Presented at ASDSO Dam Safety '09
Sept. 27-Oct. 1, 2009 -- Hollywood, Florida

QUANTIFYING ERODIBILITY OF EMBANKMENT MATERIALS FOR THE MODELING OF DAM BREACH PROCESSES

Tony L. Wahl, Gregory J. Hanson, and Pierre-Louis Regazzoni

Abstract

Two methods of soil erodibility testing, the hole erosion test (HET) and submerged jet erosion test (JET), were evaluated for potential application to the modeling of embankment dam erosion and breach processes. The two methods were compared by using them to determine erodibility parameters for similarly prepared remolded soil specimens covering a range of cohesive soils. The methods produced significantly different quantitative estimates of the detachment rate coefficient and the threshold shear stress needed to initiate erosion. Differences in erodibility between the test methods were one or more orders of magnitude in erosion rate and two or more orders of magnitude for the threshold shear stress, but both tests produced results that seemed consistent with a single relation between erosion rate and threshold shear stress. Differences between HET and JET results are believed to be due to simplified stress descriptions used to analyze each test and fundamental differences in the mechanisms of erosion exploited in each test environment. The JET proved to be a more easily applied test method, with a higher ratio of successful tests and a greater ability to successfully test soils of widely varying erodibility. The JET also has the advantage of being suitable for in situ field testing wherever a soil surface of interest can be exposed. The significant differences in the magnitude of the erodibility parameters produced by each test make it crucial for numerical models of dam erosion and breach processes to be designed and applied with awareness of those differences.

Introduction

The prediction of geometric and temporal parameters of embankment dam breaches is widely recognized as one of the greatest sources of uncertainty affecting simulations of dam-break events and the resulting downstream flooding and associated consequences. When populations at risk are just downstream from a dam (the so-called “near field”), peak flow rates and resulting inundation levels are directly a function of breach parameters. Even in the far field where channel attenuation mutes the effect of breach parameters upon the peak discharge, the timing of flood wave arrival, the available warning time for evacuation, and the resulting survival rates for the downstream population are still very dependent on the rate of breach development. For these reasons, there is an ongoing effort to improve breach modeling technologies, with a general shift away from regression-based techniques and a focus on applying physically-based models that simulate erosion processes and breach development mechanics in considerable detail.

The most significant fundamental improvement in the several physically-based breach models under development today is the incorporation of erosion process models that rely on quantitative measures of material erodibility. This paper examines two methods for measuring the erodibility of embankment materials to obtain these input data. The methods are compared, contrasted, and evaluated to identify their advantages and disadvantages for application to future dam breach modeling problems.

Erodibility Measurement Methods

The hole erosion test (Wan and Fell 2004) and the jet erosion test (Hanson and Cook 2004) are two of several available methods for evaluating the erodibility of cohesive soils. The hole erosion test (HET) utilizes an internal flow through a hole pre-drilled in the specimen, similar to the flow condition that occurs during piping erosion of embankment dams, while the jet erosion test (JET) utilizes a submerged jet to produce scouring surface erosion, similar to that which occurs at a headcut or a free overfall. As presently performed and interpreted, both tests yield a critical shear stress needed to initiate erosion and a coefficient that defines the rate of erosion per unit of applied excess stress. These two tests are fully described in the literature and utilize relatively straightforward test equipment that can be readily reproduced. Both tests have been performed widely in recent years, and the erosion parameters measured with them are being utilized in numerous applications, including numerical models for overtopping erosion (Temple et al. 2005) and tool boxes for estimating risks related to internal erosion of embankment dams (e.g., Cyganiewicz et al. 2008). Prior to this study, no detailed comparison of these two erodibility tests had been made. This test is focused on the comparison of the two tests to one another. Details and other aspects of this work have previously been reported by Regazzoni et al. (2008) and Wahl et al. (2008).

Hole Erosion Test

The hole erosion test (Wan and Fell 2004) is conducted in the laboratory using an undisturbed tube sample or a soil specimen compacted into a Standard Proctor mold. A 6 mm 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. (Lefebvre et al. [1984] described a hole erosion test performed with a constant flow rate under varying head, with a more detailed data collection and analysis procedure). Once erosion is observed, the test is continued at a constant hydraulic head for up to 45 minutes, or as long as flow can be maintained. 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 the erosion rate. Significant post-test work is needed to obtain the measurement of the final hole diameter (oven-drying, casting of a plaster mold of the eroded hole, measurement of mold diameter at several locations using calipers).

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

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

where $\dot{m}$ is the rate of mass removal per unit of surface area (kg/s/m^2), τ and τ_c are the applied shear stress and threshold shear stress for soil detachment, respectively, and C_e is a proportionality constant, often called the coefficient of soil erosion. The equation applies only for $\tau > \tau_c$; otherwise, the erosion rate is zero. Values of C_e in S.I. units are kg/s/m^2/Pa, or s/m. The coefficient of soil erosion varies over several orders of magnitude in soils of engineering interest. For convenience, Wan and Fell proposed a second parameter, the Erosion Rate Index (I_{HET}):

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

with C_e provided in units of s/m. Typical values of this index range from 1 to just above 6, with larger values indicating decreasing erosion rate or increasing erosion resistance. The fractional part of the index is often dropped and the test result reported as a simple integer group number for erosion resistance. Soils with group numbers less than 2 are usually so erodible that they cannot be effectively tested in the HET device. Table 1 shows proposed descriptive terms associated with the I_{HET} index.

Table 1. — Qualitative description of rates of progression of internal erosion or piping for soils with specific erosion rate indices (Wan and Fell 2004).

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

Figure 1 shows the HET equipment installed in the Bureau of Reclamation soils (a) and hydraulics (b) laboratories in Denver, Colorado. Flow rate through the test specimen is measured by a custom-calibrated V-notch weir on the downstream side of the apparatus. Measurements of differential head across the specimen and head on the weir are automated using pressure transducers and a computerized data acquisition system that records data at 5 second intervals throughout a test. The maximum heads that can be applied are 1600 mm (Figure 1a) and 5400 mm (Figure 1b). Both facilities operate with water originating from the tap and stored for long-term use.

It is important to be aware that several erosion processes can be observed in the HET. The analysis proposed by Wan and Fell (2004) assumes that the primary mode of erosion is the enlargement of the pre-drilled hole, but slaking of the upstream and downstream surfaces of the specimen is also possible that changes the length of the erosion hole at the same time that enlargement of the hole is occurring. Some soils also tend to experience collapse of the roof of the pipe, and clogging of the erosion hole by soil chunks or small gravel particles is also possible. These phenomena make interpretation difficult in some cases. Another important phenomena to recognize is that of non-progressive erosion, or cleanout of the pre-drilled hole. At the start of many tests, disturbed material along the hole boundary is quickly removed, but erosion then diminishes and the flow rate through the hole stabilizes temporarily because the threshold shear stress for the undisturbed material has not been exceeded. When the test head is increased to the point that the threshold shear stress is exceeded, erosion becomes progressive; as the hole enlarges, the increased flow and constant head lead to an increase in applied shear stress, so the erosion rate increases further. In this progressive erosion phase, the flow rate accelerates quickly. *This is the condition that must be produced to enable the determination of the erodibility parameters.*

Wahl et al. (2008) evaluated alternative methods for analyzing HET data to obtain the erodibility parameters τ_c and I_{HET}. A method proposed by Bonelli et al. (2007) requires only the knowledge of the starting hole diameter, the initial applied shear stress, and the time series of measured flow rates. It does not require the measurement of the final hole diameter, but can only be applied to the portion of a test in which progressive erosion occurred. If progressive erosion does not begin immediately at the start of the test, then some means of estimating the hole diameter at the start of progressive erosion is needed. This often requires that one resort back to the Wan and Fell (2004) method.

Wahl et al. (2008) also investigated other underlying assumptions of the HET analysis procedure proposed by Wan and Fell (2004), most importantly the variation of the friction factor for the eroding hole. Significant improvements to HET data analysis procedures were made as a result of this research.

(a) (b)

Figure 1. — The standard HET apparatus in the soils laboratory (a) is limited to about 1600 mm net head, while the new high-head facility (b) can produce a maximum head of about 5400 mm.

Submerged Jet Erosion Test

The submerged jet erosion test (JET) was developed at the Agricultural Research Service Hydraulic Engineering Research Unit, Stillwater, Oklahoma (Hanson and Cook 2004). This test can be performed *in situ* on exposed, horizontal or inclined (Hanson et al. 2002) soil surfaces, or in the laboratory using tube samples or remolded samples in compaction molds (Hanson and Hunt 2006). Testing has been successfully carried out on specimens as small as 75-mm (3-inch) diameter, but a minimum specimen size has not been firmly established at this time. The test is described in ASTM Standard D5852.

The JET apparatus attacks 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 (typically up to 2 hours) using a point gage aligned with the axis of the jet. No post-test handling or processing of the specimen is needed.

