A Consolidation Model for Estimating Changes in Rill Erodibility

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ABSTRACT

SOIL erodibility changes with time after tillage. A mathematical model is presented that estimates variations in rill erosion parameters as a function of consolidation. Consolidation is defined as the increase in soil stability which occurs because of effective stresses in soils. Effective stresses are induced by negative soil water matric potentials that occur during moisture redistribution after rainfall. A method for calculating effective stresses is presented, as well as a relationship for relating effective stress history to changes in rill erosion resistance. An application of the model for field rill erosion of silt loam soil is presented.

INTRODUCTION

The Universal Soil Loss Equation was developed to predict long-term average annual soil erosion for a set of environmental and agricultural conditions. The soil erodibility parameter, K, was defined by Wischmeier and Smith (1978) as a constant value for a given soil, and is calculated from values of time invariant soil parameters. However, since the USLE was developed it has become increasingly apparent that soil erodibility is not time invariant (Dickinson et al., 1982; Mutchler and Carter, 1983; Pall et al., 1982). Prediction capability for short term or storm event soil loss is being developed with the advent of new erosion prediction technology (Foster, 1982) and will require mathematical descriptions of temporal variations in bare soil erodibility.

The development of a mathematical representation of changes in soil erodibility requires knowledge of the fundamental processes which cause destabilizaton and stabilization of a soil. Erosion measurements are not available that fully delineate factors affecting soil stabilization or destabilization and hence erosion indices such as soil strength (Dickinson et al., 1982; Formanek et al., 1984; Pall et al., 1982; Watson and Laflen, 1986) or aggregate stability (Imeson and Vis, 1984; Kemper and Rosenau, 1984; Utomo and Dexter, 1982) help to assess these factors. Mechanical stabilization of a soil mass is defined here as any process that tends to increase the number or strength of interparticle or interaggregate bonds. Bonding increases strength (Mitchell, 1976) and

resistance to detachment by surface flows of water (Kandiah, 1974; Sargunam, 1973). Destabilization processes tend to decrease soil bonding.

Primary factors that potentially influence the mechanical stability of a soil include effective stress history (Holtz and Kovacs, 1981; Lambe and Whitman, 1969; Towner and Childs, 1972) and time (Bjerrum and Lo, 1963; Mitchell, 1960). For erosion, surface sealing and crusting may also cause changes in stability in interrill areas, but these processes are not considered here. Evidence shows that effective stress history affects erosion resistance. Al-Durrah and Bradford (1981) and Cruse and Larson (1977) showed that effective stress induced by negative pore water potential increases resistance of soils to splash by raindrops. Kemper and Rosenau (1984) reasoned that soil water suctions (which cause effective stresses) work to bond soils and increase cohesion, and their data is consistent with the theory. Formanek et al. (1984) showed that cohesional strength (which they took to be an erodibility index) increased with logarithm of effective stress, which they assumed equal to soil water suction.

The mechanisms of consolidation, time and suction, were studied by Nearing et al. (1988) for a clay soil by Nearing and West (1988) for fine sand, silt loam, and clay soils. Results of those studies indicated that while both time and suction influenced soil stability, the soil water suction effect was much more significant than time effects. Nearing and West (1988) concluded that considering the high variability encountered in field environments, changes in soil stability due to time alone would be difficult to characterize. These studies utilized the concept of prestress as a mechanism of consolidation, which is important for erosion problems. When soil was equilibrated under suction for a period of time and subsequently resatiated, the soil maintained a portion of its strength gain associated with the suction that caused consolidation. The retention of a portion of the strength gain upon rewetting is particularly applicable to erosion since soil consolidates between rainfall events, but is rewet during erosion events. A portion of the consolidation related strength gain is retained due to the prestress effect.

Primary factors that destabilize a soil's resistance to erosion are tillage and freezing. Formanek et al. (1984) showed that the cohesional strength of a wet silt loam as measured with a Swedish fall-cone decreased to about 50% fo its original value with one freeze-thaw cycle. Benoit (1973) also showed decreases of soil aggregate stability due to freeze-thaw cycles. Erosion resistance increases with time after tillage. Meyer and Harmon (1981) performed interrill erosion experiments on a Vicksburg silt loam soil under two conditions. One condition was freshly tilled and the other had not been

cultivated for approximately 5 months. Both were bare. The interrill erosion coefficient was approximately 80% higher for the tilled condition, indicating a much higher erosion rate for the disturbed soil.

