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Soil Detachment by Shallow Flow at Low Slopes

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ABSTRACT

Detachment of soil particles by shallow surface flow is influenced by soil cohesion, soil aggregate properties, and hydraulic flow characteristics. This study was conducted to evaluate relationships between soil detachment rates, soil aggregate size, soil tensile strength, flow shear stress, and flow stream power. Detachment rates were measured in a hydraulic flume on three aggregate size classes of two soils. Tensile strength and wet aggregate stability were measured to characterize each aggregate class. Flow depths ranged from 0.5 to 2.0 cm and slopes ranged from 0.5 to 2%. Detachment rates increased with both increasing flow depth and increasing bed slope. Multiple linear regression analyses indicated that the logarithm of detachment rate vs. flow depth, slope, and either mean weight diameter or tensile strength were good models (R^2 = 0.94 and 0.91, respectively) for predicting detachment rates. Detachment rate for a given soil material was not a function of either shear stress or streampower of the flow. The largest size class of aggregates were detached at a faster rate than the smaller two aggregate size classes.

SOIL DETACHMENT BY WATER occurs primarily via the processes of splash from raindrop impact and scour by shallow flow from surface runoff. Detachment by splash under controlled laboratory conditions has been studied in detail (Bradford et al., 1987; Poesen and Savat, 1981; Gantzer et al., 1987; Al-Durrah and Bradford, 1982). Detachment of cohesive soils by shallow clear-water flow under laboratory conditions has received less attention.

Flow-induced soil loss rate at a point on a hillslope can be described as a net balance between the rates of detachment of in situ soil particles by the flow, deposition of sediment in the flow, and the entrainment of previously detached sediment (Rose, 1985). The maximum soil detachment rate is for the case of clear-water (no-sediment) flow whereby the sediment deposition and entrainment rates are zero. This maximum rate at which the flow can detach soil is called the detachment capacity of the flow (Foster, 1982). The resistance of the soil to detachment is related to soil characteristics, and is referred to as the soil detachability. The other extreme case for detachment by flow results when sediment load in the flow equals the ability of the flow to transport sediment, which is called the sediment-transport capacity. In that case, deposition rate equals sediment entrainment rate and, therefore, soil detachment rate at the point is zero (Nearing et al., 1989a).

In field or flume studies where long soil beds are used, the measured parameter is sediment load leaving the plot. In order to calculate the soil detachability, some relationship between measured sediment load, estimated sediment-transport capacity, and detachment capacity must be assumed (Nearing et al., 1989b). Since our ability to estimate sediment-transport capacity for a flow is quite poor, and since the true relationship between sediment load, transport capacity, and detachment capacity is unknown, past efforts at experimentally measuring detachment capacity have not been as precise as is necessary to study detailed aspects of detachment by flow processes. Few studies of soil detachment by shallow flow have used sample sizes small enough to eliminate the need for taking into consideration the effect of sediment load in the flow on measured net soil loss rate.

Several experimental studies have shown a relationship between soil detachment rates and shear stress in a rotating-cylinder device (Alizadeh, 1974; Arulanandan et al., 1973; Kandiah, 1974). Other studies have related detachment rates from a hollow water tunnel apparatus to flow shear stress (Christensen and Das, 1973; Gularte, 1978). Results from the rotating-cylinder tests indicate a linear relationship between detachment rates and flow shear stresses, while the results from the hollow-tunnel tests have shown the logarithm of detachment rates to be proportional to flow shear stress. A problem with both the rotating-cylinder and hollow-tunnel tests that the flow regimes in those tests are very different from those for open-channel flow. It would be expected, for example, that the turbulent fluctuations under those conditions would vary from those for open-channel flow. The

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experimental results from the flume study of Lyle and Smerdon (1965) indicate a unique relationship between detachment rate and shear stress for a given soil, but these results were obtained using flumes of constant slope. A common assumption is that detachment rates are a function of stream power, which is the energy of the flow dissipated to the flow boundary (Bagnold, 1977; Rose et al., 1983; Moore and Burch, 1986). The hypothesis that flow shear stress and streampower are related to detachment rates of soil can only be tested by varying both bed slope and flow depth independently. This would allow for similar shear stress and streampower under different combinations of bed slope and flow depth.

