RELATING HET AND JET TEST RESULTS TO INTERNAL EROSION FIELD TESTS

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Abstract Three soils used in a series of embankment dam piping erosion and breach tests at the Agricultural Research Service's (ARS) outdoor hydraulics laboratory in Stillwater, Oklahoma were analyzed to determine their erodibility. Erosion indices were determined using the hole erosion test (HET) method, and the submerged jet erosion test (JET) method. Tests were performed in the laboratory on three series of remolded specimens, the first compacted at optimum moisture content to approximately 95% of Standard Proctor maximum density (*representative conditions*), the second compacted to match the real soil conditions from the ARS breach tests, and the third spanning a range of compaction moisture contents. Erodibility of the soils varied from specimens so weak that they could not be tested by the HET method (likely HET group 1 or 2; extremely rapid to very rapid erosion rate) up to specimens in the upper end of HET group 4 (moderately slow erosion rate). For the samples compacted to match field conditions, the two test methods ranked the erodibility of the soils similarly, but erodibility rankings were reversed for the samples compacted at the representative conditions. Submerged jet tests on the samples compacted to match field conditions were relatively consistent with *in situ* jet tests conducted in Oklahoma following each breach test. Differences between detachment rate coefficients and critical shear stresses determined by the two methods were significant and consistent with other research comparing these test methods over a broad range of soil types.

BACKGROUND

The hole erosion test (HET) (Wan and Fell 2004) and submerged jet erosion test (JET) (Hanson and Cook 2004) are two techniques for economically quantifying the erodibility of cohesive soils. The HET is a laboratory test that simulates a small-scale progressive internal erosion or piping failure by causing erosive enlargement of a 6-mm diameter predrilled hole through a 116-mm long soil specimen subjected to a constant-head flow condition. The JET is a laboratory and/or field test that uses a 6-mm diameter nozzle aimed at an exposed soil surface to produce scour erosion analogous to a variety of erosion situations of engineering interest. The two tests both determine numerical values for a critical shear stress needed to initiate erosion and a detachment rate coefficient expressing the increase in erosion rate per unit of excess applied stress. Recent research (e.g., Wahl et al. 2008) has shown that although the tests attempt to determine the same parameters of the same basic erosion equation, the results are often markedly different. A number of factors are thought to be responsible for this difference, including simplified stress descriptions used in the analysis of both tests, different erosion mechanisms, geometric effects, and differences in the sensitivity of each test to variations of soil fabric or structure. The Bureau of Reclamation (Reclamation) has adopted the HET as one means of classifying soils in embankment dams for evaluating risks of internal erosion and piping failure (a piping risk toolbox). The Agricultural Research Service (ARS) Hydraulic Engineering Research Unit (HERU) has relied upon the JET as a means of characterizing the erodibility of soils used in embankment breach tests.

In 2006 and 2007, the HERU performed 3 large-scale physical model tests of the piping-initiated breach of homogeneous cohesive embankment dams at their outdoor laboratory near Stillwater, Oklahoma. Preliminary data from the first of these tests was reported by Hunt et al. (2007); a second and third test took place in late 2007 (personal communication, Greg Hanson and Sherry Hunt), with results not yet published, and a fourth test was performed in 2008, after the erodibility testing described in this paper took place. The embankments were all of homogeneous construction, 4 ft high with a 6 ft wide crest and 3:1 (h:v) upstream and downstream slopes. Piping erosion was produced by embedding a 1.5-inch diameter pipe in each embankment and pulling it out through the downstream side of the embankment to begin each test. The reservoir upstream from the embankments was supplied with a continuous flow of water during the tests and its water surface elevation was held steady during the test by allowing excess flow

Figure 1 ARS piping test P1, 9 minutes after initiation of piping failure.

to exit over a long-crested weir. Figure 1 shows the first of these tests underway. Note in this figure that piping was initiated at the elevation of the lowest set of markers visible on the downstream slope; headcutting down to the base of the embankment occurred simultaneously with enlargement of the piping hole. Table 1 summarizes the results of the embankment piping breach tests run through 2007.

Table 1 Embankment piping erosion and breach tests performed by ARS.

Test and Soil Designation	Soil Type	Time to Collapse of Soil Bridge over Enlarged Pipe
P1	Silty Sand, SM (non-plastic)	0.23 hr
P2	Silty Clay, CL-ML, LL=21, PI=7	17.2 hr
P3	Lean Clay, CL, LL=28, PI=13	20.5 hr

To characterize erodibility of the soils, submerged jet erosion tests (Hanson and Cook 2004) were performed in the field immediately after completion of each embankment breach test. Laboratory jet tests were also performed by ARS on the three soils used in the tests over a range of moisture contents and compaction efforts. At the time of these tests, there was not a firmly established correlation between results of submerged jet tests and hole erosion tests.

OBJECTIVES AND TEST PROGRAM

The ARS embankment breach tests presented an opportunity to improve the understanding of piping-induced embankment failure and specifically could serve as case studies to support the piping risk toolbox under development at Reclamation. To achieve these goals, Reclamation performed a series of laboratory HETs on samples of the ARS soils. Each of the three soils was tested at two specific conditions:

1. Optimum moisture content and 95% of maximum dry density, as established by a Standard Proctor compaction test, and
2. Moisture content and dry density approximating the compacted test embankments.