The purpose of this study was to outline a mathematical plan for calculating soil erodibility changes due to the stabilizing and destabilizing factors discussed above. Processes occurring on interrill erosion areas, particularly surface sealing and crusting, were not considered, hence the scheme was developed for rill erodibility only. Parameter values were estimated from available information and an example was given.

EROSION EQUATIONS

Soil detachment equations for rill or channel erosion are typically of the form

$$E = K (\tau - \tau_c) \qquad \qquad [1]$$

where
- E = soil detachment capacity
- τ = shear stress
- τ_c = critical shear stress
- K = the change in erosion rate per change in excess shear stress which will be called herein "erodibility".

It is recognized (Arulanandan et al., 1980; Foster, 1982) that the relationship between erosion rate and shear stress is not always linear over the entire range of τ. In this paper it will be considered linear over the range of shear stress of interest. This assumption is used in modern erosion prediction models (Lane et al., 1987), and is generally considered accurate for field rill erosion experiments (Laflen et al., 1987). To account for time variant erodibility equation [1] may be rewritten as

$$E = KK' (\tau - \tau_c\tau_c') \qquad \qquad [2]$$

where K and τ_c represent standard state erodibility and critical shear and K' and τ_c' represent the time variant adjustments to K and τ_c. In order to explore the nature of the time variant parameters K' and τ_c' the erosion rate equation can be written in a "force/resistance" form as

$$E = \tau_e/R \qquad \qquad [3]$$

where τ_e is excess shear $(\tau - \tau_c\tau_c')$ and R is soil resistance $(1/KK')$.

The resistance term, R, will be a function of some standard state resistance, R_o, an increase in resistance due to consolidation, R_c, and potentially some decrease in resistance due to freezing effects, f. The standard state resistance, R_o, is defined as the inverse of K from equation [1] as measured immediately after standard tillage or mechanical disruption of the bulk soil. This model does not address the effects of different tillage systems, which must be considered individually. Thus

$$R = fnc (R_o, R_c, f) \qquad \qquad [4]$$

The resistance function will be hypothesized here to have the same form as that for electrical resistors in series, but potentially modified by the freeze factor, f. Thus it is hypothesized that total resistance, R, is given by

$$R = f(R_o + R_c) \qquad \qquad [5]$$

If the consolidation resistance term is normalized to the standard state resistance, R_o, then equation [5] may be rewritten as

$$R = R_o f(1 + r_c) \qquad \qquad [6]$$

where $r_c = R_c/R_o$ is the increase in resistance relative to standard state conditions due to consolidation. A resistance adjustment factor, R', is defined therefore as

$$R' = f (1 + r_c) \qquad \qquad [7]$$

Since $R=1/KK'$ and $R_o=1/K$, then the time variant adjustment factor for erodibility, K', for use in equation [2] is

$$K' = 1/R' \qquad \qquad [8]$$

The normalized resistance function r_c will be presented later.

It has been observed that factors which affect erodibility also affect critical shear stress, and that for a given soil as erodibility decreases critical shear increases (Ariathurai and Arulanandan, 1978). Thus the same factors affecting K' (or R') also influence τ_c', though τ_c' and R' may not be necessarily proportional. Therefore an arbitrary function β can be defined such that

$$\tau_c' = \beta R' \qquad \qquad [9]$$

An approximation for the function β can be obtained by considering its behavior in extreme cases. For case (1), let $\beta = 1$ and so $\tau_c' = R'$. The family of erosion rate vs. shear stress curves for case (1) are shown in Fig. 1a. For case (2), let $\beta=1/R'$, in which case $\tau_c' = 1$ for all R'. Erosion curves for case (2) are shown in Fig. 1b. For case (1), changes in resistance affect τ_c' to the same degree as they affect K. For case (2), the resistance changes do not affect τ_c'. Existing data (Ariathurai and Aralanandan, 1978) suggest that the true relationship for τ_c' may lie between the two extremes. For lack of better delineation, it will be assumed here that the effect of R' and τ_c' is the average of cases (1) and (2). Thus

$$\beta = 0.5 (1 + 1/R') \qquad \qquad [10]$$

Placing this function for β into equation [9] results in the function for τ_c' of

$$\tau_c' = 0.5 (R' + 1) \qquad \qquad [11]$$

Equation [2] is an erosion equation which includes time variant adjustments K' (equation [8]) and τ_c' (equation [11]) as a function of R' (equation [7]). The functions r_c and f must be estimated in order to compute R'.

