STUDY OF THE EFFECTS OF LATERAL SEEPAGE FORCES ON TENSION-CRACK DEVELOPMENT, BANK-FAILURE DIMENSIONS AND MIGRATION OF EDGE OF FIELD GULLIES

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Abstract: Pore-water pressure is one of the most dynamic and important variables controlling geotechnical failure of streambanks and gully heads. Generation of positive pore-water pressures reduce frictional strength and the matric suction component of apparent cohesion. Pore-water pressure gradients, expressed as seepage forces, are counteracted by tensile and shear strengths. The effects of positive pore-water pressures, matric suction and lateral seepage forces on streambank failures and edge of field gullies are being investigated at the Goodwin Creek Experimental Bendway, Mississippi. Nine nests of digital tensiometers were installed in a radial pattern at depths of 30, 100, 150, and 270 cm, and spaced roughly 7, 60, 160, and 580 cm back from the gully head. Data were recorded at 10-minute intervals along with rainfall data from a tipping-bucket rain gage. Repetitive surveys of the gully head provide evidence of erosion events between February and September 2005. Results show that lateral seepage forces moving away from the gully face are greatest in the shallow (30 cm) zone closest to the gully face (7 – 60 cm) and generally decrease non-linearly with depth and with distance from the gully head. The vertical and horizontal distribution of these forces indicate a zone of strength that may determine failure-block dimensions during partial saturation of the soil mass. However, it is shown that mass failure of the headwall cannot occur unless the toe of the headcut has been previously undercut by hydraulic erosion or pop-out failures. Maximum seepage-force values of 13 kN/m^3 have been calculated, with values approaching zero at depths near 1.5 m. Infiltration via macropores and crack development behind the gully head may be important mechanisms in generating the positive pore-water pressures associated with saturation and mass failure.

INTRODUCTION

Erosion of cohesive materials is a complex phenomenon owing to the electro-chemical bonding between particles and because entrainment is, therefore, not controlled solely by particle size and weight. With respect to streambanks and edge-of-filed gullies (EFG), erosion of the bank top or gully headwall is governed by multiple processes and controls. Understanding and quantifying the controls of headcut migration is critical in predicting sediment losses, gully growth and gully control. Headcuts can migrate as a result of hydraulic erosion at the precipice, by geotechnical failure of the face and/or by undercutting of the face by either hydraulic erosion or seepage-induced pop-out failure and subsequent cantilever failure of the upper part of the headcut. Thus, headcut migration can be envisioned as the result of a triangle of processes with each apex representing a different process domain; hydraulic, geotechnical, and seepage (Figure 1). However, several recent field studies have reported that much of the material eroded from gullies and migrating headcuts is provided by failure of the gully face (Dietrich *et al*, 1985; Fernandez *et al*, 1995; Collison and Simon, 2001). This study aims to investigate the interaction of aspects of these three process domains on headcut migration of an EFG at the Goodwin Creek Experimental Bendway (GCEB), Mississippi (Figure 1).

The GCEB, has been monitored since 1996 to study streambank-erosion processes (Figure 2). Twelve monumented cross sections were surveyed after every major flow event (Figure 3). Pressure transducers placed at the upstream and downstream ends of the reach recorded stage. Geotechnical properties of the bank material were determined by *in situ* direct shear tests (Simon *et al*., 2000) and bank-toe erodibility was measured with a submerged jet-test device (Hanson, 1990). Pore-water pressure data were collected every 10 minutes using digital tensiometers at four depths. During 2004, an EFG developed at the head of a 1.3 m-high failure scar in the vicinity of cross section 4, providing an opportunity to monitor processes controlling migration of the headcut.

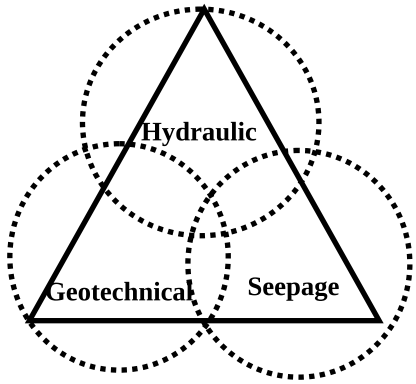

Figure 1 Conceptual drawing of the interaction of processes that can govern headcut migration.

