THE ROLE OF SUBSURFACE WATER IN CONTRIBUTING TO STREAMBANK EROSION

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ABSTRACT

Subsurface flow is known to contribute significantly to stream flow but its contribution to streambank failure, a process which may contribute significantly to sediment loading in streams, is not well known. Research is needed in understanding the contribution of concentrated, lateral subsurface flow to streambank failure and the hydraulic properties controlling seepage erosion. Laboratory experiments were conducted with two-dimensional soil lysimeters to observe subsurface flow induced erosion of bank faces under controlled conditions. Experiments were performed with single-layer sediment and also layered profiles to mimic streambanks where seepage erosion has been observed. The lysimeter experiments were compared to in-situ measurements of seepage discharge and erosion at field sites in Northern Mississippi. The soil and hydraulic conditions controlling seepage erosion were investigated. Changes in soil water pressure were monitored and modeled using a two-dimensional variably-saturated flow code to deduce information regarding soil water pressures at the time of bank failure and tension crack formation. A seepage erosion sediment transport model is proposed for the long-term goal of incorporation into a combined bank stability/ground water flow models for predicting streambank failure by seepage.

1. INTRODUCTION

There exists an incomplete understanding of one of the basic mechanisms governing sediment loading to streams by streambank failure: erosion by concentrated lateral, subsurface flow. This proposal hypothesizes that erosion by subsurface flow is important in promoting stream bank failure and sediment loading to streams in numerous geographical locations. Subsurface flow is known to contribute significantly to stream flow. Flow through large macropores or pipes, commonly

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referenced to as pipeflow (Jones, 1997), can cause subsurface flow to dominate overland flow in some catchments. High infiltration rates can cause the development of perched water tables above water-restricting horizons in riparian soils (Wilson et al., 1991). As perched water tables rise on these less permeable layers, large hydraulic gradients can initiate towards stream channels, causing fairly rapid subsurface flow (interflow or throughflow) to streams. Hagerty (1991a, 1991b) reports that even seemingly slight changes in soil texture can result in considerable hydraulic conductivity contrasts between layers and form perched water tables in layered soils. Subsurface flow over perched water tables can contribute in gully formation (Istanbulluoglu et al., 2005; Bryan, 2000; Romkens et al., 1997; Froese et al., 1999). Shallow subsurface flow plays a critical role in erosion in interacting with surface runoff mechanisms.

Research has begun to investigate the interaction of surface erosion, fluidization, and slumping whereby the onset of erosion was controlled not only by surficial flows but also hydrodynamic stress from groundwater seepage (Lobkovskey et al., 2004; Jones, 1997). Indoor flume studies indicate that surface erosion rates increase by an order of magnitude when groundwater increased unsaturated pore-water pressures thereby decreasing soil shear strength (Rockwell, 2002; Owoputi and Stolte, 2001). Most researchers investigating the role of seepage on erosion and undermining of hillslopes have focused on the seepage pressure as a body force acting on some representative sediment volume (Howard and McLane, 1988; Iverson and Major, 1986). Iverson and Major (1986) analyzed the physical effects of groundwater seepage on slope stability. They proposed that the force vector proportional to the hydraulic gradient is responsible for hillslope failure (Iverson and Major, 1986). Howard and McLane (1988) suggested that surface grains of cohesionless sediment eroded by groundwater are acted upon by three forces: gravity, a traction force defined as the sum of all forces on the seepage face, and a seepage force exerted on the sediment grain by groundwater seepage. Seepage forces predominate in a narrow "sapping zone" at the flow discharge, and erosion occurs by bulk sediment movement in this zone. Howard and McLane (1988) expressed the seepage force (F_s) and tractive force (F_t) as:

$$F_s = C_2^{"} \frac{3\pi}{n} \rho_f g i d^3 \tag{1}$$

$$F_t = C_1^{"} \frac{\pi}{4} \rho_f g y S d^2 \tag{2}$$

where ρ_f is the fluid density, g is the gravitational acceleration, y is the flow depth, S is the slope of the restrictive layer, d is the grain size, C_1" and C_2" are empirical constants, i is the hydraulic head gradient, and n is porosity. The backcutting initiates failure of the "undermining zone" which occurs above the sapping zone.

