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Impact of upstream sediment inflow on headcut morphodynamics

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Abstract: Headcut erosion can severely accelerate soil loss in upland concentrated flows and lead to significant soil degradation in agricultural areas. Previous experimental work has demonstrated that actively migrating headcuts display systematic morphodynamic behavior, and impinging jet theory can provide an excellent theoretical foundation for this erosional phenomenon. This research sought to examine systematically the effect of an upstream sediment inflow on the morphodynamics of actively migrating headcuts in upland concentrated flows. Using a specially designed experimental facility, actively migrating headcuts were allowed to develop, and then subjected to an upstream sediment load composed of sand. As the upstream sediment feed rate increased, the size and migration rate of the headcut decreased markedly, but sediment discharge was less affected. The headcut erosion process was arrested as sediment inflow rates increased above a threshold value. As sediment feed rate upstream of the headcut increased, sediment size fraction downstream of the headcut also increased. This research suggests that headcut erosion can be greatly modulated by an upstream sediment source, further complicating the prediction of soil erosion on upland areas.

Keywords: headcuts, overland flow, simulated rainfall, soil erosion

Introduction

An experimental program was initiated to examine actively migrating headcuts in concentrated flows and to address this soil erosion phenomenon in mechanistic terms. To date this research has documented the following observations: (1) steady-state soil erosion can be achieved under specific conditions; (2) larger scour holes are associated with higher overland flow rates, higher bed slopes, and larger initial step heights; (3) the presence of a non-erodible layer reduces scour depths, nappe entry angles, and sediment discharges; (4) higher tailwater heights downstream of the headcut lead to an immediate cessation of the soil erosion process; and (5) varying subsurface pore-water pressures can either enhance or suppress the headcut erosion process (Bennett 1999, Bennett et al. 2000, Bennett & Casalí 2001, Gordon et al. 2007, Wells et al. 2009a, b).

These observations were made using clear-water flow as the upstream boundary condition. It is well known that the presence of sediment in transport within upland concentrated flows can markedly affect flow hydraulics and flow resistance (Li & Abrahams 1997). The goal of this research was to systematically examine the effect of upstream sediment inflow on the morphodynamics of actively migrating headcuts in upland concentrated flows.

Methods

The present study consisted of 14 experiments: 2 clear-water (baseline) runs, and 12 runs with an upstream sediment feed. Six sediment (0.35-mm median grain size) inflow rates were imposed based on the observed sediment discharge rate Q_s for the baseline experiments ($0.2Q_s$, $0.4Q_s$, $0.6Q_s$, $0.8Q_s$, $1.0Q_s$, and $1.2Q_s$), and each sediment-feed experiment was replicated. All experiments were conducted in a 5.5-m long and 0.165-m wide non-recirculating, tilting hydraulic flume. This facility and the procedures employed to apply rainfall and monitor water surface heights, runoff, and headcut erosion processes were described in detail by Wells et al. (2009a, b).

The soil used in the present study was an Atwood sandy clay loam (*fine-silty, mixed, thermic Typic Paleudalfs*) with 72% sand, 11% silt, and 17% clay. The median grain size of the sand fraction within the Atwood soil is 0.25 mm in diameter. Water and sediment exiting the soil cavity were captured in 0.5-L glass bottles at 10-s intervals for the first 3 minutes then 20-s intervals thereafter. Sediment samples were weighed and placed in an oven at 40.5°C for 24 hr, then reweighed to determine sediment concentration.

The dry sediment samples were sieved to determine the percent mass of size for each of the following size fractions (all diameters in mm): coarser than 0.5, 0.354, 0.25, 0.178, 0.125, 0.088, 0.063, and less than 0.063 (pan remains). These fractions were combined into the following particle size bins: medium sand (coarser than 0.354 mm), fine sand (0.178 to 0.354 mm), very fine sand (0.063 to 0.178 mm), and silt and clay (finer than 0.063 mm).

Results

Initial headcut growth and development occurred at the imposed step-change in bed surface topography. Following an initial period of bed adjustment, steady-state erosion conditions were achieved: a headcut migrated upstream at a nearly constant rate and shape, and the sediment discharge exiting the flume was also nearly invariant. Approximately 120 s after the development of an actively migrating headcut, sediment feed was initiated.

It was observed that the headcut migration rate (M) slowed, the maximum scour depth (S_D) decreased, and the jet entry angle ($\grave{e}_e$) decreased (Table 1). For sediment feed rates of $0.8Q_s$ and higher, the actively migrating headcut was completely obliterated given enough time and space. That is, as the upstream sediment feed rate approached the sediment efflux generated through headcut scour and migration, the headcut itself ceased to exist.

Two additional points are contended here. First, sediment influx of $0.2Q_s$ and smaller had no effect on headcut morphodynamics. For relatively small sediment influxes, it is suggested that these flows were detachment capacity-limited, and these loadings, therefore, were of little consequence to the overland flow hydraulics and scour pool hydrodynamics. Second, sediment influxes of $0.4Q_s$ and higher would result in the slowing or cessation of headcut migration under the slope and overland flow discharge conditions imposed in these experiments.

