Mansoura Engineering Journal, (MEJ), Vol. 28, No. 4. December 2003. C. 30

COMPARISON BETWEEN CHANNEL BED SCOUR AND HEAD CUT EROSION RATES

"مقارنة بين النحر فى قاع القنوات ومعدلات تآكل القواطع الرأسية"

TAREK A. SAAFAN* AND MOHAMED I. M. GAD**

* *Assoc. Prof., Irrigation and Hydraulics Dept., Faculty of Eng., Mansoura University.*

***Head of Modeling Unit, Hydrology Dept., Desert Research Center, Cairo, Egypt. E-mail : drmohamedgad @ yahoo.com*

خلاصة:

يتناول البحث مقارنة بين النحر في قاع القنوات و معدلات تآكل القواطع الرأسية وقد تمت هذه الدراسة معمليا بمعمل الهيدروليكا-كلية الهندسة-جامعة مصر للعلوم والتكنولوجيا، وذلك باستخدام خمسة أنواع من التربة وثلاث ميول مختلفة للقناة المعملية كما تم أيضا تطبيق خمسة تصرفات مختلفة. وقد أظهرت النتائج أن معدلات تآكل التربة دالة في الميل ومعدل السريان وإجهاد القص.كما أظهرت النتائج أن الميل و السريان وتداخل السريان مع الميل مقياس كاف لمعدل النحر في القاع بينما السريان وتداخله مع الميل مقياس كاف لمعدل تآكل الآاطع الرأسي. في حالة تساوى الميل ومعدل السريان فإن معدل تآكل القاطع الرأسي أكبر على الأقل أربعة مرات من معدل النحر لكل أنواع التربة المستخدمة في البحث. وقد أظهرت المنحنيات العلاقة بين النحر والتآكل وبين إجهاد القص للحالة الخطية والغير خطية.

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 predict and prevent erosion more accurately. This study was conducted to compare the erosion rates due to simulated bed scour (D_b) and head cut (D_h) processes. Hydraulic flume was used to simulate concentrated flow erosion using five different soils. For slopes of 1.50, 3.50, and 5.0 %, flow rates of 3.78, 5.67, 7.65, 11.34, and 15.12 L/min were used to provide a shear stress (τ) ranged from low value of (0.50Pa) to a moderate value of (2.50 Pa). Soil detachment rates are functions of slope, flow rate, and shear stress. Slope, flow rate, their squares, and the product of slope by flow interaction were highly significant predictors of the bed scour D_b. Only the square of flow, and its interaction with slope were significant predictors of head cut D_b. Nonlinear power regressions using the shear stress (τ) as an independent variable were better predictors of detachment than simple linear

Accepted December 31, 2003.

regressions. Erodibility for the soils from this study did not relate well with the estimated soil erodibility using Universal Soil Loss Equation. Differences in the slope and intercept of detachment vs. τ exit among soils. The value of D_h was at least four times greater than D_h for all soils at equal slope and flow rate, indicating that head cutting was the main process of detachment for the conditions tested.

INTRODUCTION

Head-cut in natural streams often occurs when a channel incises into a bed with a special stratigraphic bed formation that a hard layer is overlaying on a softer one. The lower layer, once exposed to the channel flow, is being eroded faster than the upper layer, a discontinuity, a abrupt bed elevation drop, is thus formed. Since the drop dissipates a great amount of flow energy and creates strong erosion, the vertical surface or the overhanging brink of the drop would migrate upstream. Severe bed and bank erosion associated with the head-cut would propagate toward the upstream along the channel, jeopardise the upstream channel stability and encroach farmland. Bennett [1] conducted the head-cut experiments with movable bed. The bed near the sudden drop was scoured while the head-cut migrates, and part of the eroded bed materials deposited downstream of the scour hole. In these experiments, the shape of scour hole was approximately unchanged during the migration of the head-cut. This dynamically balanced phenomenon is quite interesting, and also gives the important information to the understanding of the mechanism of the head-cut.

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 [5]. 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 taillage 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 0.30 and 30 m in depth [13]. Gullies cannot be filled 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 [15]. Several agencies have been working on the Water Erosion Prediction Project (WEPP), using a model for erosion prediction [8]. 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 understanding, predicting, and preventing erosion [9]. To work toward that goal, Elliot and Laflen [2] began to separate these processes, but the nature of the field study made separation process seemed difficult.

