A COMPARISON OF THE HOLE EROSION TEST AND JET EROSION TEST

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Abstract: The hole erosion test (HET) and submerged jet erosion test (JET) were compared and evaluated for their ability to determine the erodibility of cohesive soils typically encountered in the modeling of embankment dam erosion and breach processes. The tests were applied to a set of remolded soil specimens prepared in parallel for each test, representing a range of cohesive soils. The methods ranked the relative erodibility of soils similarly, but produced significantly different estimates of the detachment rate coefficient and the threshold shear stress needed to initiate erosion. Both tests produced results that were consistent with a single previously established relation between erosion rate and threshold shear stress. The JET offers the greatest practical potential for characterization of a wide range of soils, but the HET may still be desirable for application specifically to piping erosion situations. The significant differences in the magnitude of the erodibility parameters obtained from each test should be accounted for in the design of erosion models.

BACKGROUND

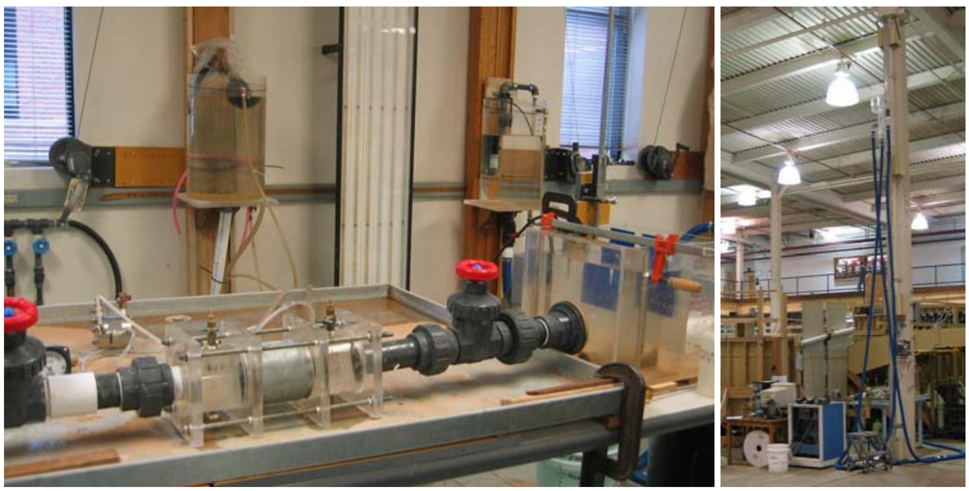
Erosion of cohesive soils is a fundamental process affecting embankment dams, levees, and associated structures. Overtopping flow and seepage flow both have the potential to cause erosion leading to embankment breach. Headcut erosion in unlined earthen spillways also has the potential to cause spillway breach with similar catastrophic downstream flooding potential. Improved methods for modeling these erosion processes are focusing on the incorporation of quantifiable erodibility parameters that can be estimated from basic soil properties or measured by laboratory or *in situ* field testing. Erodibility is such a complex parameter that direct erodibility testing is greatly preferred whenever possible. This study compares two methods for measuring the erodibility of cohesive soils, the hole erosion test (HET) and the submerged jet erosion test (JET). The methods were compared, contrasted, and evaluated to identify their practical advantages and disadvantages.

The hole erosion test (Wan and Fell 2004) and the jet erosion test (Hanson and Cook 2004) are two potential methods for evaluating the erodibility of cohesive soils. The hole erosion test (HET) utilizes an internal flow through a hole pre-drilled in a test specimen, similar to a piping erosion situation, while the jet erosion test (JET) uses a submerged hydraulic jet to produce scour erosion, similar to processes that occur at a headcut or a free overfall. Both tests yield estimates of the critical shear stress needed to initiate erosion and a detachment rate coefficient that defines the rate of soil removal per unit of applied excess stress. Because of fundamental differences in the flow situation, stress environment, and erosion processes associated with each test, there are questions as to whether both tests yield similar erodibility parameter estimates. This paper provides a summary of research undertaken to answer these questions. Additional details and other aspects of this work have 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 6.35-mm (¼ -in.) diameter hole is pre-drilled through the axis, and the specimen is 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 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 the time history of the applied shear stress and erosion rate. The relation between the shear stress and resulting erosion rate defines basic erodibility parameters for the soil. Significant post-test work is needed to obtain the measurement of the final diameter (oven-drying, casting of a plaster mold of the eroded hole, and measurement of the casting diameter at several locations using calipers).

