conduct each series of tests with the finer-grained control fraction soil compacted to the same state that would occur if the parent soil were compacted to 95% of standard Proctor maximum density. The table also shows the actual water content and dry densities achieved for each specimen. Densities were within about 1% of the target values and water contents were within 0.3%.

Table 2. — Hand-compacted soil specimens for jet erosion testing.

	Target compaction state		Actual compaction and comparison to target value	
Specimen Description	**Dry density, lb/ft^3**	**Water content, %**	**Dry density, lb/ft^3**	**Water content, %**
Parent soil	109.8 (95% of 115.6)	12.2	109.7 (-0.1)	12.0 (-0.2)
			109.7 (-0.1)	11.9 (-0.3)
			110.4 (+0.6)	12.1 (-0.1)
–No. 4	104.3	13.7	104.7 (+0.4)	13.4 (-0.3)
			104.7 (+0.4)	
			104.7 (+0.4)	
–No. 40	94.3	16.8	95.3 (+1.0)	16.7 (-0.1)
			95.3 (+1.0)	
			95.3 (+1.0)	

Erosion Testing and Analysis

Submerged jet erosion tests were conducted on the three hand-compacted specimens of the parent soil (in 6-inch moulds) with the soil surface nearly vertical, permitting gravel to fall out of the scour hole as erosion occurred. The –No. 4 and –No. 40 specimens in 4-inch moulds were tested in the traditional orientation, with the soil surface horizontal and the jet impinging vertically down on the soil surface. Two of the –No. 40 specimens were tested twice, once on the top surface of the specimen and a second time with the specimen inverted. Table 3 shows the jet erosion test results.

Figure 4 shows the results plotted in relation to erodibility categories proposed by Hanson and Simon (2001). These categories span the range of erodibilities observed in a study of natural cohesive streambed deposits in loess areas of eastern Nebraska, western Iowa, and northern Mississippi. They also represent typical ranges of erodibility measured in compacted soils used in civil engineering infrastructure, such as dams and levees (Wahl et al. 2008; Hanson et al. 2010). Five erodibility classes are recognized: very resistant, resistant, moderately resistant, erodible, and very erodible. Hanson and Simon (2001) also proposed a relation between the detachment rate coefficient and the critical shear stress, and this relation is shown on the figure. (Subsequent researchers have proposed other relationships in recent years).

Table 3. — Submerged jet erosion test results.

<table>
<tr><th rowspan="2">Specimen Description</th><th colspan="2">Compaction state</th><th colspan="2">Erodibility</th></tr>
<tr><th>Dry density lb/ft^3</th><th>Water content %</th><th>k_d ft/hr/lb/ft^2</th><th>τ_c lb/ft^2</th></tr>
<tr><td rowspan="3">Parent soil, hand-compacted to 95%</td><td>109.7</td><td>12.0</td><td>0.088</td><td>0.299</td></tr>
<tr><td>109.7</td><td>11.9</td><td>2.485</td><td>0.072</td></tr>
<tr><td>110.4</td><td>12.1</td><td>1.152</td><td>0.010</td></tr>
<tr><td rowspan="2">Parent soil from compaction test (approx. 99-100% density)</td><td>115.5</td><td>10.4</td><td>0.295</td><td>0.0594</td></tr>
<tr><td>114.5</td><td>12.9</td><td>0.17</td><td>0.1043</td></tr>
<tr><td rowspan="3">–No. 4, hand-compacted</td><td>104.7</td><td rowspan="3">13.4</td><td>0.202</td><td>0.110</td></tr>
<tr><td>104.7</td><td>0.246</td><td>0.058</td></tr>
<tr><td>104.7</td><td>0.253</td><td>0.125</td></tr>
<tr><td rowspan="5">–No. 40, hand-compacted</td><td>95.3</td><td rowspan="5">16.7</td><td>0.827</td><td>0.012</td></tr>
<tr><td rowspan="2">95.3</td><td>0.027</td><td>0.340</td></tr>
<tr><td>0.136</td><td>0.070</td></tr>
<tr><td rowspan="2">95.3</td><td>0.262</td><td>0.291</td></tr>
<tr><td>0.005</td><td>0.298</td></tr>
</table>

Figure 4 shows that there is large variability of the erosion test results, between and even within the test series. Results for the –No. 4 tests are tightly clustered, but the –No. 40 tests exhibit detachment rate coefficients that vary more than ±1 order of magnitude and the tests on the parent soil also vary by about ±0.75 orders of magnitude. Considered together, the nine tests on hand-compacted specimens exhibit detachment rate coefficients that vary by ±1.5 orders of magnitude. Erodibility rates are expected to exhibit order-of-magnitude variation, so the range observed here is noticeably large, but not extreme. The range of critical shear stress values is about ±0.75 orders of magnitude. This is somewhat unusual, as the variability of the critical shear stress is often greater than the variability of the detachment rate coefficient.

