SOILS ERODIBILITY: A COMPARISON BETWEEN THE JET EROSION TEST AND THE HOLE EROSION TEST

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Abstract

The objectives of the study are to define the soils erodibility using two different devices: the Hole Erosion Test and the Jet Erosion Test. For the comparison, 4 different naturally occurring fine-grained soils from the USA were tested. The soils were prepared in the laboratory, and tested with the 2 devices under similar conditions. The interpretation of the tests was based on the assumption of a linear erosion law relating the erosion rate to the hydraulic shear stress. The analysis of the completed tests allowed us to define the erosion parameters of each soil and classify their relative erodibility.

Introduction

The presence of water in earth structures, such as dams and dikes, may cause damage by one of three mechanisms: sliding, overtopping and internal erosion. Among 11,192 surveyed dams (Foster et al. 2000), 136 show dysfunctions, which are divided up as 5.5% related to sliding, 48% related to overtopping and 46% related to internal erosion. Determination of the safety of these structures requires the characterisation of the soil's erodibility.

Different scientists have proposed tools for studying the erosion of cohesive material. These tests apply hydraulic stress to a soil sample by a variety of methods. Two tests that have potential for effective application to dam safety problems are the Hole Erosion Test (HET) (Wan and Fell, 2004), and the Jet Erosion Test (JET) (Hanson and Cook, 2004).

The purpose of this study is to compare the two devices and methods on 4 different soils. The erosion law used in the interpretation is presented. The 2 tests with their analysis are described. The results for different soil samples are discussed according to the parameters obtained with the analysis, and the observed behaviour during the tests.

Erosion law

Erodibility can be modelled with an erosive constitutive law. This law expresses the interaction between the water flow and the material. A linear relationship between an excess shear stress and the development of erosion is proposed by different authors.

$$\dot{m} = k_{d,m} * (\tau - \tau_C) \quad (1)$$

$$\dot{\varepsilon} = k_d * (\tau - \tau_C) \quad (2)$$

The different parameters describe the material and the fluid. The main unknown is the rate of erosion expressed as a mass (or volume) per unit time per unit area, $\dot{m}$ ($\dot{\varepsilon}$). The erosion rate is assumed linearly proportional to the hydraulic shear stress developed at the boundary, τ, multiplied by an erosion coefficient, $k_{d,m}$ ($k_{d,m} = k_d \rho_D$ where ρ_D is the soil dry density). The observations on clayey soils lead to the integration of a shear threshold, τ_C, for the erosion phenomenon.

Hole Erosion Test (HET)

The HET apparatus consists of several parts, summarized in figure 1. A plastic container for the water supply is set to a selected height. A Proctor mould containing the soil specimen is installed between upstream and downstream acrylic chambers equipped with piezometer taps to allow the measurement of the hydraulic head across the sample. A V-notch weir at the exit of the sample is used to measure the flow rate. The data collected during the test are the head loss across the sample ΔH and the flow rate Q. They are acquired at intervals of 30 s to 1 minute, according to the desired accuracy.

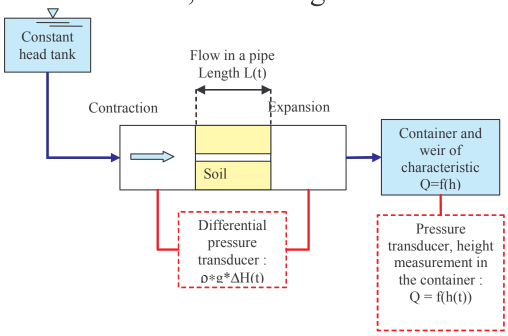

Figure 1. Synopsis view for the H.E.T.

To choose a head loss, a preliminary test is made. The head loss is increased each 15 min until erosion is observed. An accelerating flow rate and the appearance of turbidity and/or eroded material in the downstream chamber indicates that the threshold shear stress has been exceeded. For subsequent tests, a blank sample made of acrylic with a 6 mm hole is set up in the HET. The head loss is adjusted to the defined value. The blank sample is replaced by the soil sample. The HET is filled with water slowly in order to avoid the presence of air. The data acquisition is started. After the first or the second acquisition, the test is begun by opening the main valve. To interpret the HET, a momentum analysis is performed (Wan and Fell, 2004). The hydraulic shear stress in a circular pipe with a diameter ϕ is:

$$\tau = \frac{\Delta H \rho\ g}{L} * \frac{\phi}{4} \tag{3}$$

with ΔH: applied head, ρ: fluid density, L: length of the hole, and g: gravity.

