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DEVELOPMENT OF EXCESS SHEAR STRESS PARAMETERS FOR CIRUCLAR JET TESTING

by

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Summary:

The excess shear stress equation is often used to model the erosion of soil materials. The determination of the excess shear stress parameters, erodibility and critical stress, are important in the design of channels, spillways, embankments, bridges, and river restoration as well as other landscape erosion settings. In this paper analytical procedures are developed for determining the excess shear stress parameters from circular jet scour test results. Scour tests from four soil materials are evaluated for critical stress and erodibility based on this analytical development. The results are consistant with earlier open channel tests results.

Keywords:

erosion, critical stress, erodibility, scour, jet tests

DEVELOPMENT OF EXCESS SHEAR STRESS PARAMETERS FOR CIRCULAR JET TESTING

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INTRODUCTION

Jets have been used since the late 1950's to test the erosion resistance of cohesive soils. Dunn (1959), Moore and Masch (1962), and Hollick (1967), developed methods for determining the critical stress of soil materials from jet scour. Hanson (1990b, 1991) developed a submerged jet testing apparatus and procedure to determine the soil erodibility based on the rate of scour and the velocity at the jet origin. Stein et al. (1994) developed an analytical procedure relating the excess shear stress detachment equation to the scour rate of soil materials as induced by shear stress in an impinging jet. This procedure was developed for a planar jet impinging on soil material at an overfall with low tailwater conditions. In this paper a similar analytical procedure is developed for a submerged circular jet, and soil erodibility parameters from the excess shear stress equation are determined for circular jet test results.

EXCESS SHEAR STRESS EQUATION AND JET SCOUR

Excess Shear Stress Equation

The excess shear stress equation is often used to model the erosion of soil materials:

$$E = k(\tau_e - \tau_c)^a \qquad (1)$$

where E is the erosion rate of the soil material, τ_e is the effective stress at the soil/water interface, and the parameters k and τ_c account for the erosion resistance of the soil. The parameter k is the erodibility coefficient, and τ_c is the critical stress of the soil material. When the effective stress is less than the critical stress, erosion is assumed not to occur or at least to be insignificant. The exponential term is generally assumed to be equivalent to 1, and is assumed to be one in the analytical development presented in this paper. Determining the value of k and τ_c for soil materials is important in erosion modeling of channels, spillways, embankments, and bridge piers, as well as sheet, rill, and gully erosion in landscape settings.

Critical Stress, Erodibility, and Jet Scour

The term critical stress or threshold denotes the bed stress at which soil detachment begins and is a measure of the soil resistance against the initiation of erosion. Among the parameters of the excess stress equation, the critical stress is one of the least understood and is also one of the most difficult to quantify (Owoputi and Stolte 1995). There is even some debate as to whether critical stress exists for incipient motion and erosion (Lavelle and Mofjeld 1987). It is sometimes

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eliminated from the evaluation of erosion resistance (Shaikh et al. 1987, Hanson 1990a, Foster et al. 1977). In other cases it is estimated based on the percent clay of the soil material (Smerdon and Beasley 1961) or simply based on the mean particle size and Shield's diagram (Temple and Hanson 1994). Linear regression of the measured detachment versus applied shear stress is the accepted method of determining critical shear (Arulanandan et al. 1980, Franti et al. 1985, Elliot et al. 1990). The x axis intercept of the straight line is the critical stress τ_c and the slope is the erodibility coefficient k. The erodibility coefficient is a measure of the rate of change of erosion resulting from a change in stress above the critical stress. Arulanandan et al. (1980) observed in erosion studies in a flume and rotating cylinder that there was a general relationship between k and τ_c. Soils with a low τ_c tended to have a high relative k, and soils having a high τ_c exhibited a low relative k. They concluded that if one was known they [illegible]d make a qualitative prediction of the other. Franti et al. (1985) and Elliot et al. (1990) in studi[illegible]ll erosion observed that the linear nature of the excess stress equation does not always reflect reality. Franti et al. (1985) observed that it was possible to get negative critical stresses depending on the nature of the detachment data. Elliot et al. (1990) observed that high erodibility leads to a steep regression line, which may cause the intercept of the sheared stress axis to be greater, therefore causing the critical stress term to be more a function of the nature of the erosion model than of the actual erosion. Despite these shortcomings the excess stress equation has been found to be functionally useful and is used in the development that follows in this paper to model the erosion rate of soil materials.

Jet tests have been used to determine the critical stress of a soil material by determining, based on visual observation, the point at which scour is initiated and an estimate of the stress at the boundary as this occurs (Dunn 1959). Critical stress has also been determined based on the point at which the scour hole depth does not continue to increase at the equilibrium or ultimate depth, and the corresponding estimated stress (Stein et al. 1994). The time required to reach equilibrium depth can be large. Blaisdell et al. (1981) observed during studies of pipe outlets that scour continued to progress even after 14 months, and they proposed an analytical method for estimating the equilibrium or ultimate depth of scour.

Jet tests have also been used to determine the soil erodibility (Hanson 1991, Stein et al. 1994). Hanson developed a jet testing apparatus and procedure dependent on the rate of scour to determine a jet index parameter that could be empirically related to the erodibility coefficient. Stein et al. (1993) developed analytical procedures for determining the soil erodibility based on the diffusion principles of a planar jet at an overfall. This development was based on a planar jet impinging on a soil surface with initial low tailwater. The development that follows in this paper is similar, with the exceptions that the jet is a submerged circular jet, the height of the jet origin is well above the initial soil surface, and the jet core diffuses well in advance of impinging the soil surface.

ANALYTICAL DEVELOPMENT FOR SUBMERGED CIRCULAR JETS

Jet Diffusion and Stress Development

The diagram shown in Fig. 1 illustrates a circular jet at uniform velocity U_o produced by a submerged nozzle, diameter d_o, under pressure h impinging the soil bed at right angles. The jet origin is at an initial height H_i above the soil bed, and as scour continues an equilibrium depth is eventually reached, resulting in a distance from the jet origin to the maximum point of scour of H_e. As the jet travels toward the soil boundary it spreads radially and diffuses throughout the surrounding fluid, decreasing in average velocity. There is an initial reach, in which the centerline velocity remains constant U_o, that defines the potential core length from the jet origin H_p. Beyond this reach, the velocity U remains at maximum along the jet centerline but the entire velocity field is reduced by diffusion.