Figure 1 shows the HET equipment used 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 in the laboratory for long-term use.

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 diameter 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, so clogging of the erosion hole by soil chunks or small gravel particles is possible. These phenomena make interpretation difficult in some cases. Another important phenomenon 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 constant head combined with increased flow leads to an increase in applied shear stress, so the erosion rate continues to increase. 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.*



(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. The test is described in ASTM Standard D5852.

The JET apparatus attacks the soil surface with a submerged hydraulic 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 that passes through the nozzle. No post-test handling or processing of the specimen is needed.

Figure 2 shows the laboratory JET apparatus used in the Bureau of Reclamation 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 steel submergence tank for field use.

Erodibility Parameters:

HET and JET data have typically been analyzed to determine two parameters of a detachment-driven erosion equation expressed in terms of either mass rate of erosion or volumetric erosion:

$$\dot{m} = C_e(\tau - \tau_c) \quad \text{or} \quad \dot{\varepsilon} = k_d(\tau - \tau_c)$$

where $\dot{m}$ is the rate of mass removal per unit of surface area (kg/s/m^2), τ and τ_c are the applied shear stress and threshold shear stress for soil detachment, respectively, C_e is a proportionality constant called the coefficient of soil erosion (Wan and Fell 2004), and k_d is a similar proportionality constant that Hanson and Cook (2004) termed the detachment rate coefficient. The equation applies only for $\tau > \tau_c$; otherwise, the erosion rate is zero. S.I. units for C_e are kg/s/m^2/Pa which simplifies to s/m. S.I. units for k_d are m^3/N·s or cm^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.

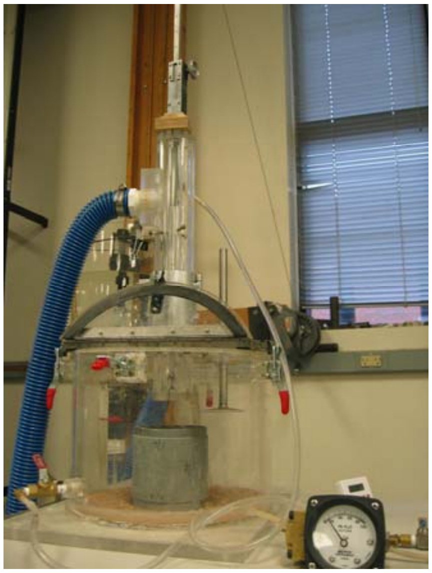


Figure 2. — Laboratory JET apparatus.

The proportionality constants for erosion rate vary over several orders of magnitude in soils of engineering interest. For convenience, Wan and Fell proposed a second parameter, the Erosion Rate Index, $I_{HET} = -\log_{10} C_e$, 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

EXPERIMENTAL APPROACH

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 soils and their basic properties are shown in Table 2. The first 5 soils in the table were obtained from stockpiles in Reclamation's laboratories, while the last 5 were provided to Reclamation by the Agricultural Research Service (ARS) hydraulics laboratory in Stillwater, Oklahoma. Soils from the same borrow sources were used previously by ARS for a series of embankment piping breach tests (Hunt et al. 2007). Samples of the P2 and P3 soils were provided to Reclamation at two different times, with only slight variation in their properties.

