THE ROLE OF PREFERENTIAL FLOW THROUGH SOIL-PIPES IN EPHEMERAL GULLY EROSION

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1. Introduction

Estimates by the USDA for 17 States suggest that ephemeral gully erosion ranges from 18 to 73% of the total erosion with a median of 35%. Poesen et al. (2003) found that ephemeral gully erosion contributed from 10 to 94% of total field soil loss, with a median estimate of 44%. Concentrated flow is generally considered the controlling process and subsurface flow is often overlooked. The two mechanisms of subsurface flow attributed to gully erosion are seepage flow and preferential flow through soil-pipes. The term piping is often used to refer collectively to both mechanisms of subsurface flow erosion (Bryan and Jones, 1997). However, the processes can be distinguished by referring to piping as strictly erosion resulting from flow through a discrete macropore or soil-pipe.

Preferential flow through soil-pipes has been attributed to about 60% of the cases of gully erosion under agronomic conditions in European fields (Bocco, 1991). A common feature for pipe-erosion is the existence of water-restrictive layers, which Faulkner (2006) termed duplex soils, that focus flow through soil-pipes. Wilson et al. (2007) reported field observations for a duplex loess soil where ephemeral gullies were eroded down to the fragipan layer with a 3 cm diameter soil-pipe at the gully head. They observed soilpipe flow rates following rainfall events, with rainfall and runon excluded, that were typically 1.4 L h^{-1}. Sediment concentrations were between 8.5 to 0.2 g L^{-1} with values typically less than 1 g L^{-1}. Tillage operations fill-in the ephemeral gully thereby leaving the soil-pipe that was previously at the gully head, buried and discontinuous.

The objective of this study was to quantify the hydrologic conditions under which discontinuous soil-pipes reestablish ephemeral gullies and continuous soil-pipes initiate ephemeral gullies.

2. Materials and Methods

Experiments were conducted on soil beds in a 100 cm wide by 150 cm long flume (Figure 1). Bulk soil was collected from a depth of 0 to 10 cm from a Providence silt loam (fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs) soil on the Holly Springs Experiment Station in North Mississippi. The soil contains 15, 69, and 16% sand, silt, and clay, respectively. Soil was sieved to < 2 mm and maintained in field-moist conditions for packing in 2.5 cm lifts. The bottom 5 cm of the soil bed mimicked a water restrictive layer by packing silty clay loam material to the average bulk density (1.57 g cm^{-3}) of fragipans in this area. The topsoil was packed to a bulk density of 1.35 g cm^{-3}, typical of surface conditions.

Experiments were conducted on a discontinuous soilpipe (2 cm i.d.) that extended 50 cm into the soil bed with 30 cm topsoil depth and a 5% slope. The following combinations of experiments were conducted: (1) pipe flow only with 15 cm pressure head, (2) pipe flow only with 30 cm pressure head, (3) rainfall only, (4) rainfall and pipe flow with a 15 cm head, and (5) rainfall and pipe-flow with a 30 cm head. Experiments were also conducted on a continuous soil-pipe (1 cm i.d.) that extended the entire length of the soil bed with 10 cm topsoil and 15% slope. These experiments included combinations of pipe-flow with and without rainfall. The soil pipe flow was at steady state flow rates of 190 L/h and 284L/h which equates to a constant pressure of 15 cm and 30 cm on a 1 cm i.d. soilpipe, respectively.

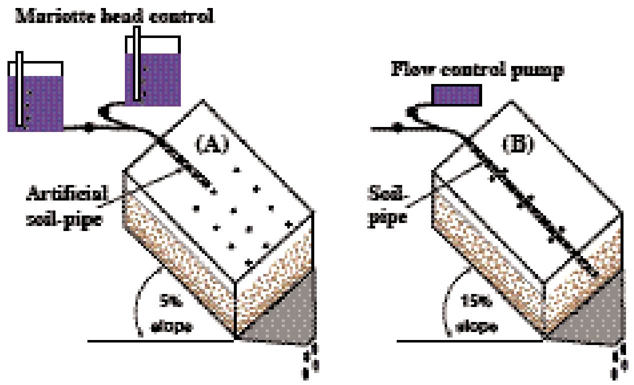

Fig. 1. Illustration of soil bed with tensiometers indicated by solid circles for (A) the discontinuous soil-pipe experiments, and (B) the continuous soil-pipe experiments.

3. Results and Discussion

3.1. Discontinuous Soil-Pipe Impact

The results for experiments mimicking an ephemeral gully with a discontinuous soil-pipe are reported in Wilson et al. (2007) and summarized in Table 1. The flow rate into the artificial soil-pipe for the 15 and 30 cm heads averaged 3.5 L h^{-1} whereas the seepage out of the soil bed averaged 0.5 L h^{-1}. The sediment concentrations from seepage for a discontinuous soil-pipe were essentially zero. In general, seepage flow rates for pipe flow alone were low, sediment concentrations were negligible and the soil bed did not exhibit mass wasting. Therefore soil loss in the runoff from pipe-flow alone was negligible. However, soil-pipe flow alone did result in the development of tension cracks and in one of the two tests it produced mass wasting.

