Simulated Small-Channel Bed Scour and Head Cut Erosion Rates Compared

J. C. Zhu,* C. J. Gantzer, R. L. Peyton, E. E. Alberts, and S. H. Anderson

ABSTRACT

Concentrated-flow erosion is often a major part of cropland erosion. The concentrated-flow processes of bed scour and head cut need improved characterization to better predict and prevent erosion. This study was conducted to compare the erosion rates due to simulated small-scale bed-scour (D_b) and head-cut (D_h) processes. A 6.4-m-long by 0.15-m-wide hydraulic flume was used to simulate concentrated-flow erosion on five Midwestern soils: Barnes (fine-loamy, mixed Udic Haploboroll), Forman (fine-loamy, mixed Udic Argiboroll), Mexico (fine, montmorillonitic, mesic Udollic Ochraqualf), Sharpsburg (fine, montmorillonitic, mesic Typic Argiudoll), and Sverdrup (sandy, mixed Udic Haploboroll). For slopes of 1.5, 3.5, and 5.0%, flow rates of 3.78, 5.67, 7.65, 11.34, and 15.12 L min^{-1} were used to provide a range from low (0.5 Pa) to moderate (2.5 Pa) shear stresses (τ). Soil detachment rates are functions of slope, flow rate, and shear stress. Slope, flow, their squares, and the slope × flow interaction were highly significant predictors of D_h. Only flow, its square, and its interaction with slope were significant predictors of D_b. Nonlinear power regressions using τ as an independent variable were better predictors of detachment than simple linear regressions. Erodibility for the soils from this study does not relate well with soil erodibility calculated using the Universal Soil Loss Equation. Differences in the slope and intercept of detachment vs. τ exist among soils. The value of D_h was at least four times greater than D_b for all soils at equal slope and flow rate, indicating that head cutting is the main process of detachment for the conditions tested.

RAINDROP SPLASH DETACHMENT and concentrated flow of runoff are the causes of soil erosion by water. *Interrill erosion* refers to movement by rain splash and transport of raindrop-detached soil by flowing water (Hudson, 1981). When runoff accumulates within small rills, water flow may cause additional soil erosion. This process is *rill erosion*. The sizes of rills are small enough so that tillage operations can smooth them over. As runoff water accumulates from first-order rills into permanent depressional swales, concentrated flow causes more erosion and produces ephemeral gullies. *Ephemeral gully erosion* is similar to but larger in scale than rill erosion. Ephemeral gullies can be smoothed over by tillage but will reoccur in the same location over time. *Gully erosion* is also caused by concentrated flow, where it accumulates in larger channels causing erosion between 0.3 and 30 m in depth (Soil Conservation Society of America, 1982). Gullies cannot be filled in by tillage operations. Rill, ephemeral gully, and gully erosion are all concentrated-flow processes. Concentrated-flow erosion is a major component or soil erosion from cropland.

The Universal Soil Loss Equation (USLE) estimates sheet and rill erosion, but does not account for ephemeral gully or gully erosion (Wischmeier and Smith, 1978). Ephemeral gully erosion may contribute 25% or more soil loss over that predicted by the USLE (Laflen et al., 1987). Failure to account for ephemeral gully erosion in prediction equations can underestimate soil erosion severity.

Recently, computer modeling of soil erosion has been used to improve soil erosion prediction. The CREAMS model was among the first to integrate the movement of chemicals, runoff, and erosion from agricultural management systems. The user's manual recommends that the first approximation of the USLE *K* factor be used to estimate concentrated-flow erodibility when detailed information is not available (Knisel, 1980). However, little evidence is presented on the suitability of the *K* factor for this use.

Meyer et al. (1975) suggested that rill erosion could be separated into components of bed scour and head cut. Work by Elliot and Laflen (1993) also used this idea and expanded the concept to include two additional processes. Recently, several agencies have been working on the Water Erosion Prediction Project (WEPP), a model for erosion prediction (Laflen et al., 1991b). The WEPP model predicts rill and interrill erosion; however, it does not separately account for bed scour and head cut. These processes need improved characterization to better understand, predict, and prevent erosion (Nearing et al., 1990). To work toward that goal, Elliot and Laflen (1993) began to separate these processes, but the nature of the field study made separation difficult.

Meyer et al. (1975) reported that the rill erosion rate was a function of flow discharge rate. Lyle and Smerdon (1965) in a flume study with varied discharge rates, found that the detachment rate could be predicted from τ for a given soil and condition. Foster (1982) also reported that discharge rate and slope might be used in calculating τ. More recently, Nearing et al. (1991) reported that the rill erosion rate was not a unique function of τ or stream power. However, Elliot and Laflen (1993) suggested that stream power may improve erosion rate prediction, but they noted that the parameters were interrelated. Some research suggests that the detachment rate can be predicted using a linear function of concentrated-flow erodibility (*K*) and τ (Elliot et al., 1988; Ghebreiyessus, 1990; Laflen et al., 1991b). However, nonlinear trends between detachment and τ are apparent in some recent erosion data, making further study of this relationship desirable (Torri et al., 1987; Ghebreiyessus, 1990; Zhu, 1992).

Few detailed reports comparing bed-scour and head-cut processes are available. Shaikh et al. (1988) reported on a laboratory hydraulic-flume experiment using 0.15-m-long samples for small-scale simulation of concen-

J.C. Zhu, C.J. Gantzer, and S.H. Anderson, Dep. of Soil and Atmospheric Sciences, and R.L. Peyton, Dep. of Civil Engineering, Univ. of Missouri, Columbia, MO 65211; and E.E. Alberts, USDA-ARS Cropping Systems and Water Quality Research Unit, Columbia, MO 65211. This work was conducted as a part of the Missouri Agric. Exp. Stn. Project 396 and the Missouri Engineering Exp. Stn. with partial financial support from a Missouri Dep. of Natural Resources grant (no. 88-2) and with additional support from the USDA-ARS. Submitted as no. 11931 in the Journal Series of the Missouri Agric. Exp. Stn. Received 12 Oct. 1993. *Corresponding author (snrzhu@mizzou1.missouri.edu).

