Energy based method for providing soil surface erodibility rankings

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Didier Marot[1]; Pierre-Louis Regazzoni[2]; and Tony Wahl[3]

Abstract: The jet erosion test (JET) and the hole erosion test (HET) are two tests used to determine soil erodibility classification, and results are commonly interpreted by two distinct methods. A new method based on fluid energy dissipation and on measurement of the eroded mass for interpreting the two tests is proposed. Different fine-grained soils, covering a large range of erodibility, are tested. It is shown that, by using common methods, the erosion coefficient and average critical shear stress are different with the JET and with the HET. Moreover, the relative soils classifications yielded by the two erodimeters are not exactly the same. On the basis of the energy method, an erosion resistance index is determined for both apparatuses, and a classification of surface-erosion resistance is proposed. For both apparatuses, values of the erosion resistance index are roughly the same for each soil, and a single classification of soil erodibility is obtained.

Keywords: Dams; Embankment; Soil surface erosion; Laboratory testing; Erosion models; Energy.

Introduction

In hydraulic earth structures and their foundations, surface erosion can occur at the interface between two soils or at the surface between soil and water. Two tests are commonly used for the evaluation of the sensibility of surface erosion of cohesive soils: the jet erosion test (JET) and the hole erosion test (HET). For both apparatuses, the interpretations of the experiments assumed a linear expression of the rate of mass erosion, $\dot{m}$, or the volumetric rate of erosion, $\dot{\varepsilon}$

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

$$\dot{\varepsilon} = k_d \, (\tau - \tau_C) \tag{2}$$

with $k_{d,m}$ and k_d = erosion rate coefficients; τ = hydraulic shear stress; and τ_c = critical shear stress.

For HET, a constant head is applied to produce flow through a predrilled hole in a soil specimen that was compacted in a standard Proctor mold. Wan and Fell (2004) related the shear stress to a friction coefficient and the fluid velocity. A linear correlation between the computed shear stresses and erosion rates during the progressive erosion period allows one to obtain $k_{d,m}$ and τ_C. For the description of the rate of erosion, Wan and Fell (2004) proposed six categories varying from extremely slow to extremely rapid and based on the value of the erosion rate index I_{HET}, with

$$I_{\text{HET}} = -\log(k_{d,m}) \tag{3}$$

The JET device produces erosion by the action of a submerged water jet impinging on the face of a soil sample (ASTM Standard D5852 2000). Based on the water velocity on the centerline of the jet, an equivalent hydraulic shear stress applied to the soil surface can be computed. The evolution of the scour depth with time leads to the determination of τ_c and the coefficient k_d (Hanson and Cook 2004). For comparison with the HET, one may convert k_d to $k_{d,m}$ using $k_{d,m} = k_d \rho_D$, where ρ_D = soil dry density. Hanson and Simon (2001) propose soil erodibility classifications based on both the critical shear stress and the erosion-rate coefficient determined from JETs. Five categories are recognized, from very resistant to very erodible materials.

This technical note describes a new method of interpretation based on energy approach for both apparatuses. Soil erodibility characterizations of a variety of soils are compared through existing methods and through a new energy method.

Laboratory Interface Erosion Tests

Seven soils were selected (see Table 1), covering a large range of erodibility as determined by previous HET investigations. Soils were prepared for HET and JET testing by using methods described in the Bureau of Reclamation *Earth Manual* (1990), for a total number of 17 tests with each device. The preparation is compacted according to standard Proctor procedure and with initial water content w_i equal to the optimum water content less 1%. The erosion tests were conducted on samples within a maximum relative variation of $\pm 14\%$ of targeted water content values and $\pm 0.4\%$ for the dry density. For HET, all specimens were drilled with a drill press (100 rpm) equipped with the same drill 6.35 mm (1/4 in.) diameter, and a Winchester cleaning brush was passed through the hole in a downward direction in order to minimize the influence of the initial conditions on results. For JET, the initial distance of the nozzle from the soil was higher than the depth corresponding to the potential core.

