Energy-Based Method for Providing Soil Surface Erodibility Rankings

Didier Marot¹; Pierre-Louis Regazzoni²; and Tony Wahl³

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. DOI: 10.1061/(ASCE)GT.1943-5606.0000538. © 2011 American Society of Civil Engineers.

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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, \( m \), or the volumetric rate of erosion, \( \dot{m} \), as:

\[
\dot{m} = k_{d,m} \left( \tau - \tau_c \right)
\]

(1)

and

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

(2)

with \( k_{d,m} \) and \( k_d \) = erosion rate coefficients; \( \tau \) = hydraulic shear stress; and \( \tau_c \) = critical shear stress.

For HET, a constant head is applied to produce flow through a predrilled hole in a soil sample 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 \( \tau_c \). 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

\[
I_{HET} = -\log(k_{d,m})
\]

(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 \( \tau_c \) 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 \( \rho_d \) = 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 ±14% of targeted water content values and ±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

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

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.

\[ \frac{dE}{dt} = \frac{dE_{ther}}{dt} + \frac{dW}{dt} \]  \hspace{1cm} (5)

with \( M \) = fluid mass; \( V \) = fluid volume; \( e_{int} \) = fluid internal energy; \( \rho \) = fluid density; \( U \) = fluid velocity components \((u, v, w)\); \( g \) = gravity; \( \mathbf{z} \) = coordinates; \( n \) = 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

\[ \frac{dW}{dt} = \frac{\partial}{\partial t} \int \int V \left( \vec{g} \cdot \vec{z} \right) \cdot \rho \cdot dV \]

\[ + \oint \left( \frac{u^2}{2} + \vec{g} \cdot \vec{z} \right) \cdot \rho \left( \vec{U} \cdot \vec{n} \right) \cdot dS \]  \hspace{1cm} (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

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

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

\[
\frac{dW}{dt} = (P_A - P_B) \cdot Q \quad (8)
\]

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 (\(\phi = \text{diameter};\) and \(L = \text{length}\)). By using a Colebrook estimation based on interpolation of experimental data, an estimation of the friction head losses is obtained for \(\text{HET}\). By the lateral distance from jet centerline \(J\) and \(B\) respectively, which in- 

\[
\Delta H_{\text{friction}} = \frac{\mu L U^2}{
\phi 
\sqrt{2g}} \quad (9)
\]

with

\[
\frac{1}{\sqrt{\lambda}} = -2 \log \left( \frac{\varepsilon}{\phi} + \frac{3.7}{3.7} \right)
\]

\(\varepsilon = \text{rugosity of the pipe (for plastic surface} \ \varepsilon = 0.0015 \ \text{mm} \ \pm 60\%);\) and \(\lambda = \text{friction coefficient of the surface.}\)

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

\[
\frac{dW}{dt} = 0.25(P_A - P_B) \cdot Q \quad (11)
\]

\(\frac{dW}{dt}\) is determined by the ratio \(\frac{r}{h_c}\), with \(r < h_c\) for \(r < h_c\) \(J_{\text{ET}}\) 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 \(l_{\alpha}\) index and taking into account previous soil erodibility classifications, six categories of soil erodibility are proposed: highly erodible for \(l_{\alpha} < 1\); erodible for \(1 \leq l_{\alpha} < 2\); moderately erodible for \(2 \leq l_{\alpha} < 3\); moderately resistant

\[
I_o = -\log \left( \frac{\text{Eroded dry mass}}{E_{\text{erosion}}} \right) \quad (14)
\]

As shown on Fig. 1, obtained values of \(l_{\alpha}\) 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).

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 $I_\alpha$ 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**