Published in Soil Sci. Soc. Am. J. 59:211-218 (1995).

trated-flow erosion; however, the research focus was on the influence of the amount of clay on only bed-scour erosion. Ghebreiyessus (1990) studied the relationships between detachment and τ with varied slopes and discharge rates in a hydraulic flume, but again only data on bed scour were reported. Kohl (1988) studied the mechanics of rill head cutting, but did not include any details on the process of bed scour. Thus, there is a need to compare the nature of bed-scour and head-cut processes in order to improve concentrated-flow erosion prediction.

To better characterize these concentrated-flow processes, we conducted a laboratory flume study of simulated concentrated-flow erosion at a scale between rill and ephemeral gully erosion. The main objective of this study was to compare the amount of bed-scour and head-cut erosion in a small-scale simulation of concentrated-flow erosion for five Midwestern soils.

MATERIALS AND METHODS

Soil Material

Five Midwestern soils were collected from the Ap horizon of each soil. They were Barnes, Forman, and Sverdrup from Morris, MN, Mexico from Columbia, MO, and Sharpsburg from Lincoln, NE. All the soils except Forman were studied in the WEPP. Soil texture ranged from sandy loam to silty-clay loam (Table 1).

Hydraulic Flume

An open-channel hydraulic flume with an adjustable slope was used (Fig. 1). The flume was 6.4 m long and 0.6 m wide. The slope of the flume was adjustable between 0 and 5.5%. The length of the soil test section was 1 m. Flow was supplied by a 9-m constant-head tank. To simulate concentrated-flow erosion, the flume was reduced in width to 0.15 m using a flume insert. The insert consisted of a painted wooden bottom raised to 0.050 m above the flume floor. The insert side walls were constructed of Plexiglas. Slopes used were 1.5, 3.5, and 5.0%. Five discharge rates used with each slope were 3.78, 5.67, 7.56, 11.34, and 15.12 L min^{-1}. The average shear stress was calculated from flow depth and flume slope using the relationship $\tau = \gamma R S$, where γ is the specific weight of water (N m^{-3}), R is the hydraulic radius (m), and S is the hydraulic gradient (m m^{-1}; French, 1985). Calculation indicates that flow conditions were between laminar and turbulent flow (Reynolds number ranged from 430 to 1660). The combination of three slopes and five discharge rates produced 15 τ values ranging from low (0.5 Pa) to moderate (2.5 Pa). Soils with stable aggregates such as Barnes, Forman, Mexico, and Sharpsburg have similar boundary and flow characteristics.

Table 1. Primary particle-size distribution, USLE *K* factor,† and surface texture of soils used in erosion tests.

Soil	Sand	Very fine sand	Silt	Clay	Organic matter	USLE *K*	Texture
	%				g kg^{-1}	T ha^{-1} EI^{-1}	
Barnes	48.6	11.4	34.4	17.0	34	0.62	loam
Forman	24.0	6.6	39.1	36.9	55	0.62	clay loam
Mexico	5.3	1.1	68.7	26.0	27	0.94	silt loam
Sharpsburg	4.8	4.6	55.4	39.8	32	0.67	silty clay loam
Sverdrup	75.3	3.7	16.8	7.9	22	0.22	sandy loam

† From Wischmeier and Smith (1978).

The flow conditions for Sverdrup, which has a sandy loam texture, are probably slightly different from other soils because of the smoother surface. For example, when the slope is set at 3.5% with 7.56 L min^{-1} discharge rate, the boundary roughness coefficient with aggregated soils is about 0.048. The boundary roughness coefficient with Sverdrup is slightly smoother than but not significantly different from that for other soils (0.043).

Sample Preparation and Data Collection

Soil Sample Container

Ephemeral gully erosion development on a Mexico claypan soil under field conditions was observed before and during the laboratory experiment (Peyton et al., 1992). The average depth and width of two ephemeral gullies after $\approx$0.03 m of runoff was $\approx$0.05 and 0.15 m, respectively. Soil sample containers were designed based on these observations. The containers were made of Plexiglas with a size of 1.00 m long, 0.15 m wide, and 0.05 m deep. The downstream end of the container could be removed to initiate a head cut. With both ends attached to the container, bed scour alone could be studied. Five 7-mm holes were drilled along a center line of the container bottom to facilitate soil wetting. Plexiglas plates were used to extend the lateral walls of the container upward to confine the width of flow to that of the sample container.

Soil Sample Preparation

Soils were sifted through a 4-mm sieve, air dried, and stored at room temperature (20–24°C) in 0.1-m^3 bins. Soil samples were transferred from bins and placed in the container in a loose condition. The soil surface was leveled to the top of the container using a spatula. The bulk densities of samples in this condition were 1.16 ± 0.01, 1.11 ± 0.01, 1.00 ± 0.01, 1.07 ± 0.01, and 1.36 ± 0.02 Mg m^{-3} for the Barnes, Forman, Mexico, Sharpsburg, and Sverdrup soils, respectively. Soil samples were then placed in a pan to allow wetting of samples with tap water. The water level in the pan was controlled with a Mariotte device (Klute and Dirksen, 1986). A soil sample was placed in the flume and tested for erosion immediately after the 24-h wetting period. The experiment was conducted with tap water having high levels of Ca^{2+}.