For the first series of tests, paired specimens of each soil were created with essentially identical compaction moisture and compaction effort and then tested by the HET and JET methods. A second series of tests were conducted on multiple specimens spanning a range of moisture conditions. The HET and JET specimens in this second test series were all prepared with the same compaction effort over the same range of moisture conditions to allow the resulting curves of erodibility versus compaction moisture content to be compared. Detailed results of the various tests are provided by Wahl et al. (2008) and Wahl and Erdogan (2008).

Table 2. — Properties of tested soils.

					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	data not available					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 individual specimens prepared with the same compaction effort and moisture content. In some cases, samples were not truly paired, as multiple 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. HET specimens were tested with the last compacted soil layer located upstream.

Figures 3 and 4 provide graphical comparisons of the erosion rate coefficients (expressed in terms of the logarithmic index proposed by Wan and Fell [2004]) and critical shear stress values. On the charts, soils are ranked roughly from most to least erodible, and with a couple of exceptions both tests indicate similar rank ordering of the soils. Figures 5 and 6 provide scatter plot comparisons with error bars that 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.

Clearly there is significant difference between the numerical 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 are 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 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 is recognized to give 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. This suggests that there would be good agreement in a direct comparison of the JET and RCT. Notably, Lim (2006) also 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}).

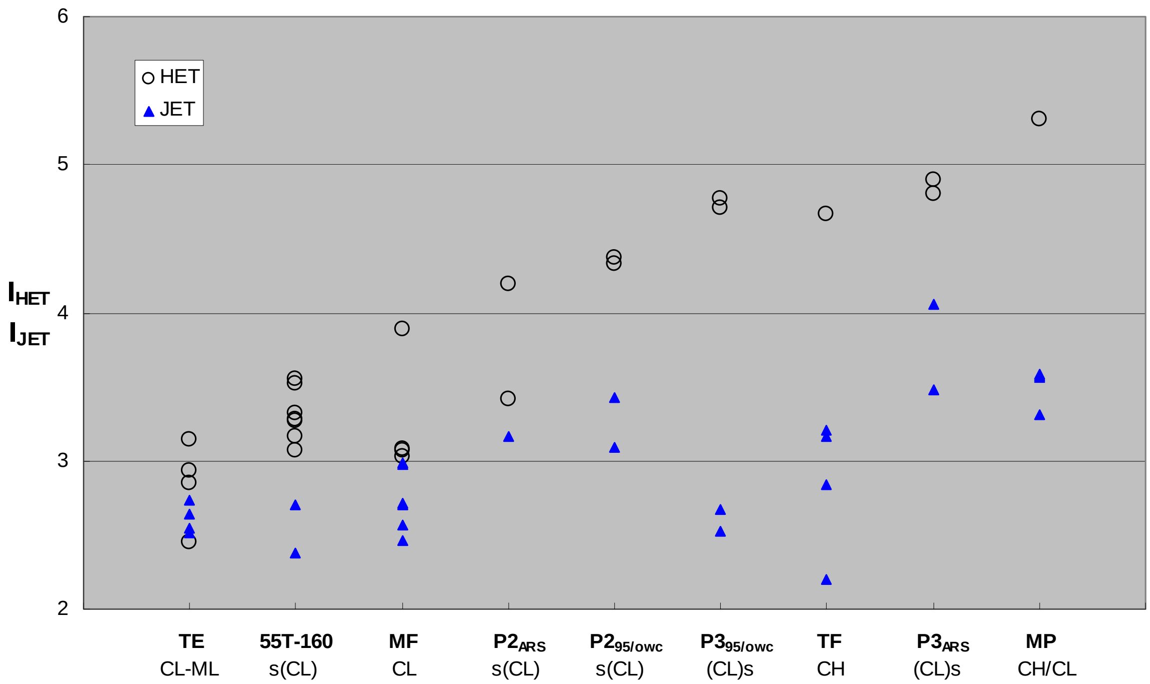


Figure 3. — Erosion rate index values obtained by HET and JET methods, ranked subjectively from most rapid to least rapid erosion rate.