Even though theoretical models exist for the initiation of seepage erosion based on stability analysis (Howard and McLane, 1988), no sediment transport models exist for predicting the magnitude of seepage erosion as a function of seepage discharge. River bank erosion studies have measured seepage or soil water pressure (Casagli et al., 1999), but consider only bank stability, mass failure and seepage erosion without deriving a seepage sediment transport model. Howard and McLane (1988) proposed a long-term sediment delivery flux from seepage erosion but this model is dependent on critical failure angles. Research on gully formation focuses more on the interaction of subsurface flow with surficial erosion processes (Rockwell, 2002; Owoputi and Stolte, 2001; Bryan, 2000). Many researchers have attempted to incorporate the additional forces of seepage flow through modification of the critical Shields criterion (Istanbulluoglu et al., 2005; Lobkovsky et al., 2004). Lobkovsky et al. (2004) and Schörghofer et al. (2004) investigated seepage erosion of hillslopes with fairly small bank angles. This research attempts to extend such experiments to more complicated experimental simulations of natural streambank profiles with steep bank slopes characteristic of incised channels.

Numerical models currently exist for analyzing streambank failure primarily as the result of stream channel processes. Numerical models do not include seepage erosion mechanisms or the influence of lateral subsurface flow on other streambank erosion mechanisms. Bank stability models are capable of analyzing for bank failure by fluvial erosion and reduced cohesion by pore water pressure. The USDA-ARS National Sedimentation Laboratory (NSL) has developed the Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) computer model (Langendoen, 2000). The CONCEPTS model simulates unsteady, one-dimensional stream flow, sediment transport, and bank-erosion processes in stream corridors. It also simulates channel-width adjustment by incorporating the physical processes responsible for bank retreat due to (1) fluvial erosion or entrainment of bank-material particles by flow and (2) bank mass failure due to gravity. Bank material may be cohesive or non-cohesive and may comprise numerous soil layers. The CONCEPTS model was recently incorporated with the Riparian Ecosystem Management Model (REMM) to simulate near-bank ground water profiles (Langendoen et al., 2005). Planned enhancements for CONCEPTS include mild meandering channels as fluvial bank erosion is closely linked to secondary flow patterns. This research hypothesizes that it is imperative to incorporate seepage erosion and its influence on bank failure into such numerical bank stability models.

2. MATERIALS AND METHODS

2.1 Field Observations of Seepage Erosion

Streams throughout the Midsouth and Midwest are located in watersheds with "flashy" hydrology and stream banks that are steep and prone to failure. Extensive channelization of streams in this region during the 1940s and 1950s increased sediment transport capacity due to less flow resistance and increased stream power. The Yazoo River basin in Mississippi is typical of these conditions and is experiencing erosion similar to numerous other basins in the Midsouth and Midwest. Erosion-induced bank failure contributes significantly to the sediment load entering streams. Streambank failure results in the incision of alluvial streams. The highly erodible silt soils (e.g. loess) are unable to halt the incision and widening of the stream systems, leading to increased sediment production and yields as material is eroded from beds and banks.

This research will focus on preidentified seepage erosion occurring in streambanks along Little Topashaw Creek (LTC). LTC is a fourth-order stream with a contributing drainage area of approximately 37 km^2. The LTC channel is tortuous, with an average sinuosity of 2.1, an average width of 33.3 m, and an average depth of 3.6 m. Observations suggest mean stream width has increased by a factor of 4 to 5 since 1955. Concave banks on the outside of meander bends are failing by mass wasting subject to basal endpoint control, and sand is accreting on large point bars opposite failing banks. Eroding banks frequently invade adjacent cultivated fields, while inside bends and abandoned sloughs are vegetated with a diverse mixture of hardwood trees and associated species. Regional geology is characterized by dispersive silty soils underlain by alternating layers of sand and clay that overly a consolidated cohesive clay material. Channel bed materials are comprised primarily of sand with median sizes between 0.2 and 0.3 mm. However, cohesive materials occur as massive outcrops and as gravel-sized particles. Scientists with the USDA-ARS NSL have indicated that streambanks of LTC are being eroded by seepage erosion from sand layers above less permeable clay layers (Wilson et al., 2005).