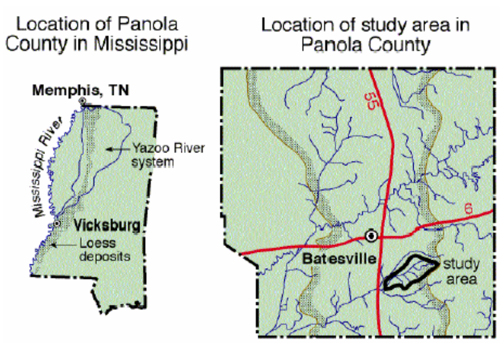

Figure 2 Location map of Goodwin Creek.

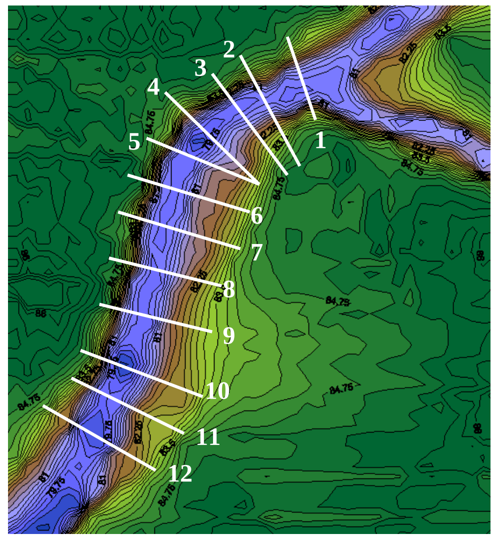

Figure 3 Location of cross sections at GCEB.

Based on previous observations and measurements of streambank processes at the GCEB, it was found that changes in pore-water pressure during rainfall events exert profound influences on bank-material shear strength and stability. Preliminary bank-stability analyses determined that migration of the headcut could not occur by mass failure even under worst-case, saturated conditions. Using a measured cohesive strength (*c'*) and friction angle (ϕ') of 6.4 kPa and 34^o respectively, undercutting by hydraulic erosion or pop-out failure would be required to destabilize the headcut (factor of safety, $F_s < 1.0$) (Figure 4). Because of the cohesive nature of the materials and the presence of cropped grasses, hydraulic erosion by overland flow is not considered an important process in headcut migration of the Goodwin Creek EFG. The study was designed, therefore, to combine repeated surveys of the EFG with real-time measurements of precipitation amount and intensity, overland flow, pore-water pressures and lateral seepage gradients, and geotechnical strength to investigate those processes responsible for further headcut migration.

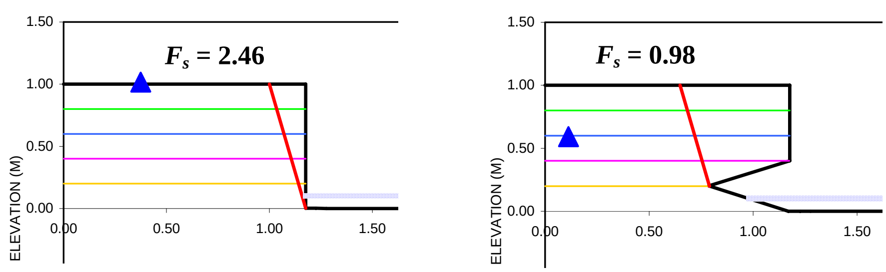

Figure 4 Bank-stability analysis of gully headwall showing destabilization by undercutting and partial saturation. F_s = factor of safety; blue triangles represent height of the phreatic surface.

FIELD AND ANALYTIC METHODS

An intital survey of the EFG was conducted in December 2004 with subsequent surveys conducted following significant storm events in February, April, July, and September of 2005. The effects of pore-water pressures and lateral seepage forces were measured by installing nine nests of digital tensiometers in a radial pattern from the headcut at depths of 30, 100, 150, and 270 cm. These nests were spaced roughly 7, 60, 160, and 580 cm back from the gully head and are referred to as edge, front, middle, and back, respectively. Precipitation was measured with a tipping-bucket rain gage and digitally recorded. All digital data were recorded at 10-minute intervals on data loggers starting on February 9, 2005. Overland flow was measured by a pressure transducer placed within a 12-inch diameter pipe where the downstream end of the gully drains down the bank face and into Goodwin Creek. Shear strength parameters of the headwall were measured *in situ* with an Iowa Borehole Shear Tester and the erodibility of the gully top edge was measured with a submerged jet-test device.