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Table 1. USCS Classification, Erosion Rate Index, Critical Shear Stress and Classification for JET and HET

		JET			HET		
Soil specimen	USCS	Erosion rate index	Critical shear stress (Pa)	Classification[a]	Erosion rate index	Critical shear stress (Pa)	Description[b]
TF-1	CH	2.9	5.4	Moderately resistant	4.5	187.4	Moderately slow
TF-2		2.2	0.1	Moderately resistant	5.0	130.7	Moderately slow
TF-3		3.2	1.8	Resistant	5.3	152.6	Slow
MF-1	CL	2.7	0.4	Moderately resistant	3.1	8.1	Moderately rapid
MF-2		2.6	0.1	Moderately resistant	3.1	7.1	Moderately rapid
MF-3		2.5	0.3	Moderately resistant	3.1	7.2	Moderately rapid
TE-1	CL-ML	2.7	0.9	Resistant	3.8	0.0	Moderately rapid
TE-2		2.7	0.7	Resistant	3.6	0.0	Moderately rapid
MP-1	CH-CL	3.6	9.2	Resistant	5.4	214.5	Slow
MP-2		3.6	8.2	Resistant	4.9	312.2	Moderately slow
MP-3		3.6	7.2	Resistant	5.1	236.1	Slow
L-1	ML	1.4	0.1	Moderately resistant	2.2	0.0	Rapid
L-2		0.8	0.0	Erodible	2.5	0.0	Rapid
M0-1	CL	1.4	0.2	Moderately resistant	3.7	95.0	Moderately rapid
M0-2		4.4	14.6	Resistant	6.4	0.0	Extremely slow
M1-1	CL	2.0	1.2	Moderately resistant	2.7	11.0	Rapid
M1-2		2.5	0.4	Moderately resistant	3.3	15.0	Moderately rapid

Note: USCS = United States customary system.
[a]Classification according to Hanson and Simon (2001) soil erodibility system.
[b]Description according to Wan and Fell (2004) soil erodibility system.

Results of the HET and JET Analysis by Existing Methods

The scaling law proposed by Bonelli and Brivois (2008) and Hanson and Cook's analysis were used to analyze the HET and JET, respectively. The erosion rate index values (see Table 1) are systematically smaller with the JET than with the HET, and the $I_{\mathrm{JET}}/I_{\mathrm{HET}}$ ratio varies from 0.32 (specimen 2 of L soil) to 0.84 (specimen 1 of MF soil). On average, the HET critical shear stress is about 50 times higher than the JET critical shear stress.

Based on the rate index obtained with both devices, a first relative classification of the erodibility can be established: L is the most erodible soil, followed by M1, MF, TE, TF; and MP is the least erodible soil. Relative to the other soils, the great variability of M0 does not allow one to classify it precisely. If we consider both the erosion coefficient and critical shear stress, the distinction between the classification of TE, MF, and M1 is less clear. Therefore, the classifications yielded by the two apparatuses are not the same. More details of tests and the analysis of the results are given in Regazzoni (2009) and Regazzoni et al. (2008).

Energy Method for Interpreting the Two Tests

The energy equation for the fluid between the entrance and the exit of the system can be written as (White 1999; Regazzoni 2009)

$$\frac{dE}{dt} = \frac{d}{dt}\int\int\int_{\mathrm{Mass}}\left(e_{\mathrm{int}} + \frac{u^2}{2} + \vec{g}\,\vec{z}\right)\cdot dM = \frac{\partial}{\partial t}\int\int\int_{\mathrm{Volume}}\left(e_{\mathrm{int}} + \frac{u^2}{2} + \vec{g}\,\vec{z}\right)\cdot \rho dV + \oiint_S\left(e_{\mathrm{int}} + \frac{u^2}{2} + \vec{g}\,\vec{z}\right)\cdot \rho(\vec{U}\,\vec{n})\cdot dS \quad (4)$$

and

$$\frac{dE}{dt} = \frac{dE_{\mathrm{Ther}}}{dt} + \frac{dW}{dt} \quad (5)$$

with M = fluid mass; V = fluid volume; e_{int} = fluid internal energy; ρ = fluid density; U = fluid velocity components (u, v, w); g = gravity; z = coordinates; $\vec{n}$ = normal vector of external surface oriented from fluid to environment; E_{Ther} = energy exchange between the system and the environment; and W = mechanical work between the entrance and the exit of the system.