An expression for hydraulic shear stress, τ (Pa), can be derived from simple force-balance considerations for uniform flow depth as

$$\tau = \rho g h S \qquad [1]$$

where ρ (kg/m^3) is water mass density, g (m/s^2) is the gravity constant, h(m) is depth of flow, and S (fraction) is bed slope expressed as a fraction. Since ρ and g are constants for our purposes, τ is proportional to h and S. Streampower, ω (kg/s^3), dissipated to the bed by the flow is given by

$$\omega = \tau V \qquad [2]$$

where V (m/s) is average flow velocity. Using the Chezy equation for relating flow depth and slope to velocity (for the case of uniform flow depth), and substituting for τ, streampower can also be written as

$$\omega = \rho g C (hS)^{1.5} \qquad [3]$$

where C (m$^{1/2}$/s) is the Chezy depth-discharge coefficient, which is approximately constant for a given bed surface. Thus τ is proportional to (hS) and ω is approximately proportional to $(hS)^{1.5}$.

The purpose of this study was to determine the influence of selected soil and hydraulic parameters on the detachment of soil by shallow surface flow. Specific objectives were to: (i) determine the influence of aggregate mean weight diameter and tensile strength on detachment rate by clear-water flow of a poorly aggregated silt loam soil and a strongly aggregated clay soil, and (ii) determine the relationship between flow parameters and detachment rates. Implicit in the second objective is to test the hypothesis that hydraulic shear stress and streampower are related to detachment rates.

MATERIALS AND METHODS

Soils

The soils used were a Paulding clay (very-fine, illitic, nonacid, mesic Typic Haplaquept) from northwest Ohio and a Russell silt loam (fine-silty, mixed, mesic Typic Hapludalf) from Indiana. The Paulding contains 550 g clay kg^{-1}, 350 g silt kg^{-1}, and 100 g sand kg^{-1}. The Russell contains 220 g clay kg^{-1}, 640 g silt kg^{-1}, and 140 g sand kg^{-1}.

The soils were separated into dry aggregate fractions by sieving with 4-, 2-, and 1-mm sieves, thereby obtaining 0- to 1-, 1- to 2-, and 2- to 4-mm fractions for each soil.

Detachment Measurements

Detachment rates were measured in a 9-m-long, 1-m-wide, flume. The flume was constructed so that bed slope could be maintained to within 0.02% and flow depth could be controlled to within about 0.5 mm. The bed of the flume was flat to within 0.25 mm over the entire surface. Elevation of the end of the flume, which controlled bed slope, was adjusted with a stepping motor. Flow rate, which controlled the depth of flow, was controlled with a series of valves. The system used recirculated water with a 30 kL, rubber-lined tank as a water source. Because of the large size of the tank and the long settling time in the tank for sedimentation to occur, sediment in the flow within the flume was negligible.

Soil was made wet by light spraying to a water content of 210 g kg^{-1} for the Russell soil and 260 g kg^{-1} for the Paulding soil and allowed to equilibrate for 2 d in a plastic bucket. Wetting of the soil allowed for forming of the samples, by static compression, into 12.7-cm-diameter brass cylinders to a bulk density of 1300 kg m^{-3} for the Russell soil and 1150 kg m^{-3} for the Paulding. Porous stones were permanently mounted inside the brass cylinders so that the depth of the soil sample was approximately 2.0 cm. The soil samples were then allowed to become satiated by wetting for 24 h at zero matric potential from the bottom of the sample through the porous stones. The tests were timed so that exactly 5 min passed between the time the samples were removed from the water until the time the flow in the flume reached the samples. During this 5-min time period, the sample was mounted in the flume so that the surface of the sample was flush with the flume bed.

The rate of detachment was calculated as the total number of soil lost (original oven-dry mass minus final oven-dry mass) divided by the time period of the test. Scouring of the samples during the test caused some reduction in the elevation of the sample, which was not always uniform over the entire sample surface. In order to standardize this effect, the time period of the test for individual samples was adjusted so that approximately the same amount of scour was reached in each test. Each treatment was replicated eight times, although some samples were lost during the testing procedure for various reasons including sample disturbance during handling or equipment problems during the tests.