The generally accepted formulation for the centerline velocity U where $H > H_p$ (Albertson et al. 1950) is:

$$\frac{U}{U_o} = C_d \frac{d_o}{H} \qquad (2)$$

where H is the distance from the origin along the centerline and C_d is the diffusion constant in which values 5.8 to 7.4 have been reported, with a commonly accepted average of 6.2 (Beltaos and Rajaratnum 1974). Turbulence and non-uniform flow velocity at the jet origin influences both C_d and H_p. The length of the potential core can be obtained by solving Eq. 2 when $U = U_o$ at $H = H_p$:

$$H_p = C_d d_o \qquad (3)$$

The flow characteristics of a circular submerged jet impinging normally on a smooth boundary have been investigated by Poreh and Cermak (1959), Beltaos and Rajaratnum (1974), Viegas and Borges (1986), and Hanson et al. (1990). The impinging circular jet has four zones of flow. Zone 1 is described as the "zone of flow establishment," which extends about nine diameters from the origin. This zone is defined by the potential core length. Zone 2 is defined as the "zone of established flow." Zone 3 is the "deflection zone" in which the jet impacts the smooth planar surface and transitions from a vertical jet to a horizontal wall jet. A stagnation point occurs along the centerline of the jet at the planar boundary. At the stagnation point, pressure is at a maximum and shear stress is zero. Radially outward from the jet centerline the pressure diminishes to the ambient pressure of the surrounding water and the shear stress increases to a maximum and then decreases with further radial distance. Zone 4 is defined as the "wall jet zone," in which the flow of the jet is parallel to the planar boundary.

Researchers, using semi-empirical relationships developed from experimental techniques, have defined shear stress distributions along the planar boundary in the deflection zone. The maximum shear stress acting upon the bed in the impingement region can be related to the maximum velocity in the impingement region U by introducing a coefficient of friction C_f.

$$\tau = C_f \rho U^2 \qquad (4)$$

Combining Eq. 2 and 4, with consideration of Eq. 3, gives the maximum applied bed shear stress τ, which within the potential core is constant at $\tau = \tau_o$:

$$\tau_o = C_f \rho U_o^2 \qquad H \le H_p \qquad (5)$$

$$\tau = C_f \rho \left(C_d U_o \frac{d_o}{H} \right)^2 \qquad H > H_p \qquad (6)$$

where H is the distance along the jet centerline from the nozzle origin to the eroding bed, H_p is the length of the jet potential core, U_o and d_o are the jet velocity and nozzle diameter at the origin, C_d is the diffusion coefficient, and C_f is the friction coefficient. The values for C_d and C_f used in the evaluations of this paper are 6.3 and 0.00416, respectively. These values were determined based on the study of stresses along a smooth boundary beneath an impinging jet by Hanson et al. (1990).

Excess Stress Parameter Development

The initial nozzle height H_i for the jet testing apparatus evaluated in this paper is beyond the potential core H_p. If we assume that the rate of change in the depth of scour dH/dt is the erosion rate as a function of the maximum stress at the boundary, Eqs. 1, 3, 5, and 6 can be combined to obtain:

$$\frac{dH}{dt} = k(\tau_o - \tau_c) \qquad H \le H_p \tag{7}$$

$$\frac{dH}{dt} = k\left[\frac{\tau_o H_p^{\,2}}{H^2} - \tau_c\right] \qquad H \ge H_p \tag{8}$$

Assuming that $\tau_o > \tau_c$, when dH/dt = 0 equilibrium is attained at H_e. Therefore:

$$\tau_c = \tau_o \left(\frac{H_p}{H_e}\right)^2 \tag{9}$$

Based on Eqs 7, 8, and 9 which are similar to the development by Stein et al. (1993) the scour rate equations can be rewritten in dimensionless form:

$$\frac{dH^*}{dT^*} = \frac{(1 - H_p^{*2})}{H_p^{*2}} \qquad H \le H_p \tag{10}$$

$$\frac{dH^*}{dT^*} = \frac{(1 - H^{*2})}{H^{*2}} \qquad H > H_p \tag{11}$$

The integral form of Eqs. 10 and 11 is:

$$\int_0^{T_p^*} dT^* = \int_0^{T_p^*} \frac{H_p^{*2}}{1 - H_p^{*2}} dH^* \qquad H^* \le H_p^* \tag{12}$$

$$\int_{T_p^*}^{T^*} dT^* = \int_{T_p^*}^{T^*} \frac{H^{*2}}{1 - H^{*2}} dH^* \qquad H^* > H_p^* \tag{13}$$

The dimensionless terms are $H^* = H/H_e$, and $H_p^* = H_p/H_e$, and some dimensionless time $T^* = t/T_r$ where t is time, and T_r is a reference time defined by Stein et al. (1993):

$$T_r = \frac{H_e}{k\,\tau_c} \tag{14}$$

The dimensionless development by Stein et al. (1993) is based on the initiation of scour with minimal initial tailwater so that the jet origin is at the soil surface at t=0.0. Therefore, scour begins within the potential core and continues until equilibrium scour is obtained. In the jet testing apparatus the jet origin is well above the initial bed and in act is well beyond the potential core. Therefore, in order to maintain a similar time scale between tests, it is necessary to include a fictitious time that would have been required to scour through the core length H_p, and the distance to the initial soil surface, $H_i - H_p$ is necessary. This involves integrating three different lengths and time, (1) from the jet nozzle to the tip of the potential core H_p and time t_p; (2) from the tip of the potential core H_p to the initial soil surface H_i and $t_i - t_p$; and (3) from the initial soil surface H_i to the depth of scour H, and $t_m = t - t_i$ where t_m is the actual measured time.

The time t_p and the corresponding depth H_p delineate the end of the potential core length. The dimensionless time $T_p^* = t_p/T_r$ can be determined by integrating Eq. 12 from the nozzle origin to the tip of the potential core:

$$T_p^* = H_p^* \left[\frac{H_p^{*2}}{(1 - H_p^{*2})} \right] \quad (15)$$

Note that dimensionless time T^* for any depth within the core can be determined by:

$$T^* = H^* \left[\frac{H_p^{*2}}{(1 - H_p^{*2})} \right] \qquad H^* > H_p^* \quad (16)$$

The time t_i and the corresponding depth H_i determines the point on the theoretical scour curve at which the test was initiated. The time from the potential core to the initial bed surface is t_i-t_p. The dimensionless time $T_i^* = t_i/T_r$ can be determined by integrating Eq. 9 from the potential core length to the initial soil bed elevation:

$$T_i^* = 0.5 \ln\left(\frac{1+H_i^*}{1-H_i^*}\right) - H_i^* - 0.5 \ln\left(\frac{1+H_p^*}{1-H_p^*}\right) + H_p^* + T_p^* \quad (17)$$

where the dimensionless term $H_i^* = H_i/H_e$. The time t, and the corresponding depth H delineate the bed scour due to sediment detachment. The measured time t_m= t-t_i represents the time since the beginning of the jet test. The dimensionless time $T^* = t/T_r$ can be determined by integrating from the initial soil surface H_i to the depth of scour H and adding T_i^*:

$$T^* = 0.5\ln\left(\frac{1+H^*}{1-H^*}\right) - H^* - 0.5\ln\left(\frac{1+H_i^*}{1-H_i^*}\right) + H_i^* + T_i^* \quad (18)$$