A new soil sample was used for each erosion trial. A trial consisted of sediment measurements from a single soil sample, discharge rate, slope, and erosion process (bed scour or head cut). During head-cut trials, head-cutting migration distance

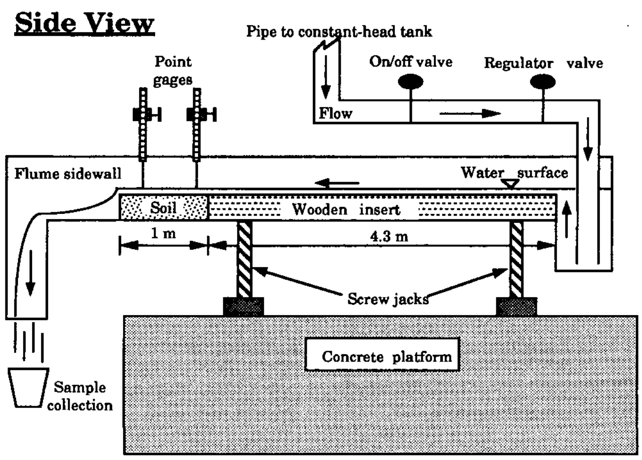

Fig. 1. Schematic diagram of modified hydraulic flume (not to scale).

was monitored with time and sediment samples were collected every 10 to 30 s for a total of 12 to 20 samples. Sediment sampling ended when the head cut reached the upstream end of the 1-m-long test bed. For bed-scour trials, sediment samples were taken every 10 s during a 2-min period for a total of 12 samples. Sediment samples were oven dried at 105°C to constant weight to determine sediment concentration (g L^{-1}).

The first sediment sample collected in each trial was excluded from the detachment rate calculation because of this sample's high variability compared with subsequent sediment samples. Bed-scour detachment rate (D_b) was averaged across all but the first sample. Head-cut detachment rate (D_h) was averaged across the range from the second sample to the sample corresponding to a point at which head cutting reached the end of the 1-m test section.

Kohl (1988) reported detachment due to head cut in units of detached soil mass per unit of rill length per unit time (g m^{-1} s^{-1}). Elliot and Laflen (1993) expressed the detachment of soil due to head cut in units of detached soil mass from a unit area per unit time (g m^{-2} s^{-1}). For bed-scour trials, there is no problem presenting the detachment in units of mass per unit area per unit time. The area will be the horizontal surface area of the entire soil test bed. However, it is difficult to determine the exact area from which detachment due to head cut takes place. The detachment rate due to head cut is not influenced by the original length of the soil test bed or preformed rill length, but by the rill width and the head-cutting migration rate. Thus, it will be incorrect to use the same sediment-contributing area in the bed-scour trials for the head-cut test. To compare the detachment rates due to bed-scour and head-cut processes, we report the detachment rate as mass per unit time (g s^{-1}). The value of D_b was computed as

$$D_b = \frac{1}{\Delta t_b}\frac{1}{n-1}\sum_{i=2}^{n} M_i \qquad [1]$$

where Δt_b is the time period for sample collection in a sample bottle during a bed-scour trial, n is the total number of samples, and M_i is the sediment mass collected in sample bottle i.

Since bed scour occurred simultaneously upstream of the head cut during the head-cut test, a method was required to separate the mass of soil eroded by the two processes in order to determine D_h. It was assumed that the total mass of soil collected in sample bottle i ($M_{t,i}$) during a head-cut trial was the sum of the following two components:

$$M_{t,i} = M_{b,i} + M_{h,i} \qquad [2]$$

where $M_{b,i}$ and $M_{h,i}$ are masses of soil collected in sample bottle i from bed scour and head cut, respectively.

The detachment due to head cut will be the difference between total mass and detachment by bed scour:

$$M_{h,i} = M_{t,i} - M_{b,i} \qquad [3]$$

Preliminary analysis showed that erosion due to bed scour below the head cut constituted only $\approx 2\%$ of the total detachment. Thus, we assumed that bed-scour erosion occurred only between the head cut and the end of the test bed. In Eq. [3], $M_{b,i}$ was determined from

$$M_{b,i} = D_b\,\Delta t_h\left(\frac{l_o - l_i}{l_o}\right) \qquad [4]$$

where D_b is the bed-scour detachment rate from Eq. [1] with soil, slope, and discharge rate equal to that for the comparable head-cut trials; Δt_h is time period for sample collection in a sample bottle during a head-cut trial; l_o is the initial length of the soil test bed at the beginning of the trial; and l_i is distance from the downstream end of the original soil test bed to the furthermost upstream point of head cutting at the time of sample i. The value of D_h was then computed from the relation

$$D_h = \frac{1}{\Delta t_h}\frac{1}{n-1}\sum_{i=2}^{n} (M_{t,i} - M_{b,i}) \qquad [5]$$

The overall experiment included five soils, two processes, four replicates, and 10 to 20 samples per replicate. Mexico silt loam was tested at 15 shear stresses ranging from 0.5 to 2.5 Pa. The other four soils were only studied at five shear stresses between 0.98 and 2.50 Pa.

The effects of slope and discharge rate on detachment for the Mexico soil were analyzed using the multiple regression model (df = 59):

$$\hat{D} = b_0 + b_1\,\text{slope} + b_2\,\text{flow} + b_3\,\text{slope}^2 + b_4\,\text{flow}^2 + (b_5\text{slope} \times \text{flow}) + \varepsilon \qquad [6]$$

The homogeneity of variance for bed-scour and head-cut erosion was evaluated with an F test of the mean square error for each process (Snedecor and Cochran, 1980). Linear and nonlinear regressions were conducted using the following equations:

$$\hat{D} = b_0 + b_1\tau + \varepsilon \qquad \text{df} = 19 \qquad [7]$$

$$\ln\hat{D} = b_0 + b_1\ln\tau + \varepsilon \qquad \text{df} = 19 \qquad [8]$$

where ε, the residual or random element, is assumed to be from a normally distributed population with mean 0 and standard deviation s.