Several locations were identified where seepage was occurring through a layer of loamy sand (LS). These seeps correspond to LS layers overlying layers of increased clay content. Soil cores were collected from bank faces where subsurface erosion was observed. A total of 18 soil cores were collected from 3 different sites at LTC. Soil cores (8.4 cm diameter and 6.0 cm long) were collected using hand core samplers. LS samples were acquired horizontally and clay loam (CL) layer samples vertically. The soil sample was encapsulated in 8.4 cm diameter by 6.0 cm long brass ring. At all three locations, triplicate soil cores were collected in order to quantify the variability. Soil samples were analyzed for soil water retention, saturated hydraulic conductivity, bulk density, and soil texture, following standard procedures described in more detail by Wilson et al. (2005). Subsurface discharge and erosion were quantified at three selected seep locations using lateral flow collection pans installed into the streambank after selected rain storm events between February and July 2003. Each lateral flow collection pan had a 50 cm wide opening at the bank face with a lip inserted 10 cm into the bank. The pans tapered to a 2 cm wide outflow end for collection of flow and sediment samples. The three seep locations were LS over restrictive CL layers.

2.2 Laboratory Lysimeter Experiments

Two lysimeters were constructed from 2 cm thick Plexiglas to mimic LTC stream banks. The small lysimeter was 100 cm long by 15 cm wide by 40 cm tall while the large lysimeter had the same dimensions except for a 100 cm height (Figure 1). The lysimeters had a water reservoir on one end to maintain a constant water head during the experiments. An inflow tube allowed water to flow into the reservoir from the bottom. Overflow openings were located at various heights from the bottom of the lysimeter (i.e., 0 and 40 cm in the small lysimeter and 0, 30, 60, and 90 cm in the large lysimeter). The outflow end of the lysimeters was flumed to allow sampling of flow and sediment.

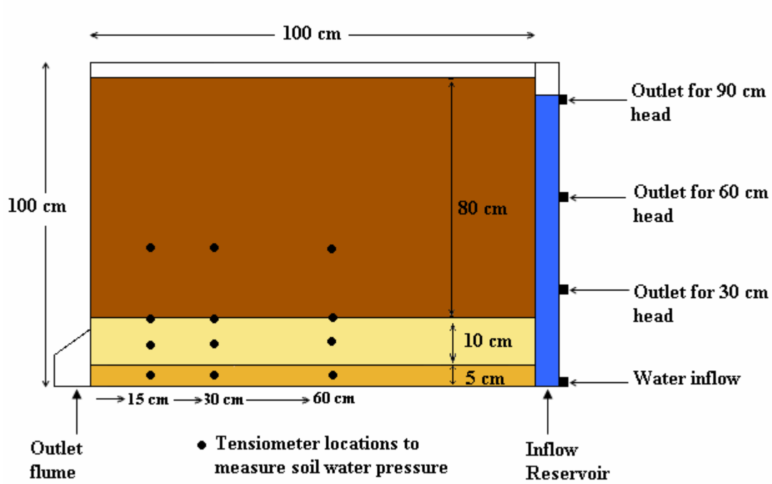

Figure 1 Depiction of the large lysimeter and location of the water inflow reservoir, water outflow section, and location of pencil-size tensiometers. Large lysimeter was 100 cm long by 15 cm wide and 100 cm tall. Small lysimeter was 100 cm long by 15 cm wide and 40 cm tall.

A porous plate made of the 1.9 cm Plexiglas was inserted between the reservoir and the main body of the lysimeter. This porous plate had 0.32 cm diameter holes filled with glass wool to prevent soil movement back into the reservoir. Before packing the lysimeter, a metal sheet was placed in front of the plate to protect the porous plate from clogging while packing. A front plate was used to cover the lysimeter from the front side. Both lysimeters also had twelve 1.5 cm diameter openings on one side of the lysimeter for installation of column tensiometers (Figure 1). The 12 tensiometers were installed at heights of 2.5, 10, 15, and 30 cm, respectively, from the inlet side of both lysimeters. These four rows (Figure 1) were located in the middle of the CL, middle of the LS, LS/silt loam (SiL) interface, and 15 cm above the LS/SiL interface. The tensiometers were at distances of 15, 30, and 60 cm from outlet in each layer. The soil-water pressure was monitored with a transducer connected to the tensiometers.

