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Effect of initial step height on headcut development in upland concentrated flows

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Abstract. Experiments were conducted to examine the effect of initial step height on growth, development, and upstream migration of headcuts in concentrated flows typical of rills, crop furrows, and ephemeral gullies. In a laboratory channel, packed soil beds were constructed with preformed headcuts ranging in height from 5 to 50 mm. Each bed was subjected to the same simulated rain, which produced a protective surface seal, followed by an overland flow, which caused soil erosion exclusively at the headcut. After a brief period of bed adjustment, migration rate, scour hole geometry, and sediment yield reached asymptotic values, but the time and length required to reach these asymptotes decreased as the initial step height increased. Steady state headcut dimensions, sediment yield, and the slope of the sediment deposit increased as initial step height increased, but sediment sorting patterns downstream of the migrating headcut remained unchanged.

1. Introduction

Intense, localized erosion of soil, sediment, and bedrock often occurs at discrete step changes in the bed elevation on hillslopes and within streams and rivers, and these steps are referred to as headcuts and knickpoints [*Brush and Wolman*, 1960; *Holland and Pickup*, 1976; *Gardner*, 1983; *Schumm et al.*, 1984, 1987]. The formation of headcuts and knickpoints and their upstream migration have been linked to erosion in rills, crop furrows, ephemeral gullies, and classic gullies, concentration of overland flow, initiation of drainage systems, erosion of bedrock channels, and landscape evolution (see review and references of *Bennett et al.* [2000]). In upland areas, erosion due to headcut migration can significantly increase soil loss and adversely affect farm productivity [*Mosley*, 1974; *Meyer et al.*, 1975; *Bryan*, 1990; *Römkens et al.*, 1996, 1997].

An experimental research program was initiated to examine the characteristics of actively migrating headcuts in soil materials typical of upland concentrated flows. Motivation for this work was the construction of a database to be used in the analytical formulation of soil erosion prediction technology that specifically addresses headcut erosion in agricultural areas. Results from this program have described systematic behavior of headcut growth and development previously unreported. For a given initial headcut height and bed slope, *Bennett et al.* [2000] observed (1) steady state erosion conditions where headcut geometry, rate of migration, and sediment yield remained unchanged as the headcut moved upstream and (2) scour hole dimensions became progressively larger in response to an increase in overland flow discharge but geometry was conserved. For a given initial headcut height and overland flow discharge, *Bennett* [1999] observed (1) an increase in scour hole dimensions with an increase in bed slope, (2) steady state erosion conditions for migrating headcuts with submerged (nonventilated) overfall nappes on bed slopes 2% and smaller, (3) nonsteady state erosion conditions for migrating headcuts with ventilated overfall nappes on bed slopes 3% and greater, and (4) the conservation of headcut geometry over the entire range of bed slopes examined.

Limited research on headcut development suggests that the depth of scour depends on (1) upstream boundary conditions, such as flow discharge, velocity, and depth; (2) the characteristics of the overfall, such as the thickness and velocity of the jet upon entry into the plunge pool, jet entry angle, and jet diffusion coefficient; (3) material characteristics, such as the sediment's critical tractive shear stress and erodibility coefficient; and (4) downstream boundary conditions, usually tailwater or backwater height [*Stein et al.*, 1993]. It is generally accepted that plunge pool erosion in a headcut scour hole is considered dynamically similar to impinging jets, drop spillways, and pipe outlets [*Donnelly and Blaisdell*, 1965; *Rajaratnam*, 1981; *Blaisdell and Anderson*, 1988; *Bormann and Julien*, 1991].

In the companion studies of *Bennett et al.* [2000] and *Bennett* [1999], the erosivity of the overland flow, hence the erosive potential of the impinging jet, was varied either by increasing the discharge for a given bed slope or by increasing the bed slope for a given discharge, but in each case, the initial headcut height was 25 mm. Assuming that upstream boundary conditions can be replicated, does the initial step height or bed discontinuity have an effect on the asymptotic steady state scour hole dimensions? To address this question, the present study sought to extend this experimental methodology by examining, for a given bed slope and overland flow discharge, the effect of initial step height on headcut growth and development, steady state scour hole dimensions, migration rate, and sediment yield. Error analysis of the data, repeatability of experiments, a quantitative definition of steady state erosion,

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and sediment sorting processes associated with headcut erosion are also discussed.

2. Experimental Equipment and Procedure

The design and description of the experimental facility and the procedure for preparing the soil bed, applying the rainfall, and monitoring runoff and headcut erosion processes are described in detail by *Bennett et al.* [2000] and *Bennett* [1999]. These utilities are briefly described herein. A summary of all experimental parameters is given in Table 1.

2.1. Bed Preparation and Rainfall Application

All experiments were conducted in a nonrecirculating, 5.5 m long tilting flume. Water was fed initially into an inlet tank 0.8 m long, 0.4 m wide, and 0.3 m deep. Once filled, water spilled onto a raised floor, 1 m long and 0.165 m wide, located immediately upstream of a soil cavity 2 m long, 0.165 m wide, and 0.25 m deep. A subsurface drainage system was placed along the base of the soil cavity, allowing the escape of air and water during rainfall application.

The material used in this study is a sandy loam to sandy clay loam texture (Ruston Series; fine-loamy, siliceous, thermic, Typic Paleudult [*Römkens et al.*, 1997]), commonly found in the southeastern United States. The soil material was air-dried, mechanically crushed, and passed through a 2 mm sieve. It was packed incrementally into the flume in layers of ~20 mm and tamped in a uniform and systematic manner. Soil bulk density ranged from 1.486 to 1.680 Mg m^{-3}, with a mean density of 1.557 Mg m^{-3} (Table 1).

After packing the soil to a predescribed depth, an aluminum frame was placed 1.52 m downstream of the soil cavity's entrance for the purpose of forming a headcut. Since this study focused on the effect of initial step height on headcut development, 10 different heights were used: 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 mm. In addition, experiments using the 5, 30, and 50 mm step heights were replicated (designated, for example, 5(1) and 5(2), Table 1). After installation, soil was packed upstream of the frame, producing a preformed vertical step in the bed profile.