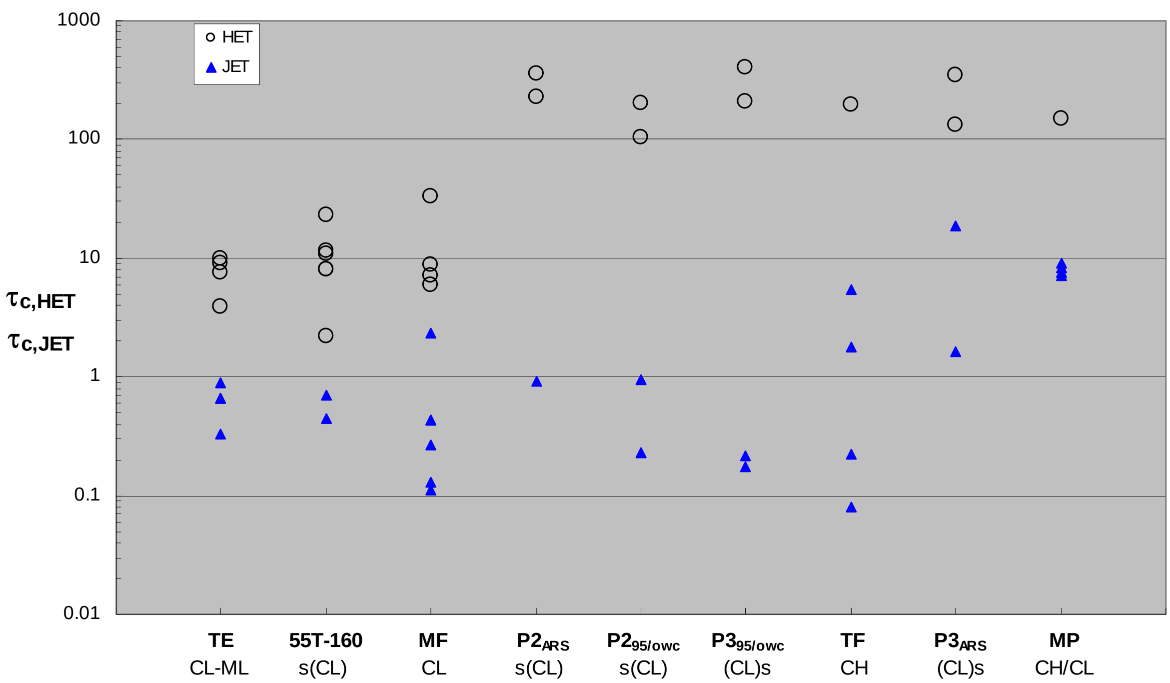


Figure 4. — Critical shear stresses obtained from HET and JET methods, ranked subjectively from most rapid to least rapid erosion rate (same ranking as Fig. 3 above).