Four assumptions can be used to simplify the equation. The temperature, and thus the internal energy (e_{int}), is assumed to be constant in volume. The system can be considered as adiabatic—only mechanical work (W) takes place between the entrance and exit of the system. The assumption of a steady state allows one to neglect the unsteady term of the kinetic energy. As both tests are performed on fine soils, detached particles are supposed to leave the system without any redeposition, and variation of fluid density can be neglected. Finally Eqs. (4) and (5) become

$$\frac{dW}{dt} = \frac{\partial}{\partial t}\int\int\int_{\mathrm{Volume}}(\vec{g}\cdot\vec{z})\cdot\rho\cdot dV + \oiint_S\left(\frac{u^2}{2} + \vec{g}\cdot\vec{z}\right)\cdot\rho\cdot(\vec{U}\cdot\vec{n})\cdot dS \quad (6)$$

HET Analysis in Terms of Energy

The energy equation is applied between the upstream section A and the downstream section B. The apparatus is horizontal, so the term $\vec{g}\cdot\vec{z}$ is null on average. The fluid passes successively through a contraction, a hole, and finally an expansion. The balance of the energy in the system must take into account the energy dissipation in the contraction and expansion, which are named singularities. The total energy dissipation is the sum of energy dissipation by the pressure, by viscous work at the control surface, and by singularities. The viscous work is assumed to cause erosion in the hole, and it is assumed to be neglected in the other parts of the system. Therefore, the dissipation of total energy in the system can be written as

$$\left.\frac{dW}{dt}\right|_{\text{Erosion}} + \left.\frac{dW}{dt}\right|_{\text{Singularities}} = \oiint_S \left(\frac{P}{\rho} + \frac{u^2}{2}\right) \cdot \rho \cdot (\vec{U} \cdot \vec{n}) \cdot dS \quad (7)$$

The mass conservation with the same diameter on the whole length lets one assume the same average speed in sections A and B. Therefore, Eq. (7) becomes

$$\left.\frac{dW}{dt}\right|_{\text{Erosion}} + \left.\frac{dW}{dt}\right|_{\text{Singularities}} = (P_A - P_B) \cdot Q \quad (8)$$

with P_A, P_B = pressure in sections A and B, respectively; and Q = injected flow rate.

A test is performed in the HET with a nonerodible polyacrylic model of the specimen with its predrilled hole (ϕ = diameter; and L = length). By using a Colebrook estimation based on interpolation of experimental data, an estimation of the friction head losses in the pipe is made. For a turbulent flow (Reynolds number: $\mathsf{R} = (\rho \cdot \bar{U} \cdot \phi)/\mu > 2000$, where μ = fluid dynamic viscosity), the friction head loss can be expressed by (White 1999)

$$\Delta H_{\text{friction}} = \lambda \frac{L}{\phi} \frac{\bar{U}^2}{2g} \quad (9)$$

with

$$\frac{1}{\sqrt{\lambda}} = -2 \log\left(\frac{\varepsilon/\phi}{3.7} + \frac{2.51}{\mathsf{R}\sqrt{\lambda}}\right) \quad (10)$$

ε = rugosity of the pipe (for plastic surface $\varepsilon = 0.0015$ mm $\pm$ 60%); and λ = friction coefficient of the surface.