The lysimeters were packed in lifts to bulk densities measured in the field. For the reconstructed streambank profiles, both lysimeters were packed with a 5 cm thick CL layer at the bottom and a 10 cm thick LS layer. The small lysimeter utilized a 40 cm SiL topsoil layer. Two SiL layer thicknesses were investigated in the large lysimeter: 50 cm and 80 cm. Before the start of the experiments, the lysimeters were saturated for 24 hours to achieve a consistent antecedent moisture condition. Following the 24 hour period, the lysimeters were drained for 24 hours to achieve field capacity. Two cameras were installed to monitor the experiments. One camera captured the front view of the lysimeters and another camera captured the discharge end of the lysimeters focused on the LS layer. Water was added to the inflow reservoir to achieve the desired head. The time water first discharged through the LS layer into the outlet flume was recorded. As the LS layer eroded and the undercutting occurred, flow and sediment samples were collected in sampling bottles at regular intervals. The undercutting of the LS layer was recorded by measuring the distance of undercutting from the end of the lysimeter. Experiments were performed until bank collapse occurred. In total, two experiments were performed for the single noncohesive soil layer with a constant inflow water head of 30 cm, horizontal lysimeter, and vertical bank face. Eleven lysimeter experiments were performed with reconstructed LTC streambank profiles by varying the inflow water head (30, 40, 60, or 90 cm), bank height of SiL (40 cm, 50 cm or 80 cm), and lysimeter slope (0%, 5%, or 10%). The bank face was cut to vertical for the 5 and 10% slopes. Discharge and sediment concentrations measured during seepage erosion in the lysimeter experiments were used to derive a sediment transport model that related discharge over perched water tables to sediment discharge.

3. RESULTS AND DISCUSSION

3.1 Field Observations of Seepage Erosion

Initial soil characterizations have been performed at three LTC sites where subsurface erosion of streambank sediment is occurring. Three layers predominate in LTC streambanks: a silt loam (SiL) layer extending to depths of approximately 1.5-2.5 m, a layer of loamy sand (LS) of thickness 10-20 cm, and a clay loam (CL) layer of thickness 10-25 cm. The saturated hydraulic conductivity, bulk density, porosity, and water retention properties have been determined by standard methods. Disturbed soil samples have also been obtained for particle size analysis. Water retention data have been modeled with the van Genuchten equation using the Mualem assumption to provide the water retention curve for modeling variably saturated flow through the vadose zone and its interaction with surface flow (Lenhard et al., 1989; Carsel and Parrish, 1988). Laboratory analyses on these samples indicated a considerable hydraulic conductivity contrast. The results indicated the potential for substantial lateral subsurface flow over the less permeable CL layer, which possessed a much greater water-holding capacity than the LS. More details on the soil sampling are described by Periketi (2005) and Wilson et al. (2005).

Seepage flow rates at seeps experiencing sapping varied by an order of magnitude. Measurements were made during the recession limb of stream flow hydrographs. Mean flow rates on all sampling events at the three seep locations averaged 0.15 $m^3\ d^{-1}$ and were fairly consistent between seeps with a coefficient of variation (CV) of 62% (Figure 2). Seepage erosion from these seeps exhibited liquefaction of the conductive layer with sediment concentrations averaging 0.25 $kg\ L^{-1}$ with a CV of 93%. Sediment concentrations were correlated to the flow rates by a power law relationship (r^2 = 0.68). It was observed that this seepage flow initiated the development and headward migration of gullies by liquefaction of soil particles that were entrained in the seepage flow. Vertical gully or bank faces exaggerated the process due to undercutting of the gully face which caused mass wasting of stream banks. Because of the danger in attempting to sample such unstable banks, the process was simulated in the laboratory using lysimeters.

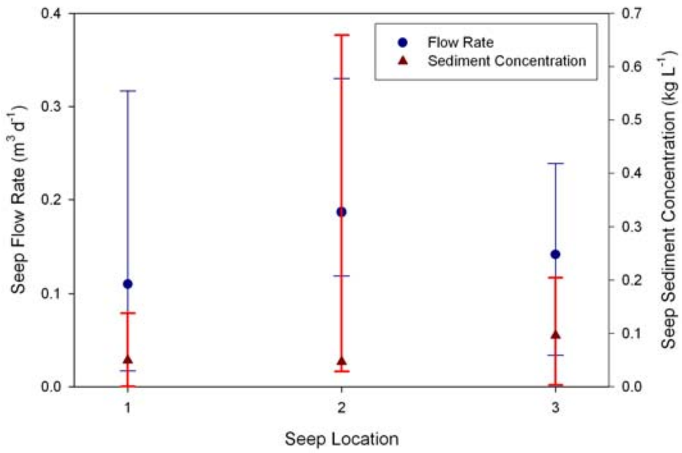

Figure 2 Flow rate and sediment concentrations measured at selected seep locations along Little Topashaw Creek. Flow rate and sediment concentrations were sampled five times at seep 1, seven times at seep 2, and four times at seep 3.