The time variation of sediment discharge did not mirror the morphodynamic behavior of the headcuts. Following the initial bed adjustment and head-

Table 1. Summary of experimental parameters: M (migration rate), S_D (maximum scour depth), θ_e (nappe entry angle), and Q_s (sediment discharge) were determined prior to sediment addition

Run	Sediment Influx	ρ_s	Q	M	S_D	θ_e	Q_s
Units	kg s^{-1}	kg m^{-3}	m^3 s^{-1}	mm s^{-1}	m	deg	kg s^{-1}
Baseline	0	1288	0.00114	2.4	0.092	58	0.0223
Baseline	0	1265	0.00120	2.3	0.089	43	0.0144
$0.2Q_s$	0.0047	1307	0.00116	1.9	0.096	47	0.0254
$0.2Q_s$	0.0047	1296	0.00119	1.7	0.096	49	0.0227
$0.2Q_s$	0.0047	1331	0.00112	1.9	0.091	47	0.0223
$0.4Q_s$	0.0094	1339	0.00109	2.8	0.087	41	0.0278
$0.4Q_s$	0.0094	1337	0.00114	2.8	0.085	43	0.0229
$0.6Q_s$	0.0142	1339	0.00116[1]	2.7	0.076	42	0.0234
$0.6Q_s$	0.0142	1339	0.00116	2.6	0.085	45	0.0227
$0.8Q_s$	0.0189	1327	0.00110	2.8	0.084	45	0.0316
$0.8Q_s$	0.0189	1270	0.00122	2.8	0.086	42	0.0217
$1.0Q_s$	0.0236	1345	0.00112	2.9	0.079	46	0.0345
$1.0Q_s$	0.0236	1759	0.00114	3.0	0.081	42	0.0210
$1.2Q_s$	0.0283	1325	0.00115	2.5	0.088	40	0.0326
$1.2Q_s$	0.0283	1351	0.00116	2.8	0.092	41	0.0235

[1]since Q is not available, a value of 0.00116 m^3 s^{-1} is adopted here

cut growth and development, all Q_s data show an asymptotic decline with time. While M, S_D, and $è_e$ all decline with time for sediment influxes of $0.4Q_s$ and higher, no such changes were noted in the Q_s data. That is, while the actively migrating headcuts became smaller with time, or in some cases ceased to exist, the sediment discharge rates remained nearly invariant with time and fairly constant amongst the experiments.The texture of the sediment efflux within the experiments, however, was affected by the sediment influx. The texture of the sediment efflux for the baseline experiment was dominated by the fine sand fraction since this fraction dominates the composition of the soil material, and no discernable time variation in texture was observed in the mass fractions of Q_s for the baseline experiment. Similar textural composition and time variation was observed for the $0.2Q_s$ experiment. Yet as the sediment influx increased above this value, a marked shift occurred in the texture of the sediment efflux. The mass fraction of medium sand increased with time and the fine and very fine sand and silt and clay fractions decreased with time.

Conclusions

Research has focused on quantifying the morphodynamics of soil erosion due to headcut migration on unconstrained hillslopes and agricultural fields. This study sought to examine the effect of upstream sediment inflow on the growth and migration of headcuts in concentrated flows. Clear-water experiments result in steady-state soil erosion wherein a headcut develops and enlarges due to the imposed flow rate, but attains a constant rate of migration, shape, and sediment discharge as a function of time. As the sediment inflow rate of fine sand increases above a certain threshold, the size and migration rate of the headcut decrease markedly, thus arresting local soil erosion. Sediment discharge, in turn, shifts from headcut-controlled flux to sediment-feed flux. The progressive obliteration of the headcut pool demonstrates that headcut migration is greatly modulated by upstream sand inflow, which renders inadequate the use of steady-state, algebraic models. Thus, more comprehensive headcut-erosion predictors are needed that treat this phenomenon as an initial, boundary-value problem solved with fast numerical engines.

References

Bennett S.J., 1999. Effect of slope on the growth and migration of headcuts in rills. *Geomorphology* 30: 273–290.

Bennett S.J., Alonso C.V., Prasad S.N. & Römkens M.J.M., 2000. Experiments on headcut growth and migration in concentrated flows typical of upland areas. *Water Resour. Res.* 36: 1911–1922.

Bennett S.J. & Casalí J., 2001. Effect of initial step height on headcut development in upland concentrated flows. *Water Resour. Res.* 37: 1475–1484.

Gordon L.M., Bennett S.J., Wells R.R. & Alonso, C.V., 2007. Effect of soil stratification on the development and migration of headcuts in upland concentrated flows. *Water Resour. Res.* 43:

Li G. & Abrahams A.D., 1997. Effect of saltating sediment load on the determination of the mean velocity of overland flow. *Water Resourc. Res*. 33: 341–347.

Wells R.R., Alonso C.V. & Bennett S.J., 2009a. Morphodynamics of headcut development and soil erosion in upland concentrated flows. *Soil Sci. Soc. Am. J.*, 73 (2): 521–530.

Wells R.R., Bennett S.J. & Alonso C.V., 2009b. Effect of soil texture, tailwater height, and pore-water pressure on the morphodynamics of migrating headcuts in upland concentrated flows. *Earth Surf. Proc. Landf.* 34: 1867–1877.