The soil material within the uppermost 20 mm of the packed bed was treated with 0.75 cmol of $Ca(OH)_2$ per 100 g of soil (~0.74 g per 1 kg of soil) to promote a physiochemically favorable condition for seal development [*Bennett et al.*, 2000; M. J. M. Römkens et al., unpublished manuscript, 1997]. Following the application of simulated rain, a well-developed and reproducible surface seal formed. During overland flow, the seal prevented surface soil detachment both upstream and downstream of the headcut. Moreover, the seal produced the requisite two-layer stratigraphy common to many stepped headcuts and knickpoints [e.g., *Holland and Pickup*, 1976; *Bryan and Poesen*, 1989].

Suspended ~4 m above the flume was a multiple-intensity rainfall simulator consisting of two oscillating nozzles spaced 1.64 m apart [see *Meyer and Harmon*, 1979; *Bennett et al.*, 2000]. Simulated rain was applied at rates of either 26.7 mm h^{-1} (10 experiments) or 21.2 mm h^{-1} (3 experiments) for 4.6 hours to a bed slope of 5% (Table 1; this slope ensured the rainfall would not create ponded water). Owing to a calibration error a lower rainfall rate was used in three of the experiments. Through the flume's sidewall, advance of the wetting front was recorded to videotape. During rainfall application, inception of surface runoff was noted, and rate of runoff was obtained (Table 1). Surface runoff occurred after 1.2 hours of rainfall, and after 3 hours, runoff rates attained values of ~80% of the applied rate.

2.2. Overland Flow, Data Acquisition, and Error Analysis

With the rainfall application completed, the headcut-forming plate was removed from the flume, the bed slope was adjusted to 1%, and an overland flow of known discharge was released onto the soil material. The overland flow discharge was ~69.9 L min^{-1}, mean upstream flow depth was ~14 mm, and mean upstream flow velocity was ~0.57 m s^{-1} (Table 1). Flow discharge was controlled by two adjustable intake valves and monitored with a manometer and a pressure transducer connected to an inline Venturi meter. All water and sediment that passed through the flume was concentrated into an outlet pipe where sampling took place.

A video camera mounted to a movable carriage recorded the growth and development of the headcut in each experiment. From these images, the following information could be determined: position and morphology of the headcut, overland flow depth, and jet entry angle. The water level meniscus of the approach flow was clearly visible through the flume sidewall and on the video recording. By repeatedly measuring on the video recording the distance from the meniscus to the soil surface, a mean flow depth was obtained. Flow depth measurements were also made with a point gauge mounted on a carriage above the flume. Point gauge depth measurements were in excellent agreement with those derived from the video recordings. During overland flow, water and sediment samples were obtained from the outlet pipe at regular intervals. Collected sediment samples were decanted, oven dried, and weighed to determine total sediment mass. At the conclusion of the run, a bed profile was taken along the flume's centerline using a point gauge. The depth of the scour trace relative to the bed surface was also measured along the flume sidewall.

There are two sources of error that could compromise the quality of the morphologic measurements obtained. First, the curvature of the video camera lens distorts the edges of the recorded image. By comparing known distances taken from the center and edges of the video frame the maximum measurement errors for the headcut morphology ranged from 0.5 to 4.6%, and the errors for flow depth measurement ranged from 3 to 10%. Second, operator variance was assessed by repeating measurements obtained from the same videotape on two different occasions. The maximum measurement errors for headcut morphology ranged from 1.3 to 6.6%, and the error for the flow depth measurement was 5.2%.

3. Results

3.1. General Description of Headcut Development and Migration

The general characteristics of headcut growth, development, and upstream migration were consistent in each experiment. At the beginning of each run, the overland flow passed over the preformed step, and the flow impinged on the surface seal just downstream of the step. The nappe at the brinkpoint is essentially a two-dimensional plane jet. This impinging jet caused surface seal failure and soil erosion, and a scour hole developed and enlarged. Jet entry angle as described herein is the acute angle the jet centerline forms with the water surface as it enters the backwater pool. In general, the scour hole rapidly increased its maximum scour depth S_D (the vertical distance

Table 1. Summary of Experimental Characteristics[a]