A series of seven combinations of flume bed slopes and flow depths were used, as shown in Table 1. Shear stress in the tests ranged from 0.49 to 1.96 Pa. Flow velocities were measured for each flow depth and slope combination to determine the Chezy discharge coefficient and stream power. Flow velocities were determined by using fluorescent dye and measuring the time required for the center of the dye plume to move a distance of 2.15 m in the turbulent flow. The Chezy coefficient was relatively constant for the range of tests used in the experiments. Streampower ranged from 0.25 to 1.96 kg/s^3.

Least-significant-difference tests were performed to determine the significant differences between means as a function of aggregate classes for each flow depth and slope combination. Comparisons of means within each aggregate class were made using a Duncan's multiple-range test to determine the significant differences of means as a function of slope and flow depth. Significance was determined at the 0.05 level.

Table 1. Flow characteristics for conditions used in the experiments.

Depth of flow	Slope of bed	Flow velocity	Chezy discharge coefficient	Shear stress	Stream power
cm	%	m/s	m$^{1/2}$/s	Pa	kg/s^3
1.0	0.5	0.50	70.7	0.49	0.245
1.0	1.0	0.69	69.4	0.98	0.681
1.0	1.5	0.79	64.7	1.47	1.167
1.0	2.0	0.92	65.1	1.96	1.805
0.5	1.0	0.45	63.2	0.49	0.220
1.0	1.0	0.69	69.4	0.98	0.681
1.5	1.0	0.87	70.8	1.47	1.276
2.0	1.0	1.00	70.5	1.96	1.956

Wet Aggregate Analyses

Wet aggregate analysis was performed on each of the soil aggregate classes. Size distribution of the soil materials was assessed with minimal disruption from the application of external energy. Raindrop impact is the primary source of energy input that disrupts aggregates during erosion, and raindrops were not a part of this experiment. The premoistened soil material was sieved by hand with a very gentle stream of water through a series of sieves with 0.15-, 0.30-, 0.50-, 0.84-, 1.17-, 1.41-, 2.00-, 2.36-, 2.79-, and 3.32-mm openings. Mean weight diameters were calculated for each aggregate class for both soils.

Tensile Strength Measurements

Tensile strength measurements were made using the technique of Nearing et al. (1988). Briefly, samples were formed by static compaction into tensile cells at the same prewetted water content and to the same densities as used in the detachment experiments. The samples in the tensile cells were 7.5 cm long by 3.88 cm in diameter and were split in the middle so that the cell halves could be pulled apart during the test. The force required to cause tensile failure of the soil sample was measured with a load cell. As with the detachment tests, samples were allowed to satiate in the tensile cells for 24 h prior to testing. Treatments were replicated six times. For further details regarding the tensile test procedure and equipment, refer to Nearing et al. (1988).

RESULTS

The experimental results for aggregate mean weight diameter and tensile strength are shown in Table 2. Measured detachment rates are reported in Table 3 for the Russell soil and Table 4 for the Paulding soil. Detachment rates varied as a function of *h*, *S*, and mean weight diameter of aggregates, mwd, as shown in Fig. 1 through 3 for the Paulding soil. Results for the Russell soil were similar, and therefore not plotted. Results for the Russell soil can be found in Table 3.

Statistical comparisons of the means showed that, within each aggregate class of each soil, means did differ significantly as a function of flow depth and slope for most cases (Tables 3 and 4). Thus, slope and flow depth were significant parameters with regard to detachment rates. Results of comparisons of means between aggregate classes were not as definite. Least-significant-difference tests for each of the seven flow depth and slope combinations for both soils showed a significant difference in every case between detachment of the 0- to 1- and the 2- to 4-mm size classes and between the 1- to 2- and the 2- to 4-mm size classes at the 0.05 level (Fig. 4 and 5). However, differences between the 0- to 1- and 1- to 2-mm size classes were significant with the least-significant-difference test at the 0.05 level only for the 1.0-cm flow depth at 0.5% slope for the Russell soil. The trend in all but two of the 14 cases did show a greater detachment rate for the 1- to 2-mm size class than for the 0- to 1-mm size class.