Simplifying Eq. 14 by including the terms for T_i^* and T_p^* results in the following equation:

$$T^* = 0.5\ln\left(\frac{1+H^*}{1-H^*}\right) - H^* - 0.5\ln\left(\frac{1+H_p^*}{1-H_p^*}\right) + H_p^* + \frac{H_p^{*3}}{1-H_p^{*2}} \quad (19)$$

where $T^* = t/T_r$, and $t = t_m + t_i$ in which t_m is the actual measured time since scour began and t_i is the scale adjustment time it would have taken to scour from the jet origin to the initial soil bed, assuming there was soil there and its erodibility was constant with depth and time. The equation for the measured time can then be expressed as:

$$t_m = T_r\left[0.5\ln\left(\frac{1+H^*}{1-H^*}\right)-H^*-0.5\ln\left(\frac{1+H_i^*}{1-H_i^*}\right)+H_i^*\right] \tag{20}$$

MATERIALS AND METHODS

Apparatus

Hanson (1990b) developed a submerged jet device for site-specific testing of cohesive soils. The concept of the device is similar to the laboratory devices utilized by Dunn (1959), Moore and Masch (1962), and Hollick (1976). The apparatus consists of a submerged jet with a nozzle diameter of 13 mm, set at a height H_i of 0.22 m above the initial soil surface. The velocity at the nozzle is controlled by the pressure differential at the nozzle, h. The depth of scour during a test was determined over a series of time periods using a pin profiler that could be interchanged with the jet apparatus. Four soils (A, B, C, and D) were compacted in the field and jet tested in-situ (Hanson 1990b, 1991). The depth of compacted material was 0.23 m.

Scour Data

Based on the results of scour tests on these four soils with a range of physical properties (Table 1), a soil parameter (jet index, J_i) was developed for the purpose of providing a common method of expressing erosion resistance of soil materials (Hanson 1991). The results were compared with open channel test results on the same four soils (Hanson 1990a). Therefore, an empirical relationship was developed between J_i and the soil erodibility coefficient k from the open channel test results. Development of the excess stress parameters for the circular submerged jet apparatus allows for direct determination of the erodibility coefficient and critical stress as described in this paper. The scour data from Hanson (1990b) are analyzed in this paper and compared with the jet index results described by Hanson (1991) and the open channel test results described by Hanson (1990a).

Seven to eight jet tests were run on each soil, with U_o varying from 1.7 m/s to 7.3 m/s. Maximum depths of scour as well as the volume of scour were determined at different time intervals for total times in some cases of more than 20 hours. The maximum depth of scour H at each time interval measurement and U_o were used to determine the J_i. These same data can be used to evaluate the excess stress parameters τ_c and k based on the analytical development presented in this paper.

APPLICATION OF EQUATIONS

Three methods using these analytical procedures were evaluated for determination of the excess stress parameters τ_c and k. Method 1 involved iteratively determining parameters k and τ_c using Eqs. 19, and 20 and a nonlinear curve fitting routine. Method 2 involved predetermining τ_c utilizing a hyperbolic logarithmic method (Blaisdell 1981) and an iterative determination of k. Method 3 assumed a constant τ_c (0.14 Pa) from Sheild's diagram and an iterative determination of k. The first method was found to be unstable, allowing for multiple answers depending on the initial iteration values; therefore, it was not considered a viable approach.

The second method involved predetermining τ_c which increased the stability of the numerical computations. Eq. 9 defines the critical stress for scour as a function of the core stress, core length, and the ultimate or equilibrium scour depth. Therefore, the critical stress has the potential of being defined by the jet test results independently of the erodibility coefficient. The difficulty arises in the length of time required to reach equilibrium depth. An alternative to conducting scour tests until equilibrium depth is reached is to estimate the equilibrium depth. Blaisdell (1981) described a hyperbolic logarithmic method to estimate equilibrium depth and the corresponding time based on scour data. The general form of the equation for the hyperbola is:

$$(f - f_o)^2 - x^2 = A^2 \tag{21}$$

where:

$$f = \log\frac{H}{d_o} - \log\frac{U_o t}{d_o} \tag{22}$$

$$f_o = \log\frac{H_e}{d_o} \tag{23}$$

$$x = \frac{U_o t}{d_o} \tag{24}$$

This method was used to determine the equilibrium depth and, as a result, critical stress. A least square curve-fitting method in the software package SIGMAPLOT was used to iteratively determine the equilibrium depth. This software program was used for all the iterative solutions required to analyze the algorithms presented in this paper. The measured values of H, d_o, U_o, and t were used to determine x and f, while A and f_o were iteratively evaluated for the best values based on the minimum standard error. The erodibility coefficient could then be determined based on Eqs. 15 and 16 and an iterative determination of the best-fit value.

The third method assumed that critical stress was a function of the incipient motion for discrete particles. This would assign a small value to critical stress based on the Shield's diagram (Fig. 2). The critical stress for incipient motion computed for Shield's criteria for particle sizes less than 0.1 mm would be 0.14 Pa. The development of the excess stress parameters in this paper does not allow for τ_c to be set at zero, but using this approach minimizes its influence and simplifies the solution process. The erodibility coefficient could then be determined based on a least square curve fit solution of Eq. 16.

RESULTS

Each test as described by Hanson (1990b, 1991) was analyzed individually to determine the excess stress parameters based on methods 2 and 3. The results are presented in Table 2, sorted by soil material and test number. The τ_o term is shown in Table 2 as determined from Eq 5 to indicate the relative levels of stress for each test. The jet index is included as a comparison to methods 2 and 3. Developed by Hanson (1991), the jet index is a single parameter with the purpose of characterizing erosion resistance. Two examples of the analysis process are shown in

Figs. 3 – 10. Figs. 3 – 6 are for soil material A, test 3, while Figs. 7 – 10 are for soil material C, test 1. Figs 3 and 7 are plots of the measured scour D_s (D_s = H - H_i) versus time of scour testing. The scour tests for soil A result in a scour depth of almost 16 cm in a 3-hour period, whereas soil C resulted in scour depth of 0.3 cm in a 22-hour period. This was due to a combination of factors. Soil A is a sandy loam with low plasticity and high sand content. Soil C is a loam with a slightly higher plasticity and lower sand content. Test 1 of soil C was tested at a lower relative stress level than test 3 of soil A. Soil C was observed to be much more erosion resistant throughout all the stress levels applied in jet testing and open channel testing than soil A.

Determination of the critical stress by the hyperbolic logarithmic method is shown in Figs. 4 and 8. These figures are based on Eqs. 17 – 20. The determination of the erodibility coefficient k, based on Eqs. 12, 13, and 15, for method 2 is shown in Figs. 5 and 9 and for method 3 is shown in Figs. 6 and 10. The dimensionless time that would have been required to scour the length of the potential core and the time that would have been required to scour the distance from the potential core to the initial soil bed surface are shown in these figures with solid symbols. For soil A, test 3, the critical stress determined by method 2 is close to the critical stress of method 3, and therefore the k parameters are also close in value. For soil C test 3, the critical stress determined from method 2 is higher than the value used in method 3. As a result the k term for method 2 is higher as well to compensate for the higher critical stress. The spread on the scour data on the dimensionless time scale in Figs. 9 and 10 is small in comparison with the results for soil A in Figs. 5 and 6 even though it was tested 7 times longer. This indicates that τ_c and k have a dramatic influence on the time scale as indicated in Eq. 11.

