

# APPARATUS, TEST PROCEDURES, AND ANALYTICAL METHODS TO MEASURE SOIL ERODIBILITY *IN SITU*

G. J. Hanson, K. R. Cook

**ABSTRACT.** *The assessment of the erodibility of soil materials is essential for analyzing and modeling rill, gully, streambed, streambank, spillway, and embankment erosion. A submerged jet-testing apparatus has been developed and used for characterizing soil erodibility in several applications as cited in the literature. The apparatus has been developed based on knowledge of the hydraulic characteristics of a submerged jet and the characteristics of soil erodibility. The test is simple, quick, and relatively inexpensive to perform. The test is repeatable and gives consistent results. The coefficients obtained from the test results can be used in current equations to predict erosion. This article provides a description of the apparatus, methodology, and procedures for conducting jet tests in the field. An example case is also presented to illustrate the use of test results to predict erosion in an earthen channel. The estimated average erosion, for the example case of an open channel test based on jet test results, was 15.7 cm (6.2 in.) and the measured average centerline erosion in the open channel flow test was 14.5 cm (5.7 in.).*

**Keywords.** *Submerged jet, Erodibility, Testing, Critical stress, Erosion, Open channel.*

A number of water management problems require the assessment of the erosion of cohesive soils including river channel degradation, bank stability, bridge scour, culvert scour, earthen spillway erosion, and road embankment, levee, and earthen dam overtopping. It is common in assessing the erosion of cohesive soils to assume that the rate of erosion,  $\epsilon_r$  (m/s), is proportional to the effective shear stress in excess of the critical shear stress and is often expressed as:

$$\epsilon_r = k_d (\tau_e - \tau_c) \quad (1)$$

where

- $k_d$  = the erodibility or detachment coefficient ( $\text{m}^3/\text{N}\cdot\text{s}$ )
- $\tau_e$  = the effective hydraulic stress (Pa)
- $\tau_c$  = the critical stress (Pa)

Numerous investigators have used erosion rate relations of this general form (Hutchinson, 1972; Foster et al., 1977; Dillaha and Beasley, 1983; Temple, 1985; Hanson, 1989; Stein and Nett, 1997). The terms  $k_d$  and  $\tau_c$  are referred to in this article as excess stress parameters from the perspective that the rate of erosion is determined by these two soil parameters and  $\tau_e$  when the  $\tau_e$  exceeds the  $\tau_c$ . The rate of erosion has been expressed in the literature as either an eroded volume/time or an eroded mass/time depending on the application of the information. If the application is meant to aid in determining channel incising then volume/time is important. If the application is meant to aid in determining

tons of soil eroded from the agricultural landscape then mass/time is important. The interest in this article is the former, therefore, equation 1 and the development throughout this article is expressed in terms of eroded volume/time. The erosion rate may be converted from a volume base to a mass base by converting the eroded volume to mass given the bulk density (mass of solids/total volume).

Historically, it was hoped to find simple relationships between the excess stress parameters  $k_d$  and  $\tau_c$ , and soil index parameters such as plasticity index or percent clay (Smerdon and Beasley, 1959; Kamphius and Hall, 1983; Briaud et al., 2001). Through these comparisons it has been revealed that erosion of cohesive soils is a complex system dependent on many parameters requiring testing of specific soils and conditions to determine erodibility. The most dependable method of testing to determine erodibility is a large open channel flow test with the soil of interest forming the entire bed. This testing procedure poses many problems, particularly if the material to be tested is a native streambed material. It is impossible to move that bed to a large open channel flume without introducing a disturbance. Even for materials that are to be disturbed and remolded through compaction for construction purposes, it is difficult to justify conducting a large open channel test. Therefore there is a need for a method of testing these materials in the laboratory as well as *in situ*. A number of studies have used a submerged jet for testing soils in the laboratory (Moore and Masch, 1962; Hollick, 1976; Hanson and Robinson, 1993; Mazurek et al., 2001). A submerged jet has also been used for testing materials *in situ* (Hanson, 1991; Allen et al., 1997). Hanson (1991) developed a soil-dependent jet index that is based on the change over time of the maximum scour depth caused by an impinging jet. The jet index has been empirically related to soil erodibility. The testing apparatus and method for determining the jet index is described in ASTM Standard D5852 (2003).

Since the initial development of the apparatus (Hanson, 1990), it has been modified to increase convenience and flexibility in field-testing (Hanson and Cook, 1999). Also, in

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Article was submitted for review in March 2003; approved for publication by the Soil & Water Division of ASAE in December 2003.

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an attempt to remove empiricism and obtain direct measurements of the excess stress parameters  $\tau_c$  and  $k_d$ , analytical procedures for determining the soil erodibility based on the diffusion principles have been developed to replace the jet index approach (Hanson et al., 2002). The basis of the diffusion principles was developed for a submerged planar jet impinging on a soil surface by Stein et al. (1993). Stein and Nett (1997) validated this approach in the laboratory using six soil types. Hanson et al. (2002) developed similar analytical procedures for determining soil erodibility parameters for a submerged circular jet.

The apparatus and methodology have been used in several applications to determine the erodibility of cohesive soils (Hanson et al., 1999; Langendoen et al., 2000; Robinson et al., 2000; Hanson and Simon, 2001; Semmens and Osterkamp, 2001; Simon and Thomas, 2002). The objective of this article is not to re-develop the theory and related research but to provide more details of the apparatus, testing methodology, and analytical procedure for general field application to measure the excess stress parameters,  $\tau_c$  and  $k_d$ . An example case is also presented to illustrate the use of test results to predict erosion in an earthen channel.