Detachment was also plotted vs. flow shear stress and streampower (Fig. 4 and 5, respectively). The detachment rate was not a unique function of shear stress, because the relationship was different when flow depth was held constant than when slope was held constant. Since shear stress is a direct function of both depth of flow and slope, it is evident from this data that shear stress is not a universal hydraulic parameter to use in relating flow characteristics to soil detachment. The same conclusion holds for flow streampower for the same reasons.

Table 2. Aggregate sizes and tensile strength of the soil materials.

Soil	Aggregate size	Mean weight diam.	Tensile strength Mean	SD	*n*
	mm	mm	kPa	kPa	
Russell	0–1	0.470	1.54	0.40	6
	1–2	1.022	1.26	0.30	6
	2–4	2.065	1.09	0.16	6
Paulding	0–1	0.596	2.04	0.18	6
	1–2	1.428	1.14	0.18	6
	2–4	2.719	1.05	0.16	6

Table 3. Measured detachment rates for the Russell soil.

Aggregate size	Depth of flow	Slope of bed	Detachment rate Mean	SD	*n*
mm	cm	%	g/m²/s	g/m²/s	
0–1	0.5	1.0	0.46f†	0.41	8
	1.0	1.0	1.69e	0.34	8
	1.5	1.0	8.85d	4.99	7
	2.0	1.0	41.75b	13.68	8
	1.0	0.5	0.64f	0.50	7
	1.0	1.5	20.15c	12.18	6
	1.0	2.0	77.21a	41.69	6
1–2	0.5	1.0	0.73f	0.22	8
	1.0	1.0	1.38e	0.72	8
	1.5	1.0	6.34d	2.37	7
	2.0	1.0	51.36b	45.79	6
	1.0	0.5	1.27e	0.39	8
	1.0	1.5	34.08c	15.03	8
	1.0	2.0	92.45a	37.64	7
2–4	0.5	1.0	1.70f	0.25	8
	1.0	1.0	5.62e	1.12	7
	1.5	1.0	34.23d	14.52	8
	2.0	1.0	108.28c	28.38	8
	1.0	0.5	2.27f	0.54	8
	1.0	1.5	136.30b	45.34	8
	1.0	2.0	295.20a	55.82	7

† Means within each aggregate class followed by the same letter are not statistically different at $P = 0.05$ as determined by Duncan's multiple-range tests.

Table 4. Measured detachment rates for the Paulding soil.

Aggregate size	Depth of flow	Slope of bed	Detachment rate Mean	SD	*n*
mm	cm	%	g/m²/s	g/m²/s	
0–1	0.5	1.0	0.61ef*	0.18	7
	1.0	1.0	1.01e	0.39	6
	1.5	1.0	5.45d	3.15	7
	2.0	1.0	13.68c	11.12	8
	1.0	0.5	0.48f	0.53	8
	1.0	1.5	20.14b	9.28	8
	1.0	2.0	46.16a	22.26	7
1–2	0.5	1.0	0.63f	0.25	7
	1.0	1.0	2.04e	0.94	8
	1.5	1.0	7.95d	4.41	8
	2.0	1.0	38.64b	13.53	8
	1.0	0.5	0.61f	0.40	8
	1.0	1.5	23.43c	10.62	8
	1.0	2.0	91.52a	33.46	8
2–4	0.5	1.0	1.35f	0.43	7
	1.0	1.0	10.74e	7.41	8
	1.5	1.0	50.97d	16.70	8
	2.0	1.0	130.43b	41.91	8
	1.0	0.5	0.85f	0.29	8
	1.0	1.5	101.48c	45.23	6
	1.0	2.0	282.62a	97.60	8

* Means within each aggregate class followed by the same letter are not statistically different at $P = 0.05$ as determined by Duncan's multiple range tests.

