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Practical Improvements for the Hole Erosion Test

Tony L. Wahl[1], Pierre-Louis Regazzoni[2], and Zeynep Erdogan[3]

[1] Hydraulic Engineer, U.S. Dept. of the Interior, Bureau of Reclamation, P.O. Box 25007, Denver, CO 80225-0007; (303) 445-2155; twahl@usbr.gov.
[2] Ph.D. student, Université de Nantes, Institut de Recherche en Génie Civil et Mécanique, GeM, Saint-Nazaire Cedex, France.
[3] Civil Engineer, U.S. Dept. of the Interior, Bureau of Reclamation, Denver, CO.

ABSTRACT

The constant-head hole erosion test (HET) is one of several available procedures for characterizing the erodibility of cohesive soils important to internal erosion investigations of dams and levees. Measurements of accelerating flow rate through an eroding pre-drilled hole in a test specimen yield estimates of the critical shear stress and erosion rate coefficient. Two methods for analyzing HET data were investigated. The first is a deterministic method in which initial and final eroded hole diameters are used to compute initial and final friction factors, and intermediate hole diameters are then computed from flow rates measured during the course of the test. The variation of the friction factor during HETs was studied and an improved modeling method was developed for estimating intermediate values of the friction factor. The second method for HET data analysis is the fitting of the observed flow rate record to a nondimensional numerical model for piping erosion. This method does not require determination of friction factors nor the measurement of the final hole diameter, which can be problematic. Applying both analysis methods to numerous tests showed that they yield generally similar results. As a result, the Bureau of Reclamation has drafted new procedures for performing HETs and analyzing test data. Unfortunately, tests do not always proceed as planned, so both analysis methods are not applicable to all tests. Thus, Reclamation uses each analysis method as appropriate, based on judgment of the analyst. This increases the rate of test success, although there are still some tests that defy analysis. The applicability of the HET to soils of varying erodibility is discussed and compared to other erodibility test methods.

INTRODUCTION

The hole erosion test (HET) is a widely recognized laboratory procedure for evaluating the erodibility of cohesive soils that might be susceptible to internal erosion. It was first developed in a constant-flow configuration (Lefebvre et al. 1984) and more recently in a constant-head configuration by Wan and Fell (2004). The HET utilizes an internal flow through a hole pre-drilled in the specimen, a flow condition similar to that occurring during piping erosion of embankment dams. In the constant-head configuration, the test head is typically doubled, starting from 50 mm, until progressive erosion of the pre-drilled hole is produced. HET data are analyzed to determine two parameters of a basic detachment-driven erosion equation describing the growth of the erosion hole:

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

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 (critical) shear stress for soil detachment, respectively, and C_e is a proportionality constant, often called the coefficient of soil erosion. Although no standard exists yet for performing the test, it is attractive because of the relative simplicity of the apparatus and the description of data analysis procedures in the literature.

The focus of HET applications thus far has been on the coefficient of soil erosion, which varies over several orders of magnitude in soils of engineering interest. For convenience, a second parameter, the Erosion Rate Index (I_{HET}) is often computed:

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

with C_e 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. Table 1 shows proposed descriptive terms associated with each group number. Soils with group numbers less than 2 are usually so erodible that they cannot be effectively tested in the HET device. The I_{HET} index has been incorporated into recently developed risk analysis models for internal erosion.

Table 1. — Qualitative scale for rates of progression of internal erosion (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 apparatus in the Bureau of Reclamation soils laboratory in Denver, Colorado. Flow rate through the specimen is measured by a custom 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 head that can be applied in the apparatus shown in Figure 1 is about 1600 mm. A newer high-head HET facility was recently constructed in Reclamation's hydraulics laboratory, where a higher ceiling makes it possible to produce test heads up to about 5400 mm.