Parameter	Experimental Run 1	2	3	4	5	6	7	8	9	10	11	12	13
Initial Experimental Parameters													
Initial headcut height, mm	5 (1)	5 (2)	10	15	20	25	30 (1)	30 (2)	35	40	45	50 (1)	50 (2)
Soil bulk density, Mg m^{-3}	1.557	1.679	1.621	1.526	1.533	1.519	1.486	1.602	1.545	1.514	1.537	1.557	1.562
Rainfall rate, mm h^{-1}	26.7	26.7	26.7	26.7	26.7	21.2	21.2	26.7	21.2	26.7	26.7	26.7	26.7
Rainfall duration, hours	4.60	4.60	4.60	4.60	4.60	4.57	4.62	4.60	4.55	4.60	4.60	4.60	4.60
Total rainfall, mm	122.9	122.9	122.9	122.9	122.9	96.9	97.9	122.9	96.5	122.9	122.9	122.9	122.9
Bed slope during rainfall, %	5	5	5	5	5	5	5	5	5	5	5	5	5
Time of runoff initiation, h	1.57	1.18	1.08	1.32	1.08	1.37	1.18	1.33	0.85	1.00	1.03	0.93	1.33
Runoff rate at conclusion, mm h^{-1}	18.9	19.8	21.3	21.2	22.5	18.4	17.0	22.1	19.5	20.5	21.4	21.2	19.8
Bed slope during overland flow, %	1	1	1	1	1	1	1	1	1	1	1	1	1
Overland flow run time, s	2130	1230	1065	1035	1110	915	730	660	885	840	660	810	1080
Flow discharge, L min^{-1}	69.6	70.8	69.5	69.8	70.0	69.9	70.1	69.3	69.8	70.2	69.9	69.9	69.9
Upstream flow depth, m	0.014	0.014	0.014	0.013	0.014	0.014	0.016	0.014	0.015	0.014	0.014	0.014	0.014
Upstream flow velocity, m s^{-1}	0.521	0.519	0.501	0.530	0.521	0.496	0.440	0.509	0.479	0.508	0.516	0.506	0.523
Steady-state Parameters													
Headcut migration rate, mm s^{-1}	0.648	1.030	0.886	0.959	0.833	1.090	1.424	1.527	1.051	1.135	1.546	1.225	0.94
Maximum scour depth S_D, m	0.054	0.053	0.067	0.072	0.081	0.094	0.094	0.089	0.106	0.108	0.103	0.125	0.132
Length to S_D (S_L), m	0.093	0.099	0.110	0.085	0.087	0.070	0.078	0.087	0.070	0.090	0.083	0.087	0.081
S_L/S_D	1.725	1.898	1.640	1.187	1.073	0.753	0.838	0.987	0.664	0.830	0.805	0.698	0.606
$\tan^{-1}(S_D/S_L)$, deg	30.3	28.5	29.9	40.2	43.2	53.1	50.3	45.5	56.5	50.4	51.2	55.1	58.9
Water depth at S_D (T_W), m	0.062	0.061	0.062	0.073	0.080	0.091	0.091	0.074	0.099	0.096	0.084	0.103	0.100
T_W/S_D	1.15	1.15	0.93	1.01	0.99	0.97	0.97	0.83	0.93	0.89	0.82	0.82	0.76
Jet entry angle, deg	30.3	32.1	41.6	45.0	45.3	52.1	50.1	61.6	62.2	62.2	68.8	75.5	72.5
Time of overfall ventilation, s	s.j.	s.j.	s.j.	s.j.	s.j.	s.j.	s.j.	126	86	93	53	4	6
Sediment yield S_Y, kg s^{-1}	0.0058	0.0071	0.0081	0.0103	0.0090	0.0151	0.0183	0.0214	0.0159	0.0199	0.0239	0.0270	0.0222
Deposit thickness, m	0.042	0.038	0.047	0.049	0.061	0.067	0.074	0.053	0.083	0.070	0.062	0.079	0.081
Deposit bulk density, Mg m^{-3}	1.405	1.480	1.468	1.456	1.423	n.a.	n.a.	1.396	n.a.	1.451	1.516	1.456	1.393
Slope of self-made bed, %	n.a.	0.16	0.60	1.31	1.94	1.07	1.47	1.49	2.75	2.23	4.52	2.35	4.22
Time to steady state (S_D), s	1650	870	914	496	360	444	134	218	270	220	96	161	170
Distance to steady state (S_D), m	0.834	0.812	0.749	0.411	0.303	0.400	0.193	0.332	0.314	0.285	0.182	0.262	0.192
Time to steady state (S_Y), s	n.a.	n.a.	376	347	429	312	234	220	365	250	242	255	294
Distance to steady state (S_Y), m	n.a.	n.a.	0.312	0.264	0.358	0.364	0.354	0.335	0.428	0.326	0.435	0.379	0.317

[a]Each column refers to individual experimental runs, and steady state parameters represent time or spatially averaged values. Here s.j., submerged jet, overfall never became ventilated; n.a., not available.