3.2 Laboratory Lysimeter Experiments

The small lysimeter (40 cm tall) experiments were unable to mimic flow rates observed in the field due to its limited head range at the inflow water reservoir (i.e., 40 cm). Small lysimeter flow rates averaged 0.013 m^3 d^{-1} to 0.037 m^3 d^{-1} for the 0, 5, and 10% slope experiments. However, sediment concentrations due to seepage erosion (1.1-1.3 kg L^{-1}) were higher than concentrations measured in situ due to the inability to mimic macroscopic soil structure due to organic and Fe-oxides that formed interparticle bridges. The small lysimeter was unable to mimic bank failure processes. Bank failure was not consistently observed despite significant undercutting of the bank. A 0% slope experiment failed to produce bank failure by the end of the experiment (60 minutes) while only one of two experiments at the 5% and 10% slopes produced minimal failure. Bank failures occurred prior to the establishment of positive pore water pressures in the SiL, suggesting that bank failure occurred under unsaturated conditions and that bank failure, which has a propensity to occur during the recession limb of hydrographs, may be due more so to interflow seepage erosion than deceased in bank shear strength due to the loss of matrix suction.

The large lysimeter allowed greater inflow water heads which were capable of mimicking hydraulic profiles through relatively thick SiL layers (i.e., 1.5-2.5 m) in the field and therefore seepage erosion, tension crack formation, and bank failure (Figure 3). Discharge in the eight lysimeter experiments averaged 0.12 m^3 d^{-1} with a CV of 46% and was within field measured rates. Seepage erosion rates averaged 1.87 kg L^{-1} with a CV of 16% and were again larger than observed in the field. Definitive patterns were observed between bank collapse and perched water table height and bank height. Bank failure time correlated to the depth of the perched water table. Bank failure occurred 660, 570, and 300 s after the initiation of the experiment for the 30, 60, and 90 cm inflow water heads, respectively. However, the response of cumulative seepage erosion was inconsistent. Seepage erosion was greater for shallower banks prior to bank failure as expected.

Slope insignificantly impacted bank failure time: bank failure occurred at approximately the same time for the 0, 5, and 10% slopes.

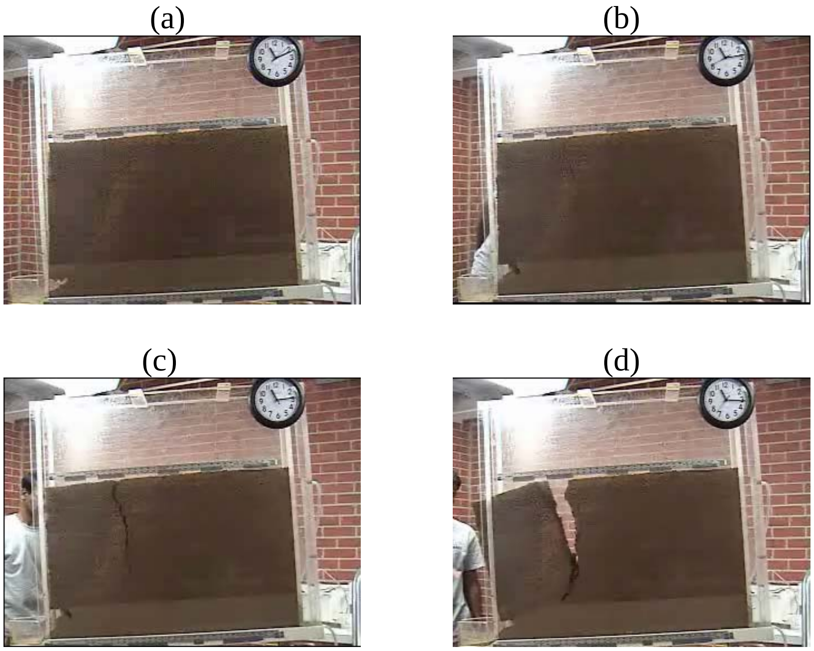

Figure 3 Typical time series of bank failure of reconstructed streambank profiles due to subsurface erosion: (a) sapping erosion, (b) undermining, (c) tension crack formation, and (d) collapse.