Tensiometer data, measuring both positive and negative (matric suction) pore-water pressures were downloaded on a weekly basis and plotted. Except for the deepest instruments, pore-water pressure values were generally negative indicating enhanced strength due to matric suction (Figures 5a and b). During and immediately following rainfall events the tensiometers reacted in a predictable manner with the shallow tensiometers (30 cm) generally responding over greater amplitudes than those set deeper. Those instruments installed at the “edge” (7 cm into the face) also showed a tendency towards greater amplitudes due to their proximity to the exposed face. Variations in pore-water pressure for all edge tensiometers showed a marked diurnal fluctuation of between 2 and 4 kPa, representing a 0.4 to 0.7 kPa change in cohesive strength (assuming $\phi^b = 10^o$; Simon *et al*, 2000).

Given the complexities of unsaturated flow in porous media, our calculations of lateral seepage gradients and seepage forces do not include changes in the coefficient of permeability and, therefore, represent approximations of this process. Pore-water pressure gradient is given by:

$$i = (h_1 - h_2)/L \tag{1}$$

where h_1 is the hydraulic head at point 1 in meters, h_2 is the hydraulic head at point 2 in meters, and L is the distance between the points, in meters. Seepage force per unit volume (j) is given by (Lambe and Whitman, 1969):

$$j = i\gamma_w \tag{2}$$

where j is the seepage force per unit volume, in kN/m^3, γ_w is the unit weight of water, in kN/m^3. This seepage force occurs by frictional drag as water moves through the soil skeleton. h_1 and h_2 generally represent vertically displaced points. In the analysis of lateral seepage forces however, h_1 and h_2 represent horizontally displaced points and imply movement of water towards the gully face (front to edge) or away from the gully face (edge to front).

To test the role that seepage forces play in headcut migration, lateral seepage gradients were calculated. Lateral seepage gradients were calculated by taking the difference between matric suction values (multiplied by -1) of two tensiometers set at the same depth and dividing by the horizontal distance between the instruments. An example is shown in Figure 5c where values from the edge tensiometers are subtracted from the associated values of the front tensiometers, then divided by L (approximately 0.6 m). Because the instruments are from the same depth (elevation), this is equivalent to evaluating differences in hydraulic head where the sign of the gradient implies the direction of a seepage force towards the headcut face (positive) or towards the floodplain (negative) (Figure 5c).

HEADCUT MIGRATION AND GULLY EROSION

The EFG at Goodwin Creek experienced several significant storms that produced overland flow during the monitoring period of February to October 2005. Rainfall associated with Hurricane Katrina (95.1 mm; August 29-30) was not sufficient to generate positive pore-water pressures 0.6 m back from the gully head owing to extremely dry conditions prior to the storm. In contrast, rainfall associated with Hurricane Rita (83.2 mm; September 25)