HET TEST METHODS AND DATA ANALYSIS PROCEDURES

The HET is performed 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. 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. The analysis technique described by Wan and Fell (2004) uses measurements of the increasing flow rate during the test and the initial and final diameter of the erosion hole to compute applied hydraulic stress and the erosion rate. Significant post-test work is needed to obtain the measurement of the final hole diameter. To complete the calculations, initial and final friction factors for the eroding hole must be computed, and estimates must be made of instantaneous values of the friction factor during the test. Wan and Fell (2004) estimated the instantaneous friction factors by linear interpolation as a function of the elapsed test time.

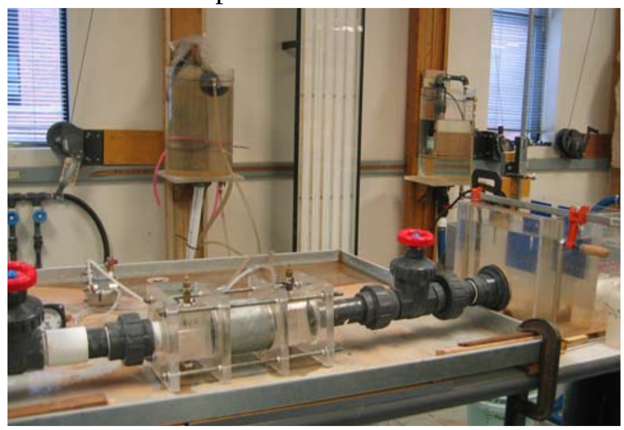

Figure 1. — HET apparatus.

Bonelli et al. (2006) and Bonelli and Brivois (2007) proposed a universal model for piping erosion, applicable to the HET. They showed that the change in dimensionless hole radius is an exponential function of the dimensionless test time and the initial and critical shear stresses. The model assumes turbulent flow conditions throughout the test and neglects any variation of the friction factor, the test head, or the length of the eroded hole. The method also presumes that the test data are collected entirely during the period of progressive erosion. Since flow rates are measured throughout a test and the initial shear stress is known from the starting hole diameter and flow rate, this model has only two unknown parameters, an erosion time scale and the critical shear stress, τ_c. Using a non-linear optimization tool like the Excel Solver, one can optimize these parameters to obtain a best fit of the observed dimensionless values of discharge and the predicted values computed for each dimensionless test time. The coefficient of soil erosion can then be determined from the fitted value of the time scale factor. The significant advantages of the method are the fact that the final hole diameter does not need to be measured, and the curve-fitting procedure minimizes the influence of short-term anomalies in erosion behavior during a test. Bonelli et al. (2006) showed that the proposed model fit the observed hole radius data computed from 17 hole erosion tests performed by Wan and Fell (2002) using 9 different soils. It should be emphasized that the formulation of the Bonelli model requires the fitted value of the critical shear stress τ_c to be less than the initial applied stress. This means that tests must be conducted at a stress level that exceeds the critical stress and produces immediate progressive erosion, or one must customize the analysis to only examine the portion of the test in which the shear stress exceeds τ_c.

INVESTIGATION

To facilitate use of the HET in dam safety investigations at the Bureau of Reclamation, an extensive research effort was undertaken to evaluate improvements to HET procedures and data analysis techniques (Wahl et al. 2008). Among other issues, the research investigated the variation of the friction factor during the HET and compared the performance of the Wan and Fell analysis procedures and the Bonelli model. The HET was applied to specimens of several different soils, described below. Classifications of the soils follow the Unified Soil Classification System (ASTM D2487).

- Soil 55T-160, a Sandy Lean Clay, s(CL). This is a research and Earth School soil used at the Bureau of Reclamation. This soil was used to conduct a series of HETs in which multiple specimens were prepared at similar moisture conditions and compaction effort and then tested for varying lengths of time to evaluate the variation of the friction factor during the HET. This soil was selected because it was expected to be easy to work with in the HET.

- Two undisturbed Shelby tube samples of Lean Clays, CL, recovered from Reclamation's recently constructed Ridges Basin Dam were tested in the HET.