The first series of tests allowed the determination of the Representative HET Erosion Rate Index, $\tilde{I}_{HET}$, for each soil, as defined by Wan and Fell (2004). This allows the normalized ranking of the soils relative to other embankment soils tested by Wan and Fell (2004) using the HET. The second series of tests established I_{HET} values for the soils at conditions approximating those of the tested embankments. These tests allow the ARS piping breach tests to be related to other case studies used to develop the piping risk toolbox.

For each series of tests, companion jet tests were performed on parallel specimens prepared with similar moisture content and compaction effort. These tests allowed a verification check against the laboratory and *in situ* tests performed by ARS. The data from these paired HET and JET specimens were also included in Reclamation's larger study of the relation between erosion indices determined by the HET and JET methods (Wahl et al. 2008).

Following the completion of these two series of tests, a third series of tests was performed in which the P2 and P3 soils were tested using the HET and JET over a range of compaction moisture contents at Standard Proctor compaction effort.

EROSION MODEL AND ERODIBILITY CLASSIFICATIONS

Both erosion tests used in this study are designed to determine the parameters of a simple soil detachment equation of the form $\dot{m} = C_e(\tau - \tau_c)$ or $\dot{\varepsilon} = k_d(\tau - \tau_c)$ where τ and τ_c are the applied shear stress and critical shear stress, respectively, $\dot{m}$ is the rate of erosion expressed as a mass per unit area per unit of applied stress, $\dot{\varepsilon}$ is the rate of erosion expressed on a volumetric basis, and C_e and k_d are rate coefficients. The equation applies only for $\tau > \tau_c$; otherwise, the erosion rate is zero. The two equations can be made equivalent by recognizing that $C_e=k_d\rho_d$, where ρ_d=dry density of the soil. The volumetric form of the equation is preferred for the jet test because the test is often performed in the field in situations where the in-place density of the tested material is not known. The hole erosion test is only performed in a laboratory setting, using either remolded or undisturbed soil samples, so density information is usually readily available, making a mass-based calculation more feasible. A volumetric erosion model is also preferred for field use, since most applications are concerned with the volumetric rate of material removal, either to predict depths or lateral extent of erosion, or rates of enlargement of internal erosion channels.

Values of C_e obtained from the HET are usually reported in S.I. units of kg/s/m^2/Pa, which simplifies to seconds per meter (s/m). C_e varies over several orders of magnitude in soils of engineering interest. For convenience, Wan and Fell (2004) proposed classifying soils according to an Erosion Rate Index, I_{HET}, defined as $I_{HET} = -\log_{10} C_e$ with C_e in units of s/m. Values of this index can typically range from 1 to 6, with larger values indicating decreasing erosion rate. The fractional part of the index value is often dropped and the test result reported as a simple integer group number. Soils with group numbers less than 2 are usually so erodible that they cannot be effectively tested in the HET device. Table 2 shows descriptive terms associated with each value of the I_{HET} index.

Table 2 Qualitative description of rates of progression of internal erosion or piping for soils with specific erosion rate indices.

HET Group Number	**Erosion Rate Index, 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

Because erodibility varies significantly as a function of the compaction moisture content and dry density, Wan and Fell (2004) further proposed that the value of I_{HET} for soils compacted to 95% of maximum dry density (Standard Proctor) at optimum moisture content should be called the Representative Erosion Rate Index, designated $\tilde{I}_{HET}$. Wan and Fell (2004) performed numerous HETs at varied compaction and moisture conditions and used multi-variable regression techniques to estimate values of $\tilde{I}_{HET}$ for 13 different soils. Soils that could not be eroded in their HET apparatus (maximum head of 1200 mm) were presumed to be in group 6. Wahl et al. (2008) showed that many soils that require head of 1200 to 5400 mm to initiate erosion still erode at rates that place them in group 4 or 5.

S.I. units of the k_d coefficient determined from the submerged jet erosion test are m^3/s/m^2/Pa which reduces to m^3/(N·s). Another S.I. unit combination commonly used for this parameter is cm^3/(N·s). When working in U.S. customary units, k_d is usually expressed in ft/hr/psf [1 cm^3/(N·s) = 0.5655 ft/hr/psf = 10^{-6} m^3/(N·s)]. Hanson and Simon (2001) have proposed a qualitative classification of the erodibility of soils, similar to that suggested by Wan and Fell (2004) for the HET. Their classification scheme identifies five erodibility groupings, illustrated in Figure 2. It uses both the k_d and τ_c value of the soil, in contrast to Wan and Fell's approach of using just the rate coefficient. Hanson and Simon (2001) used the JET to study erodibility of cohesive streambeds in loess formations in the midwestern USA and proposed a best-fit relation between the critical shear stress and the detachment rate coefficient, $k_d = 0.2\tau_c^{-0.5}$, with values of τ_c specified in Pa and values of k_d specified in cm^3/(N·s).