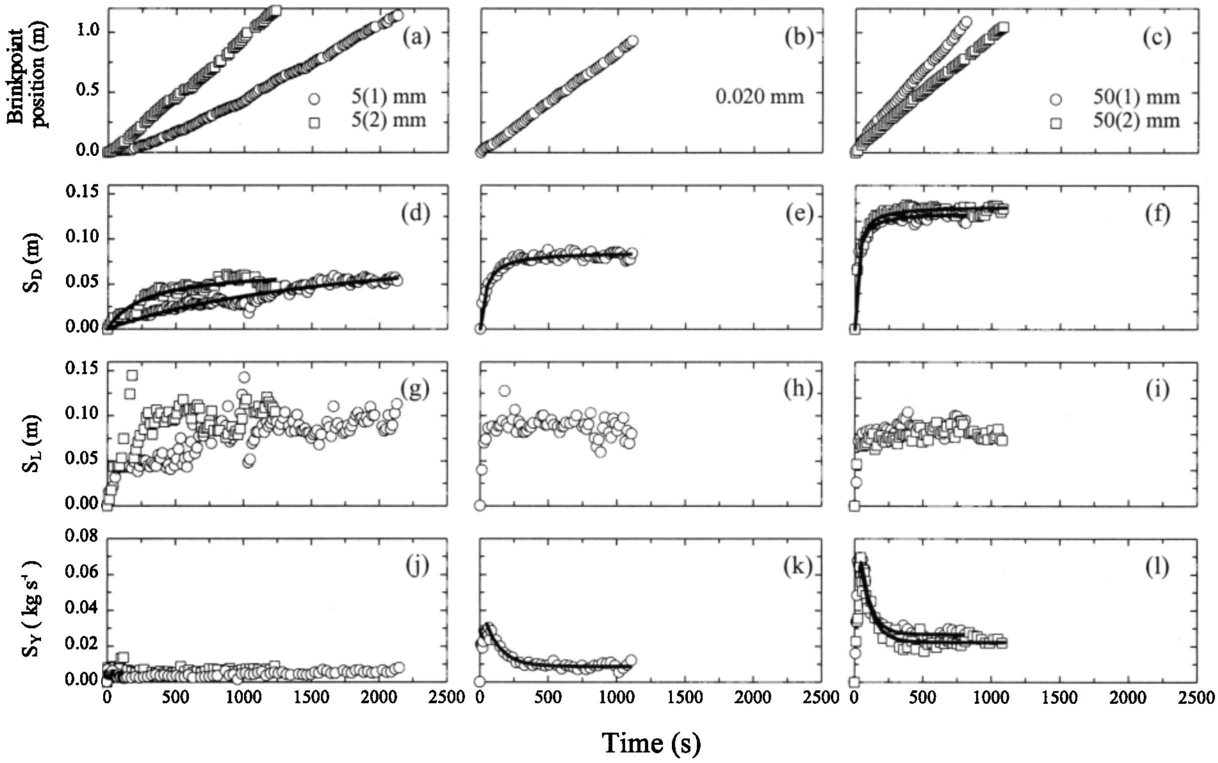

Figure 1. Time variation in headcut brinkpoint position, maximum scour depth S_D, length to maximum scour depth S_L, and sediment yield S_Y for experiments using initial headcut heights of 5 (Figures 1a, 1d, 1g, and 1j), 20 (Figures 1b, 1e, 1h, and 1k), and 50 mm (Figures 1c, 1f, 1i, and 1l). All data were measured at 15 s intervals. Also shown are asymptotic trend lines for S_D (a two-parameter hyperbolic function $S_D = (at)/(b + t)$, where a is the asymptote of the time series, b is a coefficient, and t is time) and S_Y (a three-parameter exponentially decreasing function $S_Y = y_0 + ae^{-bt}$, where y_0 is the asymptote, a and b are coefficients, and t is time). Note that trend lines were not derived for Figure 1j because these runs did not reach true steady state conditions for the sediment transport parameters.

from the headcut brinkpoint to lowest point within the scour hole; Figures 1e and 1f) and the length to the maximum scour depth S_L (the horizontal distance from the headcut brinkpoint to S_D; Figures 1g–1i). The headcut brinkpoint is defined as the position where the nearly vertical headcut face intersects the horizontal soil bed on the upstream side. Concomitantly, erosion initiated at the brinkpoint, and headcut migration ensued. The position of the headcut brinkpoint for each experiment varied linearly with time; that is, headcut migration rate was constant (Figures 1a–1c). During this initial period of bed adjustment, scour depth S_D, scour length S_L, and sediment production increased (Figure 1). The peak in sediment yield S_Y coincided with initiation of both headcut movement and downstream deposition (Figures 1j–1l). Once the scour hole attained an equilibrium or maximum depth, downstream deposition began, scour hole length was maintained, and sediment yield decreased. Along-flume profiles of the scour hole trace (erosional surface) show that during each experiment, depth of scour did not vary significantly (Figure 2 and Table 1). Between the scour depth trace and the final bed surface was a region of deposition that represents a self-made bed.

After an initial period of bed adjustment, a steady state condition ensued: a headcut of similar geometry migrated upstream at a constant velocity, producing both a constant rate of sediment yield and a constant rate of deposition in the downstream portion of the flume. For initial headcut heights of 30 mm and greater, the overfall jet became ventilated during the

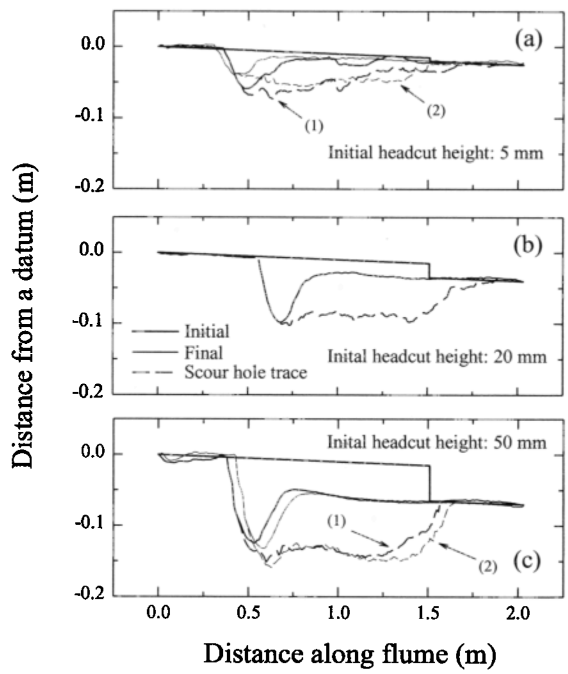

Figure 2. Along-flume profiles of the initial and final bed surfaces and the trace of the scour depth for experiments with initial headcut heights of (a) 5, (b) 20, and (c) 50 mm. Flow is from left to right.

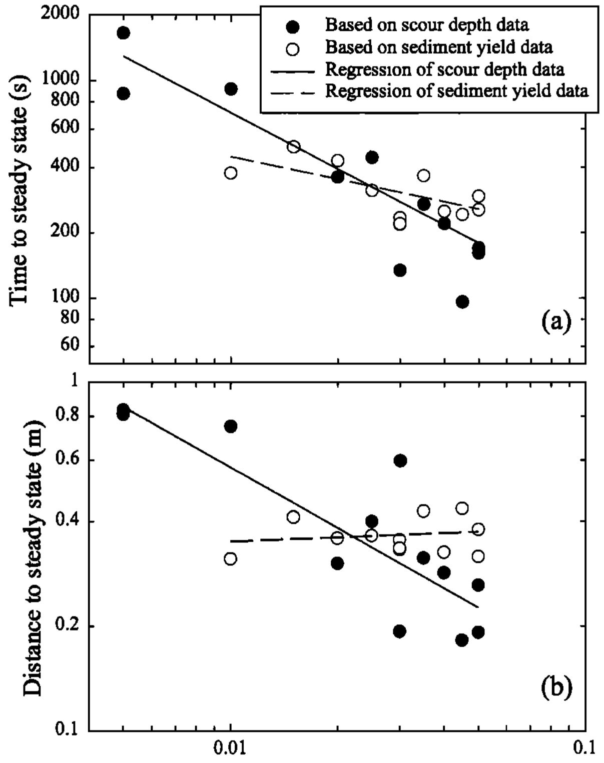

Figure 3. Variation of the (a) time and (b) distance required to reach steady state soil erosion conditions based on scour depth and sediment yield data. Shown also are regression lines for each data set where for scour depth, $R = 0.91$ and $PW = 1.0$ (using $\alpha = 0.05$ and $P = 0.001$) and, for sediment yield, $R = 0.67$ and $PW = 0.64$ (Figure 3a) and for scour depth, $R = 0.95$ and $PW = 1.0$ and, for sediment yield, $R = 0.17$ and $PW = 0.0$ (Figure 3b). R is the correlation coefficient of the regression line and PW is the probability that the regression correctly describes the relationship between initial headcut height and the dependent variable. For statistical significance, R and PW should be >0.8.

course of the experiment. The distance from the brinkpoint to the free surface of the plunge pool, which defines the overfall height, was ~10 mm. The time when ventilation occurred was noted for each experiment (Table 1).