A comparison of the τ_c and k parameters of soils A, B, C, and D for method 2 show similar trends to that observed by Arulanandan et al. (1980) (Fig. 11). The trend is for the soils exhibiting low τ_c to have a high k and for soils having a high τ_c to have a low k value. Based on the results of method 2, soil A had low τ_c and moderate k parameters. Soil B had some of the highest k values and the highest τ_c values but held true to the observation that when one of the tests for soil B resulted in a high τ_c, the k was low, and when k was high, τ_c was low. Soil C was observed to be the most resistant of the four soils tested, with low k values. Soil D was observed to be the most erodible of the four soils, with low τ_c and the highest k values. Based on these results the relative ranking of erodibility for the four soils from least resistant to most resistant would be D, A, B, and C.

This same relative ranking can also be observed from the results of method 3 (Fig. 12). A plot of k versus τ_o shows soil D having the highest k values, with soil A, B, and C following in descending order. A line indicating the average k for each soil shows soil D having an average erodibility greater than soil C by a factor of 170.

Fig. 13 shows the relationship of the jet index versus the k determined from method 3. The jet index is a single parameter indicating erosion resistance. The k determined from method 3 is based on the assumption that τ_c is constant, and therefore k based on this method is also a single parameter indicator of erodibility. The jet index and k show a good relationship to each other, with J_I increasing as k increases.

Erosion tests in the open channel environment were conducted on the same four soils (Hanson 1990a). They were not conducted at the same time, and although the materials were prepared in similar fashion it has been observed that density and moisture content of the soil at the time of preparation can have a dramatic effect on the erodibility of a soil (Hanson and Robinson 1993). Therefore, only qualitative comparisons can be made at this time. The erodibility coefficients determined from the open channel tests were of similar magnitude as the jet test results, and the relative rankings of erodibilities for each soil were the same.

SUMMARY AND CONCLUSIONS

Analytical procedures were developed in this paper for submerged circular jets based on diffusion principles. Three methods using these analytical procedures were evaluated for determination of the excess stress parameters τ_c and k. Method 1 which involved an iterative determination of parameters k and τ_c using Eqs. 12, 13, 15, and 16 and a nonlinear curve fitting routine was unstable. Method 2 involved predetermining τ_c utilizing a hyperbolic logarithmic method (Blaisdell 1981) and an iterative determination of k. Method three assumed a constant τ_c and an iterative determination of k.

Jet test scour results for four soils were evaluated using methods 2 and 3. A comparison of the τ_c and k parameters of soils A, B, C, and D exhibited similar trends in which soils having low τ_c tended to have a high k and soils having a high τ_c tended to have a low k value. The relative ranking of the erodibility for the four soils from least resistant to most resistant was D, A, B, and C. This relative ranking was the same as that determined from channel testing (Hanson 1990a) as well as from the jet index results (Hanson 1991). It was also observed that the relative erodibility of soil D, the most erodible soil material, and soil C, the least erodible soil material, was different by a factor of about 170 fold. The magnitude of the parameters τ_c and k is very similar to values reported in the literature. Even though the channel tests of the same soils reported by Hanson (1990a) were at different times and likely different moisture regimes, the magnitudes of the k parameters are similar.

Now that analytical procedures to determine the excess stress parameters τ_c and k have been developed for submerged circular jets, further research is needed to compare open channel results with jet scour results. The jet test offers a convenient procedure for evaluating the erodibility of soils both in the field and laboratory.

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TABLE 1. Summary of physical soil properties.

Physical Properties	Soil A	Soil B	Soil C	Soil D
Liquid Limit	21	37	26	-
Plastic Limit	17	19	20	NP
Plasticity Index	4	18	6	0
% Sand > 0.005 mm	57	37	18	67
% Silt > 0.002 mm	27	36	33	26
% Clay < 0.002 mm	16	27	19	7
U.S.C.	CL-ML	CL	CL-ML	SM
A.S.C	Sandy loam	Clay loam	Loam	Sandy loam

TABLE 2. Comparison of excess stress parameter results

	Test		Jet Index, J_i	Me	2	Method 3	
Soil	#	τ_o Pa		k cm^3/N-s	τ_c Pa	k cm^3/N-s	τ_c Pa
A	1	177	0.012	6.9	4.2	5.1	0.14
	2	97	0.016	7.9	1.9	5.9	0.14
	3	68	0.009	3.3	0.19	3.2	0.14
	4	11	0.005	5.6	0.80	2.7	0.14
	5	28	0.009	4.6	0.32	4.3	0.14
	6	41	0.017	5.9	0.44	5.3	0.14
	7	38	0.012	7.6	0.36	7.1	0.14
B	1	11	0.007	31	1.3	2.5	0.14
	2	27	0.006	16	[illegible]	1.4	0.14
	3	49	0.001	0.28	2.5	0.15	0.14
	4	101	0.004	1.3	10	0.15	0.14
	5	73	0.004	6.5	7.7	0.59	0.14
	6	148	0.005	0.6	12	0.14	0.14
	7	194	0.003	1.1	20	0.07	0.14
	8	220	0.003	0.02	22	0.07	0.14
C	1	13	0.001	0.85	1.6	0.07	0.14
	2	25	0.001	0.34	2.2	0.11	0.14
	3	49	0.003	0.79	4.4	0.23	0.14
	4	74	0.004	1.1	21	0.17	0.14
	5	97	0.0001	0.30	12	0.03	0.14
	6	149	0.003	0.49	15	0.08	0.14
	7	220	0.001	0.01	11	0.05	0.14
D	1	13	0.013	10.2	0.10	10	0.14
	2	27	0.011	7.3	0.05	7.6	0.14
	3	38	0.025	34.3	0.79	26	0.14
	4	51	0.019	13.9	0.79	12	0.14
	5	76	0.020	54.4	3.8	15	0.14
	6	98	0.019	-	-	32	0.14
	7	149	0.014	-	-	19	0.14