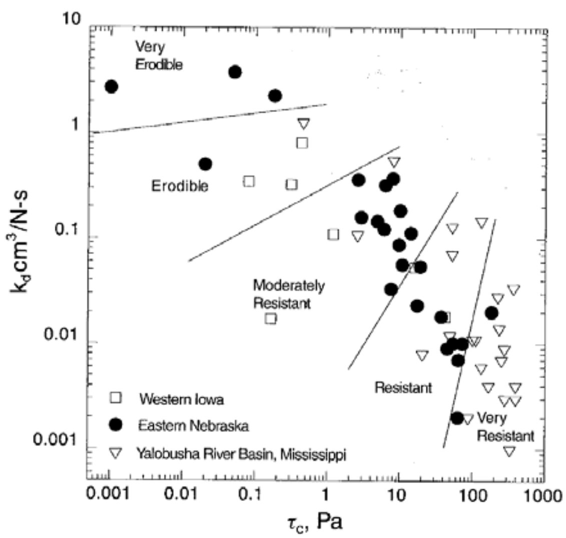

Figure 2 Proposed erodibility classifications for streambank soils (Hanson and Simon 2001).

TEST FACILITIES AND EQUIPMENT

Hole Erosion Test The Hole Erosion Test was originally developed in Australia (Wan and Fell 2002 and 2004). The test is performed in the laboratory using an undisturbed tube sample or a soil specimen compacted into a Standard Proctor mold. A 6.35-mm (1/4-inch) diameter hole is pre-drilled through the centerline axis, and the specimen is then installed into a test apparatus in which water flows through the hole under a constant hydraulic head that is increased incrementally until progressive erosion is produced. Once erosion is observed, the test is continued at a constant hydraulic head for a period long enough to observe a definite acceleration of the flow rate, which is indicative of a progressive erosion condition. Tests can last from 15 minutes to 2 hours. Measurements of the increasing flow rate during the test and the initial and final diameter of the erosion hole are used to compute applied hydraulic stress and hole diameters at intermediate times, from which the erosion rate can be deduced. Plotting the computed values of stress versus erosion rate produces a chart that allows graphical determination of the critical shear stress and erosion rate coefficient. Spreadsheets are used at the Bureau of Reclamation to facilitate analysis of the data. The final diameter is typically estimated visually immediately after a test, and then confirmed by caliper measurements made on a plaster casting of the final hole.

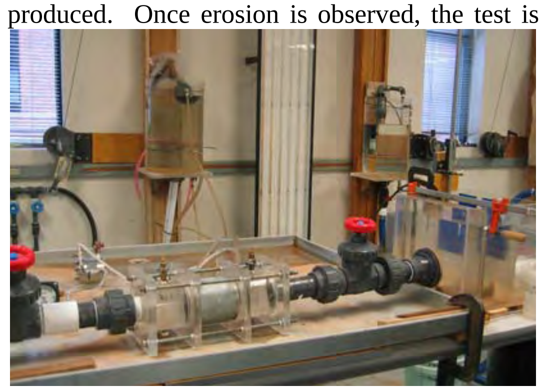

Figure 3 HET apparatus consisting of constant-head tank, test section, and downstream V-notch weir.

The Bureau of Reclamation also uses a supplementary data analysis technique based on a model for piping erosion proposed by Bonelli et al. (2006). This technique does not require measurement of the final hole diameter and is sometimes well-suited to tests in which erosion behavior is somewhat erratic due to temporary clogging of the erosion hole. The method uses a curve-fitting approach to match the test data to a theoretical model for the exponential increase of dimensionless discharge as a function of dimensionless test time (Wahl et al. 2008).

Figure 3 shows one of two HET devices installed in the Bureau of Reclamation laboratory in Denver, Colorado. Flow rate through the specimen is measured by a 10° V-notch weir on the downstream side of the apparatus. The weir was calibrated in place by volumetric methods (stopwatch and graduated cylinder). Measurement of differential head across the specimen and head on the weir is automated using pressure transducers and a computerized data acquisition system that records data at 5 second intervals throughout a test. The maximum test head that can applied in Reclamation's facilities is about 5400 mm.

Submerged Jet Erosion Test The submerged jet erosion test was developed at the Agricultural Research Service Hydraulic Engineering Research Unit, Stillwater, Oklahoma (Hanson and Cook 2004). This test can be performed *in situ*, or in the laboratory using tube samples or remolded samples in compaction molds (Hanson and Hunt 2007). The test is described in ASTM Standard D5852.

The JET apparatus is designed to erode the soil surface with a submerged jet, which is produced by a 6.35-mm (¼-inch) diameter nozzle initially positioned between 6 and 30 nozzle diameters from the soil surface. The starting nozzle position and test head may be adjusted to vary the stress applied to the soil sample, although once a test head is selected it is usually held constant for the duration of a test. Scour of the soil surface beneath the jet is measured over time using a point gage that passes through the nozzle, temporarily stopping the flow. No post-test handling or processing of the specimen is needed. The data analysis procedure is described in Hanson and Cook (2004) and has been automated with a Microsoft Excel spreadsheet. Figure 4 shows Reclamation's submerged jet test equipment.