- Four soils were tested by Regazzoni (2007). Specimens of each soil were prepared with Standard Proctor compaction at about 1% dry of optimum.

Table 2. — Properties of tested soils. Detailed gradations were not available for all 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
Ridges Basin Dam	59L-354	CL						45	25	--
Ridges Basin Dam	59L-355	CL						37	20	--
Teton	TE	CL-ML	0	12	69	19	88	29	4	17
Many Farms	MF	CL	0	25	35	40	75	47	34	17
Mountain Park	MP	CH	0	8	44	48	92	54	31	20
Tracy Fish Facility	TF	CH	0	6	39	55	94	55	40	18

RESULTS – FRICTION FACTOR

Eleven successful tests were performed with soil 55T-160 to investigate the variation of the friction factor during the hole erosion test. Specimens were mixed with water and stored for at least 48 hours. They were then compacted into standard 102-mm (4-inch) diameter by 116-mm (4 9/16-inch) long compaction molds at 12% water content, approximately optimum for this soil. Specimens were manually compacted using Standard Proctor procedures (ASTM D698) in three layers of approximately equal thickness. Each layer was compacted by 25 blows from a 50.8-mm diameter, 2.49 kg hammer dropped freely a distance of 0.305 m. Following compaction, specimens were stored overnight in plastic bags to allow for curing.

Three initial tests were used to establish the head needed to initiate progressive erosion (100 mm) and to determine the expected elapsed time for a test utilizing the full flow capability of the test facility (25 minutes of progressive erosion). Subsequent tests were run for shorter elapsed time periods, allowing an evaluation of the friction factor values after varying elapsed times (utilizing end-of-test hole diameter measurements).

Figure 2 shows the initial and final friction factors as a function of the total test time, progressive erosion time, and hole diameter. The progressive erosion time was evaluated subjectively by visually determining the time at which the flow rate began to accelerate during each test.

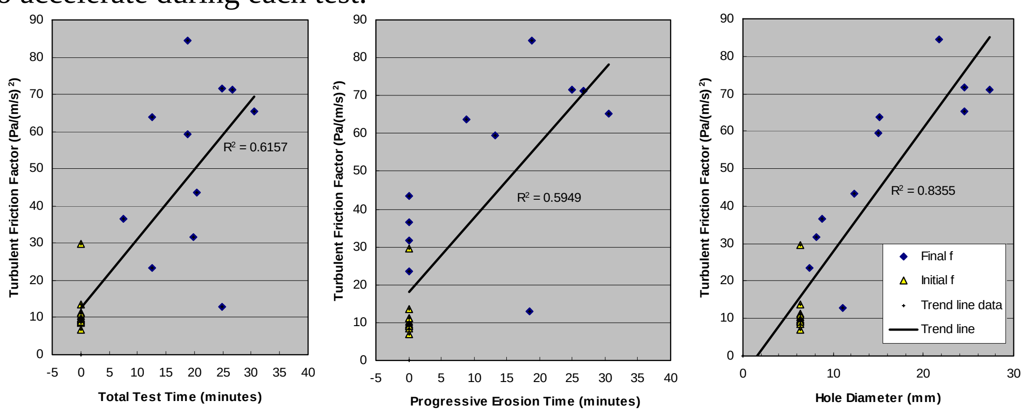

Figure 2. — Turbulent flow friction factor variation during HETs.