3.2. Definition of Steady State Erosion and the Time and Length Scales for Headcut Development

Steady state erosion is reached when all variables that define headcut behavior do not change significantly with time. An important distinction is made between steady state for morphological variables and those for sediment transport variables. As described earlier, the time variation of maximum scour depth S_D, scour length S_L, and sediment yield S_Y tended toward asymptotic values (Figure 1). Of these, S_D most clearly demonstrated this asymptotic behavior. To better characterize this asymptotic variation, a two-parameter hyperbolic function was fitted to the values of S_D (Figures 1d–1f). On average, derived correlation coefficients for these regressions were >0.95. Considering a deviation of 10% from the asymptotic value, the time and distance required for a headcut given an initial size to reach steady state can be determined (Table 1 and Figure 3). Initially, large steps reach steady state erosion conditions faster (by more than an order of magnitude) and over a shorter distance (by less than an order of magnitude) than do initially small steps.

Sediment yield was the selected variable to define steady state conditions in terms of sediment transport. Because sediment yield climbs from zero to a maximum value and then declines from a maximum value to an asymptote, a three-parameter exponentially decreasing function was fitted to the decaying section of the time series (Figures 1k and 1l). On average, derived correlation coefficients for these regressions were >0.95. Again, the time and distance required to reach steady state conditions were determined using the same 10% deviation criterion. Initially small steps take almost twice the amount of time to reach steady state conditions for sediment transport parameters as do initially large headcuts (Table 1 and Figure 3a). On the other hand, both initially small and large steps reach steady state conditions after migrating about the same distance upstream (Figure 3b). Steady state condition for deposit thickness must be reached at about the same time as sediment yield. For initial headcuts of 5 mm, a trend line could not be fitted to the sediment yield time series because these data did not attain an asymptotic value (Figure 1j); that is, these runs did not reach true steady state conditions with regard to sediment transport.

Table 2. Statistical Comparison of Steady State Parameters for Each Experiment With the Same Initial Headcut Height[a]

	Initial Headcut Height, mm		
Parameter	5	30	50
Migration rate	D	E	D
Scour depth	E	E	E
Scour length	E	D	D
S_L/S_D	E	E	E
Jet entry angle	E	D	E
Sediment yield	E	E	E
Deposit thickness	E	D	E

[a]The Kruskals-Wallis analysis of variance (ANOVA) on ranks was selected to determine if there exists a statistically significant difference in the measured experimental parameters (using $\alpha = 0.05$ and $P = 0.001$). If the groups are statistically different, the experimental parameter is denoted as D. If no statistical difference exists, then the parameter is denoted as E.

3.3. Replication of Experiments

Three experiments were repeated to assess the intrinsic variability of headcut and sediment transport parameters given nearly identical boundary conditions. Replicates were run for initial headcut heights of 5, 30, and 50 mm (Table 1). Although great care was taken during soil and bed preparation, the bulk soil densities for the 5 and 30 mm replicates differed by ~8%. Such changes in bulk density may be due to variation in soil moisture content, soil texture and composition, and energy expended during the packing process.

Tests were performed to determine if there existed a statistically significant difference between the morphologic and sedimentological results obtained in each replicated experiment. For these, instantaneous values of the following parameters were examined after steady state conditions were achieved: migration rate, S_D, S_L, S_L/S_D, jet entry angle, S_Y, and deposit thickness. The results from these statistical tests are summarized in Table 2. In general, S_D, S_L/S_D, jet entry angle, S_Y, and deposit thickness show no statistical difference in at least two sets of repeated experiments. Migration rate and S_L show statistical differences in two sets of repeated experiments. The lack of complete repeatability may be due to the limited number of replicated runs. *Bennett et al.* [2000] repeated the same headcut experiment four times. Using an initial headcut height of 50 mm and a flow discharge close to 71.0 L min^{-1}, the percent variation was reported for the following parameters: 1.6% for soil bulk density, 4.9% for final runoff rate, 0.9% for flow discharge, 10.4% for migration rate, 3.2% for maximum scour depth S_D, 7.8% for length to maximum scour depth S_L, and 7.5% for sediment yield S_Y. These results show that migration rate and S_L have the largest potential variability.

The greatest variability observed between repeated runs was using an initial headcut height of 30 mm, but these runs had markedly different overfall nappes. In run 30(1), the overfall nappe remained submerged (nonventilated) for the entire experiment, whereas in run 30(2) the overfall became ventilated after ~126 s of elapsed time (Table 1). *Bennett* [1999] showed that steady state conditions for ventilated nappes were markedly different from nonventilated nappes.

The repeatability of the experimental results also extends to the bed profiles and scour hole traces. For repeated runs using the 5 mm headcut height, the bed profiles and scour hole traces are similar but not identical (Figure 2a). However, for the repeated experiments using the 50 mm headcut height these bed profiles are virtually identical, including the subtle adjustments within the scour trace (Figure 2c). These scour trace adjustments are related to the effect of differing bed slopes between the original bed and the sediment deposit (see discussion by *Bennett et al.* [2000]).

3.4. Sediment Sorting and Bulk Soil Density

Texture of the soil material was determined by separating the soil into sand, silt, and clay size fractions. Total percent sand by mass was determined by wet sieving the dispersed soil sample through a 0.05 mm sieve. Total percent clay (<0.002 mm) by mass was determined using the pipette method [*Vanoni*, 1975]. Total percent silt was determined by adding the masses of sand and clay and subtracting these from the total sample mass. For the bulk soil material, five randomly selected samples were analyzed. For the sediment yield, four samples were analyzed for select experiments, obtained during steady state conditions. For the sediment deposit, three or four samples were analyzed for select experiments, extracted using aluminum cylinders either 0.025 or 0.051 m deep and 0.048 m in diameter. Soil bulk density was also determined for the sediment deposit samples.