To reduce the impact of variability on interpretation of the results, averages of the data from each test series were computed, and these are also shown in Figure 4. Results for two of the compaction test specimens bracketing the optimum water content value are also included. These 5 data points cluster tightly together. The –No. 4 and –No. 40 soils exhibit slightly more erosion resistance on average than the parent soil; this is consistent with the slight overcompaction of those test specimens that was shown in Table 2.

Unintentionally, there was significant delay between the time of specimen compaction and erosion testing for some specimens, and even though the specimens were sealed to prevent moisture loss, this may have had an impact on the results. Figure 5 shows the detachment rate coefficients plotted versus the number of days of sample curing that took place prior to testing. There is a suggestion of a trend toward greater erosion resistance as curing time increases, although there is also greater variability in the results from those specimens that cured for a long period of time.

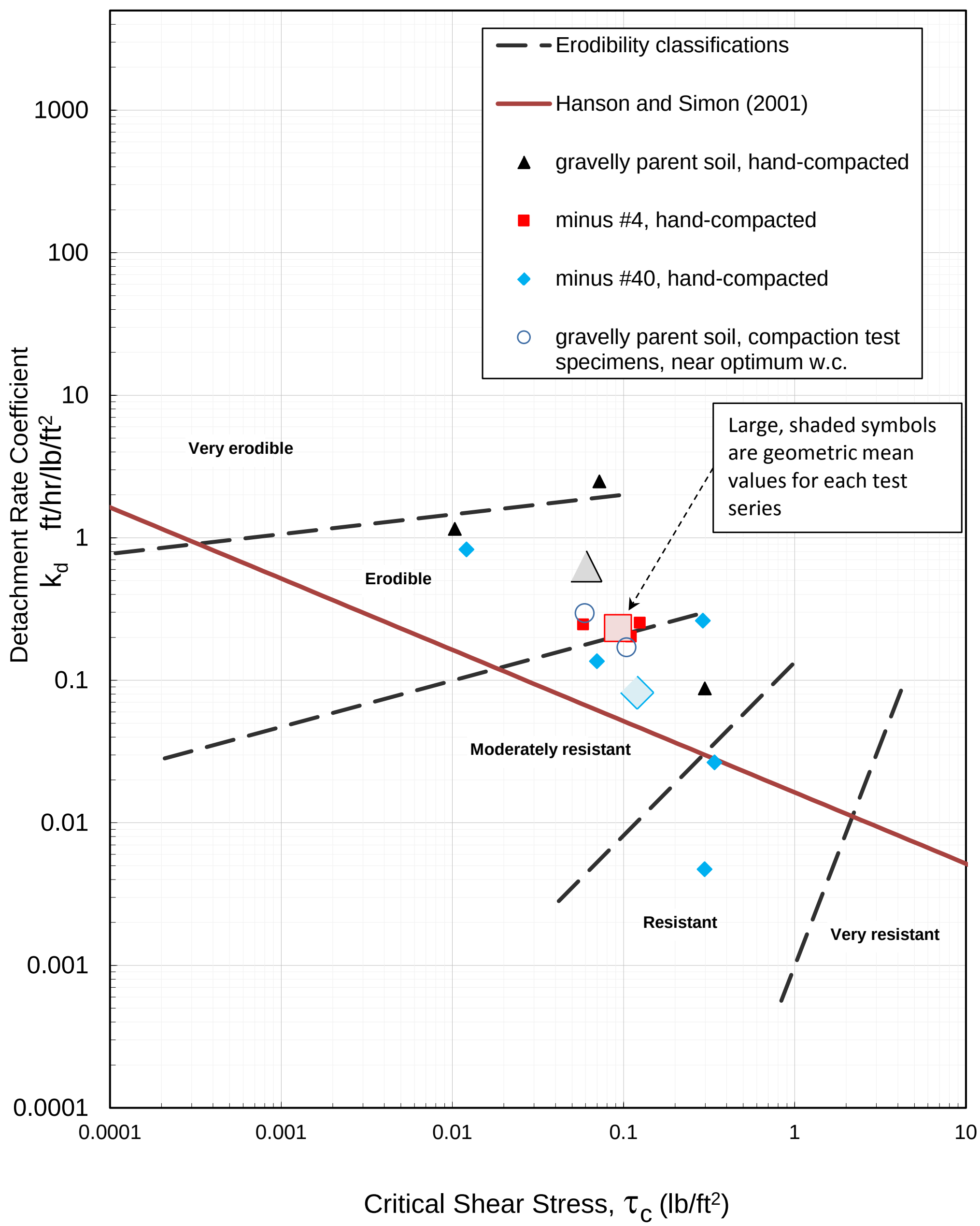


Figure 4. — Erodibility test results.

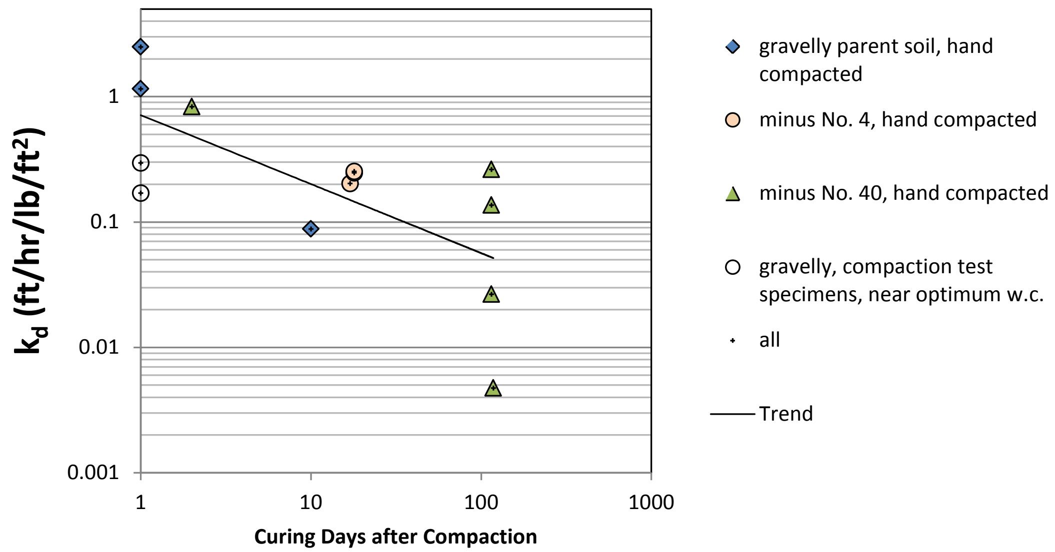


Figure 5. — Jet erodibility test results versus specimen curing time after compaction.

Conclusions

This research study tested the hypothesis that the erodibility of a gravelly fine-grained soil could be determined by evaluating the erodibility of a finer-grained control fraction. Specimens of the parent material and two different finer-grained derivative soils were evaluated with submerged jet erosion tests, and the results appear to validate the hypothesis. Although there was significant scatter among individual test results, averages of detachment rate coefficients and critical shear stresses from multiple tests of the parent and derivative soils plotted within ±0.5 orders of magnitude of a central value. The testing also sought to determine whether the gravelly sample should be screened at the No. 4 or No. 40 sieve, but the results were inconclusive on this question. It appears that screening at either size threshold would yield reasonable results. For practicality, screening at the No. 4 sieve would be adequate and easiest to accomplish in most cases.

Considering the inherent variability of soil erodibility and the fact that all important parameters could not be fully controlled in this study, further testing is recommended to confirm the findings of this study. Future research could evaluate additional soils, including soils that push the limits for applicability of the water content and density correction formulas given in ASTM D4718. Future testing could also evaluate the effects of curing time and control the curing time in order to limit its potential effects on erosion test results.