Data from the JET have typically been analyzed using a volumetric form of the same erosion model used to analyze HET data:

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

where $\dot{\varepsilon}$ is the volume of material removed per unit surface area per unit time (m^3/s/m^2, or m/s), and k_d is a detachment rate coefficient. Typical units for k_d are m^3/s/m^2/Pa which reduces to m/s/Pa or m^3/N·s in S.I. units; k_d is also commonly reported in cm^3/N·s, or 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). Values of C_e and k_d can be compared by recognizing that C_e=k_d·ρ_d, where ρ_d=dry density of the soil.

Figure 2 shows the laboratory JET apparatus installed in the Bureau of Reclamation soils laboratory in Denver, Colorado. Data are collected manually during a test using the procedures described by Hanson and Cook (2004). The top portion of the device (jet tube and lid) can also be installed onto a metal submergence tank for field use.

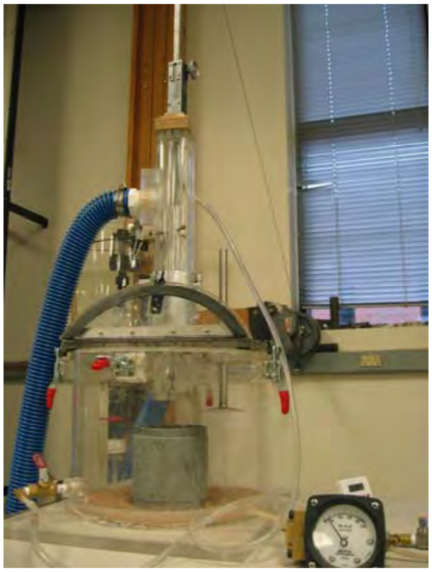


Figure 2. — Laboratory JET apparatus.

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 using both the k_d and τ_c value of the soil, in contrast to Wan and Fell's approach of using just the erosion rate index to classify soils in terms of the rate at which an internal erosion or piping event might progress.

Experimental Approach

The erodibility parameters determined by the HET and JET methods both derive from analyses that consider the shear stress applied to the eroding surface and measurements that allow determination of the erosion rate. In theory, they should be directly comparable, accounting for the fact that one test is typically analyzed on a mass basis and the other on a volumetric basis. To determine whether the results really are comparable, the HET and JET methods were used to measure erodibility of paired specimens of several different soils in the laboratories of the Bureau of Reclamation at Denver, Colorado. The soil types (USCS) used for these tests are indicated in Table 2. The first 5 soils in the table were obtained from stockpiles in the laboratories of the Bureau of Reclamation, while the last 5 were provided to Reclamation by the Agricultural Research Service (ARS) hydraulics laboratory in Stillwater, Oklahoma. These soils were used by ARS for a series of embankment piping breach tests (Hunt et al. 2007).

For most of the tests, paired specimens of each soil were created with essentially identical compaction moisture and effort and then tested by the HET and JET methods. One series of tests did not utilize paired samples, but instead, multiple samples with the same compaction effort spanning a common range of moisture conditions were prepared and tested by each method. This allowed the resulting curves of erodibility versus compaction moisture content to be compared for each test. Detailed results of the various tests are provided by Wahl et al. (2008) and Wahl and Erdogan (2008).

Table 2. — Properties of tested soils. Detailed gradation analyses were not available for the Many Farms soil.

					FINES					
			Gravel	Sand	Silt	Clay	Total Fines			
			> 4.76 mm	0.075-4.76 mm	0.005-0.075 mm	< 0.005 mm	< 0.075 mm			
Source	Designation	USCS	%	%	%	%	%	LL	PI	w_{opt}%
Earth School	55T-160	s(CL)	0	37	32	31	63	34	23	12
Teton Dam	TE	CL-ML	0	16	70	14	84	29	4	17
Many Farms	MF	CL						47	34	17
Mountain Park	MP	CH/CL	0	9	50	41	91	51	30	20
Tracy Fish Facility	TF	CH	0	6	51	42	93	55	40	18
ARS Piping Test P1	P1	SM	0	76	19	5	24	NP	NP	12.5
ARS Piping Test P2	P2	s(CL)	0	31	50	19	69	25	9	12.2
ARS Piping Test P3	P3	(CL)s	0	20	50	30	80	36	24	14.2
ARS P2 July 2008	P2	s(CL)	0	31	49	20	69	26	9	11.8
ARS P3 July 2008	P3	(CL)s	0	21	47	32	79	33	19	12.3

Results and Discussion

Paired Samples

A total of 25 hole erosion tests and 28 jet erosion tests were performed to compare results for specimens prepared with the same compaction effort and compaction moisture contents. In some cases, samples were not truly paired, as more tests were conducted with one or the other of the two devices. Most specimens were prepared with Standard Proctor compaction energy by manual compaction methods. All jet tests were performed with the specimens inverted so that the jet attacked the bottom surface of the first compacted soil layer.

The JET is typically analyzed to obtain the detachment rate coefficient k_d, which is expressed volumetrically, as opposed to the HET which yields C_e and I_{HET}, with C_e expressed in terms of mass and $I_{HET} = -\log_{10}(C_e)$. To allow a convenient comparison, a similar index for the jet erosion test was computed, $I_{JET} = -\log_{10}(k_d \rho_d)$. Table 3 presents the numerical data, and Figures 3 and 4 provide graphical comparisons for each tested soil. Figures 5 and 6 provide a comparison across the range of the tested soils. Where multiple tests were performed, error bars in Figs. 5 and 6 indicate the full range of measured values for each particular soil type and/or compaction condition. The P2 and P3 soils were each tested at two different moisture and compaction conditions. The “ARS” subscript indicates compaction at conditions matching the embankment piping breach tests conducted by ARS, while the “95/OWC” subscript indicates an attempt to compact specimens to 95% of Standard Proctor maximum density at the optimum moisture content.

Table 3. — Summary of erosion indices and critical stresses determined by HET and JET methods.

		HET				JET			
USCS	Soil ID	wc%	ρ_d (Mg/m^3)	I_{HET}	τ_c (Pa)	wc%	ρ_d (Mg/m^3)	I_{JET}	τ_c (Pa)
s(CL)	55T-160	11.7%	1.924	3.52	0.0	11.9%	1.922	2.71	0.45
		11.4%	1.905	3.56	2.2	11.9%	1.922	2.38	0.71
		11.9%	1.922	3.33	8.0				
		11.6%	1.909	3.27	8.1				
		11.6%	1.905	3.16	10.8				
		11.6%	1.908	3.28	23.0				
		11.6%	1.908	3.07	11.5				
CH	TF	17.7%	1.507	4.67	196.	17.4%	1.659	2.84	5.4
						17.7%	1.664	2.20	0.08
						17.2%	1.587	3.16	0.22
						17.8%	1.583	3.21	1.80
CL	MF	14.7%	1.776	3.89	33.7	15.2%	1.757	2.71	0.13
		14.8%	1.808	3.03	8.7	14.9%	1.776	2.99	0.43
		14.2%	1.802	3.07	7.2	14.4%	1.783	2.97	2.3
		14.1%	1.789	3.08	6.0	14.8%	1.780	2.71	0.44
						14.2%	1.776	2.57	0.11
						14.1%	1.783	2.46	0.27
CH/CL	MP	18.6%	1.666	5.31	149.	17.8%	1.653	3.31	7.7
						17.0%	1.674	3.57	9.2
						19.0%	1.682	3.58	8.2
						18.6%	1.655	3.57	7.2
CL-ML	TE	15.6%	1.703	2.85	3.9	15.6%	1.700	2.55	0.65
		16.2%	1.695	3.14	9.0	16.2%	1.696	2.74	0.90
		16.5%	1.695	2.45	10.1	16.5%	1.701	2.65	0.66
		16.5%	1.692	2.93	7.6	16.3%	1.698	2.51	0.33
s(CL)	P2 (95/owc)	12.0%	1.758	4.33	200.	12.4%	1.766	3.09	0.23
		12.4%	1.783	4.37	103.	12.8%	1.811	3.43	0.95
(CL)s	P3 (95/owc)	14.2%	1.739	4.77	207.	14.2%	1.696	2.53	0.18
		14.2%	1.706	4.71	402.	14.2%	1.747	2.67	0.22
s(CL)	P2 (~ARS Breach Test)	12.4%	1.749	4.20	231.	12.5%	1.732	3.17	0.91
		12.0%	1.731	3.42	357.	12.5%	1.752	3.47	0.76
(CL)s	P3 (~ARS Breach Test)	15.1%	1.768	4.90	346.	15.3%	1.765	3.48	1.62
		16.2%	1.744	4.80	132.	15.4%	1.775	4.05	18.82

