IMPACT OF NON-ERODIBLE LAYER ON EPHEMERAL GULLY DEVELOPMENT

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Abstract: As headcut erosion accelerates, the formation of ephemeral gullies can significantly increase the loss of topsoil and decrease the productivity of agricultural lands. Ephemeral gullies are erosional features, usually larger than rills, caused by concentrated flow that may be erased by normal tillage practices. Most researchers agree that a critical or threshold level of concentrated flow is required to initiate ephemeral gullies and once initiated, there is positive feedback between flow and erosion. The location and size of ephemeral gullies is controlled by the generation of concentrated surface erosion of sufficient magnitude and duration to initiate and sustain erosion for a particular soil. Once formed, ephemeral gullies tend to rejuvenate near or in the same location from year to year. Experiments were conducted to examine the effect of a non-erodible layer on growth, development, and upstream migration of headcuts typical in ephemeral gullies. During migration, the depth of the non-erodible layer impacted sediment yield and rate of upstream advance.

INTRODUCTION

Mildner (1983) presented a convenient working definition for ephemeral gullies as being "*usually larger than rills, occurring and recurring in depositional areas, forming a dendritic pattern unless another pattern is imposed by row alignment, and being partially or totally erased and filled in by normal tillage operations without the need for special equipment*." As pointed out by Thorne *et al.* (1986), this definition is dependent on farming practice and equipment, not environmental considerations, and is morphologically incomplete as to form, shape and size. Classifications merely focus our attention on a particular erosion form and, therefore, clarify the boundary conditions under consideration for a particular erosion feature. Poesen (1993) addressed the concerns of Thorne *et al.* (1986) by distinguishing ephemeral gullies based on a critical cross-sectional area criterion and Nachtergaele *et al.* (2002) used a mean width criterion; others have made similar distinctions based upon minimum depth and/or minimum width criteria.

Most researchers agree that a critical or threshold level of concentrated flow is required to initiate ephemeral gullies and once initiated, there is positive feedback between flow and erosion. In addition, most agree that the location and size of ephemeral gullies are controlled by the generation of concentrated surface erosion of sufficient magnitude and duration to initiate and sustain soil erosion. Logically, once initiated, surface flow becomes increasingly channelized and more flow leads to increased erosive power and further enlargement.

The photographs in Figure 1 depict classical forms of ephemeral gullies. In both figures, note the practice of contour farming. Concentrated flow in the furrows converge, flow tops the downhill furrow, and creates a cascade of water downslope, which leads to ephemeral gully development.

Figure 1 Photos of ephemeral gullies during the growing (top) and non-growing (bottom) season**.**

Smith (1993) identified four critical parameters of ephemeral gully development: (1) a critical slope length and gradient dependent upon slope characteristics and crop row direction, (2) occurrence and depth of a fragipan, (3) agricultural practices, such as crop row direction and timing of cultivation, and (4) timing and total amount of precipitation. Thorne (1984) suggests there are three requirements for the ephemeral gully development: (1) concentrated surface runoff, (2) erosion initiation, and (3) channelization. Both agree that it is not just the magnitude and duration of a storm that determines whether surface runoff is generated from a field, but also, the sequence of storms preceding and the timing in relation to the growing season.

Bennett (1999), Bennett *et al.*(2000), and Bennett and Casali (2001) reported experimental data showing that actively migrating ephemeral-gully headcuts display steady-state migration and self-similar organization in the absence of hardpans and upstream sediment supply. Alonso *et al.* (2002) combined jet impingement theory and conservation laws to predict soil losses due to headcut erosion and migration. Headcut erosion and migration rates were shown to depend on upstream flow depth and discharge, tailwater depth, and soil and fluid properties.

In this paper, the authors discuss laboratory experiments designed to examine the impact of a non-erodible layer on ephemeral gully development and migration, and discuss the impacts on morphology, migration rate and sediment yield.

MATERIALS AND METHODS

Using a constant bed slope (1%), initial headcut height (30 mm) and flow rate (71 l sec^{-1}), the impact of a constructed non-erodible layer at depths of 40 mm, 50 mm and 70 mm was examined. All experiments were conducted at the USDA-ARS National Sedimentation Laboratory in Oxford, MS using a tilting flume, designed for soil erosion studies, and simulated rainstorms of uniform intensity (21 mm h^{-1}). One run was performed in which no non-erodible layer was constructed to replicate the work of Bennett *et al.* (2000) and will be referred to as the baseline case in this paper.