Foster [3] reported that discharge rate and slope might be used in calculating τ. Nearing et al. [8] reported that the rill erosion rate was not a unique function of τ or stream power. However, Elliot and Laflen [2] suggested that stream power may improve erosion rate prediction, but they noted that the parameters were interrelated. Some research works suggest that the detachment rate could be predicted using a linear function of concentrated flow erodibility (K) and τ [7]. However, nonlinear trends between detachment and τ are apparent in some erosion data, making further study of this relationship desirable [14].

Shaikh et al. [10] reported on a laboratory hydraulic flume experiment using 0.15 m long samples for small-scale simulation of concentrated flow erosion, however, the research focus was on the influence of the amount of clay on only bed-scour erosion. Thus, there is a need to compare the nature of bed scour and head-cut processes in order to improve concentrated-flow erosion prediction.

The 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 different types of soils (loam, clayey loam, silty loam, silty clay loam, and sandy loam) (Table 1). To better characterize these concentrated-flow processes, a laboratory flume study was conducted using simulated concentrated-flow erosion at a certain scale between rill and ephemeral gully erosion.

EXPERIMENTAL SETUP AND PROCEDURE

An open channel hydraulic flume with an adjustable slope was used, Figure (1). . The experimental studies were conducted in a channel in the hydraulic laboratory, Faculty of Engineering, Misr University for Sciences and Technology (MUST). The flume was 6.0 m long and 0.60 m wide. The slope of the flume was adjustable between 0.0 to 5.50 %. The length of the soil test section was 1.0 m. Flow was supplied by a 9.0 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 plexiglass. Slopes used were 1.50, 3.50, and 5.0 %. Five discharge rates were used with each slope and took the following values: 3.80, 5.70, 7.60,11.40, and 15.20 L min^{-1}. The average boundary 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}) [4]. 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 ranged from low value (0.50 Pa) to moderate value (2.50 Pa). Soils with stable aggregates such as, loam, clay loam, silt loam, and silty clay loam have similar boundary and flow characteristics. The flow conditions for sandy loam were probably slightly different from other soils because of the smoother surface. For example, when the slope was set at 3.50 % with 7.60 L min^{-1} discharge rate, the boundary roughness coefficient with aggregated soils was about 0.048. The boundary roughness coefficient with sandy loam was slightly smoother than but not significantly different from that for other soils (0.043).

SOIL SAMPLE PREPARATION

Soils were sifted through a 4 mm sieve, air dried, and stored at room temperature (20-24°C) in 0.10 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 the samples in this condition were 1.16 ± 0.01, 1.11± 0.01, 1.0 ± 0.01, 1.07± 0.01, and 1.36± 0.02 Mg m^{-3} for loam, clay loam, silt loam, silty clay loam, and sandy loam soils, respectively. Soil samples were then placed in a pan to allow wetting of samples with tap water. A soil sample was placed in the flume and tested for erosion immediately after the 24 hours wetting period.

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 and head cut). During head cut trials, head cutting migration distance was monitored with time and sediment samples were collected every 10 to 30 sec. for a total 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 sec. during a 20 min. period for a total 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 (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.

Elliot and Laflen [2] 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 was no problem presenting the detachment in units of mass per unit area per unit time. The area represented the horizontal surface area of the entire soil test bed. However, it was difficult to determine the exact area from which detachment due to head cut takes place. The detachment rate due to head cut was 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 would 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, the detachment rate was reported as mass per unit time (g s^{-1}). The value of D_b was computed as follows [9]:

$$D_b = \frac{1}{\Delta t_b} \frac{1}{n - t} \sum_{i=2}^{n} (M_i) \qquad (1)$$

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 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_b. It was assumed that the total mass of soil collected in sample bottle i ($M_{L,i}$) during a head-cut trial was the sum of the following two components:

$$M_{L,i} = M_{b,i} + M_{h,i} \qquad (2)$$

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:

$$M_{h,i} = M_{L,i} - M_{b,i} \qquad (3)$$

Preliminary analysis showed that erosion due to bed scour below the head cut constituted only 2% of the total detachment. Thus, bed scour erosion occurred only between the head cut and the end of the test bed. In equation (3), $M_{b,i}$ was determined from the following equation [9]:

$$M_{b,i} = D_b \,.\, \Delta t_h \left(\frac{L_o - L_i}{L_o} \right) \qquad (4)$$