A typical application scenario for this research is a situation in which one needs to evaluate the erodibility of a gravelly soil encountered in the field. To accomplish this, the in situ dry density of the soil and water content would be measured in the field, perhaps using a sand cone test or nuclear density gauge. If the soil was mechanically compacted, an estimate of the water content at the time of compaction could be made, if it is believed to differ from the in situ water content. A sample of the soil would then be obtained for laboratory testing. The soil sample would be sieved to remove +No.4 particles and the remaining soil would be used to create erosion test specimens. The absorption ratio of the gravel particles and the specific gravity of the coarse and fine fractions would be determined through laboratory testing. The adjusted dry density and water content for the –No. 4 soil would be calculated using the equations from ASTM D4718, and specimens would then be hand-compacted at the appropriate water content to achieve the desired dry density. Submerged jet erosion tests could then be conducted on these specimens in the typical vertical jet orientation. Tests should be conducted at an applied shear stress level that is comparable to the stress that is expected to be applied to the soil in the situation of interest.

References

ASTM Standard D5852, 2007. Standard test method for erodibility determination of soil in the field or in the laboratory by the jet index method. American Society for Testing and Materials.

ASTM Standard D4718, 2007. Standard practice for correction of unit weight and water content for soils containing oversize particles. American Society for Testing and Materials.

ASTM Standard D698, 2007. Standard test methods for laboratory compaction characteristics of soil using standard effort. American Society for Testing and Materials.

ASTM Standard D1557, 2009. Standard test methods for laboratory compaction characteristics of soil using modified effort. American Society for Testing and Materials.

ASTM Standard D4318, 2010. 10 standard test methods for liquid limit, plastic limit, and plasticity index of soils. American Society for Testing and Materials.

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

Daley, E.R., G.A. Fox, A.T. Al-Madhhachi, and R.B. Miller, 2013. A scour depth approach for deriving erodibility parameters from jet erosion tests. *Transactions of the ASABE*, 56(6): 1343-1351 ISSN 2151-0032 DOI 10.13031/trans.56.10350

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.

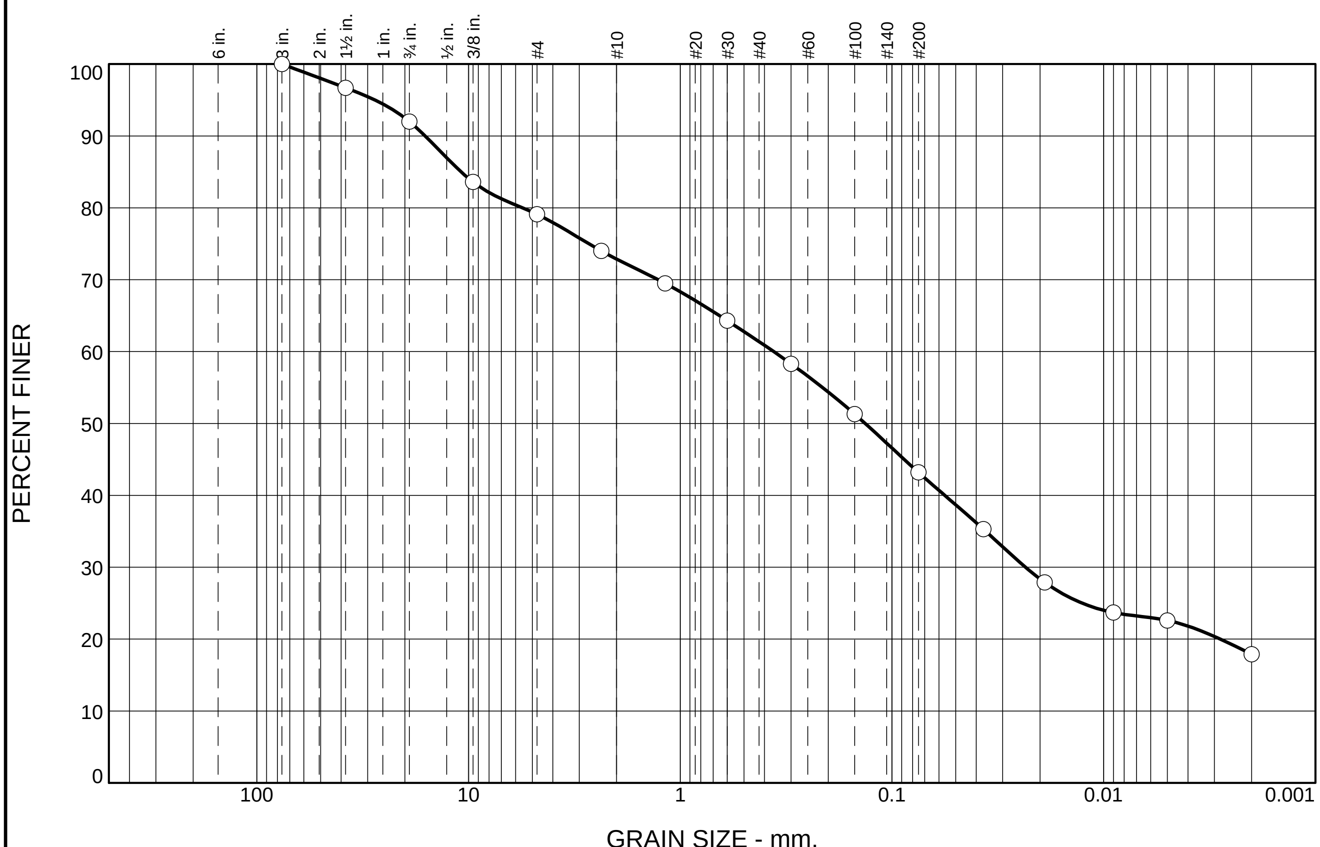
Hanson, G.J., and Cook, K.R., 2004. Apparatus, test procedures, and analytical methods to measure soil erodibility in situ. *Applied Engineering in Agriculture*, 20(4):455-462.