Headcut Flume: A non-recirculating, 5.5 m tilting flume (Figure 2) was used to examine soil erosion processes associated with migrating headcuts. The flume was comprised of four compartments: inflow tank, false floor (1 m long and 0.165 m wide), soil cavity (2 m long, 0.165 m wide, and 0.25 m deep), and outflow pipe. A large reservoir was used to provide water for the inflow tank upstream of the false floor. Flow discharge was controlled by two adjustable intake valves and monitored with a point gage during experiments. A subsurface drainage system was installed along the base of the soil cavity and provided escape routes for both air and water during rainfall application.

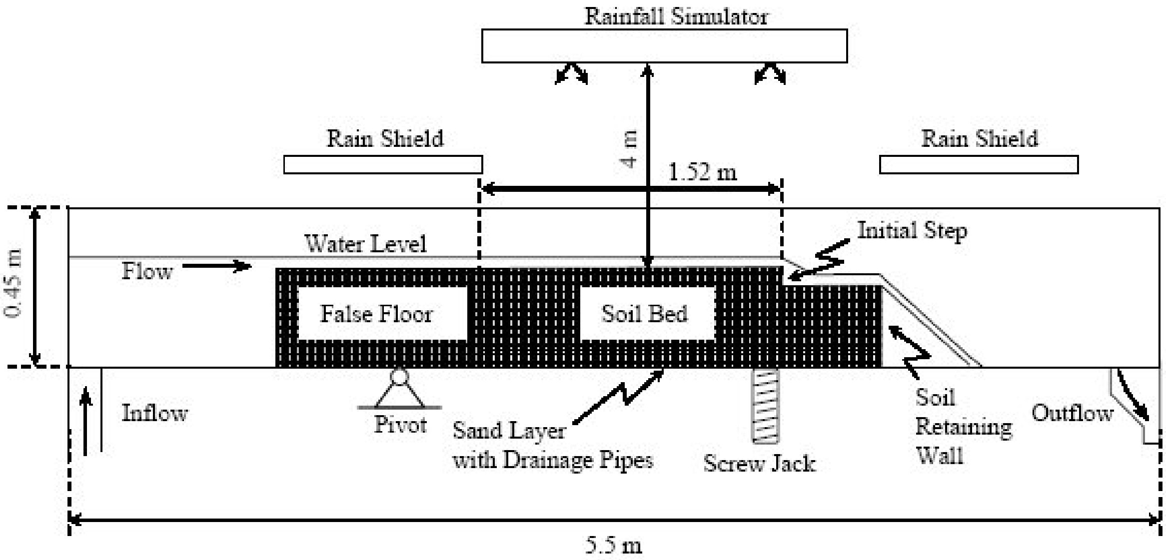

Figure 2 Schematic of headcut flume located at the USDA-ARS-NSL in Oxford, MS (Bennett *et al.*, 2000).

Soil and Step Plate: The soil used in the headcut experiments was a sandy loam to sandy clay loam textured soil (Ruston Series; fine-loamy, siliceous, thermic, Typic Paleudult; (Römkens *et al.*, 1997)), commonly found in the southeastern U.S. The soil consisted of 20.0% clay, 2.9% silt, and 77.1% sand. An appreciable amount of iron oxide in the soil greatly enhanced its stability (Rhoton *et al.*, 1998).

The soil was collected from a field site in Neshoba County, MS near Philadelphia in cooperation with the Natural Resources Conservation Service extension office. Following transport back to the laboratory, the soil was air dried, mechanically crushed, and passed through a 2 mm sieve.

Soil was packed incrementally in layers of about 0.02 m using a drop-weight of aluminum mounted to an aluminum frame, constructing uniformly packed soil beds with bulk densities ranging from 1403 to 1557 kg m^{-3}.

At depth, a non-erodible layer was constructed by subjecting a partially packed soil sample at 1% slope to a 21 mm h^{-1} rainstorm for 45 min, sprinkling sieved soil material (125 µm) on the surface and repacking the layer. Additional layers were packed incrementally to the preformed step depth (30 mm below the surface of the false floor). An aluminum frame with a 30 mm vertical face was placed 1.72 m downstream of the soil cavity entrance for the purpose of forming a headcut. After installation, soil was packed upstream of the frame producing a preformed vertical step in the bed profile. The soil material within the uppermost 0.02 m was treated with 0.75 cmol of $Ca(OH)^2$ per 100 g of soil (about 0.74 g per 1 kg of soil) to promote a physiochemically favorable condition for seal development (Römkens et al., 1995, 1997).