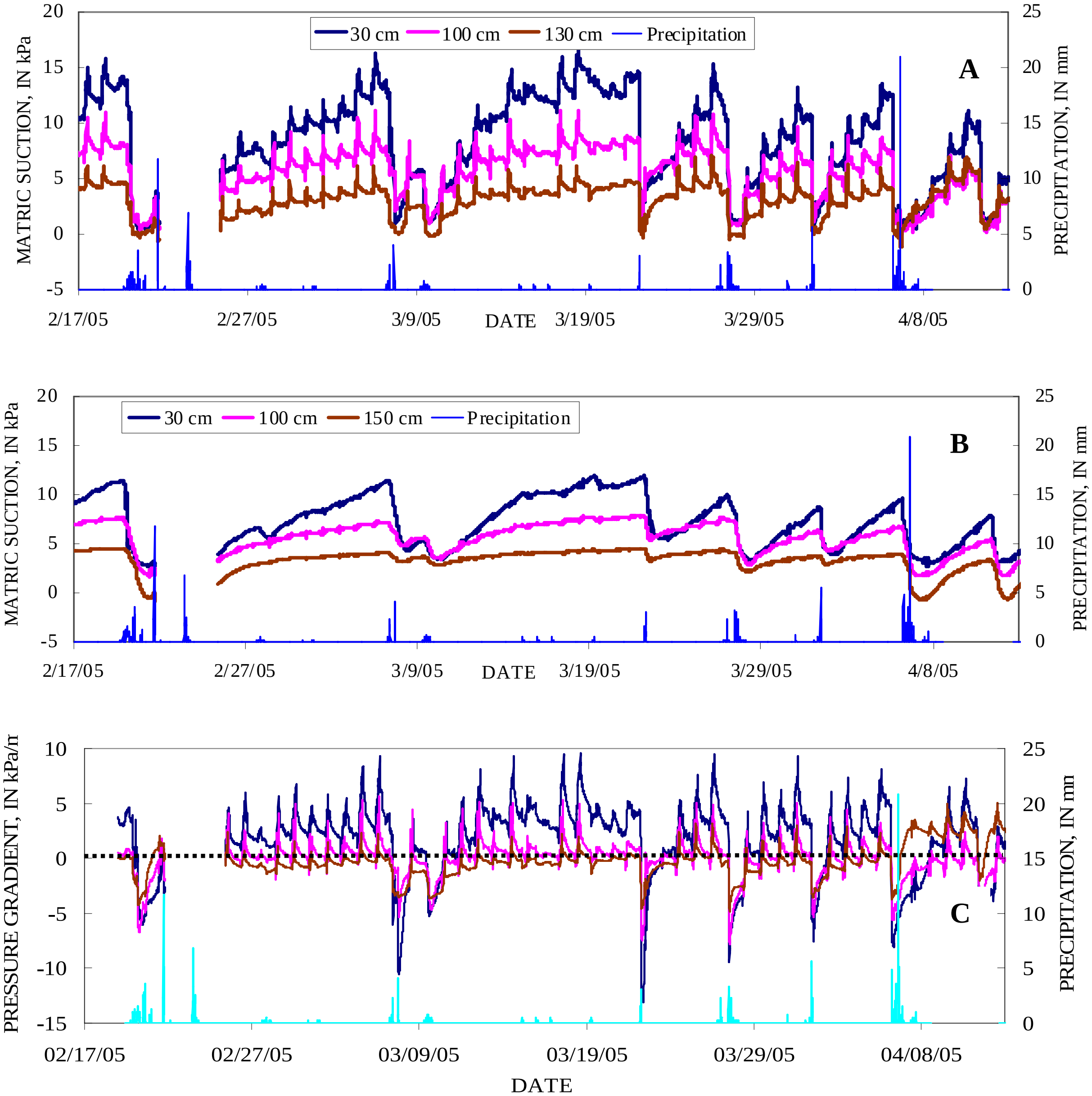

Figure 5 Data for the edge-center (A) and front-center (B) tensiometers nests, and pressure gradient between the front and edge nests (C) at three depths, all with associated rainfall.

caused considerable erosion of the EFG due to wetter antecedent moisture conditions. The most noteworthy events are shown in Table 1 and are all associated with mass failures of the gully face and migration of the headcut with the exception of the August 29-30 storm (Figure 6). None of the storm events resulted in headcut retreat by hydraulic erosion owing to relatively high, measured critical shear stresses of the surface material (6 Pa).

Views of headcut migration by mass failure, and the resulting morphology following the storm of September 25, 2005 are provided in Figure 7. Each of these events, with the exception of the August storm are associated with a complete loss of matric suction and generation of some positive pore-water pressures at both the edge and front tensiometers nests, particularly at depths between 1.3 and 1.5 m (Figure 5). This is just above an area of decreased permeability associated with a concentration of manganese nodules. Smaller rainfall events in March did not result in matric suction and shear strength reductions of the magnitude that occurred in February, April and September (Figure 5), rendering the headcut stable during March. These processes cannot, however, explain headcut migration

Table 1 Significant rainfall events and associated erosion of the EFG during the monitoring period.

Date(s) of precipitation	**Total precipitation (mm)**	**Volume eroded from headcut (m^3)**	**Average headcut migration (m)**
February 19-23, 2005	105	0.87	0.11
April 6 and 11, 2005	75.5	1.00	0.18
August 29-30, 2005	95.1	??	0.00
September 25, 2005	83.2	2.45	0.32

by mass failure at the EFG by themselves because, as we have seen with stability analyses (Figure 4), the headcut is stable under fully saturated conditions. Undercutting of the face must, therefore, be responsible for preparing the headcut for cantilever failure. Pop-out failures were observed to have emanated from an area 0.3 to 1.3 m-below the gully precipice on two occasions, forming triangular-shaped depressions at the base of the headcut. These failures could not be predicted from the observed pore-water pressure data probably because infiltration through macropores must be considerable. The pop-out failures that occurred in late August did not result in headcut failure for the reason stated above, but prepared the EFG for erosion by mass failure during Hurricane Rita three weeks later.