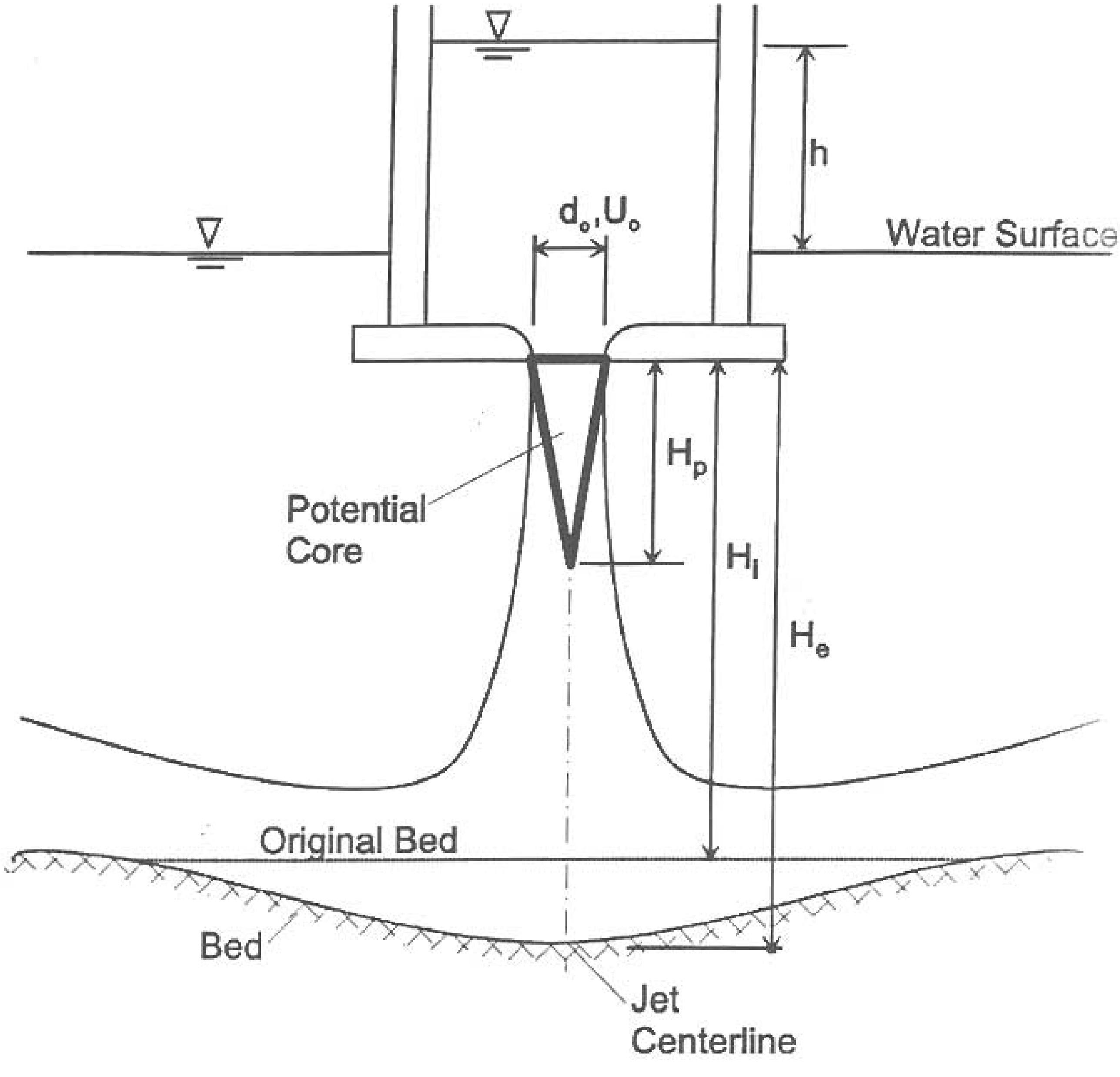

Figure 1. Illustration of an impinging jet.

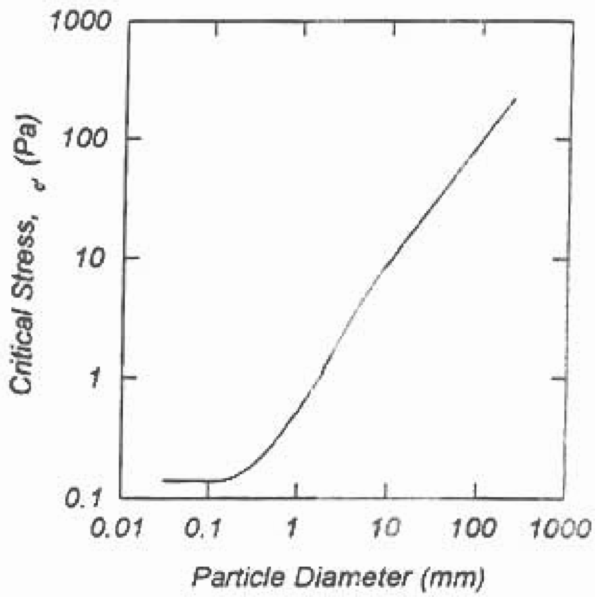

Figure 2. Critical stress for incipient motion from Shield's criteria with a sediment specific gravity of 2.65 and a kinematic viscosity of water of 9.3×10^{-7} m^2/s (Temple and Hanson, 1994).