Tensiometer data again suggested collapse of the banks prior to the removal of negative pore-water pressures in the SiL. This tensiometer data was modeled using a two-dimensional, variably-saturated ground water flow code: VS2D (Healy, 1990). The model was calibrated based on measured pore-water pressures during the lysimeter experiments with initial values of soil parameters from the field experiments (Figure 4). VS2D also demonstrated that tension cracks formed in streambank sediment where pressures were equivalent to initial starting pressures of -40 to -50 cm H_2O (Figure 5). Researchers have suggested that since the bank angle exceeds critical angles for noncohesive sediment that any flow depth will result in seepage erosion. However, flow depths on the order of 1-4 cm were required to initiate seepage erosion as determined from the calibrated VS2D models. These results suggest that it may not be appropriate to assume LS as noncohesive. Bank undercutting of 15-35 cm was generally required prior to bank failure. Following the suggested hypothesis of Howard and McLane (1988), seepage erosion rate correlated to seepage discharge based on a power law relationship with an average correlation coefficient (r^2) of 0.9. A dimensionless seepage erosion sediment transport model has also been derived based on the dimensionless sediment flux (q_s*) and shear stress (τ*), where shear stress was assumed to be dependent on the seepage force proposed by Howard and McLane (1988):

$$q_s^* = a\ \tau^{*\,b} \tag{3}$$

$$q_s^* = \frac{q_s}{\sqrt{(s-1)gd^3}} \tag{4}$$

$$\tau^* = \frac{C_2'' q \sin(\theta)}{(s-1)nK} \tag{5}$$

where a and b are empirical regression parameters, C_2'' is an empirical parameter that depends on the packing coefficient, q is Darcy's velocity or discharge per unit flow area (assumed equal to the width of the lysimeter times the average flow depth at the lysimeter outlet), K is the hydraulic conductivity, θ is the bank angle, n is the porosity, and s is the ratio of solid to fluid density. Data from the seven lysimeter experiments fit the proposed seepage erosion sediment transport model (a = 584, b = 1.04) with an r^2 of 0.86. Fox et al. (2005) discuss more details on the development of the seepage erosion sediment transport model and large lysimeter experiments.

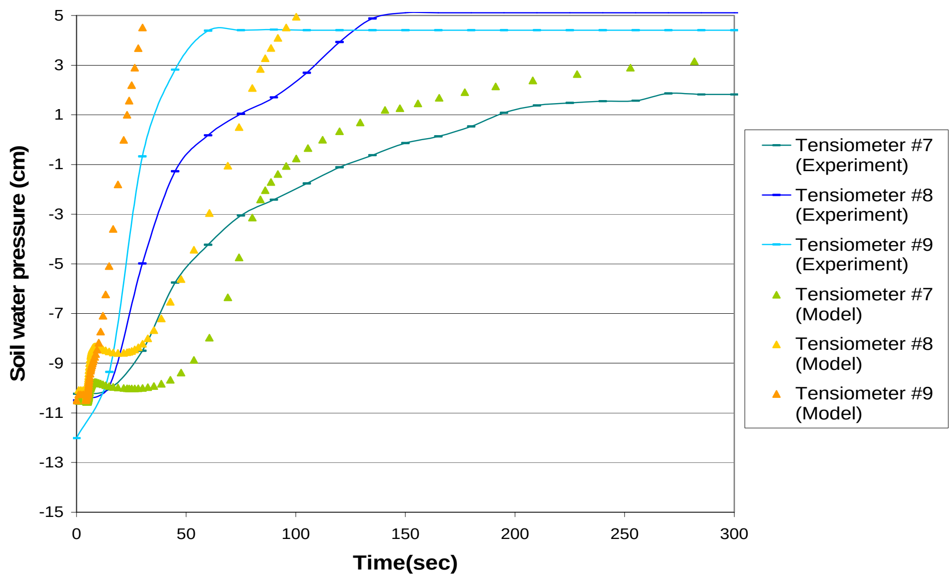

Figure 4 Comparison of simulated pore-water pressure with tensiometer experimental data within the loamy sand layer for the large lysimeter experiment with 10% slope, 60 cm inflow water head, and 50 cm bank height.