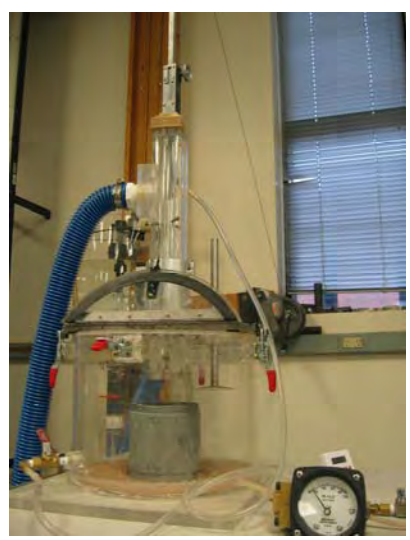

Figure 4 Laboratory JET apparatus.

SOILS AND SPECIMEN PREPARATION

Soils for the ARS piping breach tests were obtained from borrow areas and stockpiles on the ARS laboratory grounds. All of the soils are native to the Stillwater, Oklahoma area. Soils were analyzed after the breach tests at the USDA-NRCS soil mechanics laboratory in Fort Worth, Texas.

About 80 pounds of soils P1, P2, and P3 were shipped to Denver, Colorado in November 2007 for use in the first two series of tests described in this paper. There are a few notable differences between the soils used at the ARS lab and the samples tested at Reclamation (see Table 3). For the P2 soil, the PI of the Reclamation sample was 9, compared to 3 for the ARS breach test sample, which changes the soil classification from a Sandy Silt, ML, to a Lean Clay with Sand, (CL)s. For the P3 soil, the Reclamation sample also has a significantly higher PI.

A second shipment of soils P2 and P3 was provided in July 2008 to complete the third set of tests (HETs and JETs at varying compaction moisture content and fixed compaction effort). The properties of these soils were similar to those in the first shipment.

Table 3 Properties of soils used in ARS embankment tests and soil samples tested at the Bureau of Reclamation.

			Grain size distribution			Atterberg limits			Compaction Properties (Standard Proctor)	
	Soil	USCS	% sand > 0.075 mm	% silt 0.005-0.075 mm	% clay < 0.005 mm	LL	PL	PI	Optimum moisture content (%)	Maximum dry density (g/cm^3)
ARS breach test soils	P1	SM	74	19	8	--	NP	NP	11.0	1.813
	P2	ML	32	47	21	23	20	3	11.5	1.888
	P3	(CL)s	21	44	35	29	14	15	12.9	1.799
Samples at BOR lab Nov 2007	P1	SM	76	19	5	--	NP	NP	12.5	1.802
	P2	s(CL)	31	50	19	25	16	9	12.2	1.894
	P3	(CL)s	20	50	30	36	12	24	14.2	1.817
Samples at BOR lab July 2008	P2	s(CL)	31	50	19	25	16	9	11.8	1.900
	P3	(CL)s	20	50	30	36	12	24	12.3	1.906

Grain size distributions and Atterberg limits were determined through laboratory testing performed at Reclamation. Compaction properties of the soils received in November 2007 were established from data provided by ARS, with some reanalysis at Reclamation; for soil P1 some additional compaction testing was also performed at Reclamation. These optimum moisture content and maximum dry density values were used to determine the compaction conditions for the specimens to be tested at optimum moisture content and 95% of maximum density. Compaction properties for the P2 and P3 soils received in July 2008 were determined over the course of the third series of tests. The optimum moisture content for the July 2008 sample of soil P3 was somewhat lower and the maximum dry density somewhat higher than expected.

Table 4 provides the properties of the compacted embankments tested at the ARS laboratory, including the results of *in situ* submerged jet tests performed after each embankment was breached.

Soils were prepared for compaction into Standard Proctor molds in accordance with standard procedure USBR 5210 (Reclamation 1990). Soils were compacted into Standard Proctor molds in three equal lifts using manual compaction by a 5.5 lb hammer dropped from a 1 ft height. The number of blows was constant for each layer, but varied by specimen depending on the desired final dry density. Following compaction, the top layer was trimmed flush with the end of the mold and the compacted mass of the specimen was determined. Compacted specimens were cured overnight or longer before erodibility testing was performed. Hole erosion test specimens were tested with the last compacted layer placed upstream. Jet erosion specimens were tested with the bottom surface of the first compacted layer subjected to erosion (i.e., specimen inverted), since trimming of the top of the specimen is likely to disturb the last layer.

Table 4 Piping breach test soil conditions and *in situ* measurements of soil erodibility.

Test	Conditions of Tested Embankments		Erodibility - JET	
	Moisture content %	Dry density γ_d g/cm^3	k_d cm^3/(N·s)	τ_c Pa
P1	11.49	1.696	150.	0.0
P2	12.67	1.746	2.0	2.5
P3 (upper lifts)*	15.06	1.776	1.2	4.6
P3 (lowest 3 lifts)	16.45	1.785	0.17	22.

** Note: P3 embankment was observed to fail through upper lifts*

Following the completion of hole erosion tests, specimens were photographed, oven dried and weighed, and plaster casts of the enlarged holes were made. The length of the portion of a casting that was of relatively uniform diameter was determined, and the diameter of each casting was measured with calipers at five locations evenly distributed along the length of the uniform-diameter portion of the casting. By this method, excessively large scour holes at the entrance or exit of the specimens were considered in the data analysis to cause a shortening of the hole length (which increases the hydraulic gradient on the remaining length of the hole) that was assumed to occur linearly through time.