## APPARATUS

The *in situ* jet test apparatus consists of a jet tube, nozzle, point gage, adjustable head tank, and jet submergence tank (fig. 1). The jet tube, 0.92 m (36.25 in.) long, is made of

50-mm (2-in.) i.d. acrylic tubing with 6.4-mm (0.25-in.) wall thickness. Clear tubing is used to allow visual observation of air accumulation in the jet tube. The jet tube has an 89-mm (3.5-in.) diameter orifice plate 12.7 mm (0.50 in.) thick with a 6.4-mm (0.25-in.) diameter opening (nozzle) in the center of the plate. Water is delivered to the tube 0.41-m (16-in.) upstream of the orifice plate via a 32-mm (1.25-in.) o.d. hose. An air relief valve and point gage are attached to the top of the jet tube. The air relief valve is used to remove air that has accumulated in the jet tube during initial filling. Once a test is started, scour readings are taken with the point gage. The point gage is aligned with the jet nozzle so that it can pass through the nozzle to the bed to read the depth of scour. The point gage diameter is nominally equivalent to the nozzle diameter so that when the point gage rod passes through the nozzle opening, flow is effectively shut off. A deflector plate is attached to the jet tube and is used to deflect the jet, thereby protecting the soil surface during initial filling of the submergence tank. At test initiation the deflector plate can be moved out of the way of the jet, allowing the jet to impinge directly on the soil surface.

The adjustable 0.91-m (36-in.) head tank is made of 50-mm (2-in.) i.d. acrylic tubing with 6.4-mm (0.25-in.) wall thickness. Clear tubing is used to allow visual observation of the water level in the head tank. The height of the head tank can be adjusted by sliding it up and down on a mast. The user may choose to supply and measure pressure in some other way (i.e. city water supply, pump, etc.), but the head

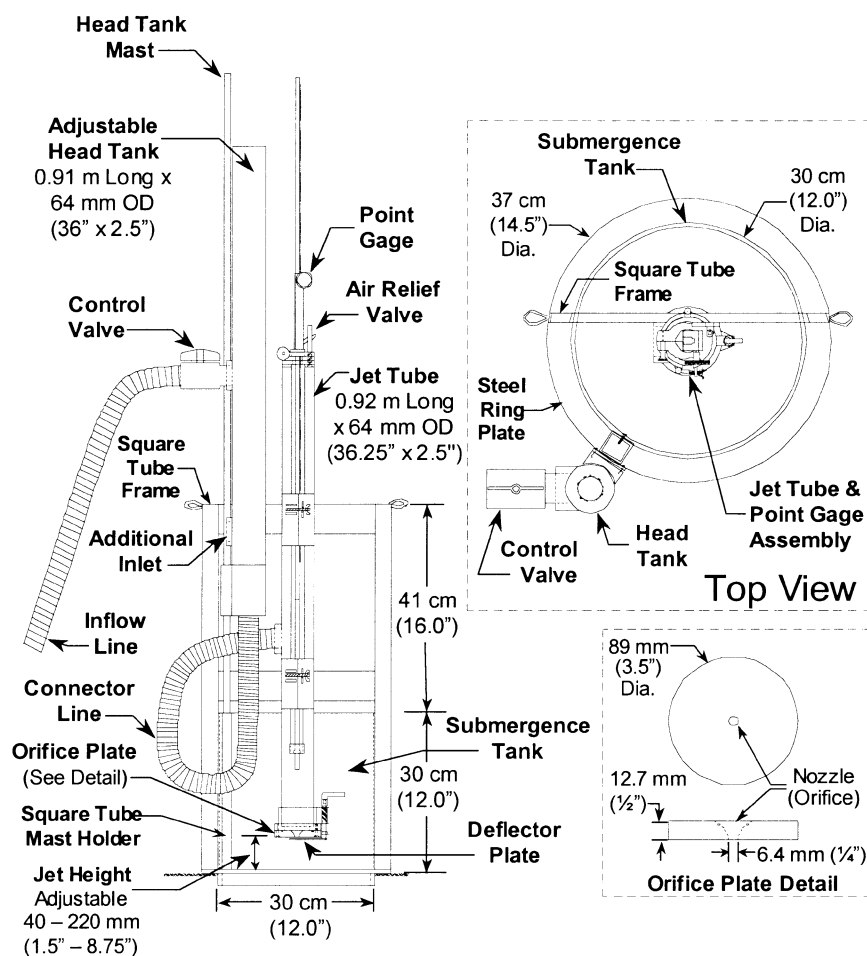


Figure 1. Schematic of submerged jet apparatus.

tank was used because it provides an easily adjusted, measured, and observed constant head.

The jet submergence tank is 0.30 m (12 in.) in diameter, 0.30 m (12 in.) in height, and is made of 16-gage steel. The tank is open on both ends and has a 25-mm<sup>2</sup> (1-in.<sup>2</sup>) tube frame attached to hold the jet tube in the center of the tank. The frame allows the jet tube and nozzle height to be conveniently set prior to initiating a jet test. The tank also has a 32-mm<sup>2</sup> (1.25-in.<sup>2</sup>) tube attached to the outside perimeter to hold the head-tank mast during testing. A steel ring plate is attached to the outside perimeter of the tank, 25 mm (1 in.) from the bottom end. The tank is driven 25 mm (1 in.) into the soil until the steel ring plate makes contact with the soil surface. Driving the tank into the soil seals the bottom and allows the tank to be filled with water, submerging the jet orifice. During testing, excess water overflowed the top rim of the tank.

## PROCEDURE

The following is a step-by-step listing of the procedure for setting up and conducting a submerged jet test in the field (fig. 2).