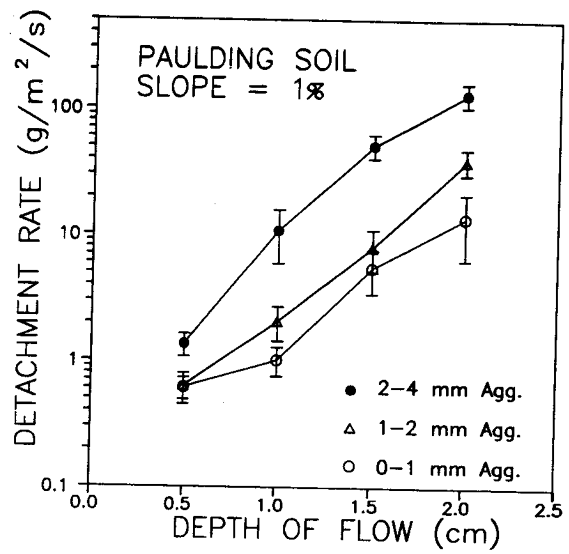

Fig. 1. Detachment rates for the Paulding soil as a function of flow depth at a 1% slope. Error bars represent 95% confidence intervals.

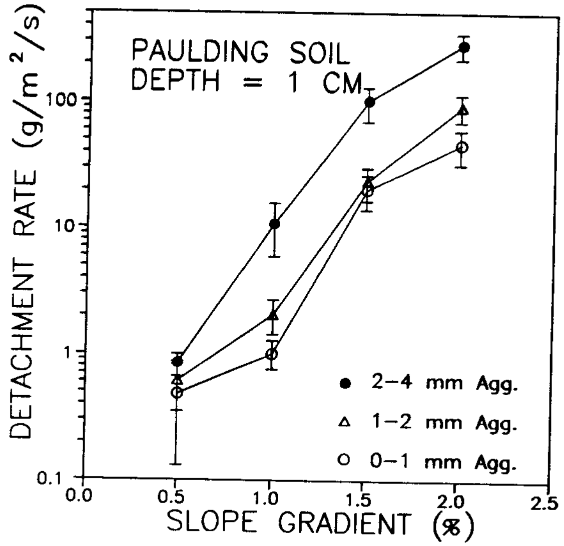

Fig. 2. Detachment rates for the Paulding soil as a function of bed slope at a flow depth of 1 cm. Error bars represent 95% confidence intervals.

Multiple linear regression analyses between the natural logarithm of detachment, D, and S, h, (cm), and mwd (mm) was

$$\ln(D_p) = 3.562S + 2.637h + 0.734\text{mwd} - 5.895 \quad [4]$$

where D_p (g/m^2 s) is the predicted detachment rate. Equation [4] represents a best-fit equation for the data collected in this study, which is limited to two soils, flow depths to 2 cm and slopes of up to 2%. It should not be interpreted as being valid for greater slopes and flow depths. The coefficient of multiple determination, R^2, was 0.94. Figure 6 shows the relationship between measured D and D_p from Eq. [4]. The regression relationship between the logarithm of D vs. h, S, and tensile strength gave an R^2 value of 0.91, indicating that mwd gave only a slightly better fit for the data than did tensile strength. Analysis by soil type improved the regression coefficient for Eq. [4] only slightly, to 0.95 for the Russell and 0.96 for the Paulding soil.

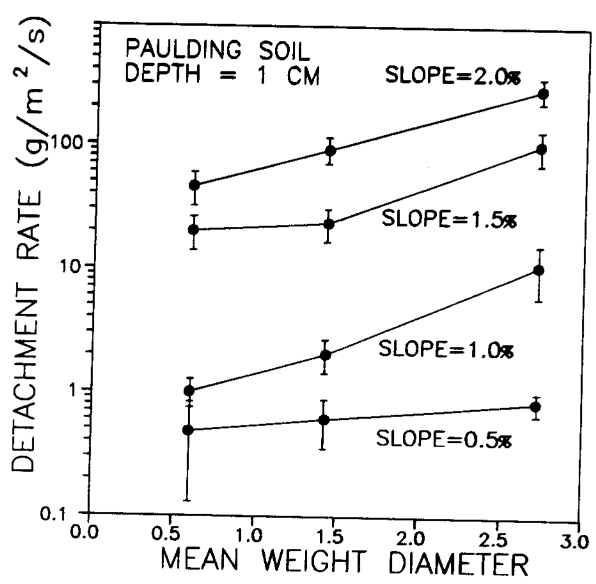

Fig. 3. Detachment rates for the Paulding soil as a function of aggregate mean weight diameter for a flow depth of 1 cm and slopes of 0.5, 1.0, 1.5 and 2.0%. Error bars represent 95% confidence intervals.