The shear stress is related to a friction coefficient and the fluid velocity, depending on whether the flow is turbulent or laminar.

$$\text{Turbulent flow, Re} > 5000, \qquad \tau = f_T\ \overline{U}^2 \tag{4}$$

$$\text{Laminar flow, Re} \leq 5000, \qquad \tau = f_L\ \overline{U} \tag{5}$$

Re is the Reynolds number of the flow in the pipe and $\overline{U}$ is the mean velocity in the pipe. At the initial and final states, flow and diameter measurements allow one to determine the friction coefficient values for these two conditions. The instantaneous value is then defined by a linear interpolation with time between the initial and final values. Finally, it is possible to compute a diameter at each time using the measured flow rates, differential head, and instantaneous friction factors:

$$\text{Re} > 5000, \qquad \phi(t) = \left(\frac{64\,Q(t)^2 L f_T}{\pi^2 \Delta H \rho g}\right)^{1/5} \tag{6}$$

$$\text{Re} \leq 5000, \qquad \phi(t) = \left(\frac{16\,Q(t) L f_L}{\pi \Delta H \rho g}\right)^{1/3} \tag{7}$$

The rate of erosion is deduced from the diameter variation with time. It is then possible to develop a linear correlation of the computed shear stresses and erosion rates to obtain k_d and τ_C.

Jet Erosion Test (JET)

The JET is composed of 3 parts as seen in figure 2. A similar water supply system to the HET is used to supply water to a tube with a nozzle at the extremity.

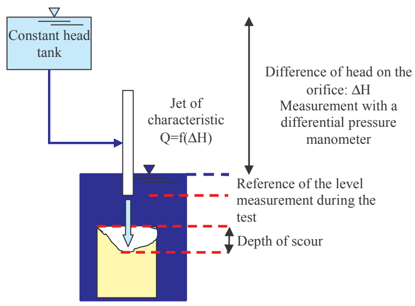

Figure 2. Synopsis view for the J.E.T.

A limnimeter is adjusted to close off the nozzle, and also allows one to measure the depth of scour beneath the nozzle. A submergence tank holds the sample. The jet tube is mounted to the submergence tank cover so that the height of the nozzle above the soil surface can be adjusted to different heights prior to the start of a test. The jet tube and cover can also be mounted to a heavy-duty field tank for in situ measurements.

The data collected during the test at specific times includes: the depth of scour J measured from a reference level and the head applied to the nozzle, ΔH. Data are recorded at intervals chosen by the operator, depending on the erosion rate. Typical intervals range from 15 s to 30 min, with total test times of 2 hours or less.

A preliminary test is carried out for choosing the head on the nozzle. The head is chosen in order to have a significant speed of erosion in the first minutes. The submergence tank is filled with water and the head is adjusted to a specified value. The sample is set up under the nozzle. The measurement of the initial reference distance from the nozzle to the sample is made with the limnimeter. Once the flow is constant, the plate protecting the sample is removed. As the test progresses, measurements of scour depth are made at selected times. For each measurement, the sample is first protected from the jet with the deflector plate and the time clock is paused. The limnimeter is then lowered in the nozzle, which temporarily stops the flow. The deflector plate is then moved aside, allowing one to make the measurement by lowering the limnimeter to the soil surface. The test is then continued by reversing the process. The analysis is based on the linear erosion law (Stein and Nett, 1997; Hanson and Cook, 2004). Its parameters are deduced from the depth versus time and the estimation of hydraulic shear stress. Based on the water velocity U, it is proposed to deduce an equivalent hydraulic shear stress under the jet:

$$\tau = C_f \rho U^2 \qquad \text{with } C_f = 0.00416 \tag{8}$$

J is defined as the distance between the jet origin and the jet impact, and U_0 is defined as the water velocity at the jet origin. The water velocity at the center of the jet is supposed constant for distances of J less than J_P (although tests are conducted so that this situation never occurs); for larger distances the velocity varies inversely with the jet distance:

$$\frac{U}{U_0} = \frac{J_p}{J} \tag{9}$$

The evolution of the jet distance with time is fitted to a hyperbolic function that predicts the ultimate depth of scour, named the equilibrium depth, J_e. The scour depth approaches the equilibrium depth asymptotically with time. Then, using the fact that at the equilibrium depth J_e there should be no further erosion of the system, an expression for the shear threshold is obtained as a function of U_0:

$$\tau_C = (J_p / J_e)^2 \, C_f \, \rho \, U_0^2 \tag{10}$$

With the help of equations 9 and 10, the erosion law is nondimensionalized and a characteristic time is defined (equation 11). By integrating the nondimensional erosion law, time is expressed as a function of nondimensional depth J*.

$$t = T_R \left(-J^*\Big|_{J_i^*}^{J^*} + \frac{1}{2} Ln\left(\frac{1+J^*}{1-J^*}\right)\Bigg|_{J_i^*}^{J^*} \right) \quad \text{with} \quad T_R = \frac{k_d \ \tau_C}{J_e} \qquad J^* = \frac{J}{J_e} \qquad (11)$$

The value of the erosion coefficient k_d is deduced from the error optimization of the time calculation.

Tested soils and their preparation

The four different soils tested were obtained from several Bureau of Reclamation (BOR) projects, (Wormer and Torres, 2004). As part of the preparation procedure, the soils were air dried and stock piled in a metallic container.

The Unified Soils Classification System is used for description of the soils. The size curve distribution of particles; the Atterberg Limits (Liquid Limit, Plastic Limit, Plastic Index), the organic matter content are known. A determination of the normal Proctor curve for each soil was also conducted. The results are summarized in the table 1.