1. Select the site and determine the layout of test apparatus, hoses, and pump. The layout is important for operator traffic relative to hoses and running water during testing. Site selection is based on the materials of interest. If the channel bed material is homogeneous then several sites should be selected to verify this and to obtain an average value. If the channel bed is made of different materials along its profile or cross-section, these different materials will affect performance and morphology, therefore tests should be conducted on each material to represent the channel bed. Surface slope is another aspect of site selection that is important relative to the apparatus depicted in figure 1 since the apparatus requires submergence of the jet during testing of the soil material, therefore slopes should be less than two horizontal to one vertical or 26 degrees. The other point to be aware of is that on steep slopes the apparatus must be stabilized to avoid tipping over.
2. Once the site is located and layout is determined, drive the submergence tank into the soil surface. The tank is designed with two locations on the 25-mm<sup>2</sup> (1-in.<sup>2</sup>) tubing frame for driving the tank into the soil using a driving hammer. The tank is driven into the soil until the bottom of the steel plate ring is flush with the soil surface.
3. Once the tank is set, the jet tube and point gage are attached to the square tube frame on the submergence tank to orient the tube in the center of the submergence tank. The initial height of the jet nozzle, relative to the ground surface, should be set between 6 and 35 nozzle diameters [40 and 220 mm (1.6 and 8.7 in.)]. An initial height setting of 12 nozzle diameters is recommended, but this setting is somewhat at the discretion of the operator. It should be noted that the height of the jet nozzle does play a role in the boundary stress. The jet tube has marks along the side at two nozzle diameter intervals for ease of initial height settings. Once the jet tube is set, the initial jet nozzle height,  $J_i$ , is measured more precisely using the point gage.
4. The next step is to place the 2-m (79-in.) mast in the head tank mast holder on the submergence tank and set the head tank height relative to the top of the submergence tank.

The head tank is designed to slide up and down the mast to set the flow pressure on the jet nozzle. The pressure or head is based on the elevation of the top of the head tank relative to the top of the submergence tank. When the top of the head tank is set at heights above 1.8-m (6-ft), rope guides may be required to stabilize the apparatus. (Note: The operator may choose to use alternative approaches for setting the head tank or supplying pressure to the jet test. An approximate head setting should be determined prior to testing based on an estimate of the anticipated maximum stress that the channel would experience under flow conditions of interest.)

5. If a pump is to be used for the water supply, place the pump on the streambank or elevate on a platform in the streambed to keep the engine from being submerged in water. (Note: The operator may choose to use an alternative means to supply water to the jet test.)
6. Connect hoses from (1) the stream channel to the pump, (2) the pump to the head tank, and (3) the head tank to the jet tube. The operator may also require a hose from the pump to the streambed to handle excess flow from the pump. If the pump has excess capacity this hose will reduce the amount of flow through the head tank to an optimum level. The hose from the pump to the streambed may also be a convenient location to add a valve to help control pressure to the jet test. A valve on the hose from the pump to the head tank may also be helpful in controlling flow and pressure.
7. Using the point gage, determine the height of the jet nozzle (orifice),  $J_i$ , by taking point gage readings at the nozzle and initial scour depth reading (soil surface) at time zero. Also take a zero-point gage reading at the deflector plate as a reference point. Enter the point gage readings on the data sheet (fig. 3).
8. Place the deflector plate in front of the jet nozzle and set the point gage against the plate. The point gage closes off the nozzle. Initiate flow to the head tank and jet tube. This process should remove air from the hose between the jet tube and head tank. At the top of the jet tube is also an air release valve to remove air from the jet tube.
9. Once the system is filled with water, set the point gage upstream of the jet nozzle at least 10 nozzle diameters to eliminate any flow disturbance from the point gage. The water then proceeds to impact the deflector plate and fill the submergence tank.
10. Once the submergence tank is filled, take an initial head reading by measuring the distance from the top of the head tank to the top of the water surface in the submergence tank or stream channel, whichever is higher. Then move the deflector plate out of the way of the orifice to begin testing. Record the time of test initiation and duration. Head readings should also be taken periodically throughout the test, approximately every 5 to 10 min.
11. Take point gage readings of the bed at predetermined time intervals. Typical time intervals for readings are every 5 or 10 min. A set of 10 to 12 readings is recommended for analysis purposes. The operator may find that it is necessary to feel the tip of the point gage touch the soil surface to avoid pushing the tip into the soil. Feeling the tip of the point gage is often necessary in soft soils.  
Prior to conducting the jet tests, a determination of the tractive stress range of interest should be made to match the stress range of interest to the stress magnitude of the jet test.



Figure 2. View of apparatus set-up *in situ*.

The tractive stress distribution beneath an impinging jet is not uniformly distributed, but theoretically is zero at the center of the impingement zone, increasing to a peak value at a given radial distance from the center, and then decreasing at further radial distances from the center (fig. 4) (Hanson et al., 1990). The analysis of the jet test is based on the assumption that the peak stress value causes the maximum scour beneath

JET DATA						
				DATE 10/9/97		
JET TEST				OPERATOR gjh		
LOCATION Station 53 in flume				TEST # 2		
ZERO POINT GAGE READING 1.222				PT GAGE RDG @ NOZZLE 1.263		
PRELIMINARY HEAD SETTING 87				NOZZLE DIAMETER (IN) 0.2505		
				NOZZLE HEIGHT (FT) 0.200		
SCOUR DEPTH READINGS				HEAD SETTINGS		
TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)	TIME (MIN)	HEAD (IN)	
0	0	1.063	0.000	0	87.00	
10	10	1.032	0.031	10	87.00	
20	10	1.023	0.040	20	87.00	
30	10	1.014	0.049	30	87.00	
40	10	0.999	0.064	40	87.00	
50	10	0.990	0.073	50	87.00	
60	10	0.977	0.086	60	87.00	
70	10	0.974	0.089	70	87.00	
80	10	0.973	0.090	80	87.00	