On a range of flow rates from 0.02 l/s to 0.42 l/s (corresponding to the HET range), the percentage of head losses transformed into friction and erosion is roughly 25%. Thus Eq. (8) becomes

$$\left.\frac{dW}{dt}\right|_{\text{Erosion}} = 0.25(P_A - P_B) \cdot Q \quad (11)$$

JET Analysis in Terms of Energy

In the case of JET, the energy equation [Eq. (6)] is applied between the nozzle and the exit of the submergence tank. The assumptions of a steady flow in time leads to neglect the term: $(\partial/\partial t) \int\int\int_{\text{Volume}} (\vec{g} \cdot \vec{z}) \cdot \rho \cdot dV$.

In comparison with a free jet, a jet in front of a soil-water interface is subjected to a deviation from the centerline. It is assumed that the erosion is mainly associated with this deviation, which induces an increase of shear stress and a great variation of pressure. At J depth beneath the nozzle, Beltaos and Rajaratnam (1974) expressed variation of vertical velocity in the function of lateral distance r from the centerline of the jet as

$$u(r, J) = \exp\left[-0.693 \left(\frac{r}{b_u}\right)^2\right] u(0, J) \quad (12)$$

with b_u = distance from centerline corresponding to a decrease of half vertical velocity [$u(b_u, J) = 0.5u(0, J)$]; $b_u = 0.093(J - J_p)$; J_P = depth corresponding to the potential core; and $u(0, J)$ = vertical velocity at the center of the jet.

In front of a wall, Beltaos and Rajaratnam (1974) observed that wall shear stress increases linearly with r up to a maximum value obtained for $r = 0.14J$. Moreover, when the r/J ratio increases from 0 to 0.14, the wall pressure decreases rapidly, reaching 10% of maximum value of stagnation pressure on the jet centerline axis. Thus, at J depth, erosion is assumed to appear in space defined by the lateral distance from jet centerline $r \leq 0.14J$.

Most of the work lost at the impact is supposed to be transformed into erosion, and the energy dissipation occurring inside the jet itself is neglected. The assumptions of a hydrostatic pressure in the downstream tank and a negligible fluid velocity outside the jet at the impact complete the set of equations.

The temporal derivative of the mechanical work by erosion can be expressed by

$$\left.\frac{dW}{dt}\right|_{\text{Erosion}} = 2\pi \int_0^{0.14\,J} \frac{u^2}{2} \rho\, (\vec{U} \cdot \vec{n})\, rdr$$
$$= \pi\rho u(0, J)^3 \int_0^{0.14J} \left(\exp\left[-0.693\left(\frac{r}{b_u}\right)^2\right]\right)^3 rdr \quad (13)$$

For $J < J_P$, $u(0, J) = u(0, 0)$, with $u(0, 0)$ = initial velocity at the jet origin. For $J > J_P$, $u(0, J)$ is determined by the ratio $u(0, 0)$ J_p/J proposed by Hanson and Cook (2004).

HET and JET Analysis by Energy Method and Erodibility Classification

The energy dissipated by erosion (E_{erosion}) is computed by integrating the erosion work over the test duration for both devices. Values of eroded dry mass are computed by eroded wet mass$/(1 + w_i)$ ratio, where w_i = initial water content.

An erosion resistance index is proposed as

$$I_\alpha = -\log\left(\frac{\text{Eroded dry mass}}{E_{\text{erosion}}}\right) \quad (14)$$

As shown on Fig. 1, obtained values of I_α index are roughly the same for both devices. The $I_{\alpha\text{JET}}/I_{\alpha\text{HET}}$ ratio is, on average, equal to 1.00 and varies from 0.62 (specimen 2 of MP soil) to 1.33 (specimen 2 of TE soil).