In the selected panels of soils, none has organic matter, and their particle diameter is less than 4.75 mm. The choice of the soils was made in order to study the performance of the two erosion test methods on soils with a range of erodibilities.

Table 1. Properties of the tested soils.

Soil name	USCS	Liquid limit [%]	Plastic limit [%]	Plasticity index [%]	Max dry density [kg/m^3]	W opt [%]
TE	CL-ML	29	25	4	1694	16
MF	CL	47	13	34	1742	17
MP	CH-CL	54	23	31	1681	20
TF	CH	55	15	40	1685	18

First, water content is determined for the original soil. Two samples are prepared at the same time, one for the JET, the other for the HET. The water necessary to attain the desired water content is added to the soil mass in order to reach the targeted the optimum Proctor water content less 1 % (on the dry side). The prepared soil sample is placed in a plastic bag and put in a humidity room for 36 h. The soil was compacted according to the normal standard Proctor procedure (BOR 1990). After compaction, the sample was set in the humidity room for another 12 h. Prior to conducting the Hole Erosion Test, a hole is drilled with a 6 mm wood-drill at the center of the cylinder.

Results and comments

The data are discussed here in two ways. First, the soils are compared to each other with one apparatus. A soil erodibility classification is then established for the soils with each apparatus. Second, the results for each soil using the two different test methods are evaluated, to allow a comparison of the HET versus the JET.

Different behaviours were observed for the erosion, dependent on the soil tested. The TE and MF soils seemed to erode by detachment of individual fine particles. In contrast, TF eroded by detachment of aggregates of chunks and MP erosion by the detachment of thin flakes. Quantitative results are given for the tests in table 2.

Table 2. Average value for the erosion coefficient obtained for the H.E.T. and the J.E.T.

	H.E.T.		J.E.T.	
Soil	k_d [m^3/(N.s)]	Critical stress [Pa]	k_d [m^3/(N.s)]	Critical stress [Pa]
MF	$3.82\ 10^{-07}$	10.12	$1.20\ 10^{-06}$	0.50
TE	$3.42\ 10^{-07}$	-9.38	$1.47\ 10^{-06}$	0.64
TF	$1.86\ 10^{-08}$	277.49	$1.38\ 10^{-06}$	1.87
MP	$1.98\ 10^{-09}$	225.50	$1.59\ 10^{-07}$	8.18

For the HET, based on the head required to initiate erosion, the following classification is obtained. TE and MF are of similar erodibility, followed by TF and MP. Comparing the computed values of the erosion coefficient, MF is more erodible than TE, followed by TF and MP. It is important to note that the analysis of the HET can lead to negative values for the critical shear stress, which is physically meaningless, since even the weakest soils require application of a non-zero stress to initiate erosion.

For the JET, a similar relative classification is obtained. Based on the critical shear stress and the erosion coefficient, it appears than MF is more erodible than TE, followed by TF and MP. TF and TE appear to have a similar erosion coefficient.

To compare the test methods the ratio of the erosion coefficient between JET and HET is computed. A similar ratio is computed for the critical shear stress. The results are presented in table 3. The computed values of k_d with JET are 3 to 80 times higher than with the HET, and the critical shear stress values are 20 to 100 times smaller with the JET.

Table 3. Ratio of the values obtained with a J.E.T. and an H.E.T. for k_d and τ_C.

	k_d J.E.T./ k_d H.E.T.	τ_C J.E.T. / τ_C H.E.T.
MF	3,68	0,05
TE	4,31	-0,07
TF	69,33	0,01
MP	77,57	0,04

These differences may be due to a number of factors, including the models used to estimate the shear stress applied by each test and fundamental physical differences in the erosion mechanisms exploited by each test. The differences may also underline the limits of our present ability to quantify erodibility as a function of just the applied tangential stress.

Conclusion

The HET and the JET are two methods available for evaluating the erodibility of a cohesive soil. For these devices, the erosive action of water on the soil is related to computed values of applied shear stress. The parameters of the used erosion law are the critical shear stress τ_c and the erosion coefficient k_d. τ_c represents the minimal value of hydraulic shear stress to initiate the erosion and k_d characterizes the erosion development.

With these devices, four naturally occurring fine-grained soils are tested. The comparison of the computed erodibility parameters emphasizes important differences between the two devices. These differences may be due to limitations of the proposed analysis methods, and basic differences in the nature of the stresses applied by the devices and the erosion mechanisms they produce.

Based on the k_d for the HET and the critical shear stress for the JET, the two tests indicate similar relative erodibilities for the four soils. This conclusion leads one to assume the existence of an intrinsic erodibility property.

To improve the soil erodibility classification, a more detailed JET and HET comparison has to be carried out. The interpretation will be improved by the study of the fluid flow in the apparatus and the observed erosion. The erodibility classifications developed with these devices will be useful for the modelling of internal erosion in earth hydraulic structures.

Acknowledgements

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