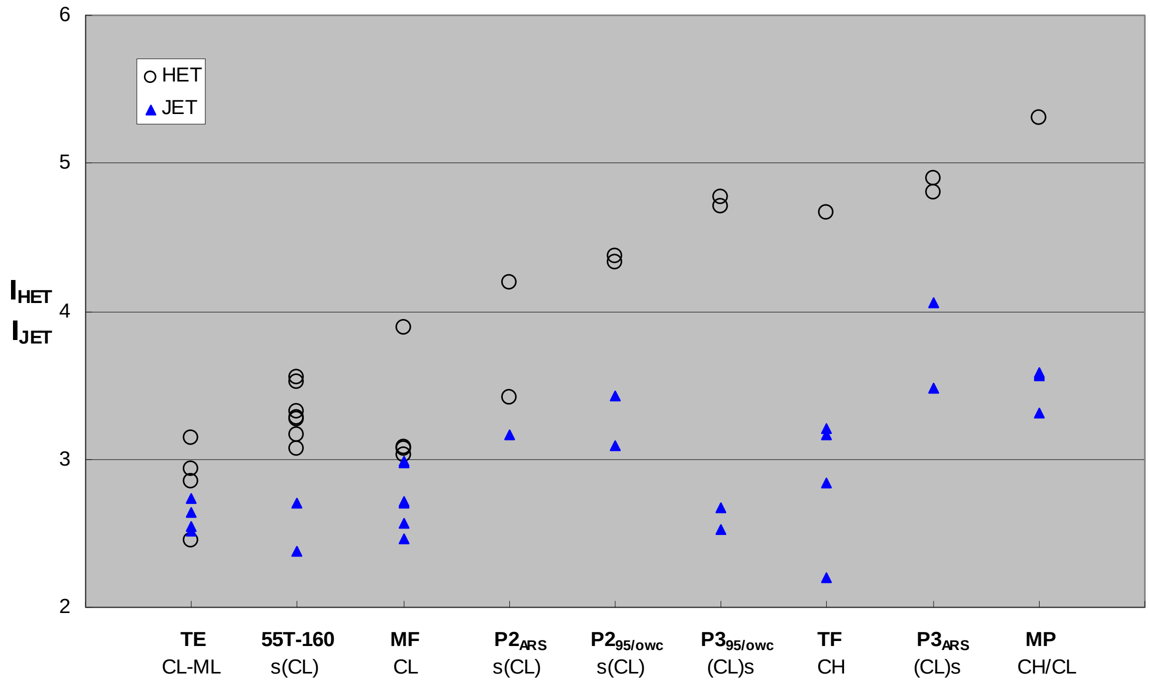


Figure 3. — Erosion rate index values obtained by HET and JET methods, ranked subjectively from most rapid to least rapid erosion rate.

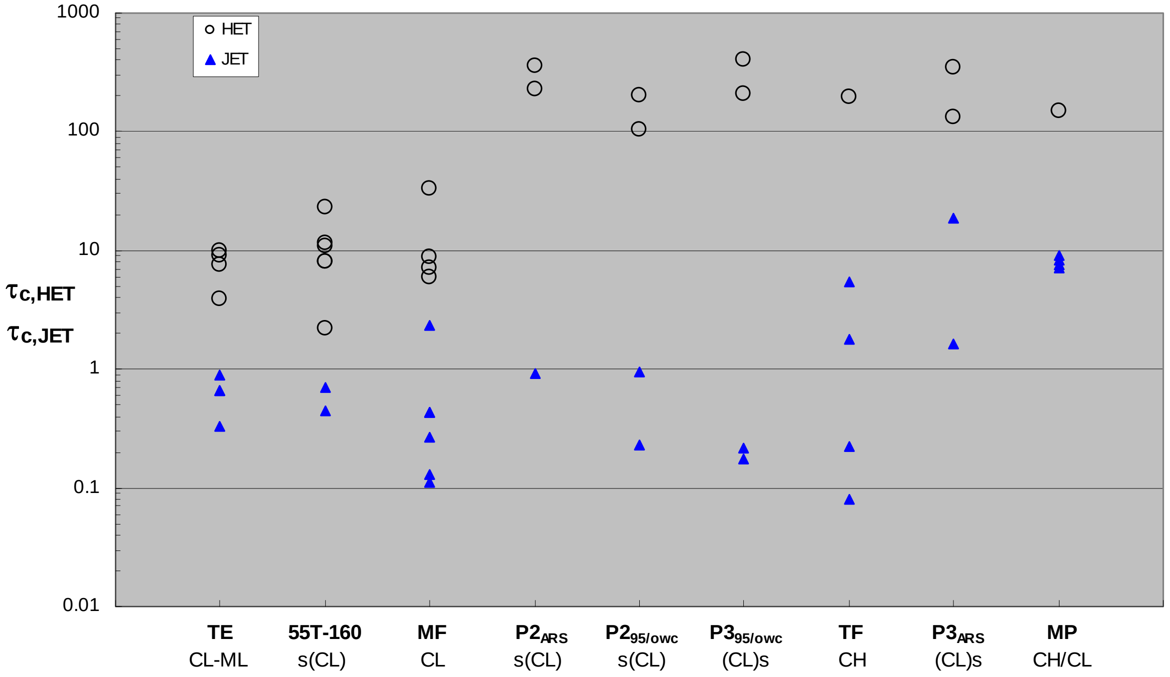


Figure 4. — Critical shear stresses obtained from HET and JET methods, ranked subjectively from most rapid to least rapid erosion rate (same ranking as Fig. 3 above).

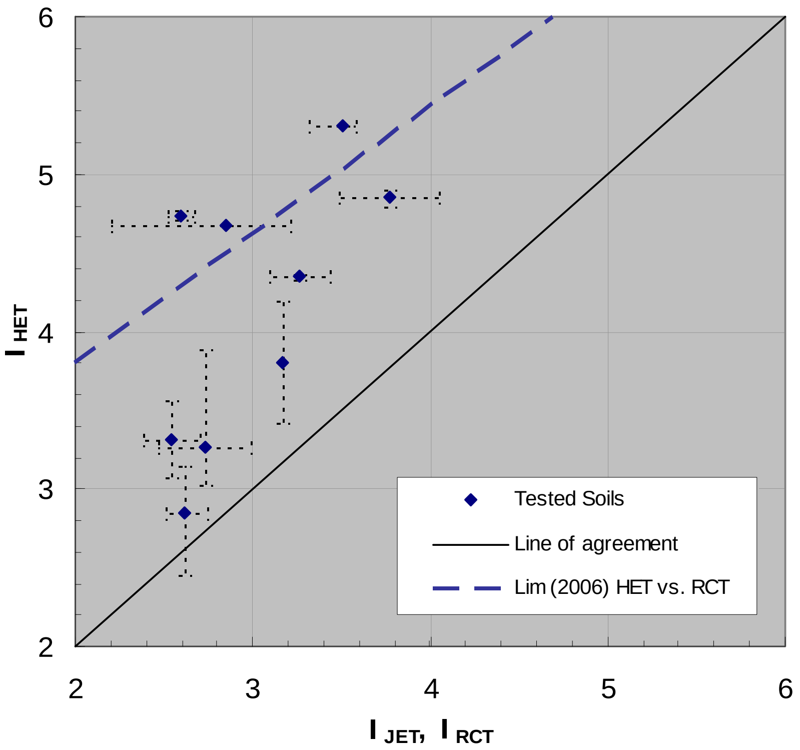


Figure 5. — Comparison of erosion rate indices determined by HET and JET methods, and the relationship found by Lim (2006) relating HET and rotating cylinder test (RCT) results for non-dispersive soils.

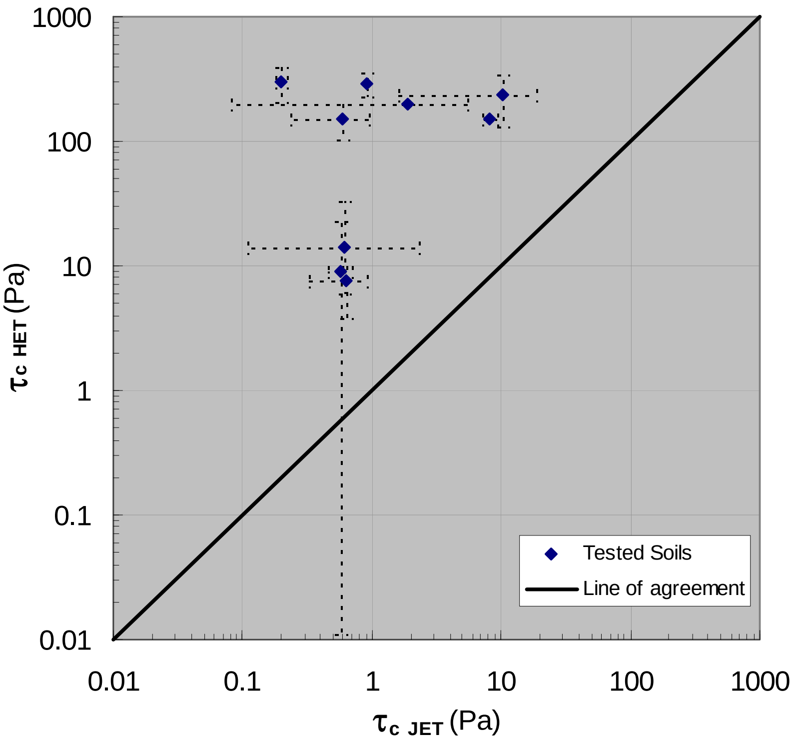


Figure 6. — Comparison of critical stresses determined by HET and JET methods.