At 2 hour intervals during rainfall application, rainfall was interrupted for 5 minutes, additional sieved soil material (125 µm) was sprinkled across the surface and rainfall application was resumed. The additional sieved soil material was used to enhance surface seal formation.

Rainfall Simulation A multiple-intensity rainfall simulator consisting of two oscillating nozzles spaced 1.64 m apart (Meyer and Harmon, 1979; Figure 2) was suspended approximately 4 m above the flume. With the bed prepared and headcut-forming plate installed, a rainfall intensity of 21 mm h^{-1} was applied for 6 h to a bed slope of 5%. Following the application of simulated rain, a well-developed and reproducible surface seal formed.

Data Acquisition The soil cavity of the tilting flume contained a plexiglass wall which had a superimposed grid system allowing for visual observation of many morphologic and hydraulic parameters. A video camera mounted on a tripod during rainfall application and to a movable carriage during overland flow recorded each experimental run. From these images, the following information could be determined with sufficient accuracy: position and morphology of the headcut, overland flow depth, and angle of the overfall nappe. Upstream flow depth was monitored with a point gage and was in agreement with video recordings.

RESULTS AND DISCUSSION

Headcut Migration: As overland flow passed over the preformed step, flow impinged the surface seal just downstream of the step. The impinging overfall caused surface seal failure and soil erosion, initially migrating downstream, followed by scour hole development and upstream migration. After an initial period of scour hole development, scour hole length (horizontal length from brinkpoint to maximum scour depth) was dependent upon depth to the non-erodible layer (Figure 3). In each case, a headcut of similar geometry migrated upstream at a constant velocity, producing both a constant rate of sediment yield and a constant rate of sediment deposition in the downstream portion of the flume; however, the base of the scour hole was elongated and flattened due to the presence of the non-erodible layer. Figure 3D shows the characteristic shape of the scour hole for the baseline case, where no non-erodible layer was constructed, which was similar to experimental results reported by Bennett *et al.*, 2000.

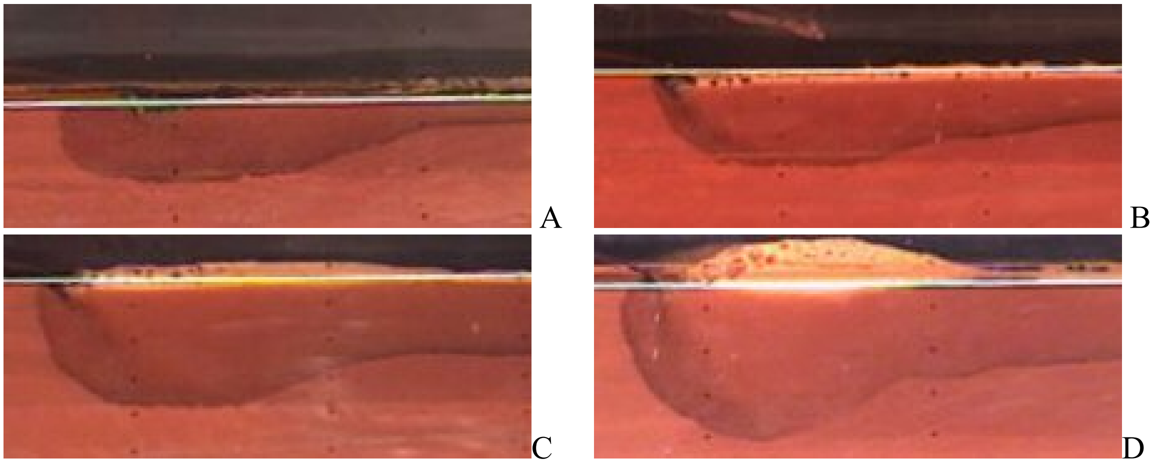

Figure 3 Photos of headcut geometry for (A) 40 mm layer, (B) 50 mm layer, (C) 70 mm and (D) baseline case.