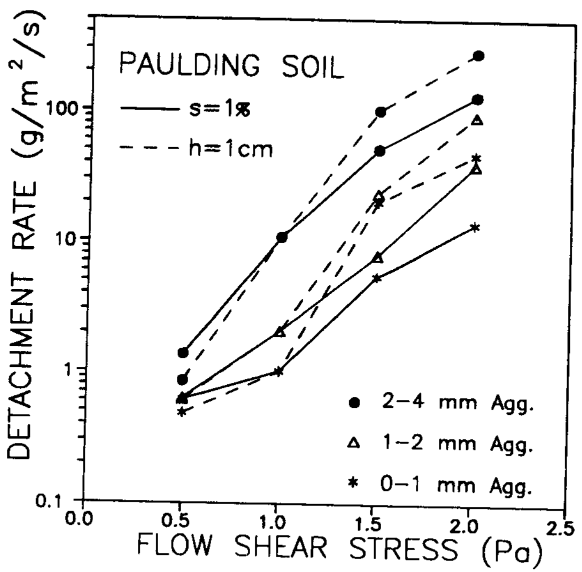

Fig. 4. Detachment rates for the Paulding soil as a function of flow shear stress (S = bed slope and h = depth of flow).

DISCUSSION

The mechanism by which a soil particle is detached from the bulk soil mass is tensile failure. The grains must be lifted from the bed against the resisting force of interaggregate cohesion and the weight of the aggregate. The driving force for detachment of a particle or aggregate in surface flow is a turbulent "event" that occurs at the water-soil interface. These turbulent events are called *bursts*, and are very localized in time and space (Grass, 1970; Praturi and Brodkey, 1978). Detachment of a particle occurs when the burst force is greater than the resisting interaggregate force be-

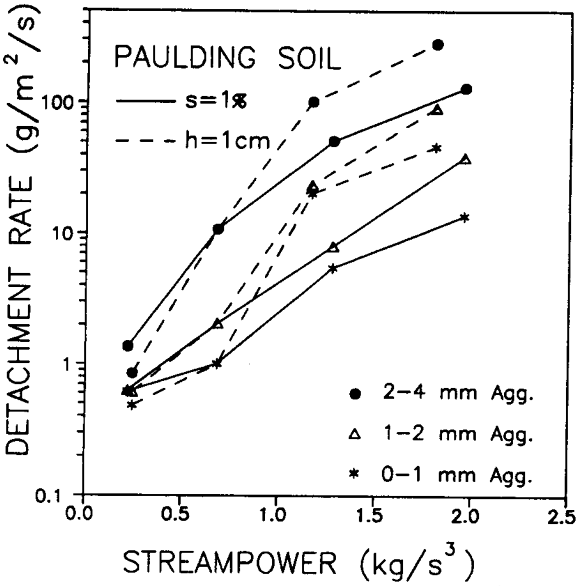

Fig. 5. Detachment rates for the Paulding soil as a function of streampower (S = bed slope and h = depth of flow).

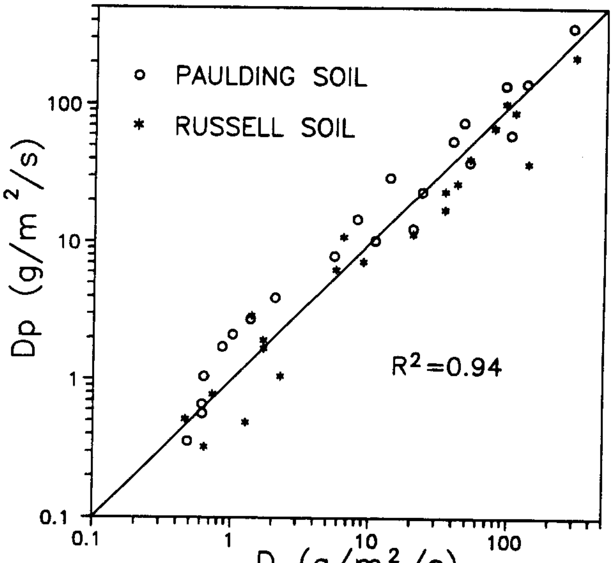

Fig. 6. Predicted detachment rates, D_p, using Eq. [4] vs. measured detachment rates, D, for both soils and all aggregate sizes.