CONSOLIDATION RESISTANCE PARAMETER

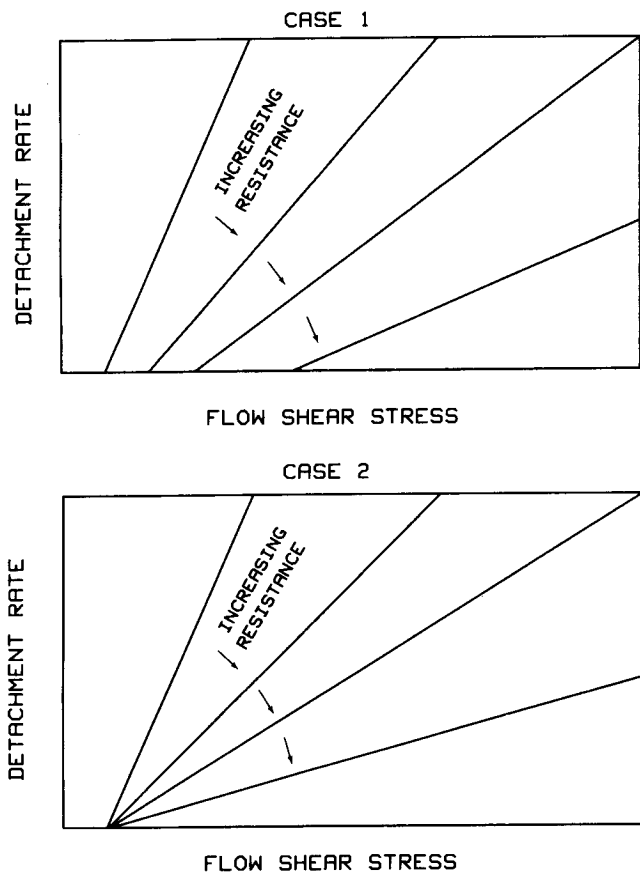The normalized resistance factor, r_c, represents the

Fig. 1—Erosion rate vs. flow shear stress for the case of a) $\tau_c' = R'$ and b) $\tau_c' = 1$.

relative increase in erosion resistance from standard state conditions due to consolidation. Soil consolidation, as the term is used here, can be described from the observed fact that soil water suctions (such as occur with moisture redistribution after rainfall) induce effective stresses in soils which cause increases in soil strength. Thus the key to describing consolidation is the mathematical description of effective stress. The classical effective stress equation (see e.g., Holtz and Kovacs, 1981) for saturated soils is

$$\sigma' = \sigma - u \qquad \qquad [12]$$

where

σ' = effective stress
σ = the total applied stress
u = soil pore water pressure

For unsaturated soils the effective stress equation is modified to account for the fact that the pore water stress is not acting in the unfilled soil pores, thus (Blight, 1967; Towner, 1983)

$$\sigma' = \sigma - \chi \Psi \qquad \qquad [13]$$

where ψ is soil water matric potential and χ is an empirical coefficient. For surface soils under no load, the applied stress, σ, is essentially zero, hence

$$\sigma' = -\chi \Psi \qquad \qquad [14]$$

for that case.

Soil strength increases linearly with effective stress. Thus, as a soil dries, its strength increases proportionally to $-\chi\Psi$. (Bishop and Blight, 1963; Blight, 1966; Blight, 1967; Jennings, 1961; Towner and Childs, 1972). The term χ can be estimated by

$$\chi = \begin{array}{ll} 2S - 1 \ \text{for} & S \geqslant 0.5 \\ 0 \ \ \ \text{for} & S \leqslant 0.5 \end{array} \qquad [15]$$

where S is the degree pore saturation. This function for χ is a mathematical representation of data from the study of Nearing et al. (1988) for a clay soil. The results of that study indicated that the relationship between χ and S was independent of soil structure.

The degree of soil stabilization is a function of the maximum previous effective stress, or prestress, to which the soil has been exposed, σ' (Nearing et al., 1988). Hence, from equation [14]

$$\sigma_p' = [-\chi\Psi]_{max} \qquad \qquad [16]$$

where $[-\chi\Psi]_{max}$ is the maximum previous value of $-\chi\Psi$ (maximum previous σ'). For any given soil, χ and Ψ are both functions of S, therefore σ_p' is determined at any given time from its moisture content history since time zero. An example of $\chi - S$ and $\Psi - S$ relationships for a silt loam soil near West Lafayette, IN is given in Fig. 2. The effective stress, σ', is the multiple of $-\chi\Psi$ and is plotted in Fig. 3. For this soil the maximum possible effective stress is 10 kPa and occurs at approximately $S=0.59$. For purposes of this model, a soil is considered to begin consolidation with the first wetting, therefore, time zero is the first rainfall after disturbance. The soil will then drain to some minimum saturation level before the next rainfall occurs. For the first rainfall event, r_c is considered to be zero; the soil maintains standard state condition until after the first wetting cycle. For subsequent rainfall events a minimum S value, S_{min}, must be determined, from which σ_p' is calculated. The value of S_{min} is equal to the value of S at the driest point since the first rainfall event.