Where D_b is the bed scour detachment rate from equation (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 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 following relationship:

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

The overall experiment included five types of soils, two processes, four replicates, and 10 to 20 samples per replicates. Silt loam soil was tested at 15 shear stresses ranging from 0.50 to 2.50 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 silt loam soil were analyzed using the muliple regression model in which the degree of freedom df (df = 59):

$$\check{D} = b_o + b_1 \text{slope} + b_2 \text{ flow} + b_3 (\text{ slope })^2 + b_4 (\text{ flow })^2 + b_5 (\text{slope} . \text{ flow}) + \varepsilon \qquad (6)$$

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 [12]. Linear and nonlinear regressions were conducted using the following equations:

$$\check{D} = b_o + b_1 \tau + \varepsilon \qquad df = 19 \qquad (7)$$

$$\ln \check{D} = b_o + b_1 \ln \tau + \varepsilon \qquad df = 19 \qquad (8)$$

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

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 [11].

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 silty loam soil vs. discharge rate and slope are presented in Table 2. Slope, discharge rate, flow depth, and detachment rate due to bed-scour and head-cut processes for loam, clayey loam, silty loam, silty clay loam, and sandy loam soils are presented in Table 3. Detachment rates increased with discharge rate for both processes and 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 (57.10 vs.2.36).That was 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 non-normality, hence were assumed normal and independent for both processes. Table 4 also presents the probability levels for the independent variables of equation (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 were much greater at the head cut, it was not surprising that test bed slope was not significant for D_h ($P = 0.060$) but was highly significant for D_h ($P < 0.01$). That both the first-and second–degree terms of flow were significant predictors of D_h 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 silty loam soil was found to be a linear function of shear stress, Figure (2). Visual observations showed that the head cut maintained a local slope angle ranged 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 [3], it is not surprising that τ was also found to be a highly significant predictor of D_b and D_b ($P < 0.001$). Both D_b and D_h were positively related for τ, Figure (3). For bed scour, detachment was noticed to be small when τ was < 1.0Pa, after which D_b values was increased at a greater rate (from 1.0 to ≈ 1.50 Pa). Beyond this shear, D_b was increased linearly with τ. The value of D_b was increased linearly with τ when τ was greater than 1.40 Pa, Figure (3). The results for the loam, clayey loam, silty clay loam, and sandy loam 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 fit detachment data for the silt loam soil to power and linear functions is facilitated with Figure (3). The linear function did 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 respect to r^2 values of 0.98 vs. 0.92 for simple linear functions. 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 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, local flow shear stress was neither measured nor calculated. However, data in this work 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 (2.50Pa). Overpredicting bed-scour and head-cut erosion by about 4 and 7 %, respectively. This behavior suggests that for τ values > 1.50 Pa, a linear fit may provide a "good" approximation of the relationship. This would be in agreement with studies where this function was used [16]. This suggests that the fit 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 silt loam soil are presented in Figure (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, Figure (3), responses were not the same for both processes. Detachment for head cut was always greater than for bed scour. The difference between the two processes was greater 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 for the silty loam soil, Figures (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, Figure (5) and Table (5). An almost linear increase in the shear stress was observed within the upper range of τ values. The value of D_h fited closely across the entire range of τ while somewhat greater variations in bed-scour detachment were observed for $\tau < 1.0$ Pa. This behavior was also noticed in Figure (4). Somewhat poorer prediction of detachment values for $\ln \tau < 0.0$ ($\tau < 1.0$ Pa) was observed. Theoretically speaking, 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 was 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 simplicity, only natural log-natural log transformations were used. The simple power equation was sufficient and an excellent predictor of bed-scour and head-cut behavior was achieved. Critical τ for the head-cut process was not observed, Figure (4).