Residual errors were evaluated for independence and normality. The residuals were plotted against τ on a linear scale to evaluate the systematic variation and dependency. A model would not be adequate if systematic variation in residuals were noticed in the residual plot. Nonnormality of residuals was investigated using the Shapiro–Wilk statistic (Shapiro and Wilk, 1965). All analyses were conducted using selected SAS procedures (SAS Institute, 1985).

RESULTS AND DISCUSSION

Detachment vs. Slope and Discharge Rate

Soil detachment rates for bed-scour and head-cut trials (D_b and D_h) for Mexico silt loam vs. discharge rate and slope are presented in Table 2. Slope, discharge rate,

Table 2. Slope, discharge rate, flow depth, and detachment rate due to bed-scour (D_b) and head-cut (D_h) processes for Mexico silt loam.

Slope	Discharge rate	Flow depth	D_b	D_h
%	L min^{-1}	mm	g s^{-1}	
1.5	3.78	3.58	0.04	1.04
1.5	5.67	5.98	0.09	3.16
1.5	7.56	7.95	0.29	5.42
1.5	11.34	10.03	0.87	10.25
1.5	15.12	11.85	1.71	15.80
3.5	3.78	2.41	0.09	3.07
3.5	5.67	3.59	0.89	6.60
3.5	7.56	4.57	1.57	11.31
3.5	11.34	5.54	3.60	22.38
3.5	15.12	6.71	6.42	35.25
5.0	3.78	2.06	0.27	3.40
5.0	5.67	2.98	1.42	10.47
5.0	7.56	3.47	3.15	16.52
5.0	11.34	4.61	6.05	31.67
5.0	15.12	5.50	10.49	45.82

Table 3. Slope, discharge rate, flow depth, and detachment rate due to bed-scour (D_b) and head-cut (D_h) processes for Barnes, Forman, Sharpsburg, and Sverdrup soils.

Slope	Discharge rate	Flow depth	D_b Barnes	D_b Forman	D_b Sharpsburg	D_b Sverdrup	D_h Barnes	D_h Forman	D_h Sharpsburg	D_h Sverdrup
%	L min^{-1}	mm	g s^{-1}							
3.5	7.56	0.64	1.54	0.10	0.84	1.63	12.55	9.02	9.50	12.05
3.5	15.12	0.94	5.96	5.32	7.94	6.69	18.40	18.28	19.21	23.62
5.0	3.78	0.29	0.44	0.03	0.38	1.04	5.39	1.84	4.71	4.11
5.0	7.56	0.49	2.81	0.79	2.02	3.76	14.03	10.47	11.79	13.76
5.0	15.12	0.77	13.43	10.76	11.78	11.71	27.79	22.26	26.64	35.53

flow depth, and detachment rate due to bed-scour and head-cut processes for Barnes, Forman, Sharpsburg, and Sverdrup soils are presented in Table 3. Detachment rates increased with discharge rate for both processes and agreed with the findings of Meyer et al. (1975). Detachment rate also increased with slope. Results of the multiple regression of detachment on slope and flow, their squares, and cross product are presented in Table 4. The residual mean square error of head-cut detachment was significantly greater ($P < 0.005$) than that of bed-scour detachment (57.1 vs. 2.36), possibly due to the larger variation in detachment rates and greater geometrical profile changes for head-cut trials. However, the coefficients for the two processes were not significantly different. Inspection indicated that variations were proportional to the mean, suggesting that further analysis should be conducted on the log-transformed data. Residual errors of the log-transformed data were evaluated and showed no signs of dependency or systematic variation or nonnormality, hence were assumed normal and independent for both processes. Table 4 also presents the probability levels for the independent variables of Eq. [7]. All factors were highly significant for bed scour ($P < 0.01$). For head cut, factors associated with flow were found to be significant ($P < 0.05$). The probabilities for slope and its square were 6 and 25%, respectively, for D_h. Since head-cutting trials were initiated with the removal of the downstream end of the soil container, an overfall was formed at the head cut that created locally much higher energy and slope than the test bed. Thus, head cutting was started as soon as the flow started for each trial of flow and slope. Because local slope and energy are much greater at the head cut, it is not surprising that test bed slope was not significant for D_h ($P = 0.06$) but was highly significant for D_b ($P < 0.01$). That both the first- and second-degree terms of flow were significant predictors of D_b and D_h indicates that the relationship between detachment and flow is probably not a simple linear function.

Head-cut migration proceeded in a predictable fashion. The head-cutting migration rate for Mexico silt loam was found to be a linear function of shear stress (Fig. 2). Visual observations showed that the head cut maintained a local slope angle ranging from about 45 to 90° (vertical). The depth of the cut ranged from 50 to 95% of the test sample thickness (25–48 mm).

Since flow and slope are the main components in the calculation of τ (Foster, 1982), it is not surprising that τ was also found to be a highly significant predictor of D_b and D_h ($P < 0.001$). Both D_b and D_h were positively related to τ (Fig. 3). For bed scour, detachment was small when τ was <1.0 Pa, after which D_b values increased at a greater rate (from 1.0 to ≈ 1.5 Pa). Beyond this shear, D_b increased linearly with τ. This agrees with the results of Ghebreiyessus (1990). The value of D_h increased linearly with τ when τ was greater than ≈ 1.4 Pa (Fig. 3). The results for the Barnes, Forman, Sharpsburg, and Sverdrup soils at selected τ values were similar. When detachment vs. τ was evaluated across the entire range of τ values tested, a nonlinear relationship was found between detachment and τ for both processes.