Figure 3. Data sheet, first page of spreadsheet

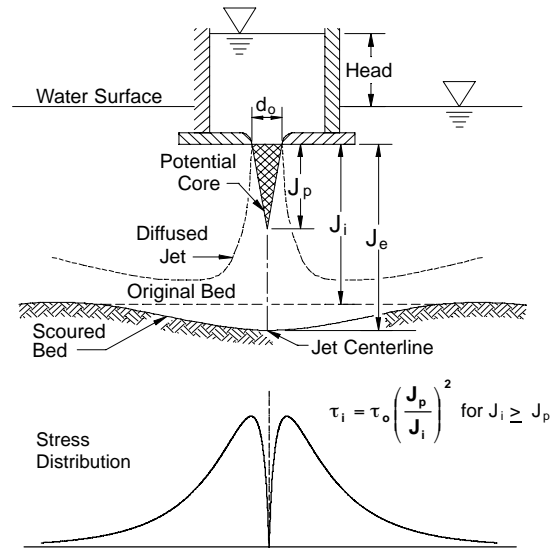


Figure 4. Schematic of circular submerged jet with parameter definitions and stress distribution.

the impinging jet. Therefore, it is important that the value of the peak stress in the jet impingement zone be similar in magnitude to the design stress environment of the open channel. The initial stress,  $\tau_i$ , in the jet impingement zone for test set-up can be determined from the following equations:

$$\tau_i = \tau_o \left( \frac{J_p}{J_i} \right)^2 \quad (2)$$

$$J_p = C_d d_o \quad (3)$$

$$\tau_o = C_f \rho U_o^2 \quad (4)$$

$$U_o = \sqrt{2gh} \quad (5)$$

where

- $\tau_i$  = initial peak boundary stress prior to scour
- $\tau_o$  = the maximum stress due to the jet velocity at the nozzle
- $J_p$  = the potential core length
- $J_i$  = the initial jet orifice height
- $C_d$  = the diffusion constant = 6.3
- $d_o$  = the nozzle diameter
- $C_f$  = the coefficient of friction = 0.00416
- $\rho$  = the fluid density
- $U_o$  = the velocity at the jet nozzle
- $g$  = the gravity acceleration constant
- $h$  = the differential head measurement

The potential core length,  $J_p$ , represents the distance from the jet orifice that the jet velocity at the jet center is still equivalent to the velocity at the orifice. This distance typically extends six orifice diameters from the jet orifice.

The initial stress,  $\tau_i$ , can be set for testing by controlling the height of the nozzle,  $J_i$ , and the head on the jet,  $h$ . Figure 5 shows the relative value of  $\tau_i$  with changes in  $J_i$ , expressed as ratio of  $J_p/J_i$  and the change in  $h$ . As an example, for a ratio of  $J_p/J_i = 1$  and a head of 1 m (3.28 ft) the initial stress,  $\tau_i$ , would be 82 Pa (1.7 lb/ft<sup>2</sup>), which would be appropriate for a design stress of 60 to 100 Pa. A simplified equation (metric

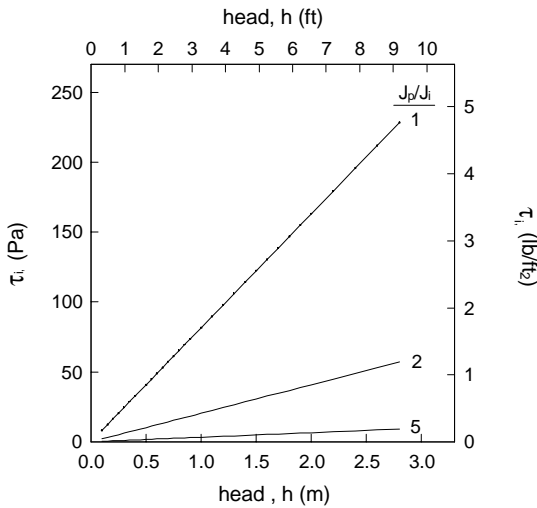


Figure 5. Comparison of initial boundary stress,  $\tau_i$ , to the jet height expressed as the ratio of  $J_p/J_i$  and head setting  $h$ .

units) to determine  $\tau_i$  by combining equations 2, 3, 4, and 5 is:

$$\tau_i = 0.13 \left( \frac{h}{J_i^2} \right) \quad (6)$$

where

- $\tau_i$  = initial peak stress prior to scour (Pa)
- $h$  = the differential head measurement (m)
- $J_i$  = the initial jet orifice height (m)

## ANALYSIS

A spreadsheet routine developed by the authors has been used to enter and analyze the data. The first sheet of the spreadsheet routine is used to record the data in the field (fig. 3). The information entered on this sheet provides all the data necessary to determine the excess stress parameters. The essential input data for the first sheet are the jet test location, date, operator, zero point gage reading (i.e. reading at the deflector plate), test number, preliminary head setting, point gage reading at the nozzle, nozzle diameter, readings for the two center columns in the scour depth readings table, and readings for the two columns in the head settings table. The two columns that must be filled in by the operator for the scour depth readings table are the diff time (time between readings) and point gage reading (point gage reading of the soil surface). The two columns that must be filled in by the operator for the head setting table are the time (cumulative time) and head. The first sheet is used to calculate the nozzle height,  $J_i$ , time (cumulative time for maximum scour depth table based on diff time), and maximum depth of scour. Based on the entries and initial calculations of the first sheet, additional sheets of the routine are used to calculate the excess stress parameters for equation 1, critical stress,  $\tau_c$ , and the erodibility coefficient,  $k_d$ . The jet test results are analyzed based on equations developed for the diffusion principles of a submerged jet, which are described in detail by Hanson et al. (2002). For purposes of conducting the test and the analysis it is important to note that the jet velocity at the

nozzle origin,  $U_o$ , jet height,  $J$ , and jet diameter,  $d_o$ , are the important parameters for controlling the initial stress at the bed (fig. 4).