On average, the bulk sediment mixture was composed of 64.6% sand, 8.3% silt, and 27.1% clay by mass (Table 3). Figure 4 and Table 3 compare the grain size distributions of the sediment yield and the deposit with the bulk soil material. In general, the sediment yield had a sand content of 57.6%, a silt content of 12.1%, and a clay content of 30.3%. This represents an enrichment of 46% and 12% in silt and clay content, respectively, and a depletion of 11% in sand content as compared to the original soil material. While the removal of silt and clay from agricultural lands depletes soil productivity, these size fractions also are more likely to be transporting agrichemicals (see review by *Leonard* [1990]). Conversely, the sediment deposit generally had a sand content of 77.6%, a silt content of 4.2%, and a clay content of 18.2%. This represents an enrichment of 20% in sand content and a depletion of 50% and 33% in silt and clay content, respectively, as compared to the original soil material. Given the presence of silt and clay in the deposit, a significant proportion of these sediment sizes were eroded, transported, and deposited as aggregates. The textural characteristics of the sediment yield and the sediment deposit showed no dependency on initial headcut height.

The bulk density of the sediment deposit was always lower than the packed soil bed (Table 1). The bulk density of the deposit was 1–13% less dense than the packed soil bed (7.8% on average). The reduction in bulk density can be explained by the change in sediment texture and by how the deposit was formed. The higher proportion of sand presumably increased sediment porosity, hence decreasing bulk soil density. In addition, these sediments were deposited hydrodynamically and not compacted mechanically in place.

3.5. Effect of Initial Step Height on Steady State Headcut Parameters

Time-averaged values for steady state parameters related to headcut morphology are summarized in Figure 5 and Table 1. As initial step height increased, headcut migration rate increased (not statistically significant; Figure 5a), maximum scour depth increased (statistically significant; Figure 5b), length to maximum scour depth decreased (not statistically significant; Figure 5c), and headcut aspect ratio S_L/S_D decreased (statistically significant; Figure 5d). The jet entry angle also increased as initial step height increased (statistically significant; Figure 5e).

Two other steady state parameters also increased with initial headcut height. The effective tailwater height, defined as the ratio of depth of water within the scour hole to maximum scour depth T_W/S_D, decreased from ~1.15 to ~0.76 (Table 1); that is, the larger steps had smaller tailwater heights. Also, the projected angle of inclination of the headcut face (Table 1), defined as $\tan^{-1}(S_D/S_L)$, increased from ~30° to ~55°; that is, larger headcuts had steeper erosional faces. For a given bed slope and overland flow discharge, larger initial steps caused the formation of deeper, steeper headcuts with ventilated nappes, but their rates of migration and their scour lengths did not change significantly.

3.6. Effect of Initial Step Height on Steady State Sediment Transport Parameters

Time-averaged values for steady state parameters related to sediment transport are summarized in Figure 6 and Table 1. As initial step height increased, sediment yield, deposit thickness, and the slope of the sediment deposit increased (each statistically significant). For a given bed slope and overland flow discharge, larger initial steps caused the formation of headcuts with greater rates of sediment production, deposition, and yield and a steepening of the bed slope downstream.

4. Discussion

4.1. Systematic Headcut Erosion

Although a variety of causes for headcut development in soils have been observed, including the effects of the soil and surface material characteristics and the nature of overland and subsurface flow [e.g., *Mosley*, 1974; *Bryan and Poesen*, 1989; *Bryan*, 1990; *Bryan and Oostwouud Wijdenes*, 1992; *Slattery and Bryan*, 1992; *Römkens et al.*, 1996, 1997; *Bryan and Rockwell*, 1998], experimental results presented here and elsewhere have shown systematic behavior in headcut erosion processes. On bed slopes 2% and lower, for flow discharges ranging from 20

Table 3. Textural Analyses Given as Percent by Mass for Sediment Yield and the Self-Made Bed for Select Experiments and for the Bulk Sediment Mixture

Initial Headcut Height, mm	Sediment Yield			Self-Made Bed		
	Sand, %	Silt, %	Clay, %	Sand, %	Silt, %	Clay, %
5 (1)	65.5	9.4	25.1	78.2	0.3	21.5
5 (1)	62.2	10.2	27.6	76.0	6.1	17.9
5 (1)	64.3	9.6	26.1	77.1	5.9	17.0
5 (1)	64.8	8.1	27.1	...	...	...
5 (2)	60.5	10.6	28.9	79.7	5.3	15.0
5 (2)	52.9	11.0	36.1	79.6	5.0	15.4
5 (2)	51.9	13.9	34.2	78.5	5.6	15.9
5 (2)	55.9	9.9	34.2	79.1	5.0	15.9
10	59.2	13.7	27.1	78.1	6.3	15.6
10	57.2	13.3	29.5	77.1	5.9	17.0
10	59.0	12.8	28.2	77.5	6.6	15.9
10	54.9	13.8	31.3	78.9	6.0	15.1
15	...	...	...	78.9	1.4	19.7
15	...	...	...	79.4	1.7	18.9
15	...	...	...	75.6	1.9	22.5
15	...	...	...	77.1	2.5	20.4
20	51.8	15.5	32.7	77.6	3.8	18.6
20	53.8	13.8	32.4	78.1	3.9	18.0
20	56.6	11.0	32.4	78.0	2.9	19.1
20	51.6	12.9	35.5	78.3	3.9	17.8
30 (2)	51.5	15.2	33.3	75.8	5.6	18.6
30 (2)	50.4	17.0	32.6	76.1	1.0	22.9
30 (2)	52.4	15.8	31.8	77.4	3.6	19.0
30 (2)	59.0	12.0	29.0	...	...	...
40	...	...	...	80.1	3.5	16.4
40	...	...	...	78.4	4.1	17.5
40	...	...	...	80.5	3.7	15.8
45	63.9	9.6	26.5	81.2	2.7	16.1
45	65.8	8.4	25.8	78.8	2.6	18.6
45	64.0	9.1	26.9	81.9	2.9	15.2
45	65.4	8.7	25.9	81.3	3.4	15.3
50 (1)	62.0	11.4	26.6	78.7	2.3	19.0
50 (1)	60.1	12.2	27.7	80.0	2.8	17.2
50 (1)	60.6	12.2	27.2	79.8	2.2	18.0
50 (1)	59.2	12.6	28.2	79.1	1.4	19.5
50 (2)	49.2	13.9	36.9	68.6	8.3	23.1
50 (2)	52.8	13.0	34.2	69.1	8.3	22.6
50 (2)	51.8	12.6	35.6	70.5	7.5	22.0
50 (2)	52.6	13.4	34.0	71.2	8.0	20.8
Bulk mixture	64.2	7.8	28.0	...	...	...
Bulk mixture	65.0	8.1	26.9	...	...	...
Bulk mixture	64.8	8.1	27.1	...	...	...
Bulk mixture	64.6	8.3	27.1	...	...	...