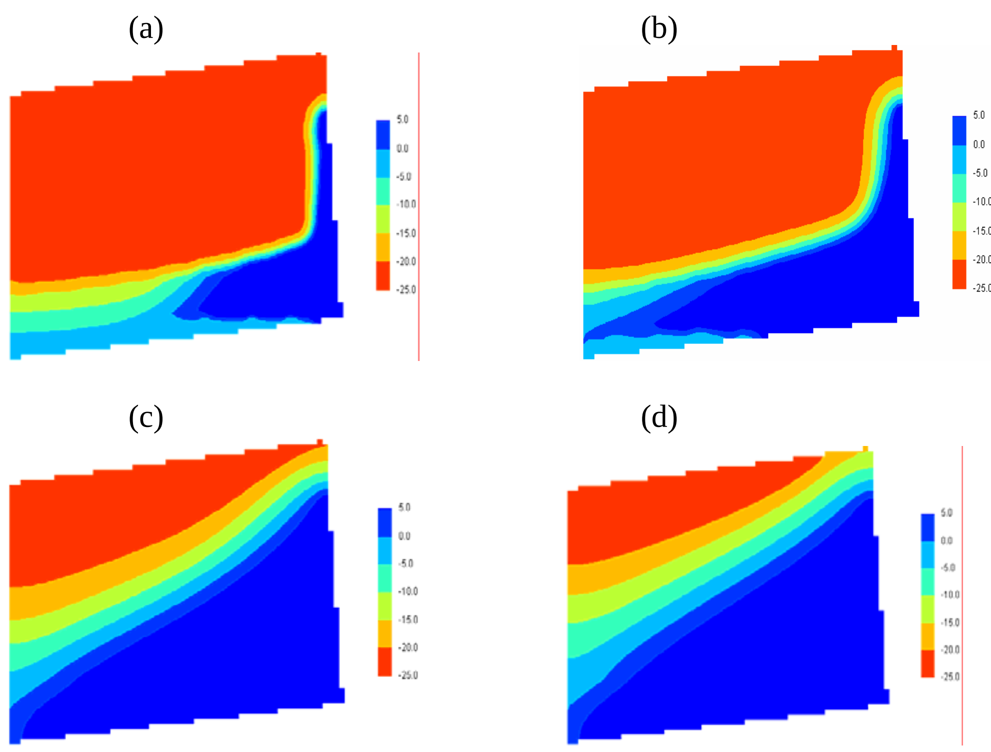

Figure 5 VS2D predicted pore-water pressures during the 10% slope, 60 cm inflow water head, and 50 cm bank height lysimeter experiment: (a) after 25 s, (b) time to flow, (c) after 500 s, and (d) at bank collapse. Red = -25 cm H_2O, Blue = 5 cm H_2O, Contour color interval = 5 cm H_2O.

It has been concluded that further laboratory experimentation is needed to fully explain the soil and hydraulic controls on seepage erosion. Using the large lysimeter, experiments are currently underway with single layered LS by packing 40 cm LS at field measured bulk density. Tensiometers have been repositioned near the outflow face to obtain more detailed information regarding flow depths required to initiate significant seepage erosion. Initial results from these experiments suggest that tensiometer data may be able to detect failures in the single LS layer and therefore provide a clearer picture as to the pore-water pressure profiles at the time of seepage erosion and bank failure. Experiments will also be performed with numerous streambank angles to verify the seepage erosion sediment transport model with slopes ranging from vertical to the critical seepage angles predicted by existing theoretical models.

5. SUMMARY

This research has indicated the importance of seepage erosion at one streambank site in Northern Mississippi. Seepage erosion rates measured in situ and simulated in the laboratory provided initial evidence as to the potential role in seepage erosion during the recession limbs of stream flow hydrographs. Seepage erosion may play a more important role compared to decreased shear strength due to the loss of matrix suction, especially in layered stream banks. For predicting seepage erosion effects on streambanks, detailed characterization of soil profile lithology is critical for accurate seepage erosion prediction. Future research is aimed towards extending lysimeter studies to simulate in-field streambank conditions, including low-stage seepage erosion and high-stage streambank storage return. Future research will evaluate the empirical sediment transport model. An existing process-based model of stream evolution (CONCEPTS) will be modified in the near future to include seepage erosion. Such a combined model will allow sensitivity analyses to be performed with the model to evaluate the importance of soil, hydraulic, and geotechnical parameters on seepage erosion and mass wasting of banks.

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REFERENCES

Bryan, R.B. (2000). “Soil erodibility and processes of water erosion on hillslope.” *Geomorphology*, 32(3-4), 385-415.

