EPHEMERAL GULLY HEADCUT DEVELOPMENT AND MIGRATION IN STRATIFIED SOILS

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1. Introduction

Headcuts and knickpoints are step-changes in bed surface elevation where intense, localized erosion takes place. In upland concentrated flows such as rills, crop furrows, and ephemeral gullies, the formation of headcuts and their upstream migration have been linked to the concentration of overland flow, rill and gully development, and significant increases in sediment yield (see review and discussion in Bennett et al., 2000).

On natural landscapes and especially where ephemeral gullies are prevalent, soils display a clear stratification with depth. Due to cultivation and/or the presence of a fragipan, a resistant layer is often present at depth within the soil profile.

The objectives of the current study were: (1) to quantify the effect of an erosion resistant (ER) soil layer placed at various depths within a soil profile on headcut development and migration; and (2) to assess the effects of this ER layer on analytic formulations for headcut erosion based on jet impingement theory.

2. Experimental Equipment and Procedure

A tilting, non-recirculating flume (see Bennett et al., 2000) was used. A multiple intensity rainfall simulator was suspended above the flume. A sandy clay loam, comprised on average of 28% clay, 15% silt, and 57% sand, dried and sieved at 2 mm, was packed incrementally in ~2 cm layers at an average bulk density of 1538 kg m^{-3}. During bed preparation, when the target depth for the ER layer was reached, the soil surface was subjected to 300 s of simulated rain at 21 mm hr-1. This rainfall application and the packing of subsequent soil layers created a resistant layer at the prescribed depth for each experimental run. While packing the uppermost layers, an aluminum plate was installed to create a 3 cm vertical step (headcut) near the downstream end of the flume.

After soil bed preparation, 5 hr of simulated rainfall at 21 mm hr^{-1} was applied to the material at a bed slope of 5%. This rainfall created a thin, pliable soil surface seal. A subsurface drainage system prevented the development of a perched water table. At the conclusion of the 5 hr simulated rainstorm, the headcut forming plate was removed, the slope of the flume was adjusted to 1%, and an overland flow rate of 71.0 L min^{-1} was immediately released onto the soil material. As flow passed over the pre-formed step, a two-dimensional plane jet impinged the bed downstream causing surface seal failure within 10 to 20 s. Once seal failure occurred, a scour hole began to enlarge that was modulated by the presence of the ER layer (Figs. 1 and 2). The ER layer was never eroded by the impinging jet. Headcut migration began after about 30s.

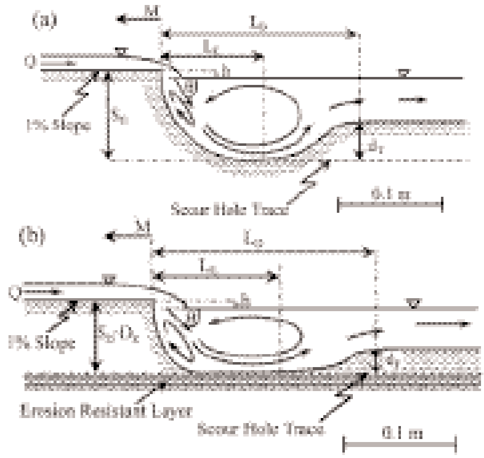

Fig. 1. Definition diagrams of water and bed surface profiles of steady state headcuts digitized directly from video images of (a) Run 1 with no ER layer and (b) Run 6 with an ER layer (D_R = 0.055 m)

3. Results

3.1. Steady State Erosion

As shown in the time-series plots of headcut scour depth S_D (Fig. 2), headcut brinkpoint position (Fig. 3a), and sediment discharge q_s (Fig. 3b), there is a time period when steady-state erosion is achieved. That is, a point in time is reached when an actively migrating headcut of similar form and sediment discharge translates upstream at a constant rate. The time and distance needed to reach steady-state erosion conditions were entirely controlled by that point in time and space when the bottom of the scour hole encounters the ER layer.

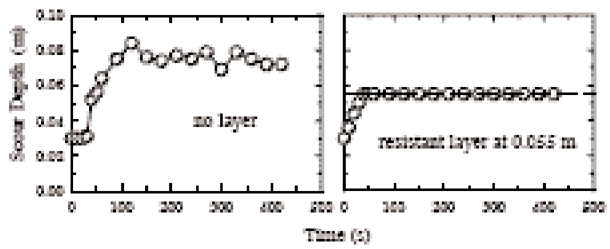

Fig. 2. Time variation in maximum scour depth.