For each test, a *subjectivity index* (Wahl et al. 2008) was assigned, indicating the degree to which erosion occurred during the test in a manner consistent with the underlying analysis assumptions, and the degree to which subjective judgment was needed to analyze the data. Higher values of the subjectivity index indicate greater uncertainty in the test results.

RESULTS AND ANALYSIS

Samples at Representative Conditions Table 5 provides results of the tests performed on specimens compacted to approximately representative conditions (optimum moisture content and 95% of maximum dry density). Results are only shown for soils P2 and P3, as we were unable to successfully perform an HET on the P1 soil at this compaction condition, or at the compaction conditions matching the ARS P1 breach test. In two attempted tests, the P1 specimens collapsed immediately when the test apparatus was filled with water. Figure 5 shows the results graphically, in comparison to the best-fit line and jet test erodibility classifications proposed by Hanson and Simon (2001). Note that the HETs yielded critical stresses about 2 to 3 orders of magnitude higher than the corresponding jet tests, and detachment rate coefficients about 1 to 2 orders of magnitude lower. Both P2 and P3 soils have I_{HET} values that place them in group 4, designated as "moderately slow" erosion rate by Wan and Fell (2004).

Table 5 HET and JET erodibility parameters for samples compacted to representative conditions.

Soil	Compacted samples: Compaction energy (kJ/m^3)	Moisture content (%)	Dry density, (g/cm^3)	Relative density, (%)	I -log(C$_e$)	τ_c (Pa)	C_e (s/m)	k_d cm^3/(N-s)	HET Subjectivity Index
P2	HET Results								
	213	11.9	1.758	92.8%	4.33	200	4.68E-05	0.0266	½
	213	12.4	1.783	94.1%	4.37	103	4.27E-05	0.0239	½
	JET Results								
	213	12.4	1.766	93.2%	3.09	0.232	8.12E-04	0.46	-
	237	12.8	1.811	95.6%	3.43	0.946	3.75E-04	0.21	-
P3	HET Results								
	213	14.2	1.739	95.7%	4.77	206	1.70E-05	0.0098	½
	213	14.2	1.706	93.9%	4.71	402	1.95E-05	0.0114	2
	JET Results								
	213	14.0	1.694	93.2%	2.53	0.177	2.98E-03	1.76	-
	237	14.0	1.745	96.0%	2.67	0.217	2.14E-03	1.23	-

The two HET samples of soil P2 bracketed the desired optimum moisture content of 12.2%, but were 1 and 3 percent lighter than the desired 95% relative density. The I_{HET} index was about 4.3 to 4.4. HET samples of soil P3 were compacted at the desired moisture content of 14.2% and bracketed the desired relative density. The I_{HET} index for these two samples was 4.7 to 4.8. These results are consistent with the ARS JET data and the breach times observed in the piping breach tests.

The JET samples of P2 and P3 provided surprising results in this series of tests. All previous ARS data had shown soil P3 to be more erosion resistant than P2, generally by about one order of magnitude when similarly compacted (Hanson and Hunt 2007), but the jet tests we performed showed P2 to be more erosion resistant, both in terms of critical shear stress and the detachment rate coefficient. This may be due to the differences already noted between the ARS soils and the samples tested at Reclamation. The difference may also be related to the fact that we used a significantly reduced compaction effort (7, 9, or 10 blows per layer, rather than the standard 25 blows per layer) in the attempt to achieve 95% relative density. Hanson and Hunt (2007) showed that the optimum moisture content for these soils increases as compaction effort is reduced, especially for soil P3. Because we were compacting at the optimum moisture corresponding to standard compaction effort (25 blows per layer), we were effectively compacting at a moisture content that is drier than optimum *for the applied compaction effort*. Hanson and Hunt (2007) further showed that the erodibility of these soils is very sensitive to moisture content on the dry side of optimum, increasing dramatically as moisture content is reduced. This is likely due to a relative coarsening of the soil structure at drier moisture contents, where the soil mass does not fully mold together and some aggregates remain independent of other groupings of tightly molded materials. The jet test seems to be more capable of exploiting this soil structure and may thus be more sensitive to changing structure than the HET. This might explain why the relative erodibilities of the two soils are ranked oppositely by the HET and JET at this compaction condition.

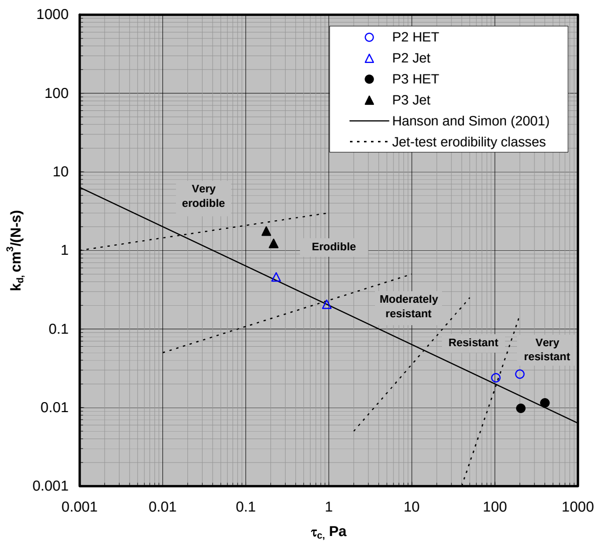

Figure 5 Erodibility parameters of soils P2 and P3 at representative compaction conditions (optimum moisture content and 95% of maximum dry density).