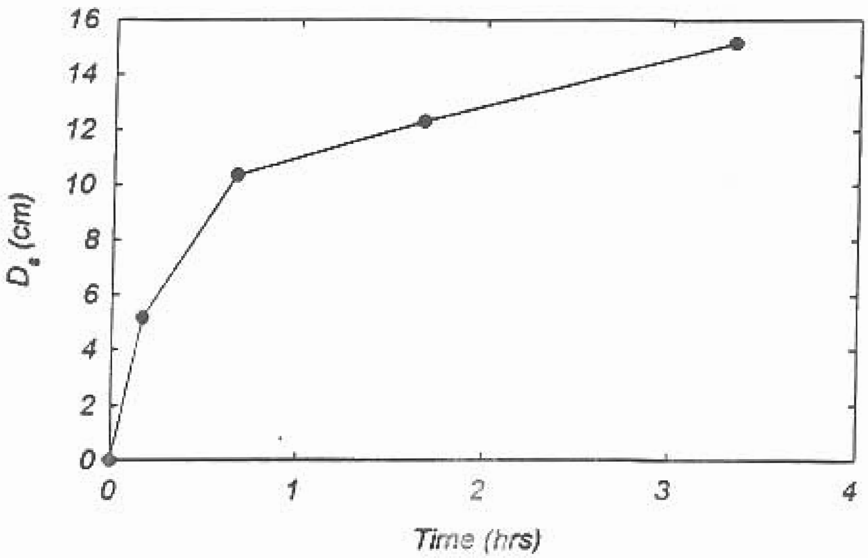

Figure 3. Maximum depth of scour versus time for soil A, test 3

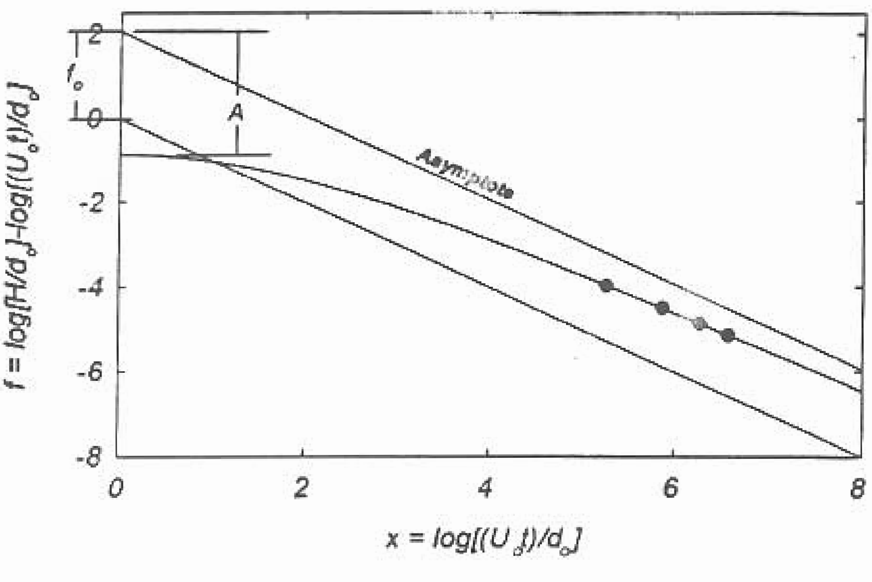

Figure 4. Graphical display of the hyperbolic determination of the equilibrium depth of scour for soil A, test 3.

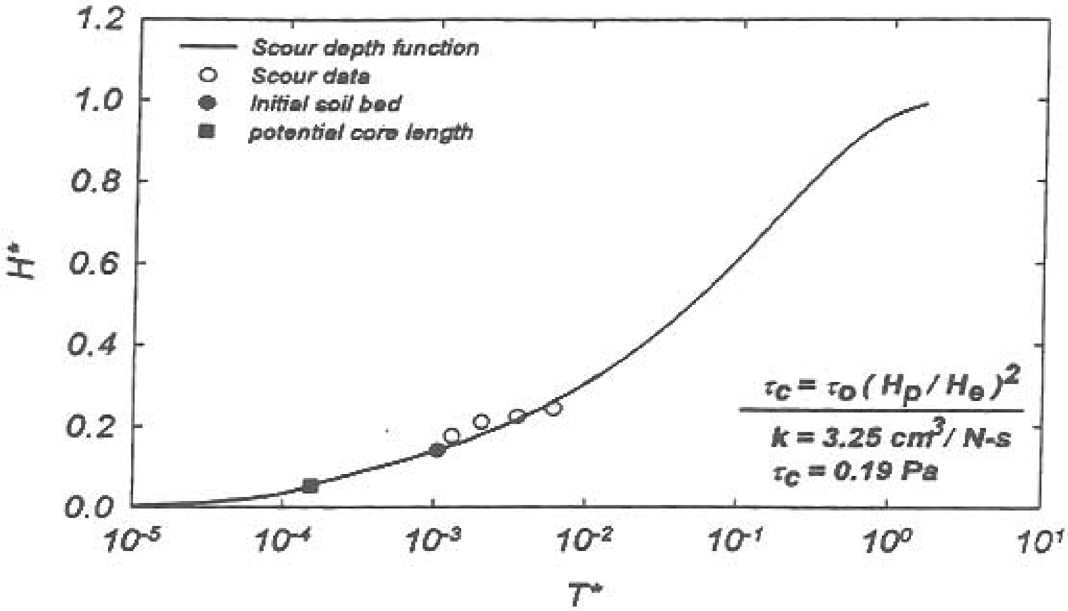

Figure 5. Dimensionless scour depth versus time for soil A, test 3, using method 2.

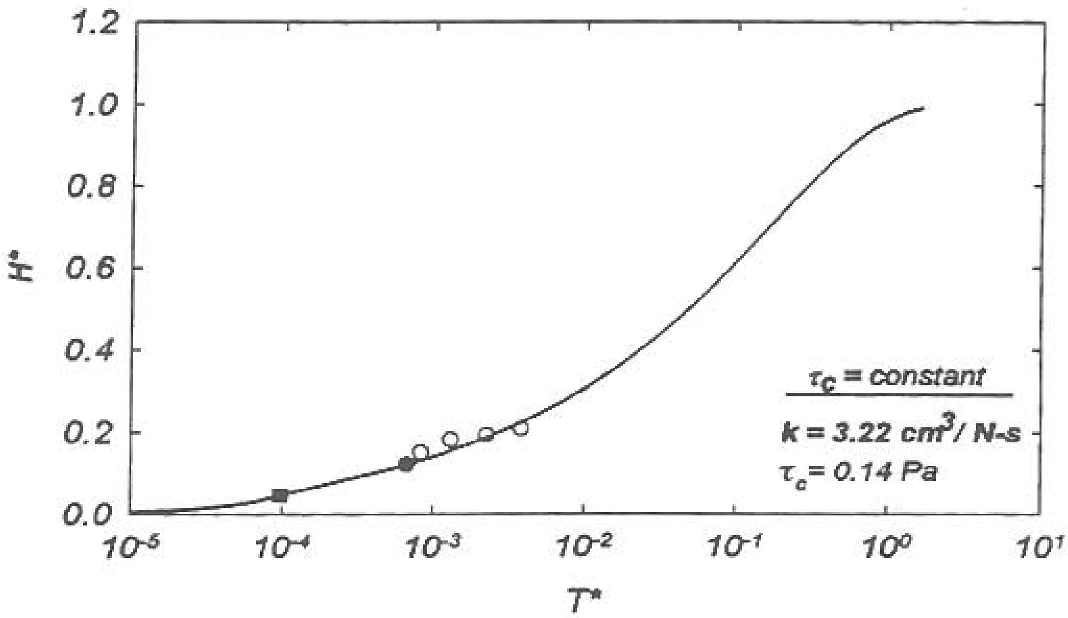

Figure 6. Dimensionless scour depth versus time for soil A, test 3, using method 3.

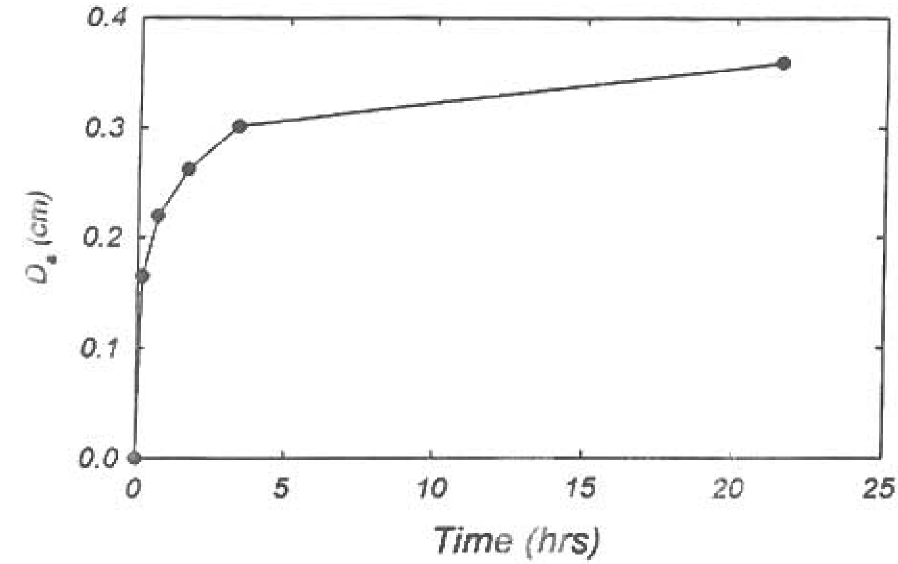

Figure 7. Maximum depth of scour versus time for soil C, test 1.