Hanson, G.J., T.L. Wahl, D.M. Temple, S.L. Hunt, and R.D. Tejral, 2010. Erodibility characteristics of embankment materials. In: *Dam Safety 2010*. Proceedings of the Association of State Dam Safety Officials Annual Conference, September 19-23, 2010, Seattle, WA. (CDROM).

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.

Appendix A: Soil Test Reports

Particle Size Distribution Report



% Cobbles	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0	8	13	6	12	18	20	23

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
3"	100		
1-1/2"	97		
3/4"	92		
3/8"	84		
#4	79		
#8	74		
#16	70		
#30	64		
#50	58		
#100	51		
#200	43		
0.037mm	35		
0.019mm	28		
0.009mm	24		
0.005mm	23		
0.002mm	18		

* (no specification provided)

Material Description

(SC)g - Clayey Sand with Gravel

Atterberg Limits

PL= 17 LL= 39 PI= 22

Coefficients

D_{90}= 16.0434 D_{85}= 10.8401 D_{60}= 0.3621
D_{50}= 0.1338 D_{30}= 0.0234 D_{15}=
D_{10}= C_u= C_c=

Classification

USCS= SC AASHTO= A-6(5)

Remarks

SpG -#4 = 2.68
SpG -#40 = 2.67
Bulk SpG (SSD) #4 - 3/4" = 2.60

Sample Number: 36B-X91

Date: 9/4/2013