Clearly there is significant difference between the erosion indices and critical shear stresses obtained with the two tests. The rankings of soils from most to least erodible were similar for most cases, but the quantitative differences between soils appear to be more pronounced with the HET, and the HET indicates higher critical shear stress and higher erosion rate index values for all of the soils. Differences between the HET and JET results seem to be greater for the fat clays (Mountain Park=CH/CL and Tracy Fish Facility=CH), and smaller for the leaner clays and silts [55T-160=s(CL), Many Farms=CL, Teton=CL-ML, P2=s(CL)].

Figure 5 also compares the present results to a relationship found by Lim (2006) for erosion rate indices of nondispersive clay soils determined by the hole erosion test and rotating cylinder test (RCT). The rotating cylinder test was developed by Moore and Masch (1962) and uses a soil block suspended and submerged inside of a rotating cylindrical chamber. Rotation of the cylinder induces a flow around the specimen which causes erosion. Torque applied to the specimen and erosion rates are measured and used to estimate applied stresses and erodibility parameters. The test apparatus is very expensive and the test is difficult to perform, but it gives an excellent measure of erodibility, with good correlation to flume experiments of flow across erodible surfaces. Figure 5 shows that the JET and RCT both produce higher erosion rates (lower values of I_{JET} and I_{RCT}) than the HET, and the differences are of a similar order of magnitude, although not in perfect agreement. Notably, Lim (2006) found that the HET and RCT produce very similar results for dispersive soils, with the RCT producing only slightly higher erosion rates (lower values of I_{RCT}).

HET and JET Erodibility versus Moisture Content

Two of the ARS soils, P2 and P3, were chosen for a more intensive study of the variation of HET and JET results as a function of compaction moisture content. Specimens were prepared using Standard Proctor compaction at a range of compaction moisture contents from about 4% dry of the presumed optimum to 4% wet of optimum at 2% increments; actual optimum moisture content for the tested soils was established after-the-fact from the test data (see Table 2).

Table 4 shows the test results, including subjectivity indices for the HETs. The subjectivity index was developed late in the course of this research as a means of quantifying the level of subjectivity required to analyze each hole erosion test (Wahl et al. 2008). A value of 0 indicates little subjective judgment was needed; larger values indicate the use of more subjective judgment and corresponding increased uncertainty in test results. This subjectivity was usually required because of undesirable modes of erosion, hole clogging, or other factors that made analysis less than straightforward. 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 because analyses could not be completed. All of the jet tests were fully successful.

Figures 7, 8, and 9 show the results graphically, first for the individual soils (Figs. 7 and 8), and then for both soils together (Fig. 9). 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. This effect is sufficient to cause the JET results for P3 to indicate more erodibility than P2 when compaction moisture contents of both soils are below about 10%. The HET results in this range of moisture contents are incomplete because the HET on the driest P3 specimen was unsuccessful, but the trend in the data appears to be similar. The general behavior of both soils was to demonstrate maximum erosion resistance when compacted near optimum moisture content, and increasing erodibility for drier and wetter compaction. The increase in erodibility was most dramatic on the dry side of optimum. These results are consistent with an evaluation of erodibility vs. compaction conditions performed by Hanson and Hunt (2006) using the JET.

Table 4. — Erodibility test results for P2 and P3 soils over a range of compaction moisture contents.

		Compaction Conditions		**Results**		
Soil	**Test Type**	**Moisture Content %**	**Dry Density g/cm^3**	**τ_c Pa**	**k_d cm^3/(N·s)**	**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	-

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 more 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, but 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 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

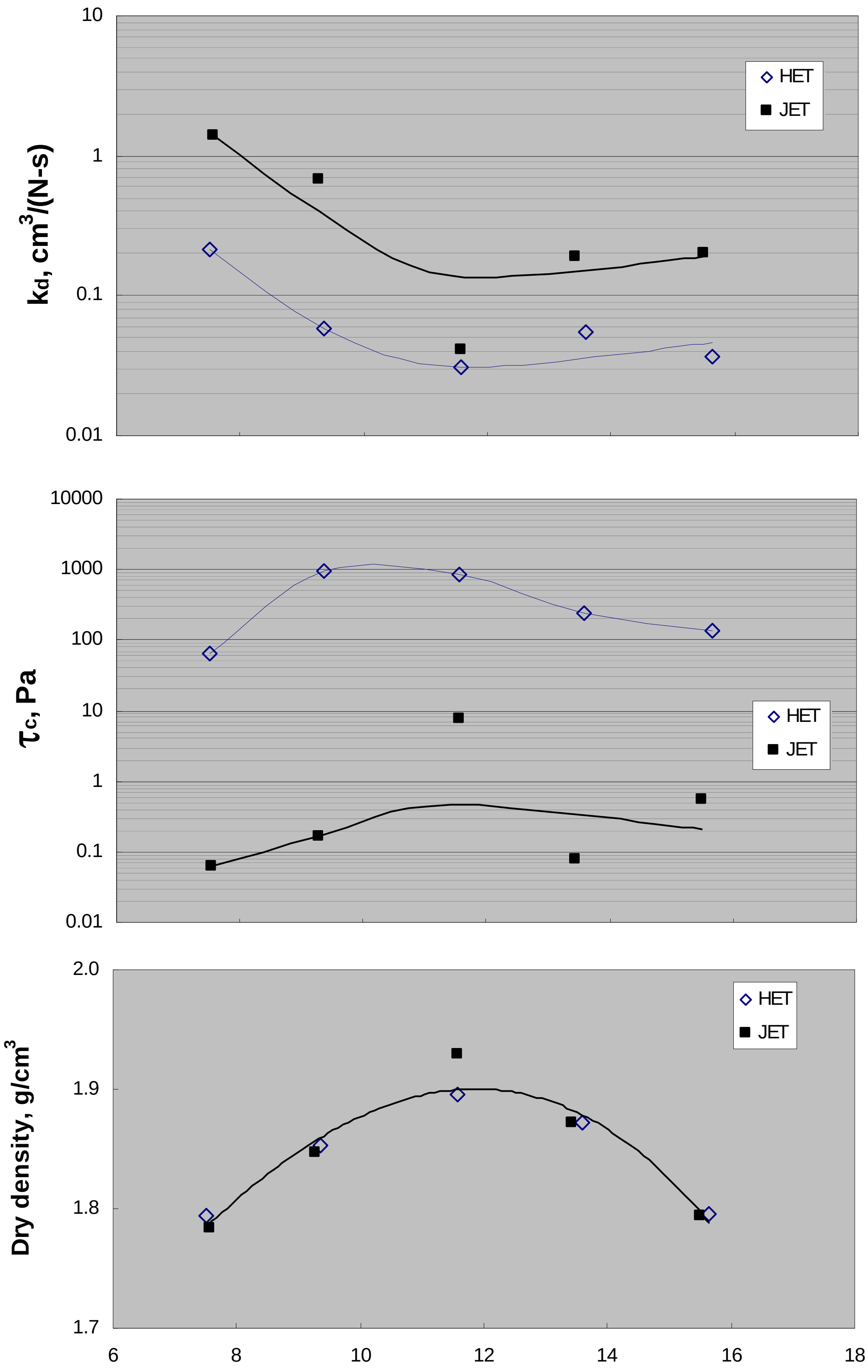


Figure 7. — Results of erodibility tests on soil P2 at compaction moisture contents ranging from about 4% dry of optimum to 4% wet of optimum.