Casagli, N., Rinaldi, M., Gargini, A., and Curini, A. (1999). “Pore water pressure and streambank stability: results from a monitoring site on the Sieve River, Italy.” *Earth Surface Processes and Landforms*, 24, 1095-1114.

Fox, G.A., Wilson, G.V., Periketi, R.K., and Cullum, R.F. (2005). “A sediment transport model for seepage erosion of streambanks.” *Journal of Hydrologic Engineering* (In Review).

Froese, J.C., Cruse, R.M., and Ghaffarzadeh, M. (1999). “Erosion mechanics of soils with an impermeable subsurface layer.” *Soil Science Society of America Journal* 63, 1836-1841.

Hagerty, D.J. (1991a). "Piping/sapping erosion. 1. Basic considerations." *Journal of Hydraulic Engineering*, 117(8), 991-1008.

Hagerty, D.J. (1991b). "Piping/sapping erosion. 2. Identification/diagnosis." *Journal of Hydraulic Engineering*, 117(8), 1009-1025.

Healy, R.W. 1990. Simulation of solute transport in variably saturated porous media with supplemental information on modification to the U.S. Geological Survey's computer program VS2D. U.S. Geological Survey, Denver, Colorado. *Water-Resources Investigations Report* 90-4025. 125 pp.

Howard, A.D., and McLane, III, C.F. (1988). "Erosion of cohesionless sediment by ground water seepage." *Water Resources Research*, 24(10), 1659-1674.

Istanbulluoglu, E., Bras, R.L., Flores-Cervantes, H., and Tucker, G.E. (2005). "Implications of bank failures and fluvial erosion for gulley development: Field observations and modeling." *Journal of Geophysical Research-Earth Surface* 110(F1), Art. No. F01014.

Iverson, R.M., and Major, J.J. (1986). "Groundwater seepage vectors and the potential for hillslope failure and debris flow mobilization." *Water Resources Research*, 22(11), 1543-1548.

Jones, J.A.A. 1997. Subsurface flow and subsurface erosion. In *Process and Form in Geomorpology*. D.R. Stoddart (ed). Routledge, London.

Langendoen, E. J. 2000. "CONCEPTS – Conservational channel evolution and pollutant transport system: Stream corridor version 1.0." Research Report No. 16, US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS.

Langendoen, E.J., Lowrance, R.R., Williams, R.G., Pollen, N., and Simon, A. (2005). "Modeling the impact of riparian buffer systems on bank stability of an incised channel." *World Water and Environmental Resources Conference, American Society of Civil Engineers,* Anchorage, AK.

Lobkovsky, A.E., Jensen, B., Kudrolli, A., and Rothman, D.H. (2004). "Threshold phenomena in erosion driven by subsurface flow." *Journal of Geophysical Research-Earth Surface* 109(F4), Art. No. F04010.

Owoputi, L.O., and Stolte, W.J. (2001). "The role of seepage in erodibility." *Hydrological Processes*, 15(1), 13-22.

Periketi, R. (2005). *Analysis of Seepage Erosion with Lysimeter Experiments and Numerical Modeling*. M.S. Thesis, Department of Civil Engineering, University of Mississippi, University, MS.

Rockwell, D.L. (2002). "The influence of groundwater on surface flow erosion processes." *Earth Surface Processes and Landforms*, 27(5), 495-514.

Romkens, M.J.M., Prasad, S.N., and Helming, K. (1997). "Effect of negative soil water pressures on sediment concentration in runoff." *Management of Landscapes Disturbed by Channel Incision*, Wang, S.S.Y., Langendoen, E.H., and Shields, F.D. (eds.), University of Mississippi, Oxford, MS, p. 1002-1007.

Schörghofer, N., Jensen, B., Kudrolli, A. and Rothman, D.H. (2004). "Spontaneous channelization in permeable ground: theory, experiment and observation." *Journal of Fluid Mechanics*, 503, 357-374.

Wilson, G.V., Jardine, P.M., Luxmore, R.J., Zelazny, L.W., Lietzke, D.A., and Todd, D.E. (1991). "Hydrogeochemical processes controlling subsurface transport from an upper subcatchment of Walker Branch watershed during storm events: 1. Hydrologic transport processes." *Journal of Hydrology*, 123, 297-316.

Wilson, G.V., Periketi, R.K., Fox, G.A., Cullum, R.F., and Shields, F.D. (2005). "Seepage erosion properties contributing to streambank failure." *Earth Surface Processes and Landforms*, In Review.