The procedure for calculating σ_p' from S_{min} is as follows. If S_{min} is less than 0.5 then set $S=0.5$. Otherwise let $S=S_{min}$. Now use S to calculate χ from equation [15] and to calculate Ψ from Ψ vs. S relationships. Then
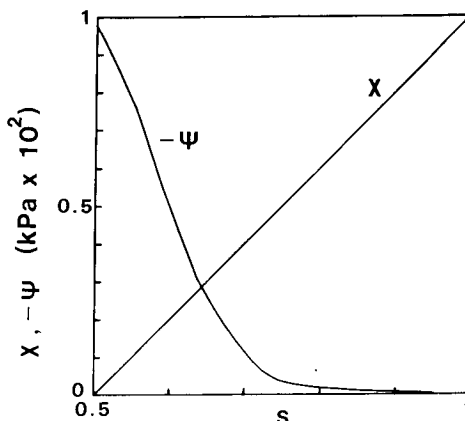

Fig. 2—Nondimensional effective stress parameter, χ, and negative soil water matric potential, $-PSI$ (in bars), as a function of degree of saturation, S, for a silt loam soil near West Lafayette, IN.
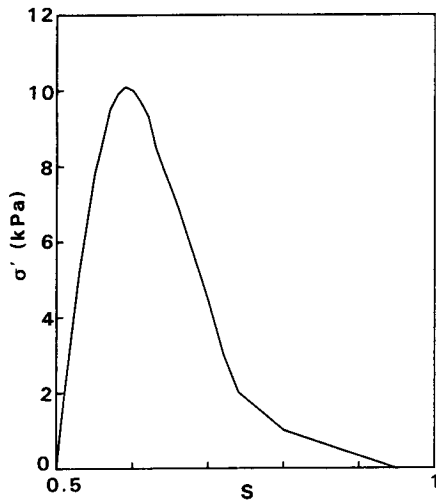
Fig. 3—Effective stress, σ', as a function of degree of saturation, S, for a silt loam soil near West Lafayette, IN.

calculate σ' from equation [14]. Now add some arbitrarily small value to S and recalculate σ'. If the second σ' value is less than the first, then set σ_p' equal to the first value of σ'. If the second σ_p' is greater than the first, then increase S in small increments until σ' decreases. The maximum σ' value is the magnitude of σ_p'.

It may be worthwhile to note that if σ_p' is not the value of σ' which is associated with S_{min}, then the soil has reached its greatest degree of consolidation, which must occur at some value of S between 0.5 and 1. This is true because as S decreases, $-\psi$ increases, but χ decreases. Maximum consolidation occurs at the point where the multiple $-\chi\psi$ is maximized. For the silt loam soil discussed above, this maximum occurs at $S=0.59$ (Fig. 3). At that point the soil is fully consolidated. No matter how low S may go during subsequent drying, no greater value of σ' (or therefore, σ_p') can be obtained. This fact has practical implications in that it shows that r_c is limited in magnitude between 0 and the value associated with maximum possible σ_p' for a given soil.

Soil shear strength, τ, behavior can be modeled with an equation of the form (Hvorslev, 1960)

$$\tau = \sigma_p' \tan \phi_c' + \sigma_f' \tan \phi_r' \qquad [17]$$

where

$\sigma_f' =$ applied normal stress on the failure plane

$\phi_r' =$ a component of friction angle associated with applied stress

$\phi_c' =$ a component of friction angle associated with permanent strength gain caused by consolidation

For the case of satiated surface soils, the applied stress to the soil is essentially zero, hence equation [17] may be rewritten as

$$\tau = \sigma_p' \tan \phi_c' \qquad [18]$$

For the case of erosion resistance it will be hypothesized that consolidation resistance increases proportionally to τ. Therefore, it is suggested that

$$r_c = a\sigma_p' \qquad [19]$$

where a is an empirical coefficient similar to $\tan \phi_c'$ in equation [18].