Samples Compacted to Match Breach-Test Conditions Table 6 shows the results of the tests performed at compaction conditions similar to the ARS piping breach tests. These tests produced more consistent results. Both the HET and JET results rank the erosion rates of the three soils in the same order as one would expect from the ARS piping breach tests. The fact that soil P1 was too weak to test in the HET suggests that it is probably in HET group 1 or 2. Soil P2 is in the upper part of group 3 to lower group 4, while soil P3 is in the upper half of group 4. The one HET on soil P2 that indicated it to be in HET group 3 was performed on a specimen compacted about 0.5% drier than the corresponding field test.

Jet test results show similar relative erodibility differences between the soils and compare reasonably to the field jet tests performed by ARS after the piping breach tests. Figure 6 shows the results in comparison with the best-fit line and erodibility classifications proposed by Hanson and Simon (2001) for jet test results. Again, HET results exhibit critical shear stresses about two orders of magnitude greater than corresponding JET results, and detachment rate coefficients about 1 order of magnitude lower. Both the HET and JET results reasonably follow the best-fit line, while the field data tend to deviate somewhat above it. The laboratory and field JET results are in similar erodibility classes, even though the field JET results are above the best-fit line. Critical shear stress values obtained from the HET show little difference between the soils, with both having critical shear stresses that are in the same order of magnitude.

Table 6 HET and JET erodibility parameters for samples compacted to conditions approximating the ARS piping breach tests.

	Compacted samples								
Soil	Compaction energy (kJ/m^3)	Moisture content (%)	Dry density, (g/cm^3)	Relative density (%)	I -log(C_e)	τ_c (Pa)	C_e (s/m)	k_d cm^3/(N-s)	HET Subjectivity Index
P1	JET Results								
	166	11.0	1.692	93.3%	0.33	0.000087	4.63E-01	274.	-
	166	11.0	1.692	93.3%	0.28	0.00031	5.23E-01	309.	-
ARS P1 field jet test(s)	192 - 287	11.5	1.696		0.59	0.0	2.54E-01	150.	-
P2	HET Results								
	166	12.4	1.749	92.6%	4.20	231.	6.38E-05	0.037	½
	166	12.0	1.731	91.7%	3.42	357.	3.80E-04	0.220	½
	JET Results								
	166	12.5	1.732	91.7%	3.17	0.911	6.77E-04	0.391	-
	166	12.5	1.752	92.8%	3.47	0.756	3.36E-04	0.192	-
ARS P2 field jet test(s)	192 - 287	12.7	1.746		2.46	2.5	3.49E-03	2.	-
P3	HET Results								
	213	15.1	1.768	98.3%	4.90	346.	1.26E-05	0.007	0
	213	16.2	1.744	96.9%	4.46	203.	3.47E-05	0.020	½
	JET Results								
	213	15.3	1.765	98.1%	3.48	1.616	3.28E-04	0.186	-
	213	15.4	1.775	98.6%	4.05	18.82	8.86E-05	0.050	-
ARS P3 field jet test(s) - lower 3 lifts	192 - 287	16.5	1.785		3.52	22.	3.03E-04	0.17	-
ARS P3 field jet test(s) - upper lifts	192 - 287	15.1	1.776		2.67	4.6	2.13E-03	1.2	-

A comparison of the HET and JET results for all of these tests shows significant differences. In general, the detachment rate coefficients determined by the HET are about one order of magnitude lower than those determined by the JET method, and the critical shear stress values are two or more orders of magnitude higher. This is consistent with results of an ongoing research effort at Reclamation that is examining the relation between the HET and JET erosion indices for a variety of soils. The fact that all of the HET and JET data roughly follow the best-fit line proposed by Hanson and Simon (2001) suggests that both tests are measuring an intrinsic erodibility property of soils, but with a significant bias between them. The source of this bias is probably a combination of factors, including simplifications of the stress descriptions used to analyze both tests, different erosion mechanisms in the two tests, effects of the different geometry of the exposed surfaces in each test, and differences in the sensitivity of each test to variations of soil fabric or structure.

HET vs. JET – Effect of Compaction Moisture Content The third series of tests consisted of HET and JET tests on soils P2 and P3 at a range of moisture contents, using Standard Proctor compaction. Three soil layers were compacted into 4-inch diameter, 1/30 ft^3 molds, with 25 blows per layer from a 5.5 lb hammer dropped 12 inches. Five moisture contents were targeted: the presumed optimum, -4%, -2%, +2%, and +4% from optimum. Actual optimum moisture content for each soil was determined after-the-fact. HET and JET specimens were prepared individually, so there is no direct comparison of specific tests, since the actual moisture content of each specimen varied.