The hydrologic response to rainfall alone was more dynamic than for pipe-flow alone. Surface runoff was

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initiated within 4.5 min and 2.3 min of rainfall for the two tests. The average runoff rate, over the course of the three rainfall events for the two tests was 67.5 L h^{-1}. The average sediment concentration was 22.5 g L^{-1} for a total soil loss by sheet erosion for rainfall alone, under bare soil conditions and a 5% slope, was 3.4 kg. This equates to 25 ton ha^{-1} which is 3.6 times larger than the tolerable soil loss limit established for this soil. Rainfall alone failed to produce mass wasting of the soil bed.

Table 1. Response to flow into a discontinuous soil-pipe, under 15 and 30 cm heads, with and without rainfall.

Treatment	Ro	PF	SC	SL	MW
	L/h	L/h	g/L	kg	kg
rain only	67.5	Na	22.5	3.4	0.0
15 cm head	0.6	2.8	0.2	0.0	12.0
30cm head	0.04	4.1	0.0	0.0	0.0
15cm+rain	78.2	0.8	26.8	4.5	16.2
30cm+rain	78.6	2.9	85.3	13.6	62.9

Time averaged values reported for runoff rate (Ro), pipe-flow rate (PF), sediment concentration (SC), and cumulative soil loss (SL) by sheet erosion, and mass wasting (MW).

The runoff rate for rainfall with pipe flow under a 15 cm head was 5.2 cm h^{-1} and the average sediment concentration was 26.8 g L^{-1}. The total sediment loss by sheet erosion averaged 4.5 kg which is only slightly higher than for rainfall alone. It would appear that soil-pipe flow with rainfall has a negligible influence on erosion. However, both 15 cm and 30 cm heads with rainfall exhibited sudden mass wasting by pop-out failures. For the two 15 cm head tests, the first pop-out failure resulted in 1.6 and 2.3 kg of soil loss by mass wasting in 5 s spans, respectively. These failures were followed by additional pop-out failures for a total of 16.2 kg of soil loss by mass wasting. The 30 cm head with rainfall tests had even more dramatic mass wasting. The first test had seven pop-out failures, each lasting a matter of seconds, with mass wasting ranging from 0.6 to 12.2 kg for a total of 37.4 kg. The second test had 16 pop-out failures for a total soil loss by mass wasting of 88.3 kg.

3.2. Continuous Soil-Pipe

The results presented here for flow through a continuous soil-pipe, Table 2, are preliminary as experiments are ongoing. The flow rates into the continuous soil-pipe (PF) under 15 and 30 cm heads were almost two orders of magnitude higher than observed when the soil-pipe is blocked by filling of the ephemeral gully. Like the discontinuous pipe experiments, pipe flow alone generally failed to cause mass wasting for the continuous soil-pipes. In contrast, the sediment concentrations were fairly high and were in the range observed by Wilson et al. (2007) for similar conditions in the field. The high sediment concentrations were the result of internal erosion within the soil-pipe caused by the high velocity exceeds the shear strength of the pipe walls. The pipe-erosion at times occurred in surges as the soil-pipe became clogged by internal mass wasting until pressure build ups flushed the sediment out of the pipes. The soil pipes were observed to enlarge significantly from 1 cm i.d initially to over 5 cm. However, tunnel collapse was not observed. The combination of rainfall with flow through a continuous soil-pipe produced significant soil losses by mass wasting, although substantially less than the discontinuous soil-pipe.

Table 2. Response to flow through a continuous soil-pipe, at flow rates equal to 15 and 30 cm heads, with and without rainfall.

Treatment	Ro	PF	SC	SL	MW
	L/h	cm/h	g/L	kg	kg
15cm head	160.6	189.0	4.4	2.1	0.0
30cm head	265.5	285.0	6.4	5.3	0.0
15cm & rain	222.4	189.0	8.2	6.0	4.1
30cm & rain	307.0	283.5	11.6	8.8	8.8

Time averaged values reported for runoff rate (Ro), pipe-flow (PF) rate, and sediment concentration (SC), and cumulative values for soil loss (SL) by sheet erosion, and mass wasting (MW).

4. Conclusions

Preliminary findings on continuous soil-pipes did not exhibit sudden development of mature ephemeral gullies by tunnel collapse as suggested by Faulkner (2006) but experiments on discontinuous soil-pipes did exhibit sudden re-establishment of filled in gullies. When pipe flow occurs with rainfall, a synergistic effect is produced that results in cataclysmic pop-out failures which may be up to 20 times higher than sheet erosion. The result of these pop-out failures is the re-establishment of ephemeral gullies with large initial soil losses. These findings explain the reoccurrence of ephemeral gullies in the same locations despite land management efforts to control their development. This work also suggest that conservation practices that focus solely on controlling the surface runoff may be ineffective if subsurface flow is not considered.

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