Comparison of fitted detachment data for the Mexico silt loam to power and linear functions is facilitated with Fig. 3. The linear function does not fit as well as the power equation for either the head-cut or bed-scour process. For the bed-scour process, the r^2 values were 0.97 and 0.86 for power and simple linear functions, respectively. For the head-cut process, the power equation was also a better predictor of detachment, with respective r^2 values of 0.98 vs. 0.92. Evidence of significant lack of fit for the linear regression of both processes is presented in the respective plots of the residuals. In both cases, the linear fit gives rise to a systemic, parabolic trend. The linear fit underestimates detachment for both

Table 4. Summary statistics from the analysis of variance for the model $\hat{D} = b_0 + b_1S + b_2Q + b_3S^2 + b_4Q^2 + b_5SQ + \varepsilon_{ijk}$† for two processes using data of the Mexico soil.

Source	df	Bed scour Mean square	Bed scour F	Bed scour $P > F$	Head cut Mean square	Head cut F	Head cut $P > F$
Slope	1	147.98	62.60	<0.001**	211.84	3.71	0.059
Flow	1	276.70	117.04	<0.001**	256.61	4.49	0.039*
Slope × slope	1	15.98	6.76	0.012**	77.06	1.35	0.251
Flow × flow	1	154.45	65.33	<0.001**	798.71	13.99	<0.001**
Slope × flow	1	4235.70	1791.69	<0.001**	51871.33	908.50	<0.001**
Error	54	2.36			57.10		
	(R^2 = 0.995)				(R^2 = 0.994)		

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.

† where symbols D, S, and Q in the model stand for detachment, slope, and flow, respectively.

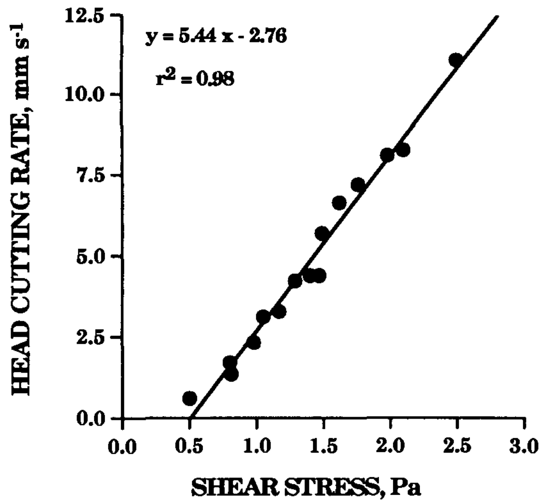

Fig. 2. Head-cutting migration rate as a linear function of shear stress for a Mexico soil. Each point represents the mean of four replicates.

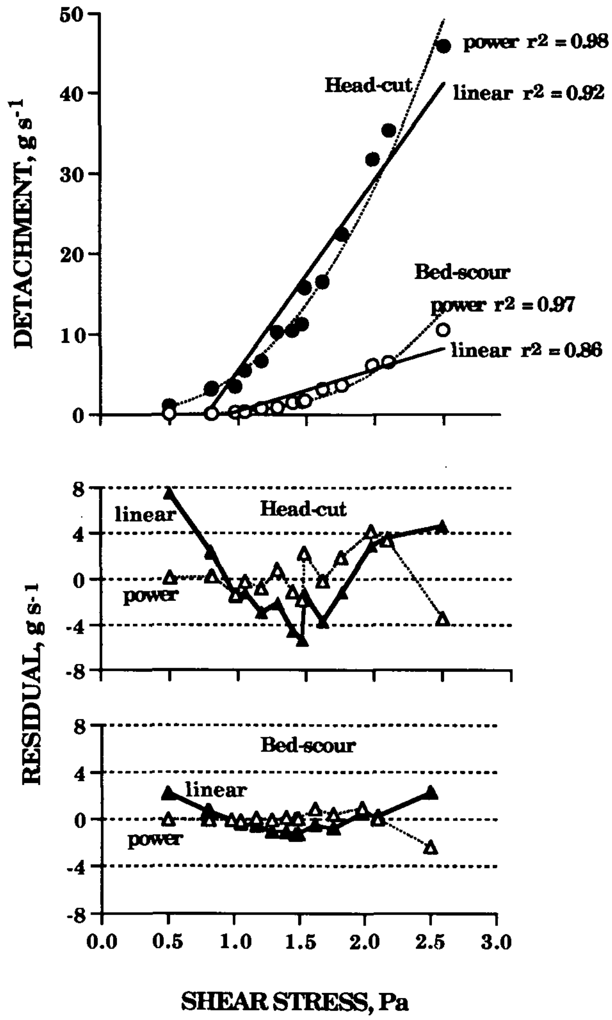

Fig. 3. Bed-scour and head-cut detachments vs. shear stress for a Mexico soil and their respective residual deviations from predicted values using the linear [$D = K(\tau - \tau_c)$] and power ($D = K\tau^b$) regressions.

high and low τ values and overestimates detachment for intermediate values. In addition, the power function has a smaller maximum residual than the linear function for both processes. Overall, the power function was a very good predictor of detachment and the residuals showed no signs of systematic variation. Because of turbulent flow conditions and different flow speeds at the head cut, we did not measure or calculate local flow shear stress. Future work should focus on a more precise determination of this quantity. However, our data showed that average τ was adequate to describe detachment due to bed-scour and head-cut processes using a nonlinear function. It should be noted that the power-curve regression did not perform as well for the highest τ value used (2.5 Pa), overpredicting bed-scour and head-cut erosion by about 4 and 7%, respectively. This behavior suggests that for τ values >1.5 Pa, a linear fit may provide a "good" approximation of the relationship. This would be in agreement with studies where this function has been used (Elliot et al., 1989; Van Klaveren and McCool, 1987). This suggests that the fitted power functions should be limited to the range of τ values evaluated. Since the power function was clearly better than linear fits, subsequent analyses to describe bed-scour and head-cut behavior for the other soils were conducted with power-curve regression by natural log–natural log transformation of detachment.