to 80 L min^{-1}, and with initial headcut heights ranging from 5 to 50 mm, steady state headcut erosion has been observed where headcut migration rate, scour hole geometry, and sediment yield reach asymptotic values [see also *Bennett*, 1999; *Bennett et al.*, 2000]. For bed slopes 3% and greater using a flow discharge of ~52 L min^{-1}, constant headcut migration rate has been reported, but steady state scour hole dimensions were not achieved because of the length limitation of the flume. Taken separately, these results show that S_D, S_L, and S_Y could be simple empirical functions of flow discharge, bed slope, and initial headcut height.

This presumption is misleading, however, because other parameters need to be quantified before an analytical solution for headcut erosion can be completed. For example, *Bennett et al.* [2000] observed the following relations using similar upstream boundary conditions and nearly identical soil materials: $S_D \approx Q^{0.87}$, $S_L \approx Q^{0.89}$, and $S_Y \approx Q^{0.44}$. The application of these relations to the data presented herein would lead to erroneous results because they do not take into account the effect of tailwater height on modulating the characteristics of the impinging jet, including its angle, its length to impingement, and its erosivity [e.g., *Donnelly and Blaisdell*, 1965; *Blaisdell and Anderson*, 1988; *Bormann and Julien*, 1991; *Robinson and Hanson*, 1996]. For small initial headcut heights, tailwater height was relatively high, and both jet entry angle and the angle of inclination of the headcut face were relatively low (Table 1). During some experiments, particularly with initial headcut heights of 5 and 10 mm, the overfall jet was observed to float periodically, at which time no scour hole erosion took place. Conversely, for large initial headcut heights, tailwater height was relatively low, and both jet entry angle and the angle of inclination of the headcut face were relatively high (Table 1). *Stein et al.* [1993] recognized that jet diffusion plays an important role in headcut erosion where the dominant process is plunge-pool scour. But their analytical model, which incorporated the characteristics of the impinging jet, was limited to those cases where the depth of the tailwater was small relative to the scour hole depth. For gully headcuts with ventilated

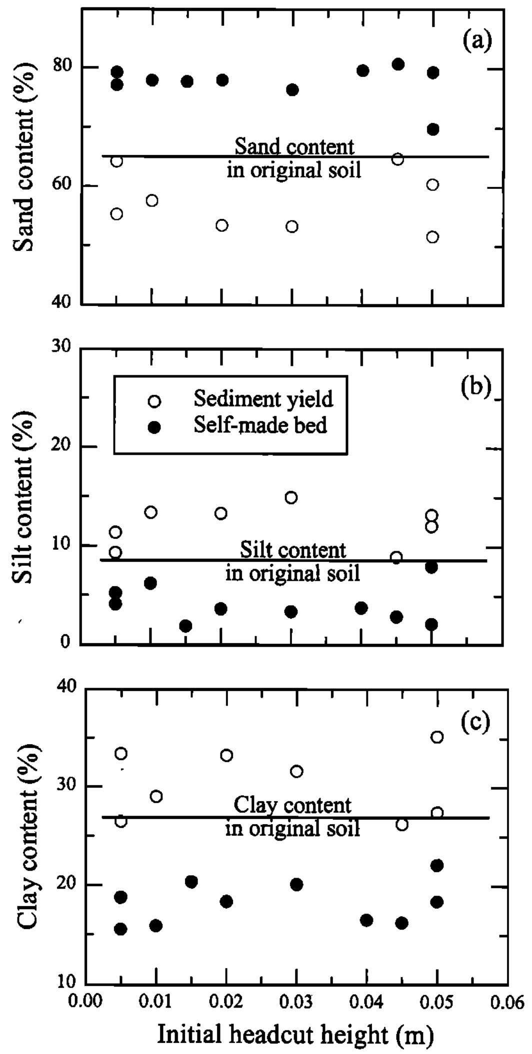

Figure 4. Variation of sediment texture for sediment yield and self-made bed with initial headcut height. Also shown are the sand, silt, and clay content of the original soil material.

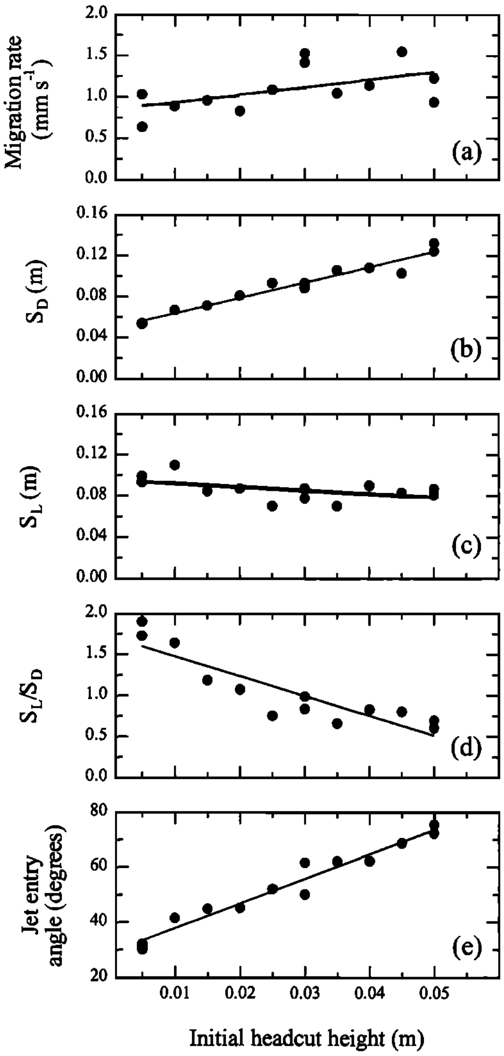

Figure 5. Variation of steady state headcut parameters with initial headcut height. Shown are (a) headcut migration rates (R = 0.55; PW = 0.49; using α = 0.05 and P = 0.001), (b) maximum scour depth S_D (R = 0.97; PW = 1.0), (c) length to maximum scour depth S_L (R = 0.51; PW = 0.42); (d) the ratio S_L/S_D (R = 0.89; PW = 1.0), and (e) jet entry angle (R = 0.98; PW = 1.0).