Table 7 shows the test results, including the subjectivity indices for the HETs (see Appendix A). There were three tests with a subjectivity index of 2, indicating poor confidence in the test result, and three additional tests of soil P3 (not shown in the table) were excluded entirely (subjectivity index 3; analyses could not be completed). All of the jet tests were fully successful. Figure 7 shows the results graphically. The tests confirm that in general the P3 soil is less erodible than P2, but the erodibility of the P3 soil is more sensitive to moisture content differences on the dry side of optimum.

Differences between HET and JET results for soil P2 were relatively consistent across the range of tested moisture contents. The JET yielded detachment rate coefficients about 0.75 to 1 order of magnitude greater than those obtained from the HET. Critical shear stresses were about 2 to 3 orders of magnitude lower in the JET than in the HET.

Differences between the tests for soil P3 appear to be somewhat sensitive to the compaction moisture content. The detachment rate coefficients were only about 0.5 orders of magnitude different on the wet side of optimum, and about 1 order of magnitude different on the dry side, although there was not a successful HET test at the 4% dry condition to completely illustrate the effect. Critical shear stresses were consistently about 1.5 orders of magnitude different in the range for which a comparison could be made. The dry-side sensitivity of the JET results (both the detachment rate coefficient and the critical shear stress) to changes in moisture content on the dry side was greater for soil P3 than for P2. The unsuccessful HET performed on soil P3 at the 4% dry condition experienced excessive local scour at the entrance and exit and erratic variations in flow during the test, making analysis impossible; this probably indicates a material with high erodibility, so the HET may have also been similarly sensitive to the effect of dry compaction of this soil. Unfortunately, performing a successful test becomes difficult with the HET as the soil becomes more erodible.

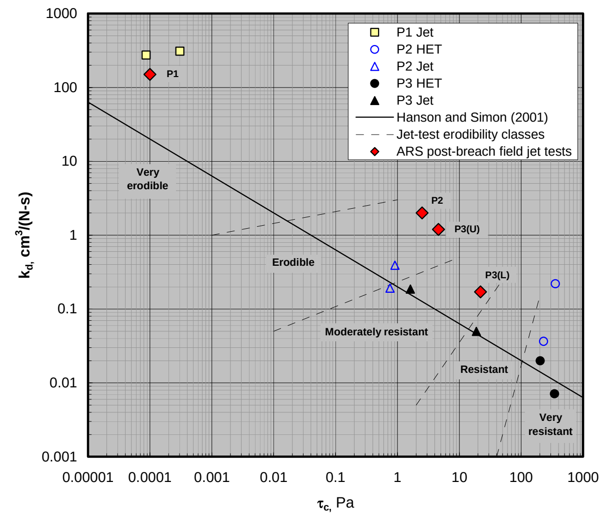

Figure 6 Erodibility parameters measured in ARS piping breach tests compared to erodibility parameters obtained from laboratory HET and JET specimens compacted to similar conditions.

Table 7 Erodibility test results for P2 and P3 soils over a range of compaction moisture contents.

Soil	Test Type	Compaction Conditions: Moisture Content %	Compaction Conditions: Dry Density g/cm³	Results: τ_c Pa	Results: k_d cm³/(N·s)	Results: HET Subjectivity Index
P2	HET	7.51	1.795	65.	0.217	2
		9.36	1.853	958.	0.0578	2
		11.56	1.895	856.	0.0311	0
		13.59	1.872	242.	0.0547	1
		15.65	1.795	133.	0.0372	1
	JET	7.55	1.785	0.062	1.39	-
		9.27	1.847	0.168	0.688	-
		11.57	1.929	7.58	0.0410	-
		13.43	1.872	0.081	0.188	-
		15.49	1.794	0.558	0.203	-
P3	HET	11.73	1.877	622	0.00420	0
		12.56	1.913	510	0.00266	1
		13.75	1.884	378	0.00253	2
		13.96	1.884	731	0.0122	1
		14.45	1.875	968	0.00524	0
		15.82	1.827	656	0.0131	1
		17.55	1.768	385	0.0205	1
	JET	10.18	1.848	0.456	0.508	-
		11.48	1.918	20.4	0.0329	-
		13.78	1.888	43.8	0.0234	-
		14.02	1.892	49.8	0.0493	-
		14.06	1.897	60.7	0.0198	-
		14.49	1.869	28.6	0.0124	-
		15.67	1.839	23.2	0.0303	-
		17.82	1.773	15.1	0.0568	-