As a submerged jet erosion test progresses with time, the scour surface in the zone of the impinging jet erodes away from the jet nozzle until an equilibrium depth,  $J_e$ , is reached. Analysis of the jet erosion test is based on the assumptions that 1) the equilibrium depth is the scour depth at which the stress at the boundary is no longer sufficient to cause additional downward erosion (i.e. critical stress  $\tau_c$ ), and 2) the rate of change in the depth of scour  $dJ/dt$  prior to reaching equilibrium depth is a function of the maximum stress at the boundary and the erodibility coefficient  $k_d$ . Therefore the analysis of the jet test to determine the excess stress parameters  $\tau_c$  and  $k_d$  is a two-step procedure.

1. The critical stress,  $\tau_c$ , is determined based on the equilibrium scour depth,  $J_e$ . The difficulty in determining equilibrium scour depth is that the length of time required to reach equilibrium can be very large (Blaisdell et al. 1981). Therefore the spreadsheet estimates the equilibrium depth using the scour depth data versus time and a hyperbolic function for estimating equilibrium depth developed by Blaisdell et al. (1981). The general form of the equation with an asymptote from which the ultimate depth of scour can be computed with:

$$x = [(f - f_o)^2 - A^2]^{0.5} \quad (7)$$

where

- $A$  = the value for the semi-transverse and semi-conjugate axis of the hyperbola
- $f$  =  $\log [J/d_o] - \log [(U_o t)/d_o]$
- $f_o$  =  $\log (J_e/d_o)$
- $x$  =  $\log [(U_o t)/d_o]$
- $U_o$  = the velocity of the jet at the origin
- $t$  = time of data reading
- $d_o$  = orifice diameter

The spreadsheet routine minimizes the sum of the deviations of the value of  $x$  based on observed test values and functionally determined values. The spreadsheet routine developed by the authors conducts these calculations on sheets 2 and 3 (not shown) and displays the results in graphical form on sheet 4 (fig. 6). This approach is used to determine the equilibrium depth. The spreadsheet routine conducts the minimization search on sheet 2 from starting values of  $A = 1$  and  $f_o = 1$ . The user has the option of searching from different initial values, expanding the number of searches, and/or repeating the search. Once equilibrium depth  $J_e$  is determined, based on the value of  $f_o$ , the critical shear stress  $\tau_c$  is then determined in the spreadsheet calculations by applying the following equation:

$$\tau_c = \tau_o \left( \frac{J_p}{J_e} \right)^2 \quad (8)$$

where  $\tau_c$  = critical stress

Based on the analysis of the data from sheet 1 (fig. 3) as displayed in figure 6, the critical stress was determined to be 0.91 Pa (0.02 lb/ft<sup>2</sup>).

2. The erodibility coefficient  $k_d$  is determined based on the measured scour depth, time, the pre-determined  $\tau_c$ , and the dimensionless time function:

$$T^* = -J^* + 0.5 \ln \left( \frac{1+J^*}{1-J^*} \right) \Big|_{J_i^*}^{J^*} \quad (9)$$

where

- $T^*$  = dimensionless time,  $t_m/T_r$
- $t_m$  = measured time
- $T_r$  = a reference time,  $J_e/(k_d \tau_c)$
- $J^*$  = dimensionless scour term,  $J/J_e$
- $J_i^*$  = dimensionless scour term at  $J_i/J_e$
- $J$  = the distance from the nozzle to the centerline depth of scour
- $J_i$  = the initial distance from the nozzle to soil surface

The equation has been re-written for the spreadsheet routine to focus on the measured time during the jet test.

$$t_m = T_r \left[ 0.5 \ln \left( \frac{1+J^*}{1-J^*} \right) - J^* - 0.5 \ln \left( \frac{1+J_i^*}{1-J_i^*} \right) + J_i^* \right] \quad (10)$$

The spreadsheet routine minimizes the sum of the deviations of the value of  $t_m$  based on observed test values and functionally determined values. The spreadsheet routine developed by the authors conducts these calculations on sheets 5–7 (not shown) and displays the results in dimensionless graphical form on sheet 8 (fig. 7). The spreadsheet routine conducts the minimization search, on sheet 7 (not shown), starting from a  $k_d$  value of  $0.01 \text{ cm}^3/\text{N-s}$  ( $0.006 \text{ ft}^3/\text{lb-h}$ ). The user has the option of optimizing from different initial values, expanding the number of searches, and/or repeating the optimization. Based on the analysis of the data from sheet 1 (fig. 3) as displayed in sheet 8 (fig. 7), the erodibility coefficient was determined to be  $0.135 \text{ cm}^3/\text{N-s}$  ( $0.076 \text{ ft}^3/\text{lb-h}$ ). The results of this jet test are used in the following example application along with two other jet test results.

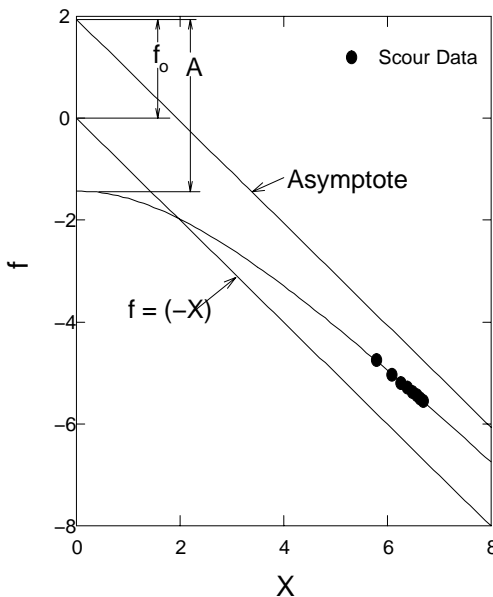


Figure 6. Graphical view of the spreadsheet equilibrium depth estimate optimization.