To facilitate comparison of processes among soils, the values predicted using equation (8) and the coefficients from Table 5 were presented in Figures (5) and (6). Measured detachments were very highly correlated with τ for all soils, with $r^2 > 0.91$. Sandy loam soil showed the greatest range in D_b and clayey loam soil showed the least range across the entire range of τ. However, the slope of detachment vs. τ, often called erodibility, was the least for sandy loam and the greatest for clay loam. This suggests that relative soil erodibility cannot be judged by just slope or intercept but both slope and intercept should be involved, Table 5. The regressions for silty loam and silty clay loam 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 $\tau = 2.50$ Pa. This may indicate that at high τ, differences in soil strength affected by soil properties are small relative to the force or the energy of the flow, and thus are practically masked.

The predicted D_h values were always much greater than those of D_b. Interactions among soils were noticed, Figure (6). The loam and silty clay loam soils had high D_h at low τ compared with silty loam and sandy loam. However, silt loam and sandy loam had higher D_h at higher τ values. Clay loam 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 Figure (7). At low τ, < 10 % of soil was detached by the bed-scour process. As τ was increased, bed scour became a somewhat more important process, but at most it was responsible for only ≈ 35% of the total detachment. These data show that head cut was the main process of concentrated-flow erosion under the conditions studied.

Total detachment (D_b+D_b) vs. τ functions are presented in Figure (8). Clay loam soil was the least erodible overall and silt loam and sandy loam were somewhat more erodible than clay loam. This ranking order does not relate well with USLE K factors, Table 2, which show that sandy loam soil would be the least erodible and that silt loam soil would be the most erodible. These data show the highest detachment for silt loam soil at high τ, which agrees with the ranking of the USLE K factor (Figure 8). Sandy loam ranks the second highest in detachment in the upper τ values; however, its USLE K factor indicated that it had the lowest erodibility, and thus it was at odds with data in this work. The point is that the data in this study show that the USLE K is not well correlated with detachment under the conditions tested. This finding is in agreement with Laflen et al.[6], who found that, "Rill erodibility and critical hydraulic shear values were poorly correlated with USLE soil erodibility values".

CONCLUSIONS

A flume study designed to simulate small-scale bed-scour and head-cut processes of concentrated-flow erosion was conducted on five different types of soils ranging from sandy loam to silty-clay loam. Results of the present 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 product of slope by flow interaction were highly significant predictors of bed scour detachment D_b.
- ☐ Only the flow rate, its square, and its interaction with slope were significant predictiors of the head-cut detachment rate D_h.
- ☐ Power functions were better predictors of detachment vs. the shear stress τ than being linear functions.
- ☐ Differences in detachment vs. τ exit among soils.
- ☐ The ranking order of detachment for the five soils did not correlate well with the USLE K factor which was a poor indicator of concentrated-flow erosion under the conditions tested.
- ☐ Values of D_h were at least four times greater than D_b at equivalent slope and flow rate for all soils, indicating that head cutting was the main process of concentrated-flow erosion for the conditions tested.

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Nomenclature

D_b = Bed scour detachment rate (g s^{-1});

D_h = Head-cut detachment rate (g s^{-1});

df = Degree of freedom;

L_i = The distance from downstream end of the original soil test bed to the furthermost upstream point of head cutting at the time of sample i;

L_o = The initial length of the soil test bed at the beginning of the trial;

n = The total number of samples, and M_i is the sediment mass collected in bottle i;

r^2 = Mean square error;

Δt_b = The time period for sample collection in a sample bottle during a bed-scour trial;

Δt_h = The time period for sample collection in a sample bottle during a head cut trial;

ε = Residual or random element; and

τ = Shear stress (Pa).