Data from the study of a Paulding clay by Nearing et al. (1988) was used to estimate the soil parameter "a". Shear strength as measured with an unconfined compression test increased from 1.50 kPa at 0 kPa prestress suction to 3.15 kPa at 32 kPa prestress suction. The χ value for the 32 kPa sample was 0.30, hence the effective prestress, σ_p', was equal to the multiple $(-\chi\psi)$, or 9.6 kPa. If it is assumed that the increase in strength approximates the increase in erosion resistance, then r_c is approximately $(3.15/1.50) - 1$, or $r_c=1.1$. Therefore, from equation [19], "a" is estimated to be 0.11. This estimate of "a" will be used in this model until better information for a variety of soil types is available.

The freeze factor, f, for purposes of this model can be estimated from laboratory experiments of Formanek et al. (1984), who used strength indices. If freeze thaw is considered to be active during the time for which the model is being applied, the value of "f", from the data of Formanek et al. (1984), is estimated to be approximately 0.5. If freeze-thaw is not an active influence then f is assigned a value of 1. As more information becomes available, better estimates of both parameters "a" and "f", possibly as functions of soil types, will be possible.

APPLICATION OF THE MODEL

The method for using the consolidation model is as follows. The value of lowest saturation level, S_{min}, since time zero must be known. Time zero is considered to be the first rainfall after tillage. Using values of S between S_{min} and 1, effective stresses, σ', are calculated from values of χ (using equation [15]) and Ψ (from Ψ-S relationships) using equation [14] until the maximum value, σ_p', is r_c, is calculated from equation [19] and the resistance adjustment factor R' is determined using equation [7]. Using R', the erodibility adjustment factor can be calculated from equation [8] and the critical shear adjustment factor from equation [11].

The consolidation model was tested using data from a study of rill erosion of a silt loam soil near West Lafayette, IN. The experimental details and results from that study were reported by Brown and Foster (1987). They studied the effect of incorporated crop residue on rill erosion rates at three times; just after tillage, at 30 days, and at 60 days after the first rainfall application. Simulated rainfall with added inflow in preformed channels were used to obtain measurements of rill erosion rates. Data from the four plots with zero residue rate were used to test the consolidation model.

The data from the study indicated that critical shear stress of the soil was negligible. Also, changes in channel morphology and roughness after the first rainfall were small, and therefore the shear stress for any given flow rate in individual channels was assumed to be constant throughout the study period. Hence it was assumed that the decrease in erosion rate relative to the initial test, for any given flow rate, was equal to the erodibility adjustment factor, K'. Using those assumptions the adjustment factor, K', as calculated from the measured erosion data was 0.73 ± 0.33 (at $\alpha=0.05$) for the 30 day test and 0.45 ± 0.29 (at $\alpha=0.05$) for the 60 day test. Only data for the lowest flow rate was used to calculate K', since for the higher inflow rates the channel eroded

to a less erodible layer (Brown and Foster, 1987).

Minimum saturation levels for all the plots for the 30 and 60 day tests were calculated from bulk density and water content data. For each plot of the 30 and 60 day tests, the saturation was below, that for which the maximum prestress occurred. Maximum prestress occurred at approximately 56 kPa water tension and saturation level of 0.59. At that saturation, χ was estimated from equation [15] to be 0.18 and hence the effective prestress, σ_p' was 10.1 kPa. The normalized resistance parameter, r_c, was calculated from equation [19] to be 1.1 and the resistance adjustment factor, R', was determined from equation [7] to be 2.1. Freeze-thaw was not considered to be active during the test period. The erodibility adjustment factor, K', was calculated from equation [8] to be 0.47. This value for K' was within the confidence interval (at $\alpha = 0.05$) for both measured values of K' stated above for the 30 and 60 day tests.

SUMMARY

The example above shows that this model has potential for estimating changes in rill erodibility which are caused by consolidation, even though the example does not test all aspects of the consolidation model. No attempt was made here to evaluate the freeze factor, f, or the critical shear stress adjustment factor, τ_c'. However, the model does provide a framework within which to evaluate erosion data for those variables. From an analystical standpoint, the values for parameters generated from the model are bounded because maximum prestress for a given soil is bounded since χ decreases as $-\Psi$ increases. From a conceptual standpoint, the model incorporates and describes the fundamental factor that causes soils to consolidate, i.e., soil water stress. The model does not include a time (thixotropic) factor and the existing data does not indicated the necessity for one. If additional investigations indicate a need for a time factor, one could be included. Further information may also help in refining estimations of the parameter "a", possibly as a function of soil type.

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