nappes, *Robinson and Hanson* [1994] developed a model for gully headcut advance that included the effect of tailwater height on the magnitude of stress at impingement, but their model did not consider erosion within the impingement area, i.e., no scour hole erosion nor the effect of downstream deposition, which also must modulate tailwater and jet characteristics. These considerations are further exacerbated in developing headcuts where the characteristics of the impinging jet and the height of the sediment deposit downstream of the scour hole are time dependent.

The asymptotic depth of scour below a headcut depends on upstream and downstream boundary conditions, the characteristics of the impinging jet, and the erodibility of the sediment (see section 1). For the runs presented here the upstream boundary conditions and soil material were nearly identical, but the characteristics of the jet and the downstream boundary condition, namely, jet entry angle and tailwater height, respectively, were not. As initial headcut height increased, the tailwater height decreased, and the jet entry angle and asymptotic scour hole depth increased.

4.2. Evolution of Bed Microtopography

On the basis of information presented here and elsewhere, there are two important parameters that determine the growth and evolution of headcut scour holes and hence soil losses in upland concentrated flows: (1) the time and length scales required for headcut development and (2) the adjustment of headcut dimensions to discharge, slope, and soil materials. The formation of microstep headcuts and their enlargement during upstream migration is commonly observed in rill erosion studies [e.g., *Bryan and Poesen*, 1989; *Bryan*, 1990; *Bryan and Oostwouud Wijdenes*, 1992]. As long as flow discharge, bed slope, and sediment characteristics remain the same during headcut migration, there is a strong relationship between the height of an initial headcut and the time and length required to reach steady state conditions (Figure 3). Such constancy is possible in field situations but over small spatial and temporal scales.

A migrating headcut is more likely to encounter a decrease in flow discharge and changes in bed slope or material char-

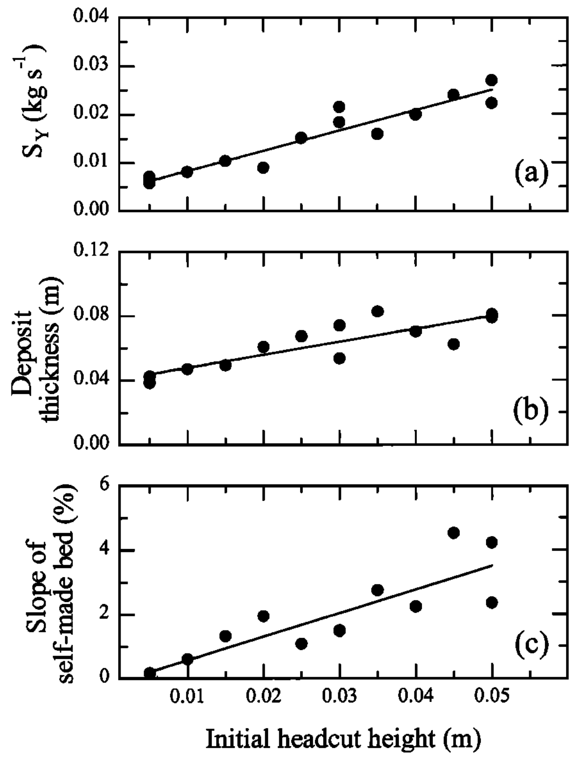

Figure 6. Variation of steady state sediment transport parameters with initial headcut height. Shown are (a) sediment yield (R = 0.95; PW = 1.0; using α = 0.05 and P = 0.001), (b) deposit thickness (R = 0.85; PW = 0.98), and (c) slope of self-made bed (R = 0.84; PW = 0.96).

acteristics or both. *Parker* [1977] and *Begin et al.* [1980a, 1980b] observed a reduction in the size and rate of migration of knickpoints as they progressed upstream in response to a decrease in basin area (discharge). *Bennett et al.* [2000] observed a systematic decrease in the size of headcuts as flow discharge decreased. For upland areas susceptible to headcut development a polymodal distribution of headcut sizes, shapes, and migration rates would be expected on a landscape as a result of microsteps growing and adjusting to flow discharge, bed slope, and soil material characteristics.

5. Conclusions

The present study sought to extend an existing experimental methodology by examining, for a given slope, overland flow discharge and, for a given soil, the effect of initial step height on headcut growth and development, steady state scour hole dimensions, migration rate, and sediment yield. Although steady state headcut erosion conditions were observed in each experiment, the time and length required reaching this state decreased as the initial headcut height became larger. Smaller initial step heights caused the formation of progressively smaller headcuts with lower sediment yields, thinner sediment deposits, shallower jet entry angles, and lower bed slopes of the sediment deposit as compared to larger initial headcut heights. These effects were controlled by a relatively higher tailwater height that decreased the erosivity of the impinging jet, thereby limiting the depth of scour. In comparison to the packed soil bed, the sediment yield was enriched in silt and clay and depleted in sand, and the sediment deposited downstream of the headcut was enriched in sand and depleted in silt and clay. The sediment deposit had a lower bulk density than the packed soil bed because it had a higher porosity owing to sand enrichment, and silt and clay were deposited in aggregate form. These results provide additional information useful in developing soil erosion prediction technology and for the evolution of bed microtopography in upland areas susceptible to headcut erosion.

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