After an initial period of growth, the headcut brinkpoint migrated upstream in a gradual and linear fashion in time (Figure 4). Headcut migration was constant in each case, ranging from 2.37 mm sec^{-1} to 2.86 mm sec^{-1}. The run in which the non-erodible layer was located 50 mm below the surface migrated at a reduced rate in comparison to other depths. The run in which the non-erodible layer was located 40 mm below the surface migrated upstream at an increased rate of 17% and 8.4% in comparison to the 50 mm or 70 mm depths. There was a 4% increase in migration rate when comparing the 40 mm run to the baseline case.

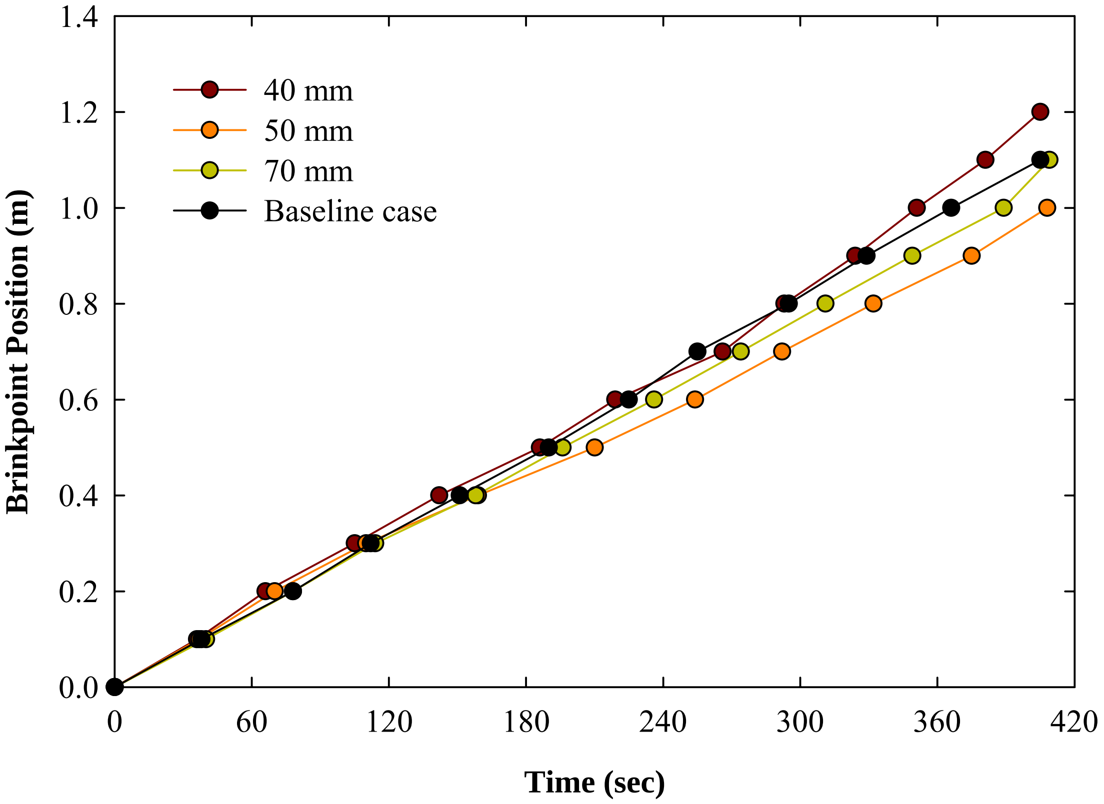

Figure 4 Time variation of headcut brinkpoint position for each run.

Sediment Yield: Water and sediment samples were collected at the outlet pipe (Figure 2) at 10 sec intervals until the headcut stabilized, and then sampling was reduced to 30 sec intervals. Sediment production increased rapidly after overland flow reached the preformed step and soil erosion was initiated. Peak sediment concentration coincided with upstream migration of the headcut and downstream deposition of eroded sediments. After this initial peak, sediment concentrations were reduced as the headcut migrated upstream (Figure 5).