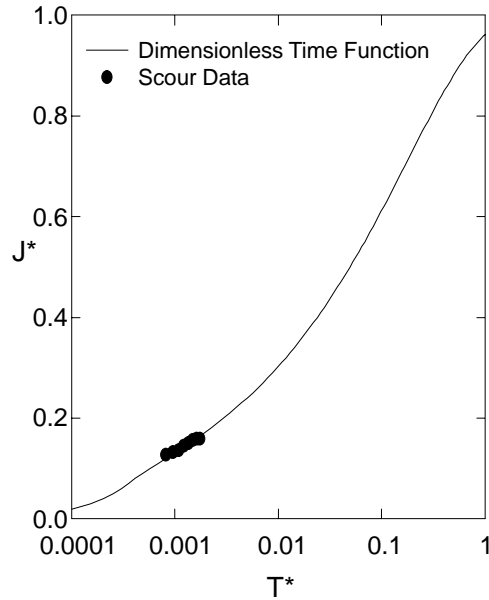


Figure 7. Graphical view of the spreadsheet dimensionless scour function optimization.

## EXAMPLE APPLICATION

An example is presented to illustrate how the jet test results and analysis methods are applied to estimate the amount of erosion that would be anticipated in an earthen channel.

### PROBLEM

Determine the amount of erosion that would be expected in a bare earth channel with the following properties:

Soil Properties:

- ASTM classification CL
- Gradation 38% Sand, 34% Silt, and 28% Clay.
- Plasticity index 15
- Liquid limit 26
- Moisture content 13%
- Dry unit weight  $1.85 \text{ Mg/m}^3$  ( $115 \text{ lb/ft}^3$ )

Channel

- Slope 3%
- Length 15 m (49 ft)
- Width 1.83 m (6 ft)
- Manning's  $n$  0.034

Flow

- 1 Time: 1089 min  $Q = 0.71 \text{ m}^3/\text{s}$  ( $25 \text{ ft}^3/\text{s}$ )
- 2 Time: 415 min  $Q = 2.89 \text{ m}^3/\text{s}$  ( $102 \text{ ft}^3/\text{s}$ )

### Excess Stress Parameters $\tau_c$ and $k_d$

These parameters were determined by conducting submerged jet tests on the soil material as described in the previous sections.

### Calculations for Estimating Erosion

Depth of flow:

Flow 1

$$Q = (1/n)AR^{2/3}S^{1/2} = 0.71 \text{ m}^3/\text{s}$$

$$n = 0.034$$



**Table 1. Jet test results.**

Test	$\tau_c$		$k_d$	
	(Pa)	(lb/ft <sup>2</sup> )	(cm <sup>3</sup> /N-s)	(ft <sup>3</sup> /lb-h)
1	0.463	0.01	0.065	0.037
2	0.913	0.02	0.135	0.076
3	1.929	0.04	0.066	0.037
Average	1.10	0.02	0.089	0.050

$$A = (\text{depth}) \times (\text{width}) = (\text{depth}) \times (1.83 \text{ m})$$

$$R = A/P = A/[2 \times A] = [(\text{depth}) \times A]/[2 \times (\text{depth}) + (1.83 \text{ m})]$$

$$S = 0.03 \text{ m/m}$$

Since the only unknown is depth it can be solved iteratively.  
depth = 0.23 m (0.75 ft)

Flow 2

$$Q = 2.89 \text{ m}^3/\text{s}$$

All other parameters the same as in flow 1

$$\text{depth} = 0.61 \text{ m (2.00 ft)}$$

### Effective Stress

Flow 1

$$\tau_e = \gamma \times (\text{depth}) \times S \times (n_s/n)^2 \text{ (based on Hanson, 1989; Temple et al., 1987)}$$

$$\gamma = \text{specific weight of water} = 9800 \text{ N/m}^3$$

$$\text{depth} = 0.23 \text{ m}$$

$$S = 0.03 \text{ m/m}$$

$$n_s = \text{Manning's roughness associated with soil grain roughness} = 0.0156$$

$$n = \text{Manning's roughness associated with the overall boundary and flow conditions} = 0.034$$

$$\tau_e = 14.2 \text{ Pa (0.30 lb/ft}^2\text{)}$$

Flow 2

$$\text{depth} = 0.61 \text{ m}$$

$$\tau_e = 37.8 \text{ Pa or (0.79 lb/ft}^2\text{)}$$

### Cumulative Erosion:

$$\text{Total Erosion} = [\text{erosion for flow 1}] + [\text{erosion for flow 2}]$$

Erosion for flow 1 (based on average values for  $k_d$  and  $\tau_c$  from jet tests)

$$= [\epsilon_r] \times \text{time for flow 1}$$

$$= [k_d \times (\tau_e - \tau_c)] \times 1089 \text{ min} \times (60 \text{ s/min})$$

$$= [(0.089 \text{ cm}^3/\text{N-s}) \times (14.24 \text{ Pa} - 1.10 \text{ Pa})$$

$$\times (\text{m}/100\text{cm}^2)] \times (65,340 \text{ s})$$

$$= 7.6 \text{ cm (3.0 in.)}$$

Erosion for flow 2

$$= [k_d \times (\tau_e - \tau_c)] \times 415 \text{ min} \times (60 \text{ s/min})$$

$$= [(0.089 \text{ cm}^3/\text{N-s}) \times (37.75 \text{ Pa} - 1.10 \text{ Pa})$$

$$\times (\text{m}/100 \text{ cm}^2)] \times (24,900 \text{ s})$$

$$= 8.1 \text{ cm (3.2 in.)}$$

$$\text{Total erosion} = 7.6 \text{ cm} + 8.1 \text{ cm} = 15.7 \text{ cm} = 0.157 \text{ m (6.2 in.)}$$