Bed-Scour vs. Head-Cut Detachment Rates

The natural log–natural log transformed detachment and standard errors of the bed-scour and head-cut processes for a Mexico soil are presented in Fig. 4 and Table 5. Bed scour involves detachment and transport of soil more or less uniformly across the entire bed, while detachment and transport associated with the head cut is more complicated, especially around the head cut itself. Though detachment rates from both bed scour and head cut were functions of slope, discharge rate (Tables 2 and 3), and shear stress (Fig. 3), responses were not the same for both processes. Detachment for head cut

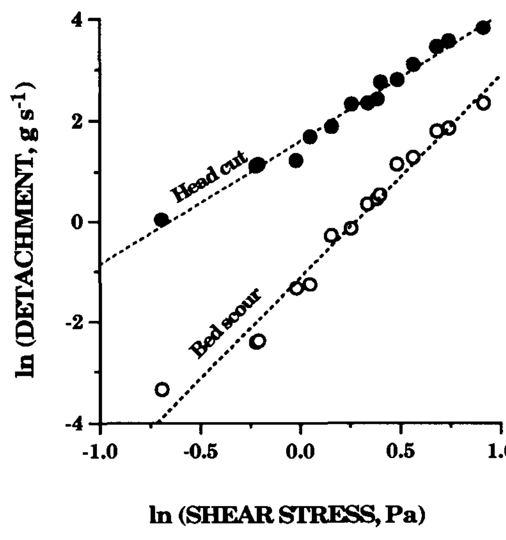

Fig. 4. Detachments due to bed-scour and head-cut processes as a function of shear stress for natural log–natural log transformed data for a Mexico soil.

Table 5. Summary of the linear regression parameter estimates of the model $\ln \hat{D} = b_0 + b_1 \ln \tau + \varepsilon_{ijk}$† for two processes and five soils.

	Bed scour			Head cut		
Soil	Intercept	Slope	r^2	Intercept	Slope	r^2
Barnes	−0.85 ± 0.05	3.64 ± 0.09	0.998	1.75 ± 0.04	1.67 ± 0.07	0.966
Forman	−3.85 ± 0.26	6.81 ± 0.44	0.927	0.89 ± 0.11	2.55 ± 0.18	0.914
Mexico	−1.12 ± 0.04	4.01 ± 0.09	0.971	1.61 ± 0.02	2.50 ± 0.05	0.977
Sharpsburg	−1.20 ± 0.14	3.95 ± 0.24	0.937	1.56 ± 0.05	1.66 ± 0.08	0.960
Sverdrup	−0.13 ± 0.11	2.67 ± 0.19	0.915	1.48 ± 0.03	2.27 ± 0.06	0.968

† where symbols D and τ in the model stand for detachment and shear stress, respectively.

was always greater than for bed scour. The difference between the two processes was greatest at low τ values and smallest at higher τ values but detachment from the head cut was always 4.0 times greater than that from bed scour.

The relationship between detachment and τ found for the Mexico silt loam (Fig. 3 and 4) was similar for all the other soils. The detachment rate vs. τ for bed scour was linear on a natural log–natural log plot for the range of τ values studied (Fig. 5, and Table 5). An almost linear increase was observed within the upper range of τ values. The value of D_h fit closely across the entire range of τ while somewhat greater variations in bed-scour detachment were observed for $\tau < 1.0$ Pa. This behavior is also suggested in Fig. 4. Somewhat poorer prediction of detachment values for $\ln \tau < 0.0$ ($\tau < 1.0$ Pa) is observed. Theoretically, a positive residual for the smallest τ and negative residuals for the next several points may support the notion of a τ_c below which erosion is zero or insignificant. However, since the magnitude of the detachment residuals were only a few grams per second, analysis to estimate τ_c was not pursued in this study. Because of its simplicity, only natural log–natural log transformations were used. Our analysis does not answer the question of whether a τ_c exists. However, the simple power equation was sufficient and an excellent predictor of bed-scour and head-cut behavior. Critical τ for the head-cut process was not observed (Fig. 4).

To facilitate comparison of processes among soils, values predicted using Eq. [8] and the coefficients from Table 5 are presented in Fig. 5 and 6. Measured detachments were very highly correlated with τ for all soils, with $r^2 > 0.91$. Sverdrup showed the greatest range in D_b and Forman showed the least range across the entire range of τ. However, the slope of detachment vs. τ, often called *erodibility*, was the least for Sverdrup and the greatest for Forman. This suggests that relative soil erodibility cannot be judged by just slope or intercept but both slope and intercept should be used (Table 5). The regressions for Mexico and Sharpsburg soils were very close. The predicted D_b values for all soils were very close at higher τ values and converged to a point near $\tau = 2.5$ Pa. This may indicate that at high τ, differences in soil strength affected by soil properties are small relative to the force or energy of the flow, and thus are practically masked. Further research will be needed to explain behavior for the high τ levels (Fig. 5).

The predicted D_h values were always much greater than those of D_b. Interactions among soils were present (Fig. 6). The Barnes and Sharpsburg soils had higher D_h at low τ compared with Mexico and Sverdrup. However, Mexico and Sverdrup had higher D_h at higher τ values. Forman was consistently the least erodible soil.

The functions of the ratio of D_b relative to the total detachment rate ($D_b + D_h$) vs. τ for the five soils are presented in Fig. 7. At low τ, <10% of soil was detached by the bed-scour process. As τ increased, bed scour became a somewhat more important process, but at most was responsible for only ≈35% of the total detachment. Our data show that head cut is the main process of concentrated-flow erosion under the conditions studied.