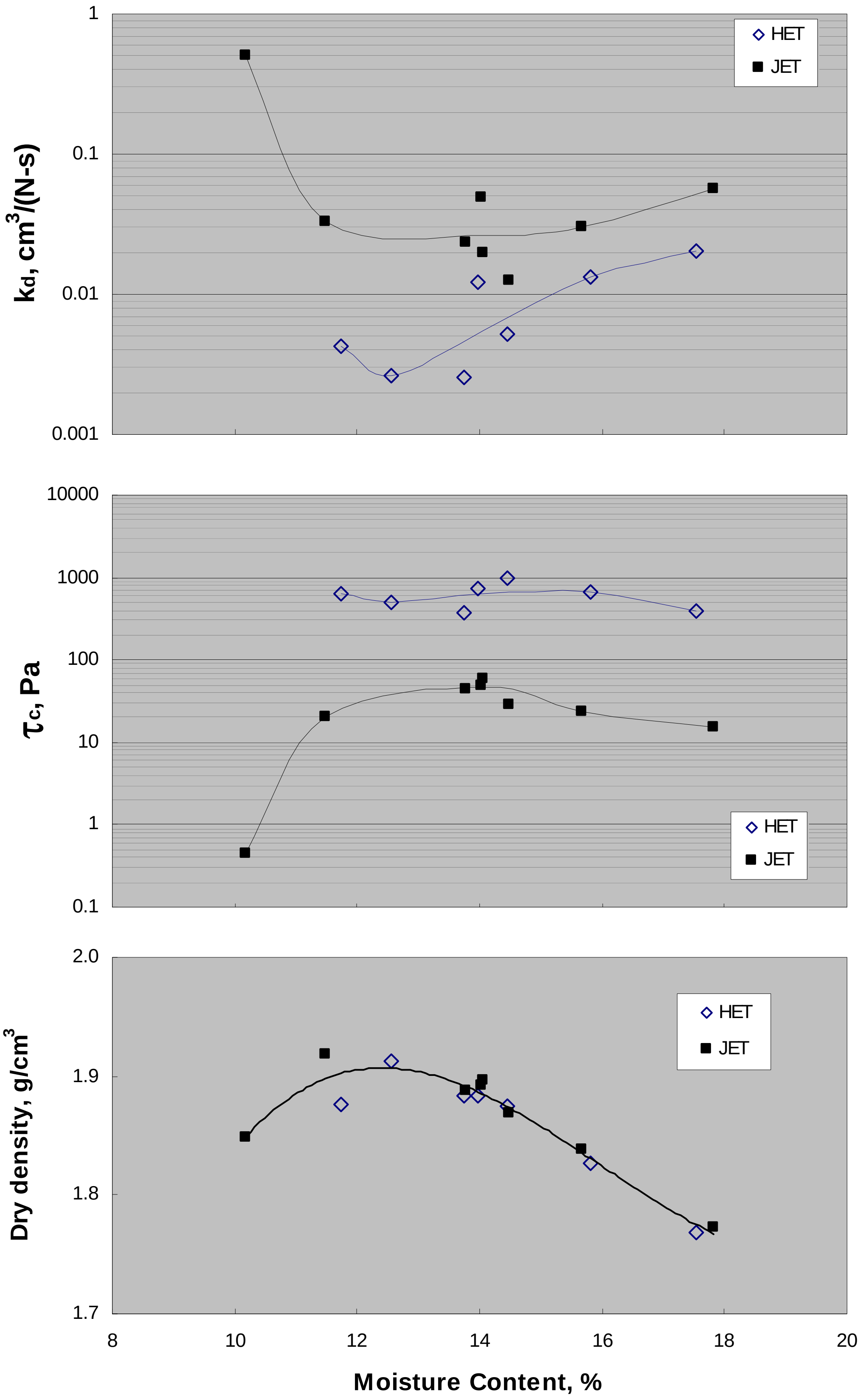


Figure 8. — Results of erodibility tests on soil P3 at compaction moisture contents ranging from about 3% dry of optimum to 5.5% wet of optimum.

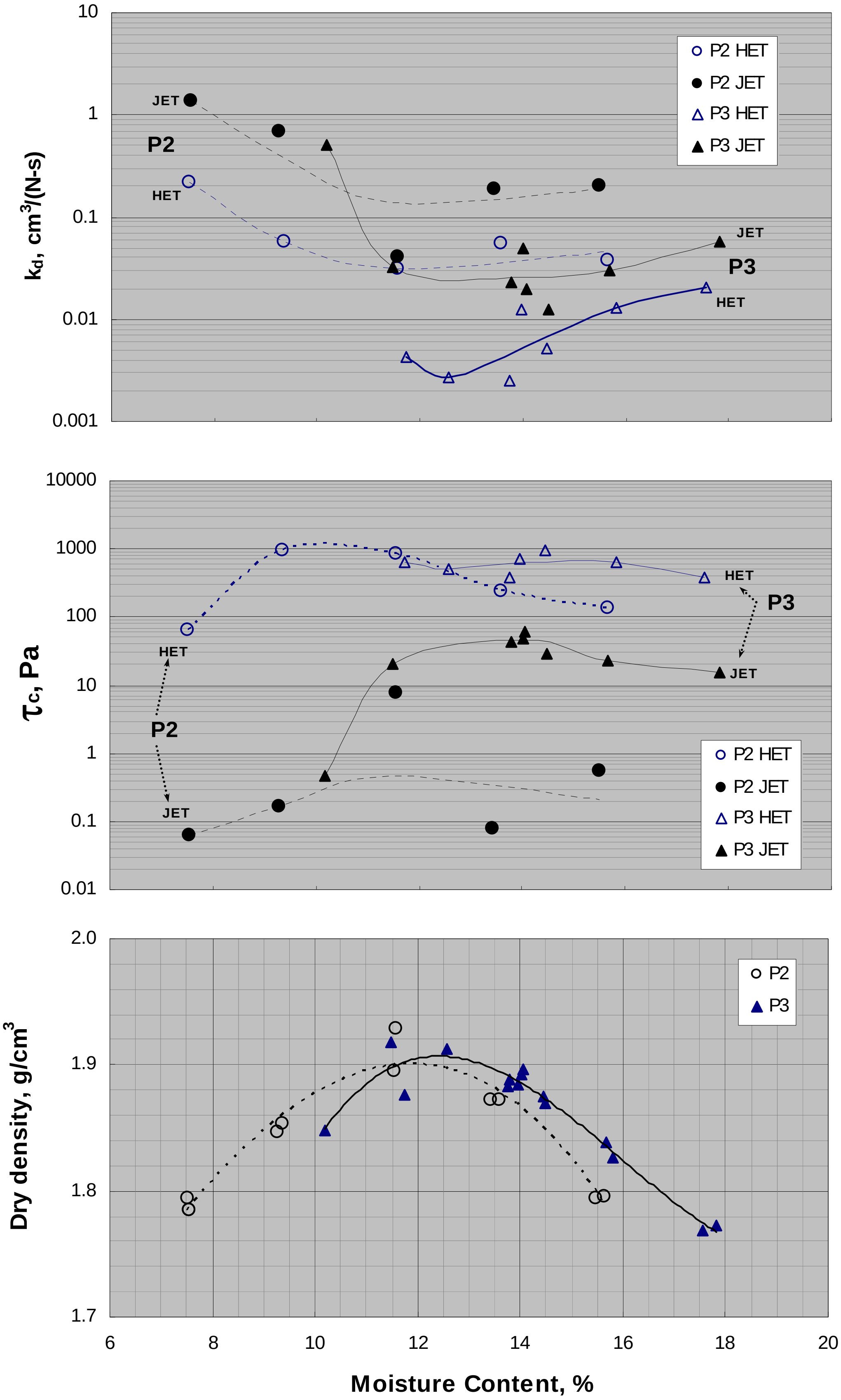


Figure 9. — Variation of erodibility for soils P2 and P3 as a function of compaction moisture content.

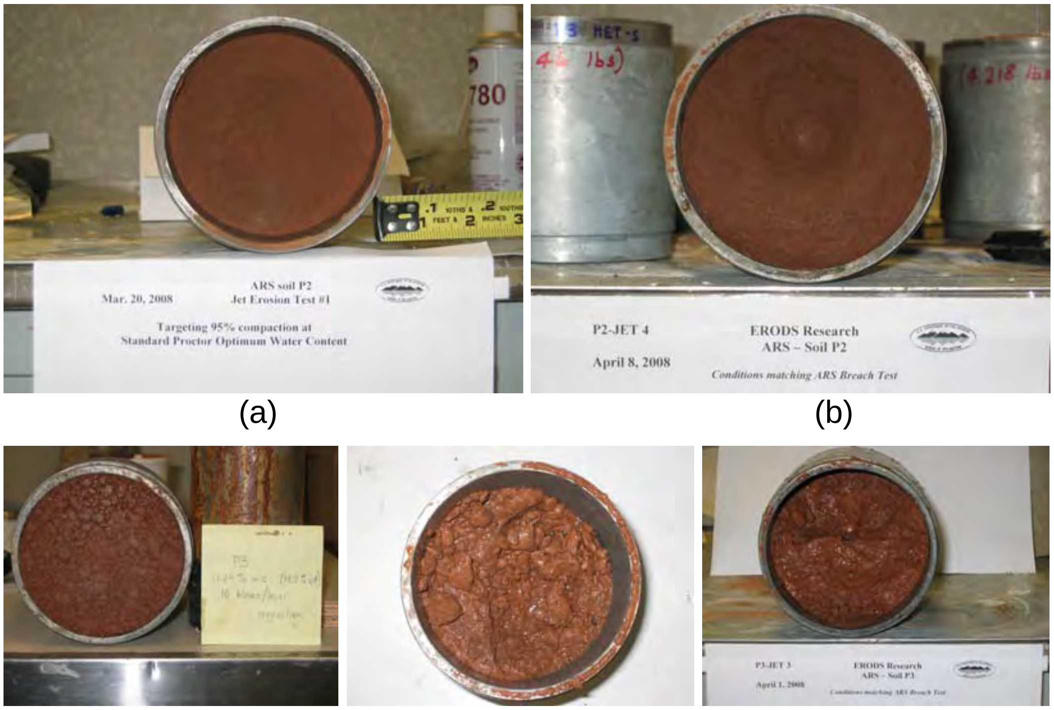
performed on soil P3 at the nominally 4% dry condition experienced excessive local scour at the entrance and exit and erratic variations in flow during the test, making analysis impossible; this probably indicates a material with high erodibility, so the HET may have been as sensitive as the JET to the effect of dry compaction of this soil. Unfortunately, performing a successful test becomes difficult with the HET as the soil becomes more erodible.