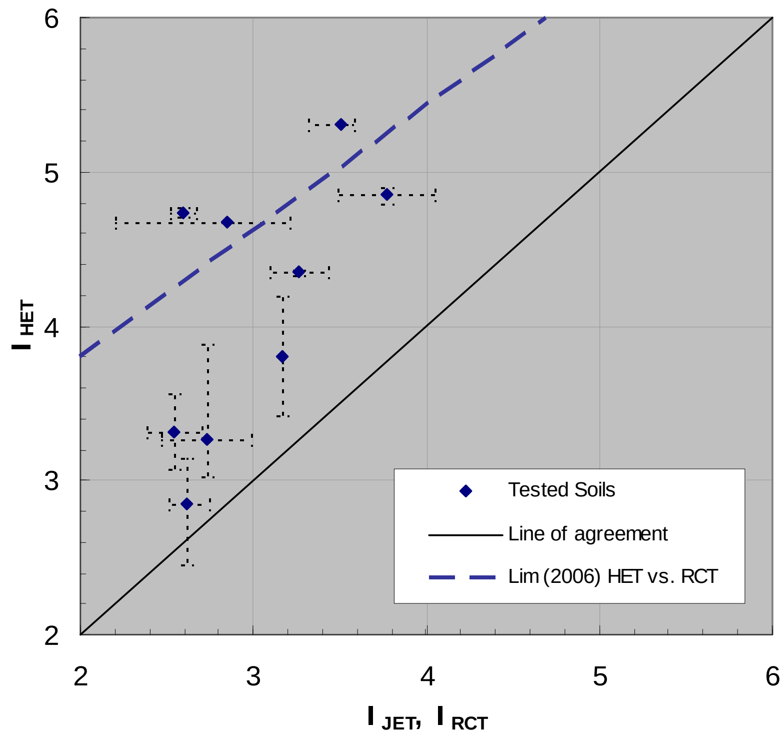


Figure 5. — Comparison of erosion rate indices determined by HET and JET methods, and the relation found by Lim (2006) relating HET and rotating cylinder test (RCT) results for non-dispersive soils.

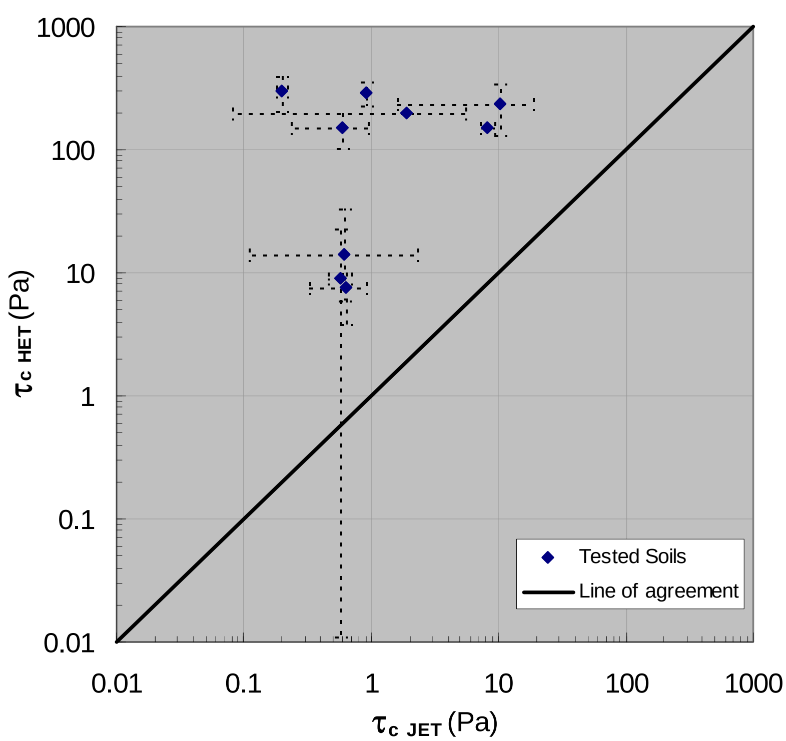


Figure 6. — Comparison of critical stresses determined by HET and JET methods.

HET and JET Erodibility versus Moisture Content: Two of the ARS soils, P2 and P3, were chosen for a 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 3 shows the test results, including subjectivity indices for the HETs. The subjectivity index was developed 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.

Table 3. — 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/cm³	τ_c Pa	k_d cm³/(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	-

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. This effect is enough 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 on other soils native to the ARS laboratory.

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 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: Wahl et al. (2008) discuss many factors that may contribute to the differences in erodibility parameters obtained from the two tests. The most important of these are believed to be the accuracy of the stress descriptions used in each analysis, inherent differences in the nature of the hydraulic attack upon the eroding surface, the way that the flow exploits different weaknesses in the soil structure, and differences in the geometry of the exposed soil surface.