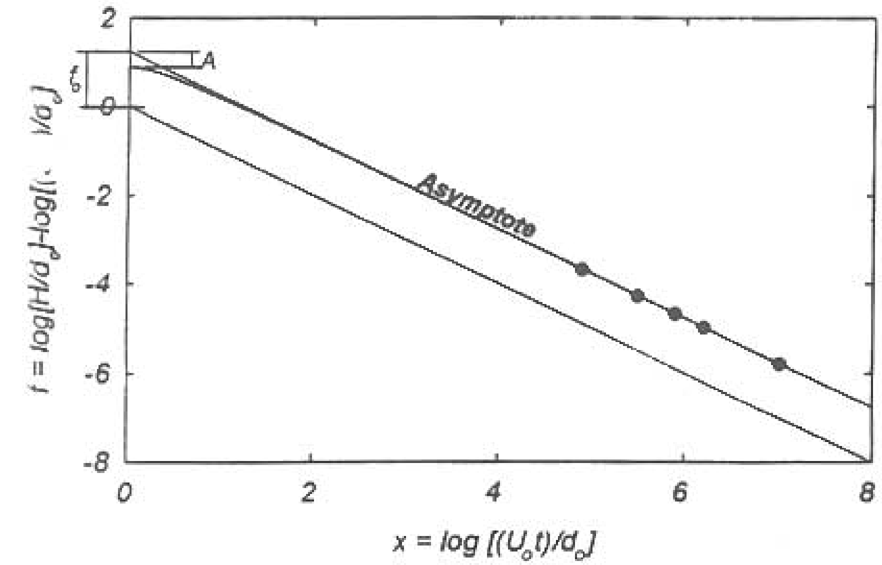

Figure 8. Graphical display of the hyperbolic determination of the equilibrium depth of scour for soil C, test 1.

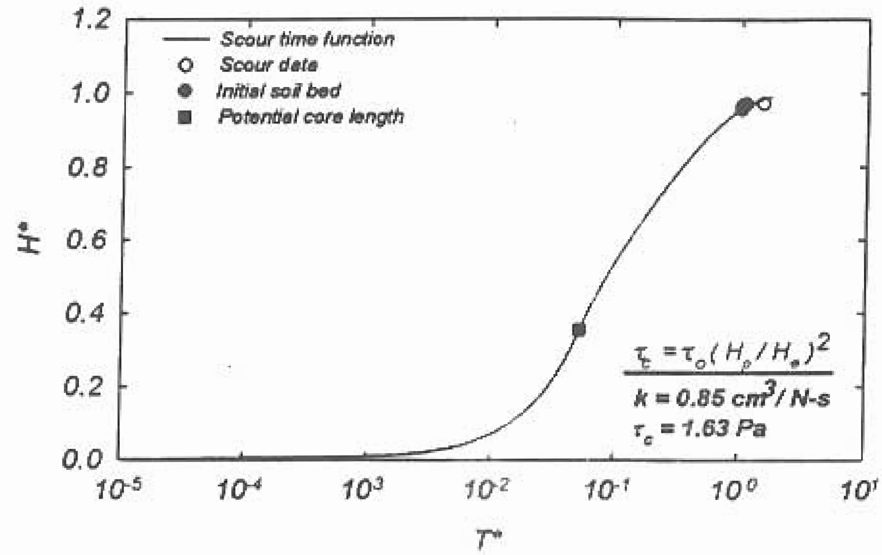

Figure 9. Dimensionless scour depth versus time for soil C, test 1 using method 2.

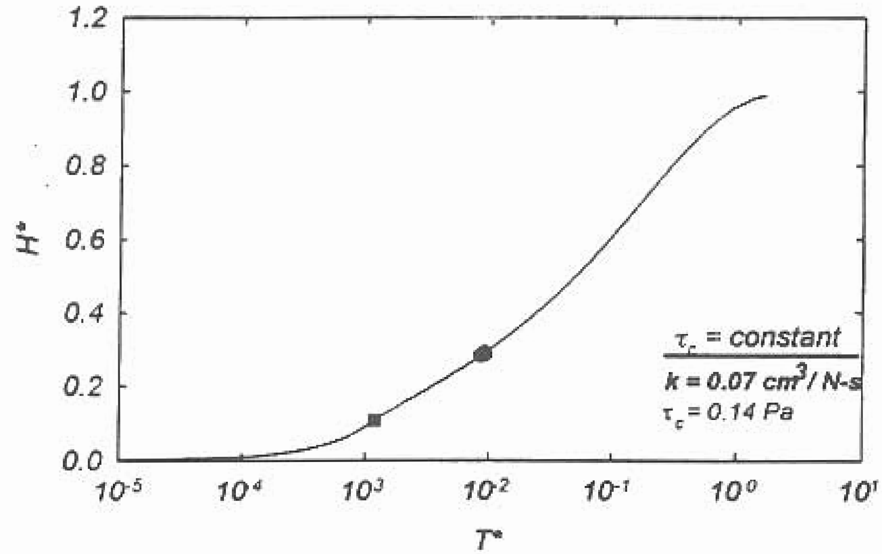

Figure 10. Dimensionless scour depth versus time for soil C, test 1 using method 3.