The heavy solid lines in Figure 2 are linear regression trend lines through the initial and final friction factor values. Although the trends versus time are in approximate agreement with the variation assumed by Wan and Fell (2004) (linear with time), the R^2 values for the trends indicate only weak relationships to time. The relationship with hole diameter is the most significant. Based on this result, it seems more reasonable to relate the variation of the friction factor to the hole diameter than the test time. This especially seems more justified for tests in which the initial head setting is too low to produce erosion. A similar result was obtained by Lim (2006)

from a similar series of tests conducted with three soils (SC, CL, and CH) that were nondispersive in tap water.
A practical difficulty encountered in applying this result to the analysis is that intermediate values of the hole diameter are not computed until the data analysis has been completed. An iterative solution method could be used, but testing with real data sets showed occasional problems obtaining convergence. Instead, it is proposed that a similar result can be obtained by relating the friction factor to the variation of $(Q/S)^{1/3}$ and $(Q/S)^{1/5}$ for laminar and turbulent flow cases, respectively, where Q is the flow rate and S is the hydraulic gradient. Each of these quantities are approximately proportional to the hole diameter (see Wahl et al. 2008, Appendix A).

RESULTS – HET ANALYSIS METHODS

Twelve tests of soil 55T-160, two tests of Ridges Basin Dam soils, and 14 tests performed by Regazzoni (2007) were analyzed using the methods of Wan and Fell (2004) and the model of Bonelli et al. (2006). Tests were individually analyzed to ensure that only the progressive erosion phase of each test was being used to determine I_{HET} and τ_c. Many of these tests started at low test heads that caused significant cleanout erosion (removal of material disturbed during drilling of the initial hole), but did not enter the progressive erosion phase until the hole diameter had increased significantly. For these tests, the Wan and Fell analysis was used to estimate the starting hole diameter needed to initiate the Bonelli analysis, which considered only the progressive erosion phase. Ideally, if one were using the Bonelli analysis procedure exclusively, tests would always be started at hydraulic gradients high enough to cause immediate progressive erosion. This would allow one to use the pre-drilled hole diameter as the initial condition in the Bonelli analysis, avoiding the need to also perform the Wan and Fell analysis (which requires measurement of the final hole diameter in order to compute intermediate hole diameters).

As expected, soil 55T-160 was relatively easy to work with and produced many successful tests. Erosion of the pre-drilled hole tended to be relatively uniform, and there was little or no localized slaking of material around the upstream and downstream ends of the erosion hole. Some of the soils tested by Regazzoni proved to be more difficult. Tests of the Fat Clay, CH, from Tracy Fish Facility (TF) were often affected by clogging of the erosion hole as chunks of material broke free from the interior walls of the hole but were too large to be transported or became jammed in the hole. This completely prevented the analysis of some tests and required careful interpretation of others. One test of the Fat Clay, CH, from Mountain Park (MP) also exhibited some clogging, but it did not prevent a successful interpretation of the test.

The Silty Clay, CL-ML, from Teton Dam (TE) was difficult to test because it was highly erodible, with large amounts of material removed near the entrance and exit of the erosion hole. This was accounted for in both the Wan and Fell and Bonelli methods by estimating the effective length of the constricted portion of the erosion hole at the end of the test, and then using a linear variation of the hole length with time (Wan and Fell) or an average length (Bonelli) to perform the analysis.

Additionally, for many of the tests on this soil, accelerating erosion could be sustained for only a few minutes. It was necessary to analyze just the first few minutes of most of these tests, as analysis of longer time periods led to the conclusion that erosion rate decreased with increasing stress (a negative coefficient of soil erosion, C_e).

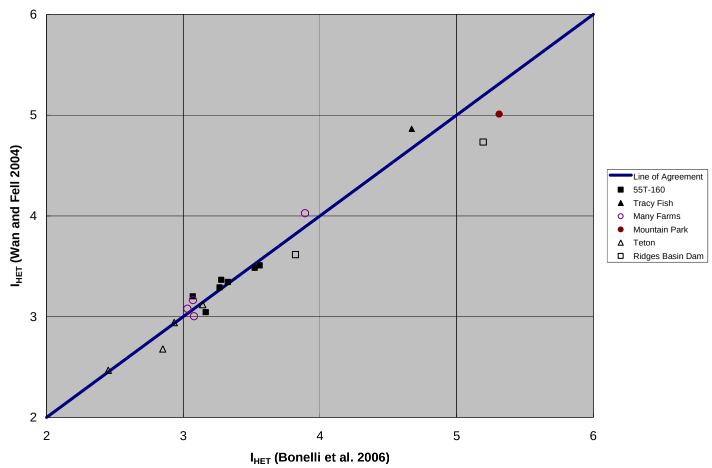

Figure 3. — Comparison of I_{HET} values computed by alternative methods for interpreting hole erosion test data.