## COMPARISON OF JET TEST BASED RESULTS TO FLUME RESULTS

An open channel erosion test as described in the example problem was conducted in a flume 1.8 m (6 ft) wide by 29 m (96 ft) long with 2.4-m (8-ft) sidewalls (fig. 8). A flat-bottomed channel bed 1.8 m (6 ft) wide and 21 m (69 ft) long was constructed in the flume as described in the problem. Soil was placed in the flume on a 3% slope. The average water content of the placed soil was 13.9%. Soil was



**Figure 8. Open channel erosion test on bare earth channel.**

placed in 15-cm (6-in.) loose lifts and compacted with four passes of a vibratory roller compactor, two passes without vibration, and two with vibration. The resulting average dry unit weight was 1.85 Mg/m<sup>3</sup> (115 lb/ft<sup>3</sup>).

Flow was introduced in the flume. Water surface and bed surface readings were taken along the centerline of the channel for a 6-m (20-ft) test section to determine erosion. The discharge was set at 0.71 and 2.89 m<sup>3</sup>/s (25 and 102 ft<sup>3</sup>/s) for time periods of 1089 and 415 min, respectively.

Table 2 presents a comparison of the erosion estimated from the jet test results and the flume measurements. The flume erosion measurements represent the average centerline erosion from the 6-m (20-ft) test section. The most dependable erosion test is the open channel with the soil forming the entire bed. The centerline profile is used to estimate the average erosion that does occur in the channel. In reality the channel has areas that are more resistant and areas that are less resistant and an average of the measured erosion along the centerline only provides an approximate measure of erosion that occurs. The jet test also provides a method of measuring the resistance in a localized area of the channel bed. The more measurements taken the more representative the results should be of the average resistance of the channel bed. In this case three measurements were conducted on the bed. The estimated erosion values of the jet test are based on the average of the three tests as well as the maximum and minimum results of the three jet tests. Note that the duration of flow was 2.6 times longer for the first flow but the stress was 2.7 times greater in the second flow. Therefore, if erosion had been uniform the amount of erosion in the final flow should have been almost equivalent to the initial flow as predicted by the jet test results, but instead the average measured erosion in the first 18 hours of flow was three times the erosion in the last 7 hours. This difference in erosion is a clear indication that erosion was not uniform over time even though the final estimated average erosion from the jet tests was very similar to the measured average erosion over the total 25 hours of testing.

The erodibility coefficient determined from the jet test results was 0.089 cm<sup>3</sup>/N-s and a critical stress of 1.1 Pa. The erodibility coefficient from the flume test results was 0.096 cm<sup>3</sup>/N-s assuming the same critical stress of 1.1 Pa. Converting these values to a mass base rather than a volume base results in an erodibility coefficient of 0.0001 s/m. This value is far less than the typical erodibility coefficient range for cropland soils of 0.002 to 0.045 s/m (Flanagan and Livingston, 1995) and is on the low end of reported rangeland

**Table 2. Comparison of measured and estimated erosion.**

Flow m <sup>3</sup> /s (ft <sup>3</sup> /s)	Time (min)	Average			
		Measured Erosion cm (in.)	Estimated Average cm (in.)	Erosion Maximum cm (in.)	Minimum cm (in.)
0.71 (25)	1089	11.1 (4.4)	7.6 (3.0)	12.0 (4.7)	5.4 (2.1)
2.89 (102)	415	3.4 (1.3)	8.1 (3.2)	12.4 (4.9)	5.9 (2.3)
Total	Erosion	14.5 (5.7)	15.7 (6.2)	24.4 (9.6)	11.3 (4.4)

erodibility coefficients (Elliot, 2001). This would be anticipated since the soil material has been compacted to a density of 1.85 Mg/m<sup>3</sup> and a compaction moisture content of 13% which indicates the benefit of proper compaction for certain applications.

## SUMMARY

The submerged jet testing apparatus, methodology, and procedure have been used in several applications, as depicted in the cited literature, to determine excess stress parameters  $k_d$  and  $\tau_c$  to characterize soil erodibility. The apparatus, methodology, and analysis procedure have changed from the original inception. The purpose of this article is to provide details of the present *in situ* jet apparatus, step-by-step testing methodology, and analysis procedures that can be applied in the field to determine soil erodibility. An example case illustrates the use of test results to predict erosion in an earthen channel and compares the calculated results with observed measurements.

Note: Detailed plans of the apparatus, as well as the spreadsheet routine are available from the authors.