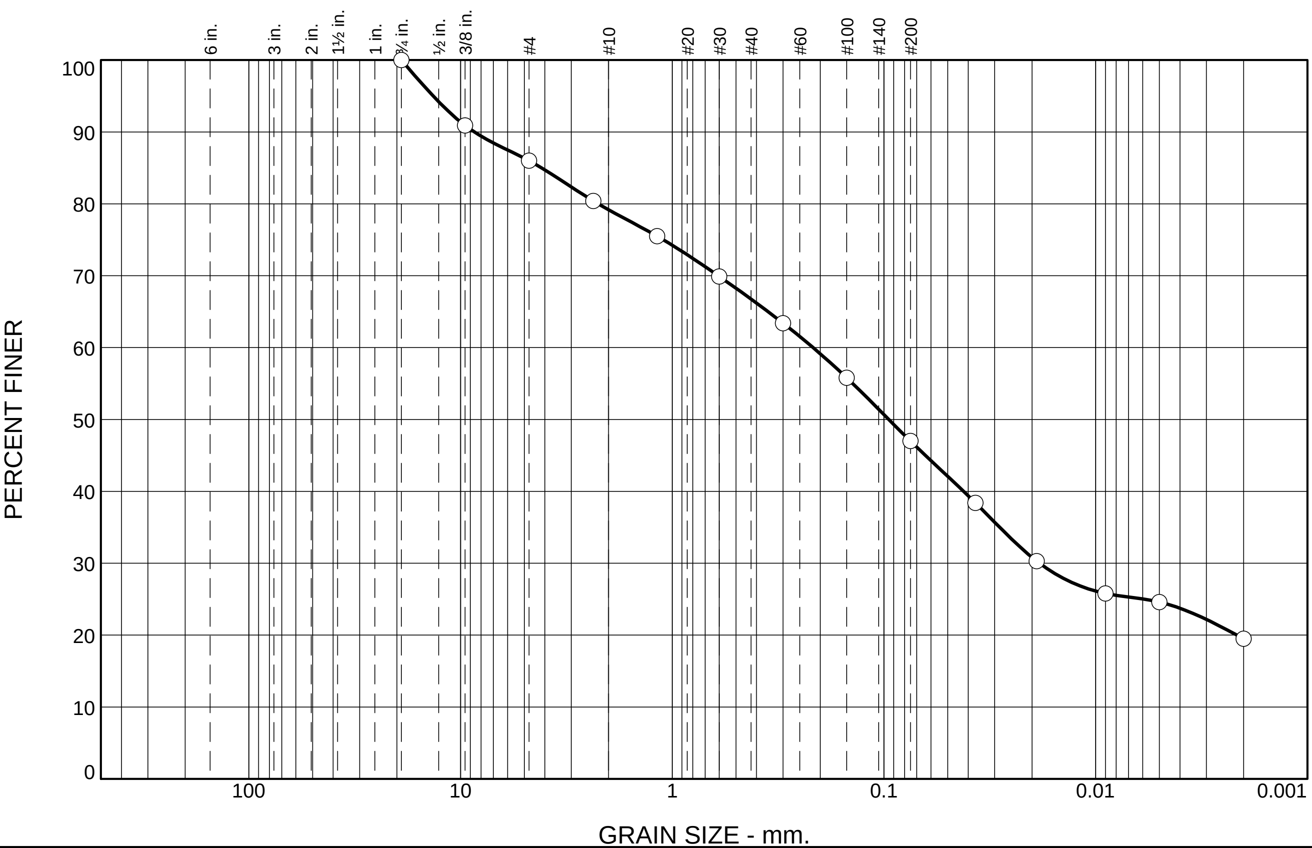
BUREAU OF RECLAMATION

Client:
Project: Colorado River Storage Project - Blue Mesa Dam

Project No: 36B **Figure**

Tested By: BNJ/RVR **Checked By:** RVR

Particle Size Distribution Report



% Cobbles	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0	0	14	7	12	20	22	25

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
3/4"	100		
3/8"	91		
#4	86		
#8	80		
#16	76		
#30	70		
#50	63		
#100	56		
#200	47		
0.037mm	38		
0.019mm	30		
0.009mm	26		
0.005mm	25		
0.002mm	20		

* (no specification provided)

Material Description

SC - clayey Sand
composite sample 36B-X91 with coarse gravel (+3/4") removed

Atterberg Limits

PL= 17 LL= 39 PI= 22

Coefficients

D_{90}= 8.6183 D_{85}= 4.1458 D_{60}= 0.2164
D_{50}= 0.0950 D_{30}= 0.0184 D_{15}=
D_{10}= C_u= C_c=

Classification

USCS= SC AASHTO= A-6(6)

Remarks

Coarse gravel removed
*gradation calculated from 36B-X91 test results

Sample Number: 36B-X92

Date:

BUREAU OF RECLAMATION

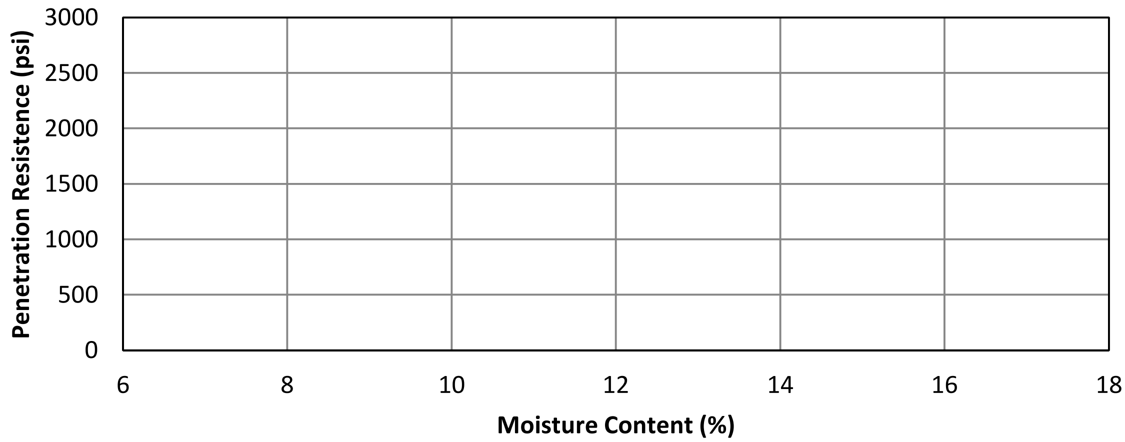
Client:
Project: Colorado River Storage Project - Blue Mesa Dam

