TURBULENT FLOW WITHIN HEADCUT SCOUR HOLES IN RILLS AND GULLIES

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1. Introduction

Soil erosion remains the principle cause of soil degradation worldwide, and off-site impacts of sedimentation can severely affect water quality, ecology, and ecological habitat (e.g., Pimentel et al., 1995). On hillslopes and agricultural fields, soil erosion occurs in areas of concentrated flow such as rills, crop furrows, and gullies. Within these relatively small channels, localized erosion often occurs due to the development and upstream migration of headcuts, which are abrupt step-changes in bed elevation (see Bennett et al., 2000). The development and migration of headcuts can significantly increase soil losses and sediment yields (see Bennett et al., 2000).

Recent analytical models for headcut erosion in soils have utilized elements of jet impingement theory (e.g., Stein et al., 1993). In these studies, flow at the headcut brinkpoint and in the scour hole domain, as well as erosion of the soil, all were treated explicitly as an impinging jet and associated wall jets that would act on the erodible boundary. This hypothesis has been further supported by the experiments of Bennett et al. (2000) and the analysis of Alonso et al. (2002), who showed that the plunge pools of actively migrating headcuts have turbulent flow patterns resembling an impinging jet. However, little information exists on the turbulent flow structure within headcut scour holes, and whether such analytic treatments are justified.

The objectives of the present study were to experimentally determine the time-mean turbulent flow characteristics within fixed-bed models of headcut scour holes typical of upland concentrated flows and to assess soil erosion mechanisms within the scour hole domain.

2. Experimental Methods

All experiments were conducted using a recirculating 5.5-m long tilting flume. The main flow channel was 2 m long and 0.165 m wide.

Two wooden models of headcut scour holes were placed into the flume. These forms were replicated from previous live-bed experiments using a sandy loam to sandy clay loam soil. The first headcut form (Model 1) is an exact replica of the time-averaged, steady-state bed profile of Run 9 from Bennett et al. (2000), representing the nonventilated, nearly submerged overfall. For the fixed-bed experiment, bed slope was 1% and unit discharge was 0.0071 m^2 s^{-1}. The second headcut form (Model 2), an exact replica of the instantaneous bed profile from Run 5 of Bennett (1999), represents the partially ventilated, free overfall. For this fixed-bed experiment, bed slope was 5% and unit discharge was 0.0052 m^2 s^{-1}.

Velocity measurements were obtained with a 300 mW Argon-ion laser Doppler anemometer (LDA). The LDA was operated in back-scatter mode using a 400 mm focal-length lens and a velocity resolution of 0.5 mm s^{-1}. Flow velocities were recorded on the flume axial plane of symmetry in the directions parallel and perpendicular to the flume slope, designated as u_i and v_i, their at-a-point time-averaged values designated as u and v, and their turbulent fluctuations designated as $u' = u_i - u$ and $v' = v_i - v$, respectively. Velocities were measured for periods up 120 s, spaced approximately 1 to 2 mm vertically and 5 mm horizontally with data rates exceeding 100 Hz.

3. Results

Streamlines based on time-averaged flow vectors within the headcut scour hole models are shown in Figure 1. The overfall nappe enters the scour pool domain and creates a core of high-velocity fluid that extends toward the bed. This high-velocity core is deflected by the scour hole curvature and remains in close proximity to the bed, achieving uniform flow conditions upon exiting the measuring section. Two relatively large recirculation zones occur on both sides of the high-velocity core.

Figure 1 demonstrates that flow within headcut scour holes typical of upland concentrated flows is a turbulent reattached wall jet. For turbulent impinging jets, the free jet axis (or high-velocity core) extends completely to the boundary, creating a point of stagnation and flow deflection (e.g., Beltaos and Rajaratnam, 1973). In contrast, the point of reattachment in the present cases, as determined from the vector data, corresponds to the upper boundary of the recirculation zone delimited by the scour hole and the free jet. Turbulent reattached wall jets, as discussed by Rajaratnam and Subramanya (1968) and shown here, have an elongated impingement zone downstream of flow reattachment, where flow evolves into a plane turbulent wall jet.

Contour plots of select turbulence parameters for headcut Model 1 are shown in Figure 2. Relatively higher turbulence intensities are associated with the free jet upon entry to the scour hole domain. Maximum values of the root-mean-square of the downstream velocity component u_{rms} ($u_{rms} = \sqrt{\overline{u'^2}}$ where the overbar represents a time-average) occur along the upper part of the free jet, in association with the shear layer separating the submerged

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jet and the downstream recirculation eddy. Conversely, maximum values of v_{rms} ($v_{rms} = \sqrt{\overline{v'^2}}$) occur along the lower part of the free jet, in association with the shear layer separating the submerged jet and the recirculation eddy near the headcut face (Fig. 2). Secondary maxima for both parameters occur within or near the large recirculation zone downstream of the jet. Maximum values of positive Reynolds stress τ ($\tau = -\rho\overline{u'v'}$ where ρ is fluid density) are in close spatial association with the upper shear layer of the submerged jet and near flow reattachment (Fig. 2). Large, positive τ values also dominate the free jet region of the scour hole domain and downstream of flow reattachment. Similar distributions of these turbulence parameters were obtained for headcut Model 2.