Discussion of HET and JET Differences

A host of factors probably contribute to the differences in erodibility parameters obtained from the two tests. The most important of these are believed to be the inherent differences in the nature of the hydraulic attack upon the eroding surface in each test, the way that the flow exploits different weaknesses in the soil structure, and differences in the geometry of the exposed soil surface.

Briaud (2008) has suggested that soil erodibility may depend fundamentally on three different types of stress: pure shear stress, turbulent fluctuations of shear stress, and turbulent fluctuations of normal stress. Adequately controlling, describing, and utilizing these different stresses individually for the analysis of soil erodibility in these test environments is beyond our present capability. If the different types of stress are correlated to one another in a given test environment, it may not be necessary to isolate the effects of each stressor in order to obtain useful results (i.e., we can still simply correlate erodibility to shear stress). However, when comparing the HET and JET methods, it is easy to imagine that the relative influence of the three types of stress may not be the same in the two test environments. This may be the greatest fundamental reason for the differences observed in the results.

Soil fabric is recognized to play an important role in determining erodibility, and these two tests may have different sensitivity to it. Clay materials that are compacted in a dry-of-optimum state have a chunky characteristic in which some soil aggregates remain independent, separating larger masses of conglomerated particles (clods) so that the entire soil mass does not mold into one coherent unit. Soils with this type of fabric structure seem especially susceptible to greater erodibility in the JET. The submerged jet is able to attack weaker areas around the multiple edges of the clods, whereas in the HET primarily one edge of any given clod is exposed to stress and erosion. The tests of the ARS P2 and P3 soils are potentially an example of the strong influence of soil fabric. Figure 10 shows several of these specimens. Figure 10(a) and (b) are two specimens of P2 that exhibit a fine texture with no visible evidence of distinct peds. Figure 10(c) and (d) are pre- and post-test views of a JET specimen of P3 which was compacted at 14.2% water content and exhibits significant fabric structure. Figure 10(e) is a specimen of P3 compacted at 15.1% water content exhibiting some clods but generally a more uniform soil fabric. When tested in the JET, the coarse-fabric specimens were more erodible than corresponding P2 specimens, but in the HET the P2 specimens were more erodible. For the specimens compacted at the wetter conditions where the soil fabrics were more similar, both the HET and JET showed the P2 soil to be more erodible. It should be noted that the JET erodibility of the P3 specimen with the coarser fabric was surprisingly high compared to jet tests performed by ARS in their laboratory (Hanson and Hunt 2007), but there were some differences between the soils tested at Reclamation and those tested at ARS (Wahl and Erdogan 2008).



(a) (b)

(c) (d) (e)

Figure 10. — Differences in soil fabric of P2 (a,b) and P3 (c,d,e) JET specimens.

The geometric configuration of the sample and the stressed surfaces may also be a factor in the differences between computed erodibility parameters in these two tests. In the HET, the circular hole configuration may allow soil clods to be locked in place by surrounding material, so that even after they have become somewhat disengaged from surrounding particles, they may still be protected by the proximity of the surrounding particles. In contrast, in the JET the exposed surface is initially a plane, which reduces the degree to which small clods can be protected by the integrity of the larger surrounding soil mass. Flakes and thin layers of soil may readily detach and small chunks can be jacked out of place by stagnation pressures that develop in fissures beneath them, whereas they might remain wedged in place inside the confines of the small pre-drilled hole used in the HET. The geometric configuration of the submerged jet also allows it to apply erosive stress to larger scale soil structures, since the jet spreads when it impinges on the soil surface and attacks an area much larger than the nozzle diameter.

In addition to considering differences in erosion mechanics between the two tests, it is also interesting to consider changes in erosion mechanics that take place for different soil specimens in just one test, the JET. Figure 11 illustrates changes in the JET erosion behavior as a function of compaction moisture content. Specimens in the front row of the photo are soil P3 and the back row is soil P2. Specimens compacted about 4% dry of optimum are on the left, and compaction moisture content increases about 2% for each specimen to the right. In the specimens compacted dry, the scour hole is quite broad, reaching the edges of the soil mold. For the samples compacted near optimum moisture, the erosion of the upper surface of the specimen was nearly uniform. For the samples compacted wet of optimum the erosion is again in the form of a scour hole, but this time very deep and narrow. Soil P3 exhibits similar behavior, although the effect is less dramatic than for P2. In contrast, the basic morphology of erosion during the HET did not change across a similar range of moisture contents. This ability for the JET to adapt its erosion mode to the changing properties of the specimens suggests that the JET can exploit weaknesses of particular specimens that often are not exploited in the HET.

Figure 11. — Changes in erosion mode for JET specimens of soils P2 (back) and P3 (front) as a function of changing compaction moisture content. Driest specimens at compaction are on the left and wettest specimens are on the right.

Other factors that may account for the observed differences include inaccurate descriptions of the shear stress environment at the soil surface in each test. For the HET, the pre-drilled hole is relatively short, preventing the establishment of fully developed flow, and causing entrance and exit turbulence and associated scour to be significant. The Slot Erosion Test (SET) also developed by Wan and Fell (2004) uses a 1 meter long soil sample to overcome this problem, but is logistically more difficult to perform as a result. For the JET, normal stresses are not considered in the analysis, but may play a significant role; normal stresses are absent or significantly lower in the HET. Also, the shear stress distribution used in the JET analysis was developed for impingement against a planar surface, but this condition is only present at the start of a test, before scour occurs. Both tests may be affected by changes in turbulence intensity that accompany changes in test head and flow rate.

Another factor may be the fact that the tests work opposite to one another, with the HET progressing from a low stress condition toward higher stresses, and the JET beginning with a high stress condition and approaching the low stress condition. If soil erodibility is not truly linear over a range of stresses, then one should expect different results from the two tests for this reason alone. Many of the HETs on soil 55T-160 exhibited nonlinear relations between erosion rate and applied stress. Figure 12 shows one example. One physical explanation for this effect is that the roughening of the interior surface of the hole as erosion takes place may create a more pronounced boundary layer in the flow, so that a given computed stress level becomes less effective for causing erosion as a test progresses.

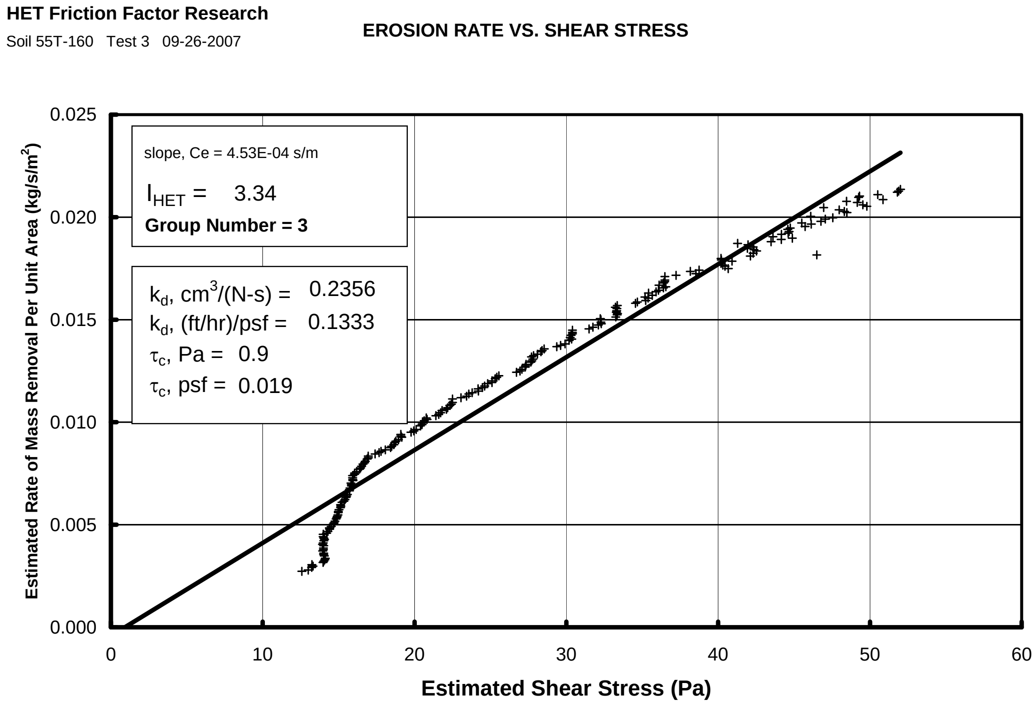


Figure 12. — Example of nonlinear relation between erosion rate and applied stress.