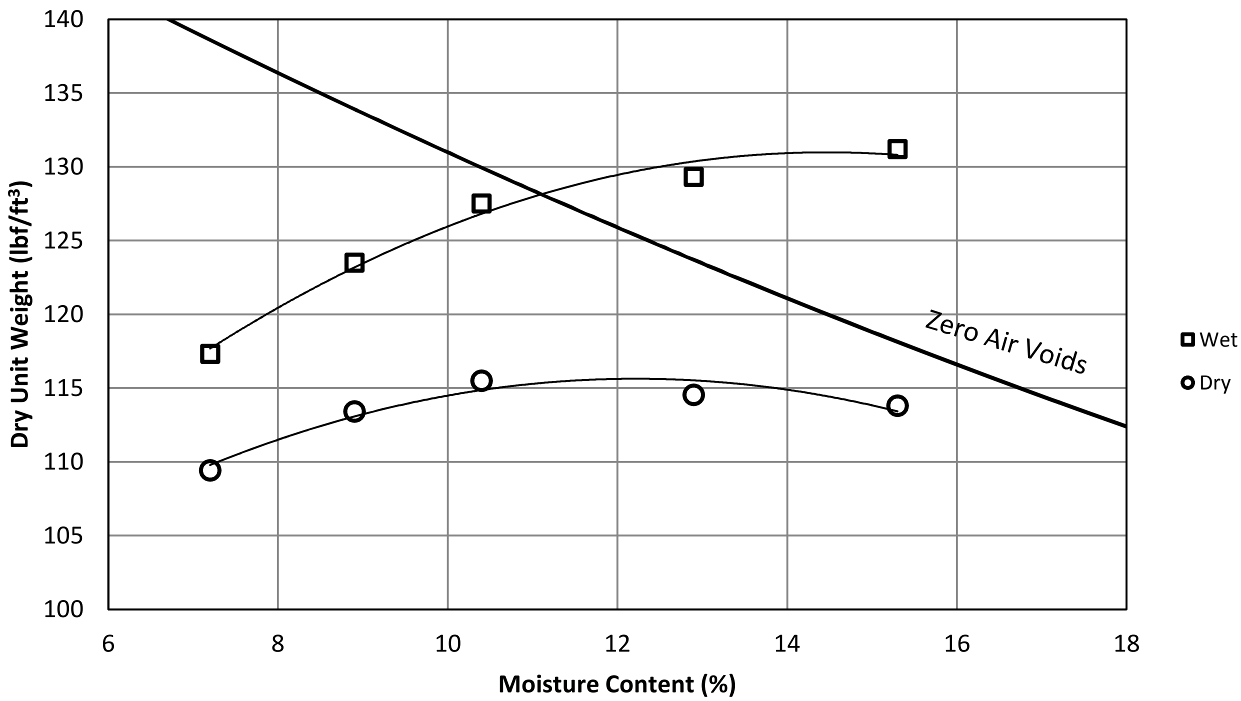
Project No: 36B **Figure**

Tested By: ____________ **Checked By:** RVR

Laboratory Compaction Test

Blows per Layer	56			**Date**	25-Sep-13
No. of Layers	3	**Mass of tamping rod (lb)**	5.5		
Height of drop (in)	12	**Volume of Mold (ft^3)**	0.0750		





Project	Jet Test Research	**<u>Specific Gravity</u>**		**<u>Compaction</u>**	
Feature	Parent material	**Minus No. 4**	2.68	**Percent larger than tested**	0.0
Location	NA	**Plus No. 4 (Bulk SSD)**	2.60	**Maximum Dry Unit Weight (lb/ft^3)**	115.6
Depth (ft)	NA	**Absorption (%)**	2.90	**Optimum Moisture Content (%)**	12.2
Sample No.	36B-X92			**Degree of saturation @ opt (%)**	73.9
				Penetration resistence @ opt (psi)	NA