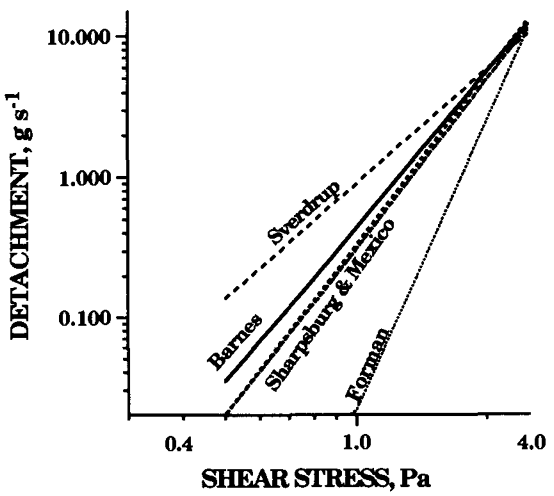

Fig. 5. Predicted bed-scour detachments using the power function ($D = K\tau^b$) vs. shear stress for five soils.

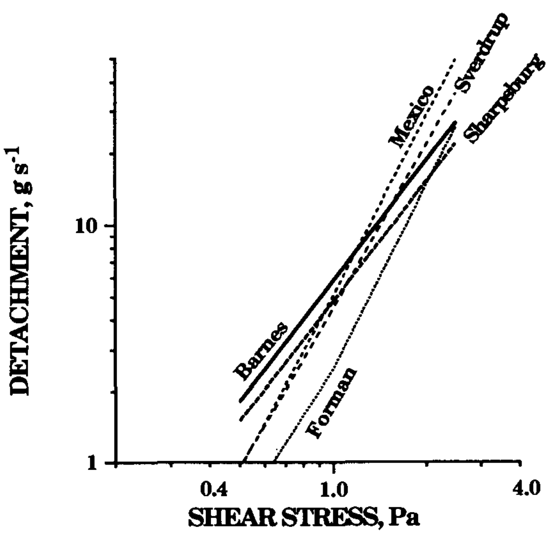

Fig. 6. Predicted head-cut detachments using the power function ($D = K\tau^b$) vs. shear stress for five soils.

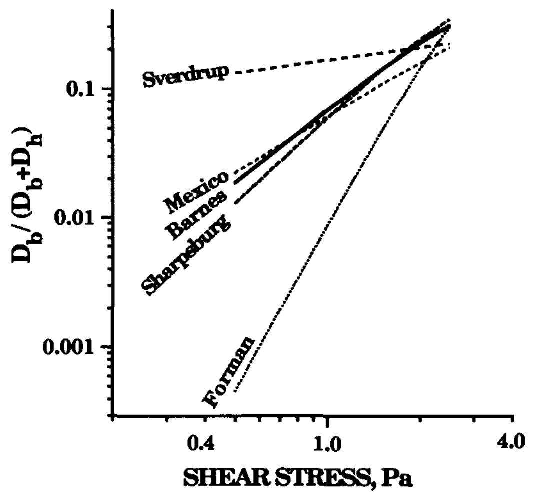

Fig. 7. Predicted bed-scour detachment (D_b) as a fraction of predicted total detachment (sum of bed scour and head cut, $D_b + D_h$) using the power function ($D = K\tau^b$) vs. shear stress for five soils.

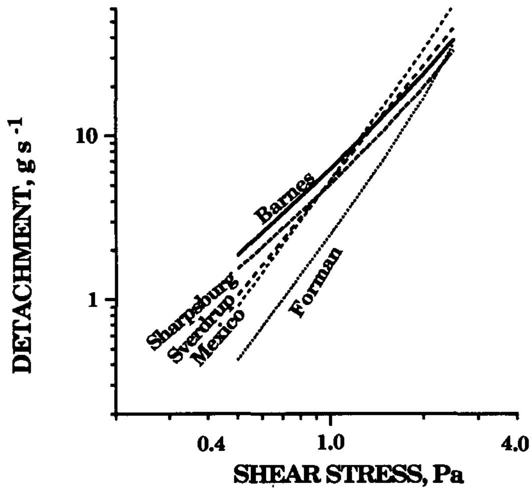

Fig. 8. Predicted total detachment (sum of bed scour and head cut, $D_b + D_h$) using the power function ($D = K\tau^b$) vs. shear stress for five soils.

Total detachment ($D_b + D_h$) vs. τ functions are presented in Fig. 8. Forman was the least erodible overall and Mexico and Sverdrup were somewhat more erodible than Forman. This ranking order does not relate well with USLE K factors (Table 2), which show that Sverdrup would be the least erodible and that Mexico would be the most erodible. Our data show the highest detachment for Mexico at high τ, which agrees with the ranking of the USLE K factor (Fig. 8). Sverdrup ranks the second highest in detachment in the upper τ values; however, its USLE K factor indicates it has the lowest erodibility, and thus is at odds with our data. This conflict is not unexpected. We chose to report it since the USLE K was recommended as a first approximation of the concentrated-flow erodibility in the CREAMS manual (Knisel, 1980). Many soil properties that are important factors related to erosion in the field, such as bulk density, infiltration rate, and runoff, were carefully controlled in our laboratory study, and are not necessarily representative of field values. Indeed, infiltration did not occur in our flume. The point is that our data shows that the USLE K is not well correlated with detachment under the conditions tested. This finding is in agreement with Laflen et al. (1991a), who found that, "Rill erodibility and critical hydraulic shear values were poorly correlated with USLE soil erodibility values" . . . reinforcing "the fact that interrill and rill processes are greatly different and that different forces and resistances are involved in the detachment process."