According to values of I_α index and taking into account previous soil erodibility classifications, six categories of soil erodibility are proposed: highly erodible for $I_\alpha < 1$; erodible for $1 \leq I_\alpha < 2$; moderately erodible for $2 \leq I_\alpha < 3$; moderately resistant

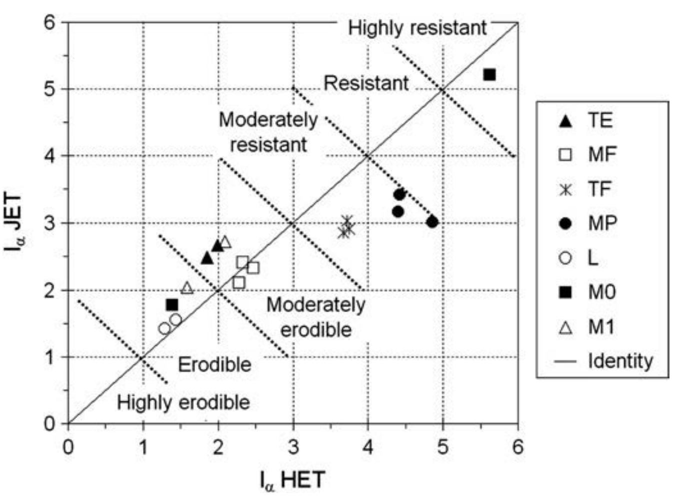

Fig. 1. Erosion resistance index determined with JET versus erosion resistance index determined with HET and soil erodibility classification

for $3 \leq I_\alpha < 4$; resistant for $4 \leq I_\alpha < 5$; and highly resistant for $I_\alpha \geq 5$.

The comparison of the position of each soil on the I_α chart shows that identical erodibility classifications are obtained from the two devices for the seven tested soils. With the HET and JET, MP and TF soils are moderately resistant; MF and TE soils are moderately erodible; M1 soil appears moderately erodible to erodible; *L* soil is erodible; and a first specimen of M0 soil is erodible, whereas a second is highly resistant.

Conclusion

The JET and the HET are two devices that can characterize the sensitivity of a soil to a hydraulic stress. Using the existing methods for these devices, the erosion rate coefficient and the critical shear stress values obtained are specific to the device that is used. An energy analysis of the systems is made, linking the expended energy to the erosion phenomenon. The energy model leads to the same classification of soil erodibility for JET and HET. This single classification permits one to choose the more suitable test, HET or JET.

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References

ASTM Geotechnical Engineering Standards. (2000). "Standard test method for erodibility determination of soil in the field or in the laboratory by the jet index method." *D5852*.

Beltaos, S., and Rajaratnam, N. (1974). "Impinging circular turbulent jets." *J. Hydraul. Div.*, 100(10), 1313–1328.

Bonelli, S., and Brivois, O. (2008). "The scaling law in the hole erosion test with a constant pressure drop." *Int. J. Numer. Anal. Methods Geomech.*, 32(13), 1573–1595.

Bureau of Reclamations: Material Engineering Branch, Research and Laboratory Services Division. (1990). *Earth Manual—part II: Water resources technical publication*, 3rd Ed., Bureau of Reclamation Denver, Department of Interior, Washington, DC.

Hanson, G. J., and Cook, K. R. (2004). "Apparatus, test procedures, and analytical methods to measure soil erodibility in-situ." *Appl. Eng. Agric.*, 20(4), 455–462.

Hanson, G. J., and Simon, A. (2001). "Erodibility of cohesive streambeds in the loess area of the midwestern, USA." *Hydrol. Processes*, 15(1), 23–38.

Regazzoni, P.-L. (2009). "Confrontation et analyse d'érodimètres et caractérisation de la sensibilité à l'érosion d'interface." Ph.D. thesis, Université de Nantes, France.

Regazzoni, P.-L., Marot, D., Wahl, T., Hanson, G., and Courivaud, J. R. (2008). "Soils erodibility: A comparison between the jet erosion test and the hole erosion test." *Inaugural Int. Conf. of the Engineering Mechanics Institute (EMOB)*, ASCE, Minneapolis, MN, w1801.

Wan, C. F., and Fell, R. (2004). "Investigation of rate of erosion of soils in embankment dams." *J. Geotech. Geoenviron. Eng.*, 130(4), 373–380.

White, F. M. (1999). *Fluid mechanics*, 4th Ed., WCB/McGraw-Hill, Boston.