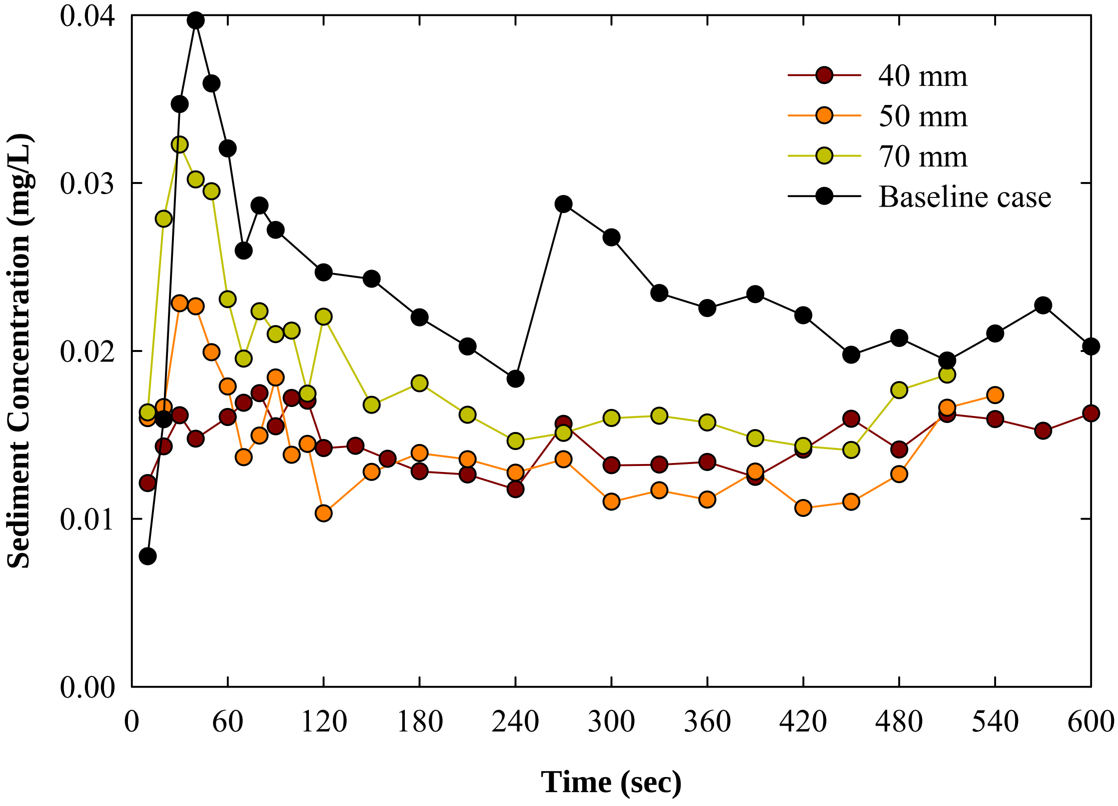

Figure 5 Time variation of sediment concentration for each run.

Peak sediment concentration increased by a factor of 2.3 (56%) when comparing results from the baseline case to the 40 mm non-erodible layer. Sediment peaks increased as the non-erodible layer was lowered in the soil profile. The run in which the non-erodible layer was 40 mm below the soil surface had an initial increase in sediment concentration that was sustained through the run. In the runs when the depth to the non-erodible layer was 50 mm and 70 mm, sediment trends were similar to those discussed by Bennett *et al.* (2000). There was a 43% increase in the sediment peak when comparing the baseline case to the 50 mm non-erodible layer and a 19% when comparing the baseline case to the 70 mm non-erodible layer.

Within individual experiments, the morphology of the headcut did not vary significantly during migration once steady-state conditions were achieved (Figure 3). Fluctuations (i.e. peak in 40 mm sediment concentration at 270 sec and the peak in baseline case at 270 sec (Figure 5)) from the mean were due to random spatial and temporal variations in the boundary conditions such as bulk density, soil water content, matrix pore-water pressure, and physical, hydraulic, and chemical characteristics of the surface seal.

CONCLUSIONS

Migration rate appeared to be governed by the depth to the non-erodible layer; however, shallow and deep layers migrated similarly, median depths migrated at a reduced rate. The sediment concentration peak was also affected by the non-erodible layer. With the non-erodible layer closer to the surface, the peak concentration was greatly reduced. There was a reduction in sediment loss as the non-erodible layer approached the surface; however, the headcut migration rate accelerated as the non-erodible layer approached the surface. There was a definite point at which the depth of the non-erodible layer reached a reduced migration rate and, in this limited data set, the 50 mm depth was the slowest. Further work in this area is planned.

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