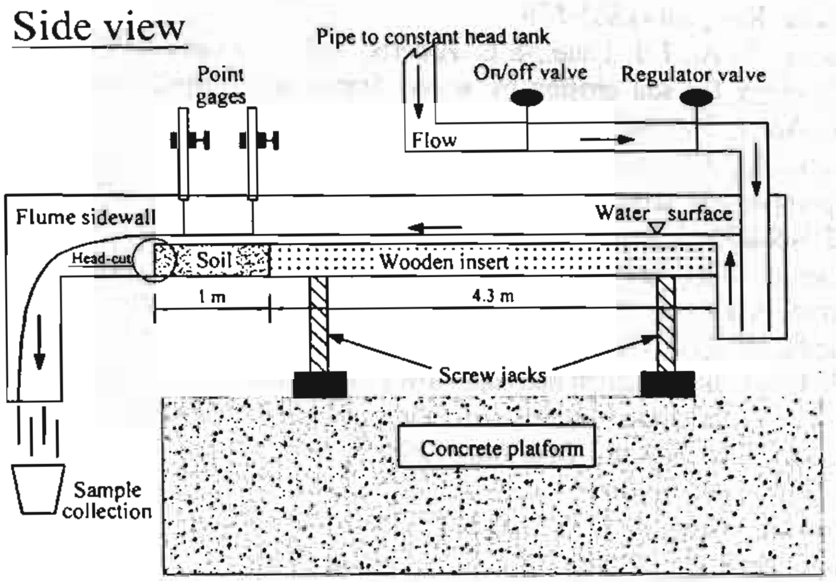

Figure 1. Schematic diagram of hydraulic flume.

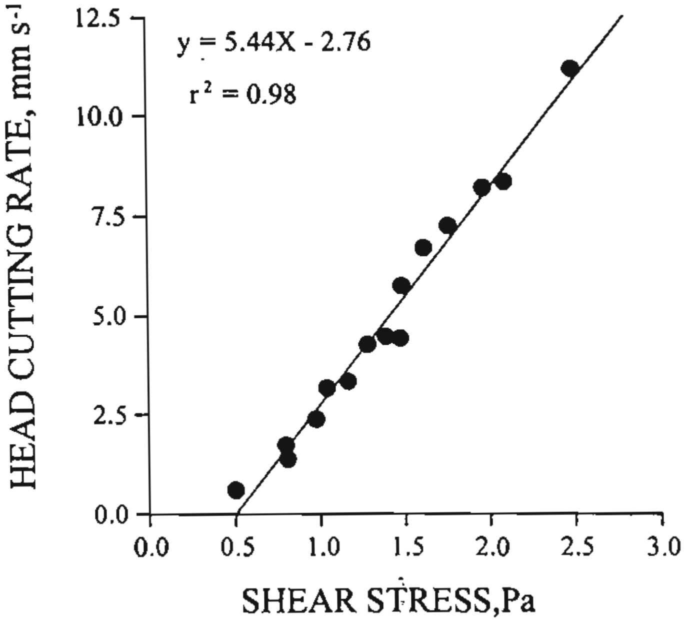

Figure 2. Head-cutting migration rate as a linear function of shear stress for a silty loam soil. Each point represents the mean of four replicates.