One important 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. The HET is typically performed in a stress range just above the critical stress value, while the JET can be performed at stress levels that far exceed the critical stress. 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.

Practical Considerations: Experience gained with the soils described in this study was valuable for assessing the practicability of the two tests.

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. Weak soils also tend to 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 they also 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 enlarge. With soils of this type, a successful test can sometimes be conducted by starting at a larger head, one that is sufficient to cause enlargement 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 Reclamation has been that at least 2 to 3 trials are often needed of a weak soil in order to produce one successful 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 Reclamation in a space where the ceiling is over 25 ft high. This facility allows test heads up to about 5400 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 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.

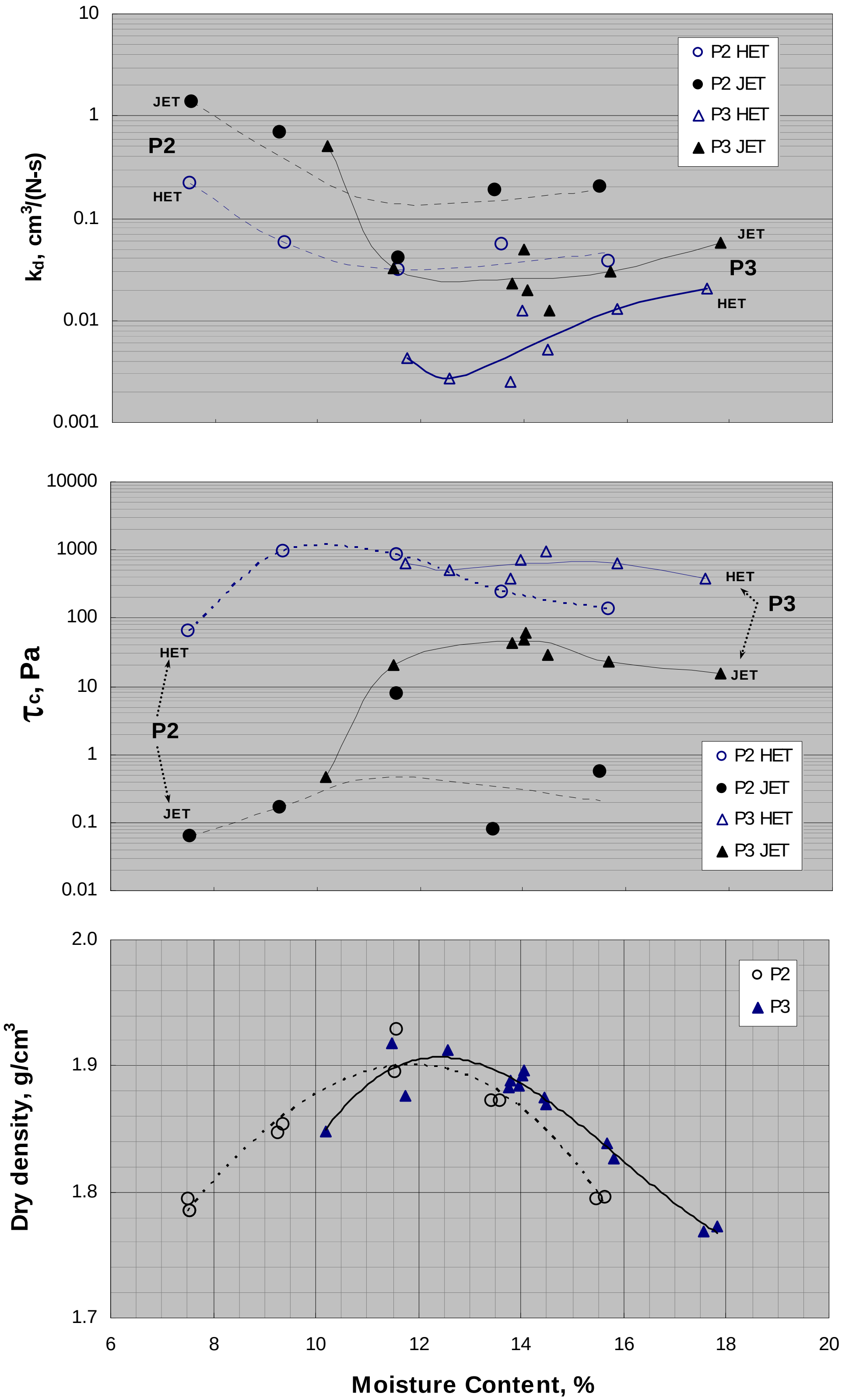


Figure 7. — Variation of erodibility for soils P2 and P3 as a function of compaction moisture content.

Another problem encountered with some erosion resistant soils is clogging of the hole during the test. Soils with high clay content that have been compacted dry of optimum often erode by detachment of clay chunks that 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.

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 Reclamation provide a useful database for examining the capability of each test to successfully test materials across the spectrum of these classification systems.

Figure 8 shows the results of 61 laboratory HETs and 47 laboratory and field JETs performed by 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 range of HET results shown in Figure 8 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 8. 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, 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

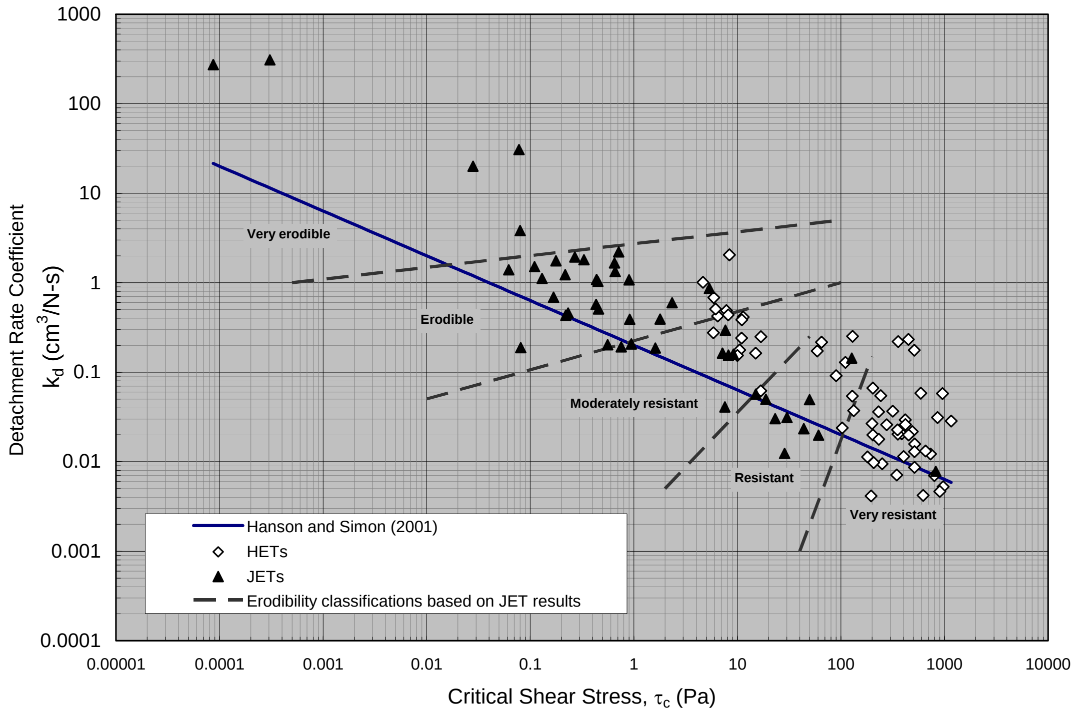


Figure 8. — HET and JET data collected by the Bureau of Reclamation in field and laboratory tests since 2007. Erodibility classifications are from Hanson and Simon (2001).