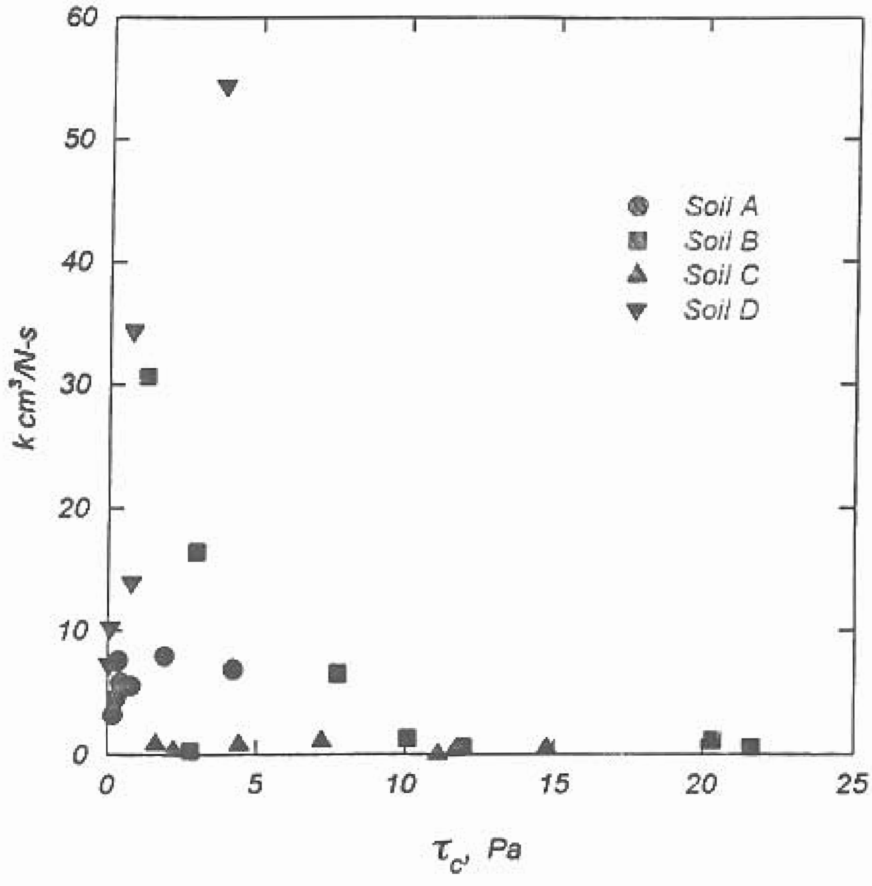

Figure 11. k versus τ_c based on method 2.

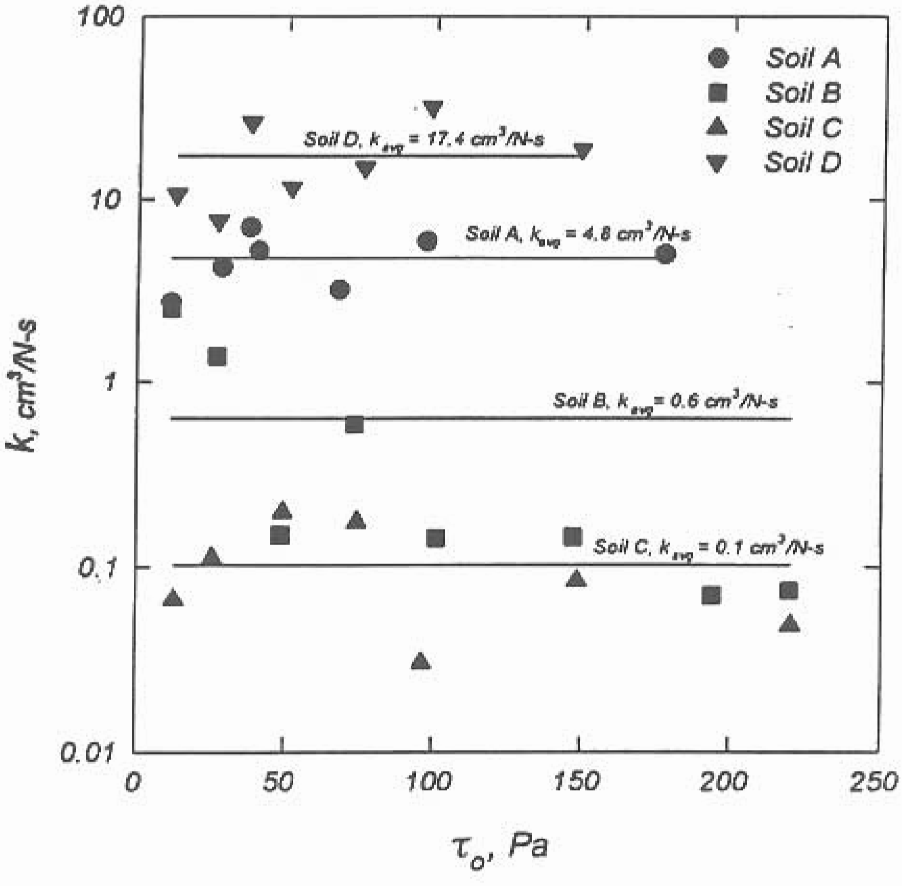

Figure 12. k versus the τ_c for each soil using method 3.

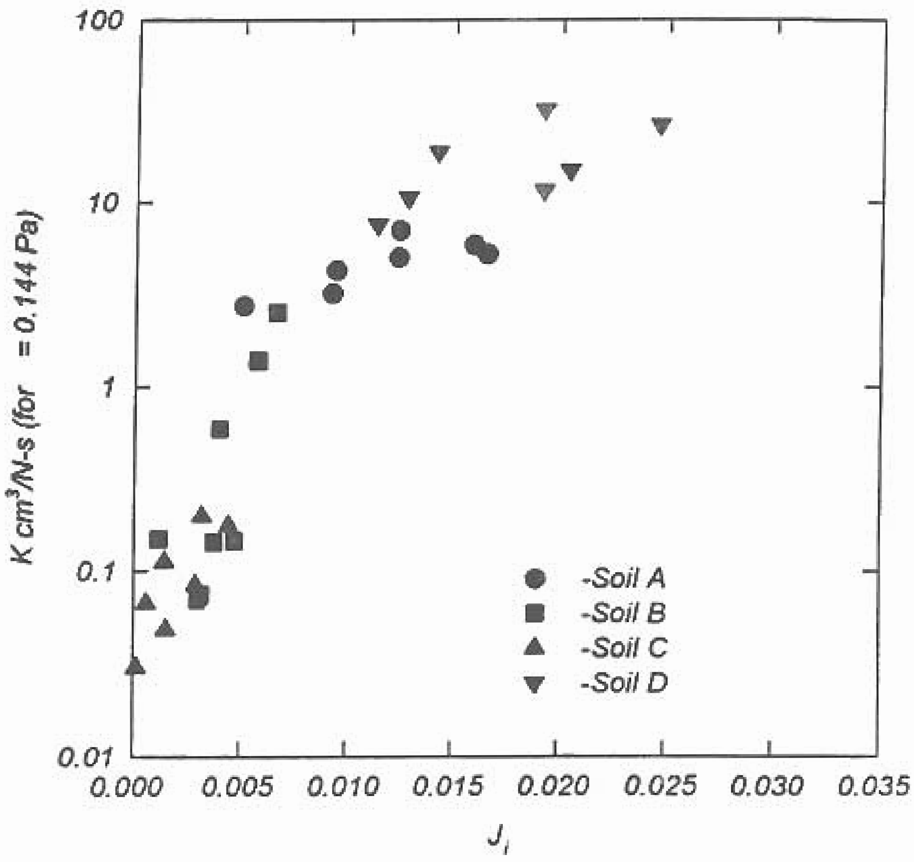

Figure 13. Relationship between J_i and k determined from method 3.