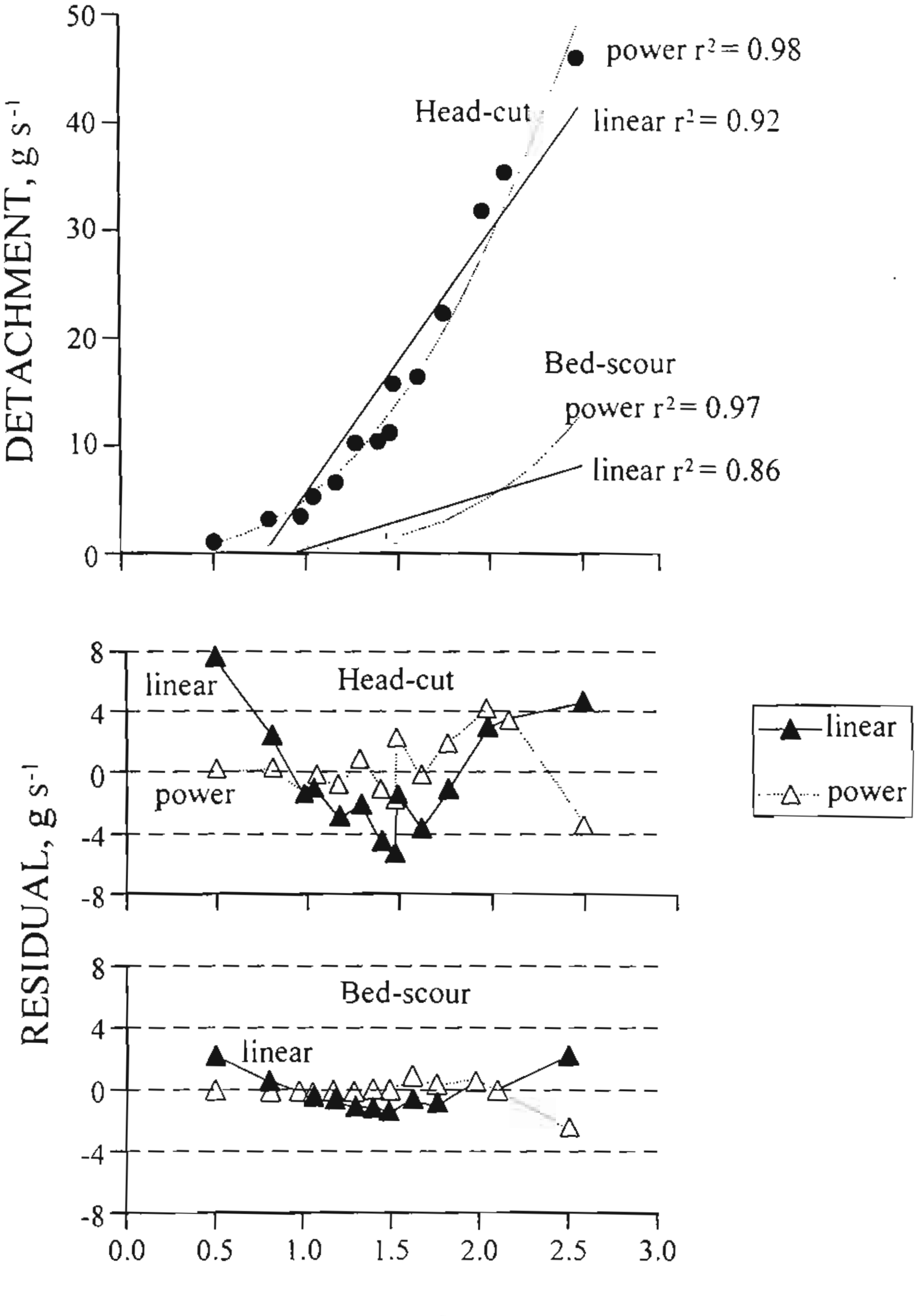

Figure 3. Bed-scour and head-cut detachments vs.shear stress for a silty loam soil and their respective residual deviations from predicted values using the linear { $D = K(\tau - \tau_c)$ } and power ($D = K\tau^b$) regressions.

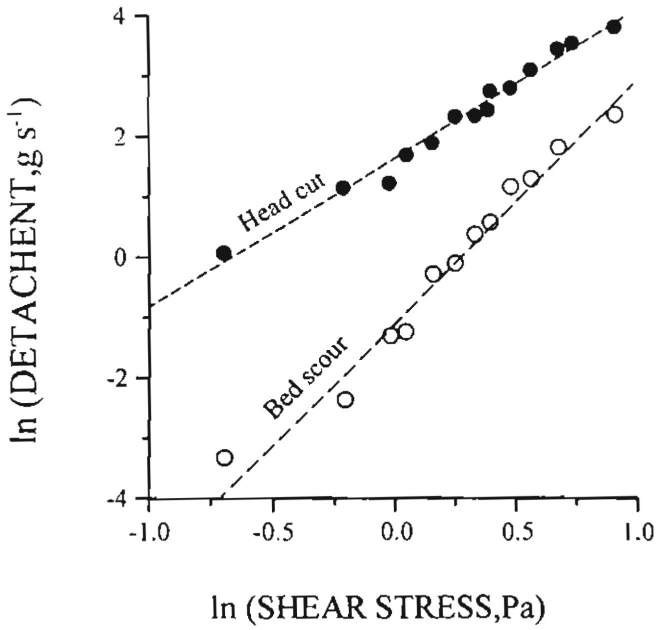

Figure 4. Detachments due to bed - scour and head - cut processes as a function of shear stress for natural log-natural log transformed data for a silty loam soil.