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 8 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 (2006) 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 8 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 8 (k_d=0.008 cm^3/N·s) 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. Hanson and Simon (2001) reported detachment rate coefficients as low as 0.001 cm^3/N·s in cohesive streambank soils from eastern Nebraska and Mississippi. For testing of very resistant soils, the shear stress applied by the JET can also be increased by using a larger nozzle, with an associated need for increased flow rate.

CONCLUSIONS

- The HET and JET methods produced similar rankings of the relative erodibility of different soils, but significantly different quantitative estimates of the key erodibility parameters themselves. Differences in the erodibility parameters 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 were relatively consistent with a single relation between erosion rate and threshold shear stress.

- 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 most likely is a result of sample-to-sample variability of the compacted materials.

- The JET method is more easily and successfully applicable to a wide 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. Very weak or strong soils often require multiple test attempts and subjective data analysis. The JET method is more often successful over a broader range of soil erodibilities.

- 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 use with the specific test, because of the widely differing erosion rates and critical shear stresses indicated by the two tests. Presently, the JET has been applied mostly to situations of overtopping flow (dam and levee breach by overtopping) and open channel flow erosion (spillways), while the HET has been applied to problems of internal erosion (piping). The greater robustness of the JET suggests that efforts should be made in the future to develop piping erosion models that can utilize erodibility parameters obtained from the JET.

REFERENCES

ASTM. 2007. Standard D5852. Standard test method for erodibility determination of soil in the field or in the laboratory by the jet index method. Annual Book of ASTM Standards, Section 4: Construction, Vol. 04.08. Philadelphia, Penn.: American Society for Testing and Materials.

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., Simon, A., and Cook, K.R., 2002. Non-vertical jet testing of cohesive streambank materials, Paper No. 022119, American Society of Agricultural Engineers, Annual International Meeting, Chicago, Illinois, July 28-31, 2002.

Hanson, G.J., and Cook, K.R., 2004. Apparatus, test procedures, and analytical methods to measure soil erodibility in situ. *Applied Engineering in Agriculture*, Vol. 20, No. 4, pp. 455-462.

Hanson, G.J., and Hunt, S.L., 2006. Lessons learned using laboratory jet method to measure soil erodibility of compacted soils. *Applied Engineering in Agriculture*, Vol. 23, No. 3, pp. 305-312.

Hunt, S.L., Hanson, G.J., Temple, D.L., and Tejral, R., 2007. Earthen embankment internal erosion research. In *Dam Safety 2007*. Proceedings of the 24th Annual Meeting of the Association of State Dam Safety Officials, Austin, TX September 9-12, 2007.

Lim, S.S., 2006. Experimental investigation of erosion in variably saturated clay soils. A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, School of Civil and Environmental Engineering, the University of New South Wales, Australia, 324 pp.

Moore, W.L. and Masch, F.D., Jr., 1962. Experiments on the scour resistance of cohesive sediments. *Journal of Geophysical Research*, Vol. 67, No. 4, April 1962, pp. 1437-1449.

Regazzoni, P.L., Marot, D., Courivaud, J.R., Hanson, G., and Wahl, T., 2008. “Soils Erodibility: A Comparison between the Jet Erosion Test and the Hole Erosion Test,” Inaugural International Conference of the Engineering Mechanics Institute, Minneapolis, MN May 18-21, 2008.

Wahl, T.L., Regazzoni, P.-L., and Erdogan, Z., Determining Erosion Indices of Cohesive Soils with the Hole Erosion Test and Jet Erosion Test, Dam Safety Office Report DSO-08-05, U.S. Dept. of the Interior, Bureau of Reclamation, Denver, CO.

Wahl, T.L., and Erdogan, Z., 2008. Erosion indices of soils used in ARS piping breach tests. U.S. Dept. of the Interior, Bureau of Reclamation, Hydraulic Laboratory Report HL-2008-04, 142 pp.

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