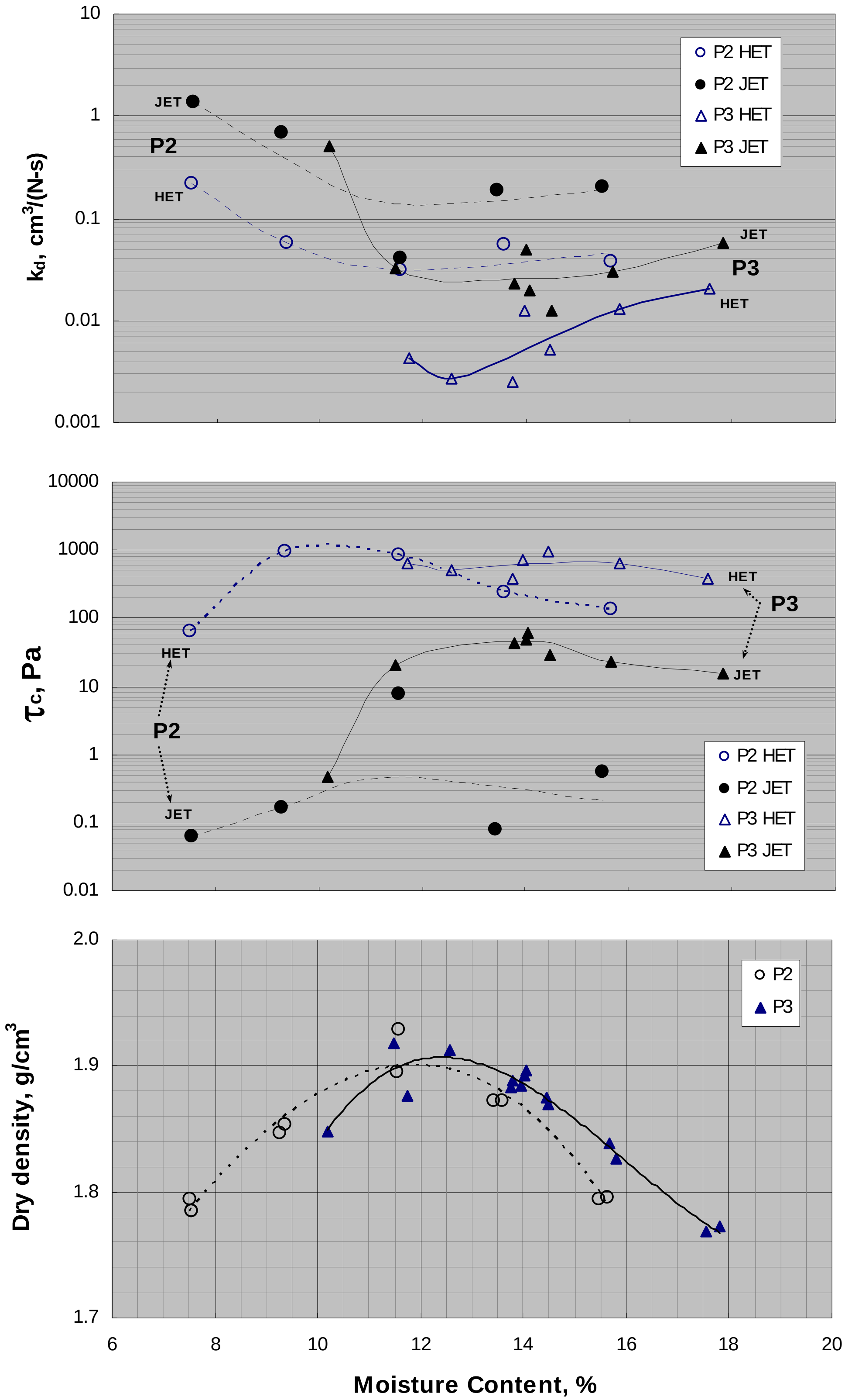

Figure 7 Variation of erodibility for soils P2 and P3 as a function of compaction moisture content.

CONCLUSIONS

Hole erosion tests and jet erosion tests performed on soils used in ARS embankment piping breach tests showed that the relative erodibility of the soils is generally consistent with the results of the breach tests. Soil P1 is so erodible that it could not be effectively tested in the HET, and as a result is believed to be in HET group 1 or 2 (extremely rapid to very rapid erosion rate). Soil P2 exhibited erosion that placed it in HET group 3 or 4 (moderately fast to moderately slow erosion rate), and all specimens of P3 were in HET group 4 (moderately slow erosion rate). Jet tests of these soils compacted to conditions approximating the ARS piping breach test conditions also exhibited similar erodibility relative to one another, but detachment rate coefficients and critical shear stresses were significantly different from those obtained by the HET method.

Tests of specimens compacted at optimum moisture content and 95% of maximum dry density produced surprising results, with the HET and JET indicating different erodibility rankings for soils P2 and P3. In reality, the moisture content was optimum for standard compaction effort but dry of optimum for the reduced effort needed to achieve 95% density. The results suggest that the JET may be more sensitive than the HET to differences in soil structure that occur when soils are compacted at drier than optimum conditions. A set of tests that evaluated HET and JET performance on samples compacted at a range of moisture contents showed that the erodibility as determined by the JET increases rapidly for samples compacted dry-of-optimum; data for similar HET samples were inconclusive because a successful HET was not obtained at the driest compaction condition.

In general, detachment rate coefficients determined by the HET method are about one to two orders of magnitude lower than those determined by the JET method for similarly prepared specimens, and critical shear stress values are two to three orders of magnitude higher. The results for these soils are consistent with results of a broader, ongoing research program at Reclamation that is examining the relation between the HET and JET erosion indices for a variety of soils. Although there is a systematic difference between absolute results of each test, the relation between critical shear stresses and erosion rate coefficients seems to be similar for both tests. The source of the differences between the tests is probably a combination of factors, including simplifications of the stress descriptions used to analyze both tests, different erosion mechanisms in the two tests, effects of the different geometry of the exposed surfaces in each test, and differences in the sensitivity of each test to variations of soil fabric or structure.

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