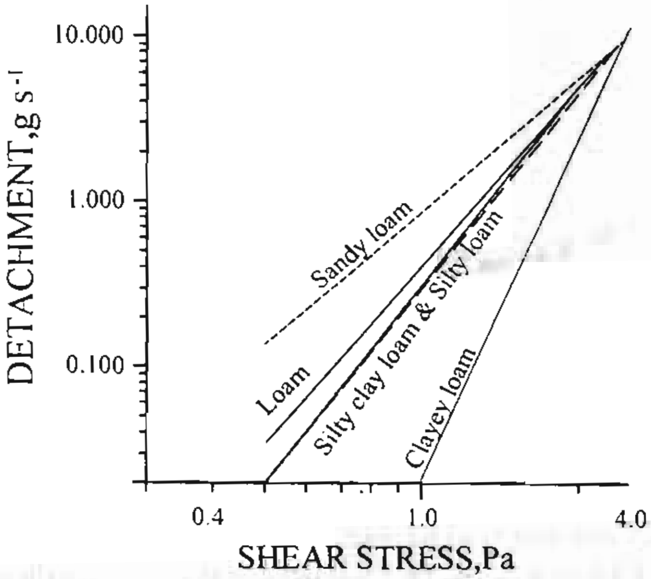

Figure 5. Predicted bed-scour detachments using the power function ($D = K\tau^{b}$) vs. shear stress for five soils.

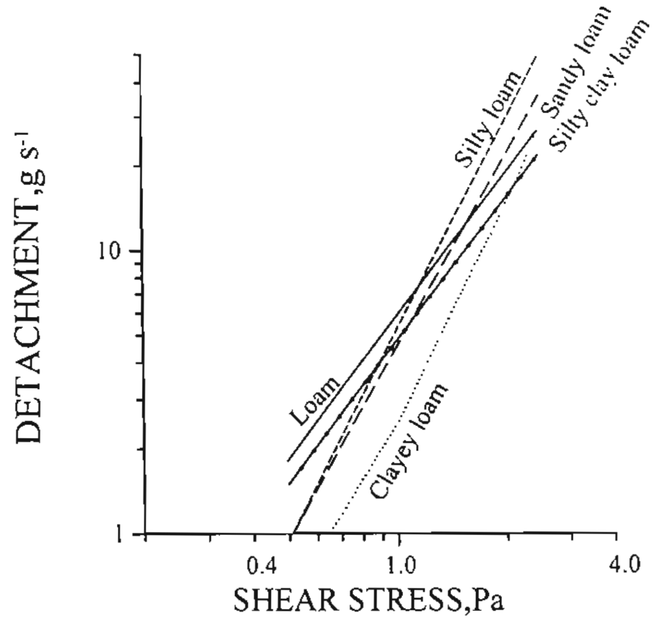

Figure 6. Predicted head-cut detachments using the power function ($D = K\tau^b$) vs. shear stress for five soils.

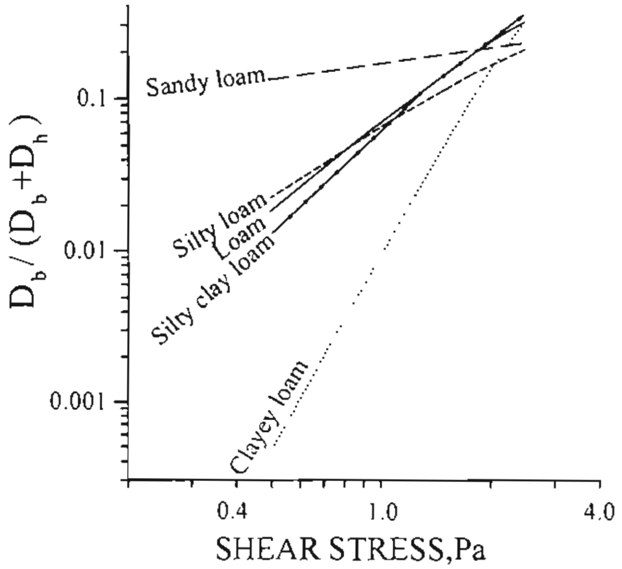

Figure 7. Predicted bed-scour detachment (D_b) as a fraction of predicted total detachment (sum of bed scour and head cut, $D_b + D_h$) using the power function ($D = K\tau^b$) vs. shear stress for five soils.