One side effect of fitting a linear model to nonlinear behavior is that the length of the test can change the result. This is shown in Figure 13, where the erosion index for soil 55T-160 increases (indicating more erosion resistance) with increasing duration of the progressive erosion phase. It is notable that the shortest duration HETs on the 55T-160 soil have erosion indices that are approaching the values obtained from the two jet tests performed on that material. It is also notable that the two jet tests performed on 55T-160 were conducted in different stress ranges (by adjusting the test head), and the test performed at the lower stress (starting closer to the critical stress condition) produced a lower erosion index. This would be

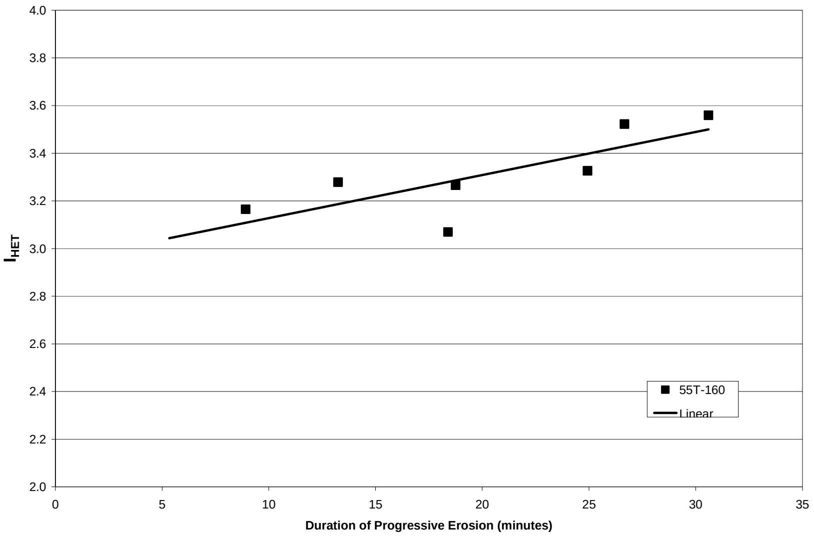


Figure 13. — Variation of I_{HET} as a function of the duration of the progressive erosion phase of each test.

consistent with the shape of the erosion versus stress curve shown in Figure 12. Finally, Figure 14 shows the effect of test duration on the critical stress obtained from the HETs on soil 55T-160. Shorter tests found higher critical stresses, which is again consistent with Figure 12.

Practical Considerations

Experience gained with the soils described in this study was valuable for identifying practical difficulties encountered in the testing of specific soil types.

The HET proved to be the more difficult of the two tests to successfully carry out. It worked well for soils with intermediate strength, but was difficult to conduct with both very weak and very strong soils. Weak soils often collapse during the test or experience scour around the entrance and exit of the hole. Some of this scour seems to be related to gravitational forces. Weak soils often experience slope failures around the entrance and exit holes, either before the test is begun, during the test, or after the test when removing the specimen for examination. Although such “failures” do indicate erodibility to some degree, they confound a quantitative analysis since their mechanism does not fit the model used to analyze HET data. The use of confining upstream and downstream end plates and porous mesh filters to reduce turbulence at the entrance is sometimes helpful, but not always successful. End plates can help to prevent slope failures at the entrance and exit, but promote scour, especially at the exit when material from the roof of the hole caves in, leaving a cavity larger than the exit orifice of the end plate. This creates recirculation at the exit that leads to further scour. Sometimes the downstream scour hole advances upstream in a manner similar to a headcut process, even though most of the length of the pre-drilled hole does not erode. With soils of this type, a successful test can sometimes be conducted by starting at a larger head, one that is sufficient to cause erosion of the hole at the same time that scour of the ends is occurring. Still, one must be careful to complete the test before the upstream and downstream scour holes reach one another and completely breach the specimen. The experience at the Bureau of Reclamation has been that at least 2 to 3 trials are often needed of a weak soil in order to produce one successful test.

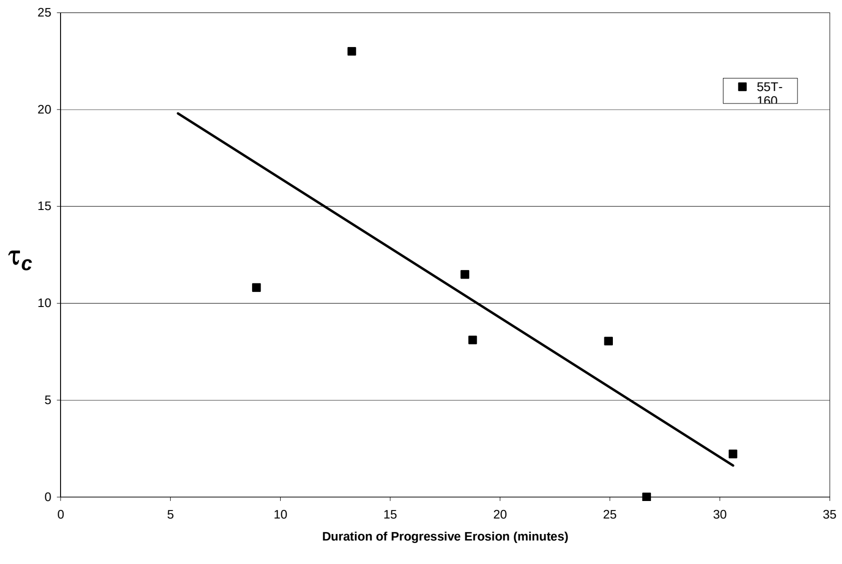


Figure 14. — Variation of critical stress obtained from HETs as a function of the duration of the progressive erosion phase of each test.

Very erosion resistant soils are too strong to test at the heads that can be easily produced in typical laboratory settings. A high-head HET has recently been constructed in the hydraulics laboratory at the Bureau of Reclamation, where the ceiling is over 25 ft high. This facility allows test heads up to 5350 mm, but even at this head, some fat clay materials have proven to be nonerodible. Wan and Fell (2004) assigned I_{HET} group 6 ratings to soils that would not erode at heads of 1200 mm, but testing on lean and fat clays in Reclamation's new high-head HET facility has shown that many materials which erode at heads between 1600 and 5300 mm still have rate coefficients high enough to place them in I_{HET} group 4 or group 5.

Another problem encountered with some erosion resistant soils is clogging of the hole during the test. Soils with high clay content and dry of optimum often erode by detachment of clay chunks, which may be large enough to clog the hole. This may be alleviated to some degree by testing at higher heads (capable of pushing the eroded chunks through the hole), or by using a larger pre-drilled hole, which also increases the applied stress.

These problems cause the HET in general to yield many less than ideal tests. The data from these tests can often be salvaged, but require significant subjective interpretation. When making such subjective interpretations it can be helpful to apply both the Wan and Fell deterministic analysis approach and the Bonelli curve-fit approach, separately, or in combination (i.e., using the Wan and Fell method to estimate the starting conditions for the Bonelli analysis).

In contrast to the HET, the JET test is more easily applied to a broader range of weaker and stronger soils. With a vertical jet orientation, gravity works to hold the sample together, rather than cause premature failure by unplanned mechanisms as in the HET. The JET works well with almost all cohesive soils, except those that contain a significant fraction of coarse sand or fine gravel particles that are not easily transported out of the hole. For very weak soils, test durations are usually quite short, but with care, enough data can be obtained to allow for successful analysis. With weak soils, one must be careful to stop data collection when the sides of the deepening scour hole begin to slide down into the bottom of the hole (otherwise, the scour depth may be observed to *decrease* with time). In general, the JET produces usable results more often than the HET and requires less application of subjective judgment to interpret the data. This makes it a more objective method that will produce more repeatable results.

Erodibility Classifications and Scope of Test Capabilities

The developers of the two tests studied here have each suggested erodibility classification schemes utilizing the test results (Hanson and Simon 2001; Wan and Fell 2004). The work reported here and other recent experience with HET and JET testing at the Bureau of Reclamation provide a useful database for examining the capability of each test to successfully test materials across the spectrum of these classification systems.

Figure 15 shows the results of 61 laboratory HETs and 47 laboratory and field JETs performed by the Bureau of Reclamation since 2007. These include the tests reported previously in this report, and other laboratory and field testing of remolded and undisturbed soil and soft-rock (claystone or siltstone) samples. The figure shows that although the HETs in general exhibit lower detachment rate coefficients and higher critical shear stresses, both sets of data generally follow the best-fit line proposed by Hanson and Simon (2001) for JET results. This suggests that both tests are measuring an intrinsic erodibility property of soils, albeit with significant bias between their results, perhaps for some of the reasons previously discussed.

The HET results shown in Figure 15 represent reasonable upper and lower limits on the application of the HET device in its current configuration, with the highest k_d values being for materials that were nearly too weak to be tested and the lowest k_d values corresponding to stiff clay materials that were so erosion resistant that progressive erosion could barely be produced at heads up to 5400 mm. The highest I_{HET} value obtained from any test in which progressive erosion took place was about 5.3, and the lowest was about 2.5. This corresponds to the nearly 3 orders of magnitude difference in k_d values shown for HETs in Figure 15. The test in its current configuration cannot provide a quantitative measure of the erodibility of many materials in groups 1-2 and 5-6.