CONCLUSIONS

A flume study designed to simulate small-scale bed-scour and head-cut processes of concentrated-flow erosion was conducted on five Midwestern soils (Barnes, Forman, Mexico, Sharpsburg, and Sverdrup) with soil texture ranging from sandy loam to silty-clay loam. Results of this study support the concept that: soil detachment rates caused by bed-scour and head-cut processes are functions of slope, flow rate, and shear stress ($r^2 >$ 0.91). Slope, flow, their squares, and the slope × flow interaction were highly significant predictors of D_b. Only flow, its square, and its interaction with slope were significant predictors of D_h. Power functions were better predictors of detachment vs. τ than linear functions. Differences in detachment vs. τ exist among soils. The ranking order of detachment for the five soils does not correlate well with the USLE soil erodibility K factor, suggesting that the USLE K factor is a poor indicator of concentrated-flow erosion under the conditions tested. Values of D_h are at least four times greater than D_b at equivalent slope and flow rate for all soils, indicating that head cutting is the main process of concentrated-flow erosion for the conditions tested.

REFERENCES

Elliot, W.J., K.D. Kohl, and J.M. Laflen. 1988. Methods of collecting WEPP soil erodibility data. Pap. no. 88-138. Mid-Central Region Meet. ASAE, Columbia, MO. 8–9 Apr. 1988. ASAE, St. Joseph, MI.

Elliot, W.J., and J.M. Laflen. 1993. A process-based rill erosion model. Trans. ASAE 36:65–72.

Elliot, W.J., A.M. Liebenow, J.M. Laflen, and K.D. Kohl. 1989. A compendium of soil erodibility data from WEPP cropland soil field erodibility experiments 1987 & 88. NSERL Rep. no. 3. Natl. Soil Erosion Res. Lab., West Lafayette, IN.

Foster, G.R. 1982. Modeling the erosion process. p. 297–380. *In* C.T. Haan (ed.) Hydraulic modeling of small watersheds. ASAE, St. Joseph, MI.

French, R.H. 1985. Open-channel hydraulics. McGraw-Hill, New York.

Ghebreiyessus, Y.T. 1990. Evaluation of concentrated flow erosion and hydraulic shear stress relationships. Ph.D. diss. Univ. of Missouri, Columbia (Diss. Abstr. 91-00197).

Hudson, N.W. 1981. Soil conservation. Cornell Univ. Press, Ithaca, NY.

Klute, A., and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. p. 687–734. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Knisel, W.G. (ed.). 1980. CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. USDA Conserv. Res. Rep. no. 26. U.S. Gov. Print. Office, Washington, DC.

Kohl, K.D. 1988. Mechanics of rill headcutting. Ph.D. diss. Iowa State Univ., Ames (Diss. Abstr. 89-09163).

Laflen, J.M., W.J. Elliot, J.R. Simanton, C.S. Holzhey, and K.D. Kohl. 1991a. WEPP: Soil erodibility experiments for rangeland and cropland soils. J. Soil Water Conserv. 46:39-44.

Laflen, J.M., T.G. Franti, and D.A. Watson. 1987. Effects of tillage systems on ephemeral gully erosion. p. 798-809. *In* Proc. Int. Conf. Soil Conserv. 4th, Maracay, Venezuela. 3-8 Nov. 1985. Sociedad Venezolana de la Ciencia del Suelo, Maracay, Venezuela.

Laflen, J.M., L.J. Lane, and G.R. Foster. 1991b. WEPP: A new generation of erosion prediction technology. J. Soil Water Consev. 46:34-38.

Lyle, W.M., and E.T. Smerdon. 1965. Relation of compaction and other soil properties to erosion resistance of soils. Trans. ASAE 8:419-422.

Meyer, L.D., G.R. Foster, and S. Nikolov. 1975. Effect of discharge rate and canopy on rill erosion. Trans. ASAE 18:905-911.

Nearing, M.A., J.M. Bradford, and S.C. Parker. 1991. Soil detachment by shallow flow at low slopes. Soil Sci. Soc. Am. J. 55:339-344.

Nearing, M.A., L.J. Lane, E.E. Alberts, and J.M. Laflen, 1990. Prediction technology for soil erosion by water: Status and research needs. Soil Sci. Soc. Am. J. 54:1702-1711.

Peyton, R.L., C.J. Gantzer, S.H. Anderson, A.L. Thompson, W.H. Neibling, E.E. Alberts, and J.C. Zhu. 1992. Ephemeral gully erosion and its influence on soil productivity. Final report to Soil and Water District Commission, Project no. 88-2. Missouri Dep. of Natural Resources, Jefferson City, MO.

SAS Institute. 1985. SAS user's guide: Statistics. SAS Inst., Cary, NC.

Shaikh, A., J.F. Ruff, W.A. Charlie, and S.R. Abt. 1988. Erosion rate of dispersive and non-dispersive clays. J. Geotech. Eng. Am. Soc. Civ. Eng. 114:589-600.

Shapiro, S.S., and M.B. Wilk. 1965. An analysis of variance test for normality. Biometrika 52:591-611.

Snedecor, G.W., and W.G. Cochran. 1980. Multiple linear regression. p. 334-364. *In* Statistical methods. Iowa State Univ. Press, Ames.

Soil Conservation Society of America. 1982. Resource conservation glossary. Soil Conserv. Soc. Am., Ankeny, IA.

Torri, D., M. Sfalanga, and G. Chisci. 1987. Threshold conditions for incipient rilling. p. 97-105. *In* R.B. Bryan (ed.) Rill erosion: Processes and significance. Catena Suppl. 8. Catena Verlag, Germany.

Van Klaveren, R.W., and D.K. McCool. 1987. Hydraulic erosion resistance of thawing soils. ASAE Pap. 87-2602. ASAE, St. Joseph, MI.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses: A guide to conservation planning. USDA Agric. Handb. 537. U.S. Gov. Print. Office, Washington, DC.

Zhu, J.C. 1992. Bed scour and head cut processes of concentrated flow erosion. Ph.D. diss. Univ. of Missouri, Columbia (Diss. Abstr. 94-00073).