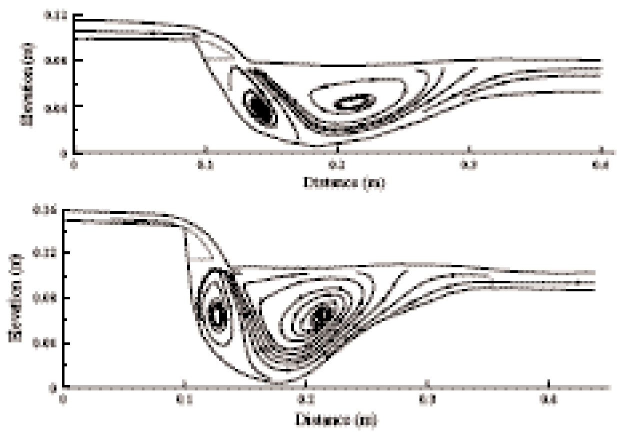

Fig. 1. Flow fields (streamlines) within headcut Model 1 (upper) and Model 2 (lower). Solid lines show water surface and bed profiles.

4. Discussion and Conclusions

In upland concentrated flows, the development and upstream migration of headcuts can significantly increase soil losses, sediment yields, and landscape degradation. Velocity data and streamlines show unequivocally that flow within headcut scour holes is analogous to a reattached plane turbulent wall jet. The overfall nappe entering the scour hole domain evolves into a free jet, with flow reattachment occurring just upstream of the maximum scour depth. Recirculation zones bound the free jet region, and the deflected flow downstream of impingement evolves into a classical wall jet. Maxima for turbulence and Reynolds stress occur along the shear layers of the free jet, near reattachment, and within the recirculation eddies.

Within headcut scour holes, three hydrodynamic mechanisms are responsible for soil erosion. These are: (1) high shear stresses due to large near-bed velocity gradients (e.g., Rajaratnam and Subramanya, 1968); (2) high near-bed Reynolds stresses due to turbulent fluctuations in velocity (Fig. 2); and (3) large wall pressure gradients near flow reattachment (e.g., Bennett and Alonso, 2006).

This study provides experimental confirmation of the turbulent flow structure within headcut scour holes typical of upland areas. Such erosional phenomena can be treated hydrodynamically as plane reattached wall jets. This conclusion enables the further development and application of jet impingement theory for predicting soil erosion processes in rills, crop furrows, and ephemeral gullies.

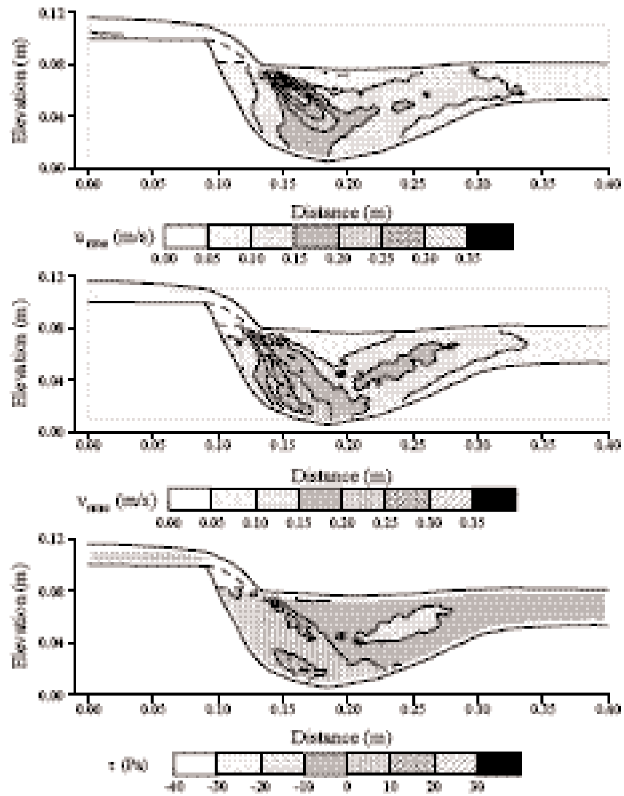

Fig. 2. Contour plots of the root-mean-square of the downstream (upper) and vertical (middle) velocity components and Reynolds stress (lower) for headcut Model 1.

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