There is the potential for the HET to be applied successfully to more erosion resistant soils by modifying the facility to allow a larger maximum head. The use of an elevated head tank is probably not feasible for higher heads, but a pressurized water source with a regulator or flow bypass/waste system could be used. A higher range pressure transducer would also be needed, which would reduce the sensitivity of head measurements during low-head tests. Considering the relation between erosion rate and critical shear stress proposed by Hanson and Simon (2001), an increase in critical shear stress of two orders of magnitude is needed for each one order of magnitude decrease in erosion rate. Thus, a facility with a 10.5 m head range (approximately 15 lb/in^2) would probably be capable of testing materials with I_{HET} values up to about 5.35; to cause progressive erosion of materials with an I_{HET} value of 6.0 might require pressures approaching 210 m of head (300 lb/in^2), which would be likely to cause cavitating flow through the pre-drilled hole. Considering soil and rock erodibility classification schemes of various authors (see Briaud 2008), it seems likely that materials with I_{HET} values of 6 or greater would be rock rather than true soils. Even these modifications would give the test a range of measurable erosion rates that spans only about 3.5 orders of magnitude. The inability to quantitatively measure erodibility of weaker soils is the most significant limit on HET applicability.

Other options for testing more erosion resistant materials with the HET include pre-drilling a larger hole, or using a shorter test specimen, thereby increasing the hydraulic gradient. The former approach has been used in a few instances at Reclamation, but significantly larger holes also require much higher flow rates, so the real benefit is limited unless flow capacity of the facility is also greatly increased. As for reducing the specimen length, it is probably already shorter than desirable from a hydraulic standpoint, with insufficient length to allow establishment of fully developed flow. An even shorter specimen would probably further exaggerate any existing discrepancies between the real applied stress and the idealized stress description used to analyze the test data.

Figure 15 shows that the JET is capable of performing successful tests across a broader range of materials, and is especially able to test weaker materials that simply disintegrate in the HET. Reclamation's applications have successfully measured detachment rate coefficients varying over about 4.5 orders of magnitude, and considering the work of Hanson and Hunt (2007) and Hanson and Simon (2001), one finds that 5.5 orders of magnitude can be covered, from k_d values of 0.001 to 300 cm^3/N·s. Tests of the most erodible materials must be performed carefully because erosion occurs very quickly, and successful use of the apparatus for the most erosion resistant materials does require the use of a pressurized water supply. The most erodible data point in Figure 15 was a Silty Sand (SM) that was tested for only about 2 minutes before the sample was completely eroded. The most erosion resistant JET data point in Figure 15 was obtained in a test performed *in situ* on a claystone/siltstone material, using a jet pressure of 24 lb/in^2 (16.9 m of water head), which was able to produce only 0.6 mm of scour in a 1 hour test. The shear stress applied by the JET can also be increased by using a larger nozzle, with a commensurate requirement for increased flow.

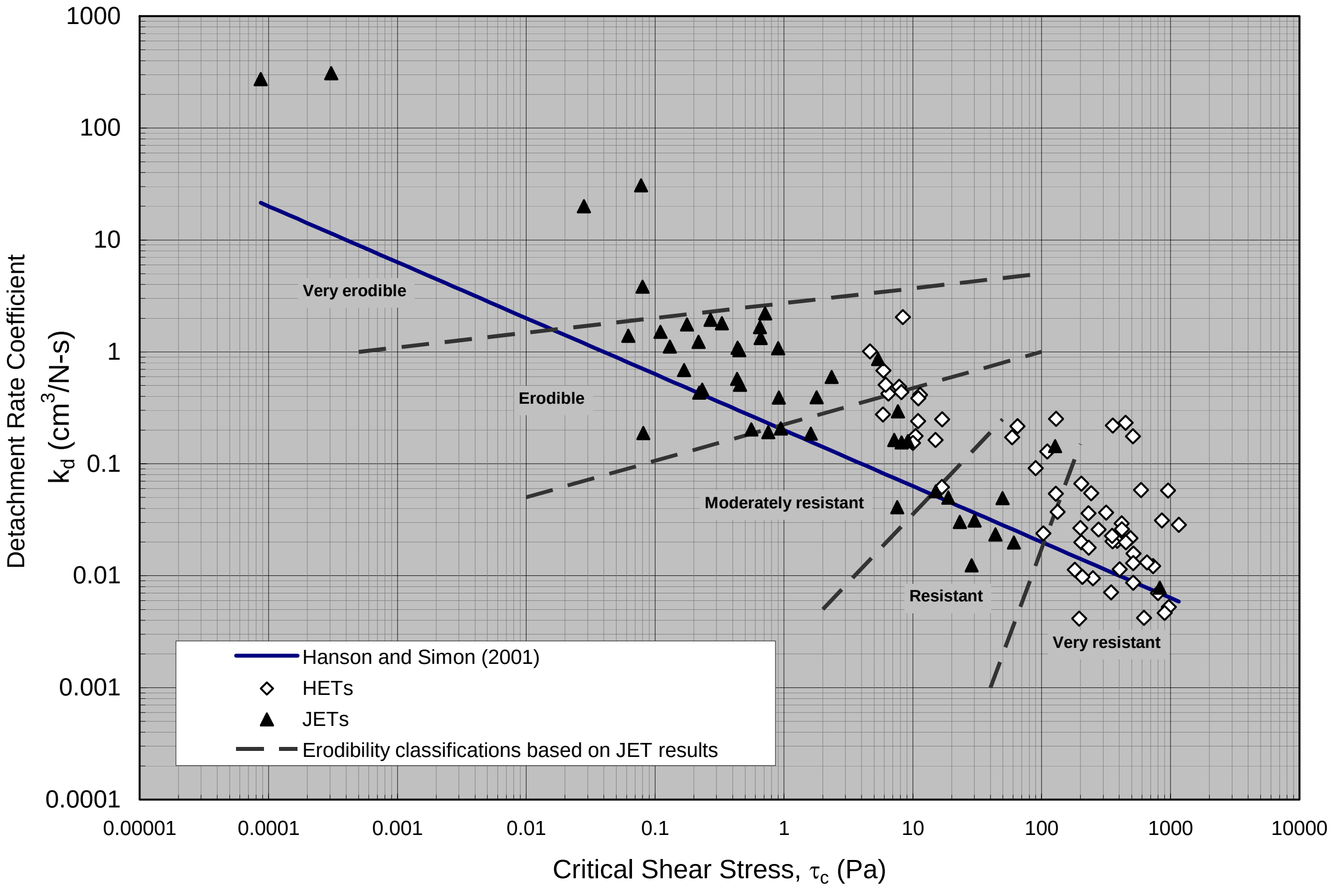


Figure 15. — HET and JET data collected by the Bureau of Reclamation in field and laboratory tests since 2007.

Applications for the HET and JET

Given the differences in test results observed here, the selection of which test to use for a specific application should be made primarily on the basis of the desired application of the data. The HET probably is the best test when one is trying to understand erosion through small holes or confined cracks, such as that which probably occurs during the initiation of internal erosion and piping failures of embankments. In contrast, the JET is probably best for studying erosion due to overtopping flow, and may also be best for studying erosion in larger, developing erosion pipes where the size of the flow channel is greater than the size of the soil structural elements that define the soil fabric. Identifying the transition between best applicability of the two tests during the progression from piping initiation to piping-caused breach of an embankment is still a subject for further research.

Conclusions

This study has shown the following:

- The HET and JET methods yield significantly different estimates of the erosion index (rate coefficient) and critical stress, especially for the more erosion resistant soils included in this investigation. The HET generally indicates slower rates of erosion and higher critical stresses.
- Differences between the HET and JET method seem to be most dramatic in soils having a coarse fabric or structure, such as clays compacted dry of optimum. These

soils often have a clumpy structure with seams of independent aggregates between lumps of clay. The JET method seems able to exploit these weak zones more effectively than the HET. Differences between HET and JET results seem reduced (but still very significant) when materials have a more uniform consistency.

- Variability of the computed erosion rate coefficients and critical shear stresses is large for both methods, about one order of magnitude for the soils tested in this study. This is probably mostly a result of sample-to-sample variability of the compacted materials.
- Test procedures may affect the correlation between the HET and JET methods, since some of the data collected here showed that the erosion-shear stress relation is not linear. This can cause the test duration and the applied stress range to affect the result.
- The JET method is more easily and successfully applicable to a wider range of soils. The HET works well with soils of intermediate erodibility which erode with relative ease but have sufficient strength to resist hole collapse and local scour—erosion mechanisms that are inconsistent with the assumptions underlying the HET analysis method. Very weak or strong soils often require multiple attempts before a set of data are produced that can be successfully analyzed. The JET method is more often successful over a broader range of soil erodibilities.
- The need for subjective data analysis is generally greater with the HET method, since many tests are affected to some degree by intermittent clogging of the pre-drilled hole or localized scour erosion at the entrance and exit of the pre-drilled hole.
- Selection of a test for a specific application should be made with consideration for the intended use of the data and the erosion mechanisms that will be most important in the application. Interpretation of the data should be made using techniques developed for the specific test because of the widely differing erosion rates and critical shear stresses indicated by the two tests.
- The greater robustness of the JET suggests that for utmost utility, effort should be devoted to the development of piping erosion models that can utilize erodibility parameters obtained from the JET.

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