tween particles. In this study, detachment rates were the greatest for the largest aggregate-size-class materials, which also had the lowest tensile strengths. This could be due to two reasons: (i) the mass of soil detached per failure event was greater for the larger aggregates, and (ii) the resisting force per unit cross-sectional area of soil, as represented by the tensile strength, was less for the coarser aggregates.

Several studies have attempted to relate soil detachment by flow to soil strength, but always to compressive rather than tensile strength (Lane, 1955; Lyle and Smerdon, 1965; Partheniades and Paaswell, 1970). The reason for this is that compressive-strength testing devices are readily available and easy to use in the laboratory and in the field. Success in using compressive tests and relating the results to detachment has been mixed. Since the mechanism for detachment by flow is tensile failure rather than compressive failure, more emphasis on tensile strength in studying detachment by flow is probably warranted.

Models for predicting sediment particle sizes typically either assume no preferential detachment by particle size (Rose et al., 1983; Hairsine, 1988) or use an empirical relationship to estimate the size fractions of detached sediment (Foster et al., 1985; Nearing et al., 1989b). The results from this study indicate that there is need for developing and testing a fundamental relationship to predict sediment aggregate-size distributions. In this study, each aggregate class for each soil had a unique characteristic mean weight diameter of the aggregates and tensile strength. A further study is needed to address the case where mean weight diameter and tensile strength are independent parameters for the same soil material. This could be accomplished, for example, by allowing the samples to consolidate for a range of durations to increase tensile strength without greatly affecting aggregate size (Nearing and West, 1988; Nearing et al., 1988).

The results from this study indicate that neither flow shear stress nor streampower are appropriate flow parameters adequate to uniquely describe detachment rates for the given soil materials. Shear stress was increased from 0.49 to 0.98 to 1.47 to 1.96 Pa for two cases: (i) by holding flow depth constant at 1.0 cm and varying slope, and (ii) by holding slope constant at 1.0% and varying flow depth. The resultant two curves of detachment rate vs. shear stress for the two cases were different for every soil/aggregate class combination. In other words, detachment in every case was more sensitive to change in slope than to change in depth. If shear stress or streampower was the correct variable for uniquely defining detachment, the sensitivity to depth and to slope would be the same (Eq. [1] and [2]). It is apparent from the results that the complete descriptor for detachment is more complex than shear or streampower alone. A fundamental description of detachment by flow is needed that incorporates and relates turbulent-flow theory, a fundamental description of soils in terms of aggregate sizes and bonding between aggregates, and the interaction between flow stresses and soil resistance.

The study was performed on disturbed soil samples and should be representative of freshly tilled conditions in the field. Further studies would be required to determine if the same trends in the results hold for consolidated soil.

CONCLUSIONS

The principal conclusions from this study are:

1. Detachment by shallow surface flow for the two soils studied was adequately described (R^2 = 0.94) using multiple-linear-regression techniques by an equation (Eq. [4]) relating logarithm of detachment flow depth, bed slope, and mean weight diameter of the aggregates. Substituting tensile strength for mean weight diameter gave a model with an R^2 of 0.91.
2. Detachment rate for a given soil material was not a unique function of either shear stress or stream-

power of the flow. If shear stress or streampower was the correct variable for defining detachment rates, then detachment would have been equally sensitive to slope as to depth of flow. The experimental results showed a greater sensitivity to slope than to depth, as indicated by the magnitude of the regression coefficients for Eq. [4]. More research is needed to better understand the flow parameters that control the detachment process.

3. The results of this study indicated that, with regard to the effect of aggregate size, there was a significant difference between the 1- to 2- and the 2- to 4-mm size classes, but the existent trends were not significant between the 0- to 1- and 1- to 2-mm size classes of dry-sieved aggregates.

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