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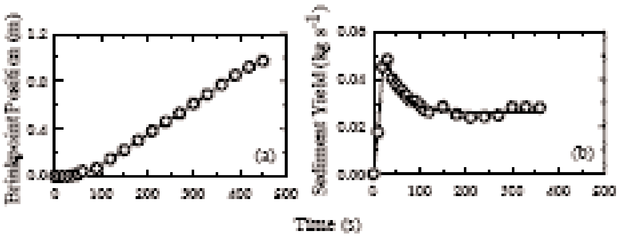

Fig. 3. Typical time variation in (a) headcut brinkpoint position and (b) sediment yield for ER layer depth = 0.055 m.

3.2 Sediment Sorting and Deposition

As the scour hole enlarges, the majority of detached sediment is transported out of the flume, sediment discharge is initially high, and the flow regime is capacitylimited. As deposition is initiated and sediment discharge approaches a steady-state condition, the flow transformed into a transport-limited regime. This transition is reflected in the textural composition of the sediment discharge, which shows that, in general, the amount of sand exiting the flume decreased with time whereas the amount of silt and clay increased with time

3.3 Effect of ER Layer Depth on Steady-State Parameters

As the depth of scour increased, or as the depth to the erosion resistant layer increased, both sediment discharge q_s (Fig. 4a) and the thickness of the downstream deposit d_T (Fig. 4b) increased significantly. Yet these deeper and more erosive headcut scour holes did not migrate at a different rate *M* (Fig. 4c). Thus, the higher sediment effluxes from the migrating headcuts were primarily due to the increased scour hole depth, as modulated by thicker downstream sediment deposits.

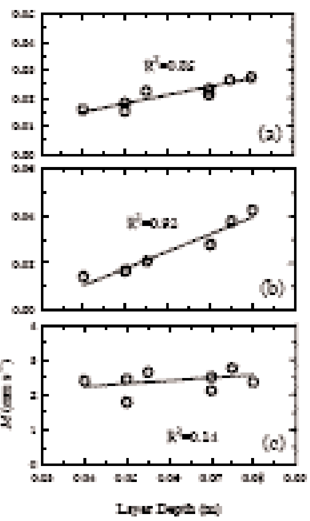

Fig. 4. Variation of steady-state soil erosion parameters as a function of the ER layer depth (steady-state scour depth S_D, m). Shown are (a) sediment discharge q_s, (b) headcut migration rate *M*, and (c) deposit thickness d_T.

4. Discussion

4.1. Comparison to an Analytic Model of Headcut Erosion

Using previous results of experiments involving headcuts in homogeneous soil materials, Alonso et al. [2002] derived predictive equations for the magnitude of headcut scour and the rate of headcut migration based on modified jet impingement theory. Alonso et al.'s (2002) model was used to predict the jet entry angle θ (Fig. 5a) and headcut migration rate *M* (Fig. 5b) in these stratified soils. Finally, the predicted erosion and deposition were compared with the measured sediment discharge at the flume outlet and this mass-balance comparison resulted in excellent agreement (Fig. 5cTime (s))

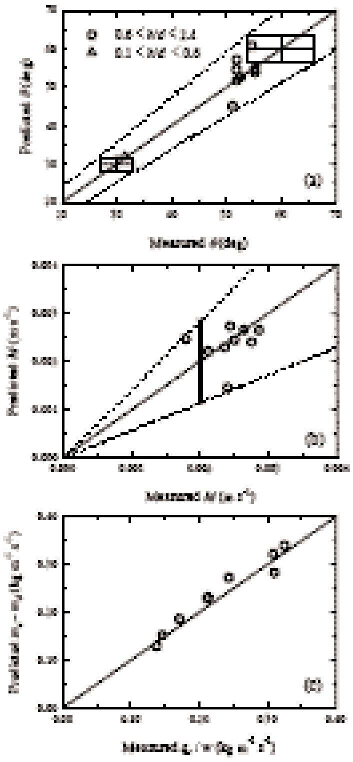

Figure 5. Comparison of (a) jet entry angle θ, (b) headcut migration rate *M*, and (c) the rate of sediment erosion m_e minus deposition m_d as computed using Alonso et al. (2002) versus measured values. The dotted lines represent the mean uncertainty range.

5. Conclusions

Mechanized tillage practices decrease significantly erodibility indices of the surface soil and arbitrarily create a non-tilled layer at depth which is often much less erodible than the overlying material. An experimental program was designed to examine the effects of an erosion resistant (ER) layer placed at depth on the growth and development of headcuts at the time and space scales of rills and ephemeral gullies.

When the ER layer was placed at or above the potential scour depth (verified by baseline runs), headcuts were limited in depth to this layer, and while their migration rates remained about the same, total sediment efflux was markedly reduced. These experimental observations were successfully compared to analytic expressions for jet entry angle, scour depth, migration rate, and sediment mass balance for headcuts in upland concentrated flows.

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References

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