Classification	SC	**<u>Atterberg Limits</u>**			
Gravel (%)	14	**Liquid Limit**	39	**Remarks:**	ASTM D698, Method C
Sand (%)	39	**Plasticity Index**	22		
Fines(%)	47	**Shrinkage Limit**	NA		

Tested By: BNJ

Checked By: RVR

JET Research - Oversize Corrections According to ASTM D4718

Fraction	%	SpG	Abs (%)
Gravel	14	2.60	2.9
Coarse Sand	7	2.68	2.9
Med Sand	12		2.9
Fine Sand	20		-
Fines	47		-

Total Sample (reflects 95% Proctor @ opt.)

$\gamma_{d,\ total}$	109.8	pcf
w_{total}	12.2	%

-#4 Material (calculated)

w_c	2.9	%
G_c	2.60	-
$\gamma_{d,\ -\#4}$	104.3	pcf
$w_{-\#4}$	13.7	%

-#40 Material (calculated)

w_c	2.9	%
G_c	2.64	-
$\gamma_{d,\ -\#40}$	94.3	pcf
$w_{-\#40}$	16.8	%

Assumptions:

1. Gravel particles are "floating" in finer matix - basic assumption of ASTM D4718
2. Gravel particles are saturated
3. Coarse & Med sand have same absorption as gravel and particles are saturated
4. Coarse & Med sand particles are "floating" in finer matrix - extension of ASTM D4718

Jet Test Research

Tested and Computed By	Date	Checked By	Date
BN Jackson	11/20/2013	Strauss	11/20/2013

Compaction of test specimens

Material	Parent	Parent	Parent	-No. 4	-No. 4	-No. 4	-No. 40	-No. 40	-No. 40
Specimen	1	2	3	1	2	3	1	2	3
Mold #	15	1	15	P2A	P2B	P3A	P3B	10	11
Mass of mold (g)	5628.0	6503.0	5627.8	1921.7	1926.6	1926.2	1913.0	4414.0	4278.1
Volume of mold (ft^3)	0.075	0.075	0.075	0.0331	0.0331	0.0331	0.0330	0.0332	0.0332
Mass of mold + wet specimen (g)	9804.3	10678.7	9837.0	3704.1	3709.1	3708.9	3577.2	6088.4	5952.5
Mass of wet specimen (g)	4176.3	4175.7	4209.2	1782.4	1782.5	1782.7	1664.2	1674.4	1674.4
Wet unit wt (pcf)[1]	122.8	122.7	123.7	118.7	118.7	118.7	111.2	111.2	111.2
Moisture content	11.9	11.9	12.1	13.4	13.4	13.4	16.7	16.7	16.7
Dry unit wt (pcf)	109.7	109.7	110.4	104.7	104.7	104.7	95.3	95.3	95.3
Specified test unit wt (pcf)		109.8			104.3			94.3	

Moisture Content

Pan	111	113	1B	613	54
Tare	154.9	165.9	135.4	128.2	122.5
Tare + wet	417.3	524.3	534.2	430.8	395.5
Tare + dry	389.3	486.2	491.2	395.1	356.5
Water	28.0	38.1	43.0	35.7	39.0
Dry soil	234.4	320.3	355.8	266.9	234.0
Moisture Content	11.9	11.9	12.1	13.4	16.7
Specfied test moisture content (%)		12.2		13.6	16.4

[1] lb/ft3 = [Mass (g)*0.0022046/Volume (ft^3)]

Appendix B: Data Sets

Share Drive folder name and path where data are stored:

\\bor\do\TSC\HYDLAB\Project Archives\Wahl\X4104 - Gravelly Soils

Point of Contact name, email and phone:

Tony Wahl, twahl@usbr.gov, 303-445-2155

Short description of the data:

- Excel spreadsheets and PDF files containing soils laboratory test results related to soil classification and compaction testing.
- Excel spreadsheets containing calculations of compaction adjustments for sub-samples of the parent soil.
- Excel spreadsheets containing raw data and analysis of submerged jet erosion tests.
- Photographs of erosion test specimens.

Keywords:

Erosion, erodibility, submerged jet erosion test, embankments, dams, dam breach.

Approximate total size of all files:

173 MB