Figure 3 shows a graphic comparison of the I_{HET} values computed by the two methods, and they are quite similar. Agreement between the two methods is good for all soils investigated across a range of I_{HET} values. There is some significant variation of the τ_c value for individual tests (see Wahl et al. 2008), but considering all of the tests together, the two methods yield similar results.

RESULTS – RANGE OF HOLE EROSION TEST METHOD

The tests described here and others conducted recently by Reclamation on a wide variety of soils have shown that the hole erosion test can at times be difficult to successfully perform, especially with weak soils that erode in undesirable ways that confound the analysis assumptions. Especially strong soils are also difficult to evaluate, since progressive erosion often cannot be produced with the head that is typically available from a constant-head tank. Operating from a pressurized water supply or using a larger initial pre-drilled hole could extend the range of the test somewhat, but in its current configuration, quantitative results could only be obtained reliably from soils exhibiting about 2.8 orders of magnitude variation in the erosion rate coefficient. In contrast, the submerged jet erosion test (JET) (Hanson and Cook 2004; ASTM D5852) is another method for measuring erodibility of cohesive materials that has demonstrated capability to evaluate erodibility across about 4.5 orders of magnitude of the erosion rate coefficient (Wahl et al. 2008). The JET and HET are not interchangeable, but Reclamation research has begun to establish relations between them.

CONCLUSIONS

The variation of the friction factor during hole erosion tests was studied and an improved modeling method was developed for estimating intermediate values of the friction factor to be used in the Wan and Fell (2004) data analysis procedure. The friction factor was found to be better related to the estimated hole diameter than to the elapsed test time. Since adopting this method for modeling the friction factor, Reclamation has obtained greater consistency in the analysis of HET data by the Wan and Fell method.

The Bonelli model for internal erosion was applied to numerous HETs that were also analyzed by the Wan and Fell method, and was found to produce generally similar results. The Bonelli model does not require the measurement of the final hole diameter, but it does require some changes to the procedures for performing tests.

Experience with a variety of soils has shown that the hole erosion test can produce reliable results for soils exhibiting about 2.8 orders of magnitude variation in the erosion rate coefficient. Other test methods, such as the submerged jet erosion test, can be applied to soils exhibiting up to 4.5 orders of magnitude variation in the erosion rate coefficient.

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. American Society for Testing and Materials.

Bonelli, S., Brivois, O., Borghi, R., and Benahmed, N., 2006. On the modelling of piping erosion. *Comptes Rendus Mecanique* 334, Elsevier SAS, pp. 555-559.

Bonelli, S., and Brivois, O., 2007. The scaling law in the hole erosion test with a constant pressure drop. *International Journal for Numerical and Analytical Methods in Geomechanics*, 24 pp.

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.

Lefebvre, G., Rohan, K., Douville, S., 1985. Erosivity of natural intact structured clay: Evaluation. *Canadian Geotechnical Journal* 22:508-517.

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.

Regazzoni, P.-L., 2007. Report on the work concerning the comparison of the jet-test and hole-erosion test. Bureau of Reclamation, Water Resources Research Laboratory, Denver, Colorado.

Rohan K., Lefebvre G., Douville S., and Milette J.-P., 1986. A new technique to evaluate erosivity of cohesive material. *Geotechnical Testing Journal* 9(2):87-92.

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.

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.

Wan, C.F., and Fell, R., 2002. *Investigation of internal erosion and piping of soils in embankment dams by the slot erosion test and the hole erosion test*, UNICIV Report No. R-412, The University of New South Wales, Sydney, Australia.