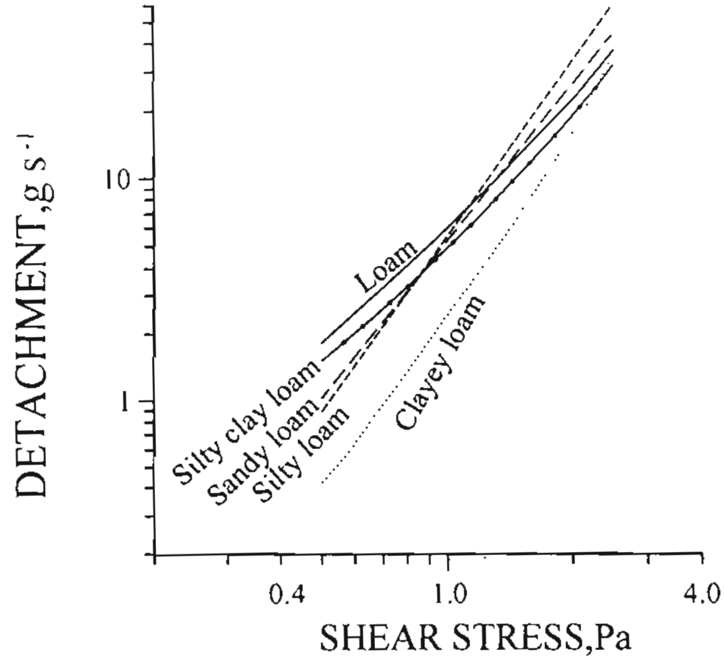

Figure 8. Predicted total detachment (sum of bed-scour and head-cut, D_b+D_h) using the power function ($D = K\tau^b$) vs. shear stress for five soils.

Table 1. Primary particle-size distribution, USLE K factor and soils used in erosion tests.

Soil type	sand	Very fine sand	silt	Clay	Organic Matter	USLE K
	%				$g\ kg^{-1}$	$T\ ha^{-1}\ EI^{-1}$
Loam	48.60	11.40	34.40	17.00	34.00	0.62
Clayey loam	24.00	6.60	39.10	36.90	55.00	0.62
Silty Loam	5.30	1.10	68.70	26.00	27.00	0.94
Silty clay Loam	4.80	4.60	55.40	39.80	32.00	0.67
Sandy loam	75.30	3.70	16.80	7.90	22.00	0.22

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

Slope	Discharge rate	Flow depth	D_b	D_h
%	$L\ min^{-1}$	mm	$g\ s^{-1}$	
1.50	3.78	3.58	0.04	1.04
1.50	5.67	5.98	0.09	3.16
1.50	7.56	7.95	0.29	5.42
1.50	11.34	10.03	0.87	10.25
1.50	15.12	11.85	1.71	15.80
3.50	3.78	2.41	0.09	3.07
3.50	5.67	3.59	0.89	6.60
3.50	7.56	4.57	1.57	11.31
3.50	11.34	5.54	3.60	22.38
3.50	15.12	6.71	6.42	35.25
5.00	3.78	2.06	0.27	3.40
5.00	5.67	2.98	1.42	10.47
5.00	7.56	3.47	3.15	16.52
5.00	11.34	4.61	6.05	31.67
5.00	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 loam, clayey loam, silty clay loam, and sandy loam.

Slope	Discharge rate	Flow depth	D_b				D_h			
			Loam	Clayey loam	Silty loam	Sandy loam	Loam	Clayey loam	Silty loam	Sandy loam
%	L min^{-1}	mm	g s^{-1}				g s^{-1}			
3.50	7.56	0.64	1.54	0.10	0.84	1.63	12.55	9.02	9.50	12.05
3.50	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

Table 4. Summary statistics from the analysis of variance for the model $\check{D} = b_o + b_1 slope + b_2 flow + b_3 (slope)^2 + b_4 (flow)^2 + b_5 (slope . flow) + \varepsilon$ for two processes using data of the silty loam soil.

Source	df	Bed scour			Head cut		
		Mean square	F	P > F	Mean square	F	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 x flow	1	15.98	6.76	0.012**	77.06	1.35	0.251
Flow x flow	1	154.45	65.33	< 0.001**	798.71	13.99	< 0.001**
Slope x flow	1	4235.70	1791.69	< 0.001**	51871.33	908.50	< 0.001**
Error	54	2.36			57.10		
	r^2 =0.995						

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

Table 5. Summary of the linear regression parameter estimates of the model in $\check{D} = b_0 + b_1 \tau + \varepsilon$ for two processes and five soils.

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