## REFERENCES

- Allen, P. M., J. Arnold, and E. Jakubowski. 1997. Design and testing of a simple submerged-jet device for field determination of soil erodibility. *Environmental and Engineering Geoscience* 3(4): 579–584.
- ASTM. 2003. Standard D5852. *Annual Book of ASTM Standards*, Section 4: Construction, Vol. 04.08. Philadelphia, Penn.: American Society for Testing and Materials.
- Blaisdell, F. W., L. A. Clayton, and G. G. Hebaus. 1981. Ultimate dimension of local scour. *J. Hydraulics Division, ASCE* 107(HY3): 327–337.
- Briaud, J. L., F. C. K. Ting, H. C. Chen, Y. Cao, S. W. Han, and K. W. Kwak, 2001. Erosion function apparatus for scour rate predictions. *J. of Geotechnical and Geoenvironmental Engineering, ASCE* 127(2): 105–113.
- Dillaha, T. A., and D. B. Beasley. 1983. Distributed parameter modeling of sediment movement and particle size distribution. *Transactions of the ASAE* 26(6): 1716–1722
- Elliot, W. J. 2001. Comparing RUSLE to WEPP cropland and rangeland formats. *Proc. International Symposium for Soil Erosion Research for the 21<sup>st</sup> Century*, eds. J. C. Ascough II and D. C. Flanagan, 388–391. St. Joseph, Mich.: ASAE.
- Flanagan, D. C., and S. J. Livingston. 1995. *WEPP User Summary*. NSERL Report No. 11. W. Lafayette, Ind.: National Soil Erosion Research Laboratory.
- Foster, G. R., L. D. Meyer, and C. A. Onstad. 1977. An erosion equation derived from basic erosion principles. *Transactions of the ASAE* 20(4): 678–682
- Hanson, G. J. 1989. Channel erosion study of two compacted soils. *Transactions of the ASAE* 32(2): 485–490.
- Hanson, G. J. 1990. Surface erodibility of earthen channels at high stresses part II – developing an *in situ* testing device. *Transactions of the ASAE* 33(1): 132–137.
- Hanson, G. J. 1991. Development of a jet index to characterize erosion resistance of soils in earthen spillways. *Transactions of the ASAE* 34(5): 2015–2020.
- Hanson, G. J., and K. R. Cook. 1999. Procedure to estimate soil erodibility for water management purposes. ASAE Paper No. 992133. *Proc. Mini-Conf. Advance in Water Quality Modeling*. St. Joseph, Mich.: ASAE.
- Hanson, G. J., K. R. Cook, and A. Simon. 1999. Determining erosion resistance of cohesive materials. *Proc. of the ASCE Water Resource Conference (CD-ROM)*. New York: ASCE.
- Hanson, G. J., K. M. Robinson, and D. M. Temple. 1990. Pressure and stress distributions due to a submerged impinging jet. *Proc. Nat. Conf. Hydraul. Eng., Am. Soc. Civil Eng.*, 252–530. New York: ASCE.
- Hanson, G. J., and K. M. Robinson. 1993. The influence of soil moisture and compaction on spillway erosion. *Transactions of the ASAE* 36(5): 1349–1352.
- Hanson, G. J., K. M. Robinson, and K. R. Cook. 2002. Scour below an overfall: Part II. Prediction. *Transactions of the ASAE* 45(4): 957–964.
- Hanson, G. J., and A. Simon. 2001. Erodibility of cohesive streambeds in the loess area of the midwestern USA. *J. Hydrological Processes* 15(1): 23–38.
- Hollick, M. 1976. Towards a routine test for the assessment of critical tractive forces of cohesive soils. *Transactions of the ASAE* 19(6): 1076–1081.
- Hutchinson, D. L. 1972. Physics of erosion of cohesive soils. Ph.D. thesis. University of Auckland, New Zealand.
- Kamphius, W. J., and K. R. Hall. 1983. Cohesive material erosion by unidirectional current. *J. of Hydraulic Engineering, ASCE* 109(1): 1076–1081.
- Langendoen, E. J., A. Simon, and C. V. Alonso. 2000. Modeling channel instabilities and mitigation strategies in Eastern Nebraska. *Proc. of the 2000 Joint Conference on Water Resources Engineering and Water Resource Planning and Management*, (CD-ROM). New York: ASCE.
- Mazurek, K. A., N. Rajaratnum, and D. C. Sego. 2001. Scour of cohesive soil by submerged circular turbulent impinging jets. *J. Hydraulic Engineering* 127(7): 598–606.
- Moore, W. L., and F. D. Masch. 1962. Experiments on the scour resistance of cohesive sediments. *J. Geophysical Research* 67(4): 1437–1446.
- Robinson, K. M., S. J. Bennett, G. J. Hanson, and K. C. Kadavy. 2000. The influence of weathering on headcut erosion. ASAE Paper No. 002066. St. Joseph, Mich.: ASAE.
- Semmens, D. J., and W. R. Osterkamp. 2001. Dam removal and reservoir erosion modeling: Zion Reservoir, Little Colorado River, AZ. *Proc. of the Seventh Federal Interagency Sedimentation Conference*, Reno Nevada vol(IX): 72–79. Reston, Va.: USGS.
- Simon, A., and R. E. Thomas. 2002. Processes and forms of an unstable system with resistant, cohesive streambeds. *J. Earth Surface Processes and Landforms* 27(7): 699–718.
- Smerdon, E. T., and R. P. Beasley. 1959. The tractive force theory applied to stability of open channels in cohesive soil. Research Bulletin 715. University of Missouri. Ag. Exp. Station. Columbia, Mo.
- Stein, O. R., P. Y. Julien, and C. V. Alonso. 1993. Mechanics of jet scour downstream of a headcut. *J. of the Hydraulic Research of IAHR* 31(6): 732–738.
- Stein, O. R., and D. D. Nett. 1997. Impinging jet calibration of excess shear sediment detachment parameters. *Transactions of the ASAE* 40(6): 1573–1580.
- Temple, D. M. 1985. Stability of grass-lined channels following mowing. *Transactions of the ASAE* 28(3): 750–754.
- Temple, D. M., K. M. Robinson, R. M. Ahring, and A. G. Davis. 1987. Stability design of grass-lined open channels. USDA Agricultural Handbook No. 667. Washington, D.C.: USDA.