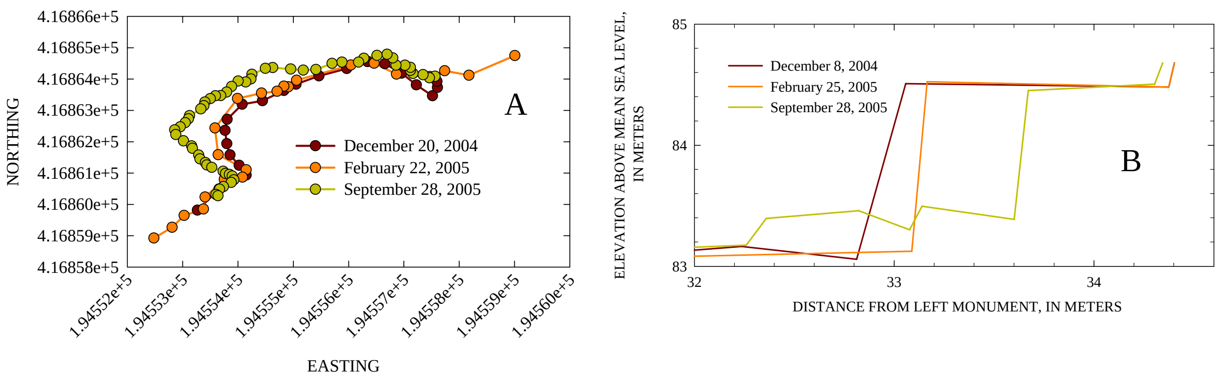

Figure 6 Time-series surveys of the EFG showing morphologic changes in plan (A) and in cross section (B).

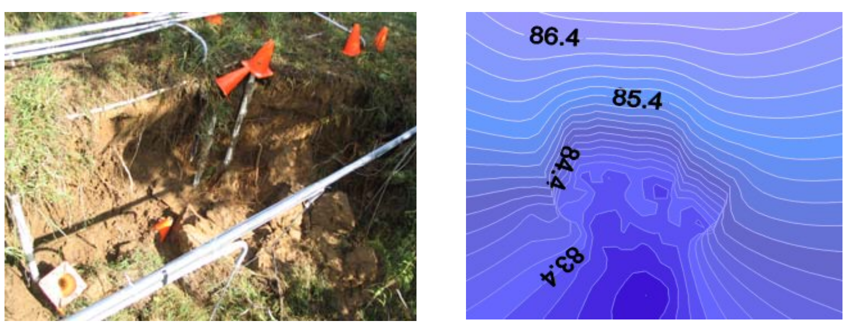

Figure 7 Photograph showing failed blocks and exposed tensiometers (left) and 3-D survey of EFG (right) following erosion event of September 25, 2005.

Using literature values to populate the finite-element stress-deformation model SIGMA/W, Collison and Simon (2001) showed that for typical loess-derived materials, high stresses are concentrated at two locations; at the base of the gully head and about 50 cm back from the gully head (Figure 8). Stress exceeded strength in these two areas with the shape of the potential pop-out failure at the base of the headcut looking strikingly similar to scars left by pop-out failures at the EFG and elsewhere. Results of the Collison and Simon (2001) study further indicate the potential importance of crack and macropore formation above the gully head to permit saturation of the headcut in a mass that is otherwise characterized by unsaturated conditions. This type of detail is not recorded by the tensiometers at the Goodwin Creek EFG that are measuring pore-water pressure at a point within the soil matrix.

DISCUSSION

Interaction of the seepage and geotechnical process domains involve viewing potential headcut failure over multiple spatial scales. At the particle scale, matric suction provides additional binding strength between grains, represented as an additional cohesion term (Fredlund *et al*, 1978). During dry periods, tensiometers some distance back from the bank face are wetter than at the edge, resulting in a considerable seepage force moving towards the gully face. In opposition to this tendency, however is the greater cohesive strength closer to the edge owing to heightened values of matric suction. During storms, infiltration of water results in a loss of matric suction and a weakening of the soil matrix. This process is amplified closer to the gully edge where overland flow over the gully precipice combines with infiltration via macropores to cause the edge of the headcut to wet faster and to lower values of matric suction relative to values some distance back from the headcut. This process leads to seepage gradients moving away from the headcut (up to 13 kN/m^3) at the very time when the tensiometers indicate that the soil is approaching saturation in a weakened state. This is also shown in the simulated data (Collison and Simon, 2001). At the block scale then, seepage forces are moving away from the gully face as indicated by calculated pressure gradients during storms (Figure 5c) creating a mechanism that can bind a block of soil together, thereby determining dimensions of potential failure blocks.

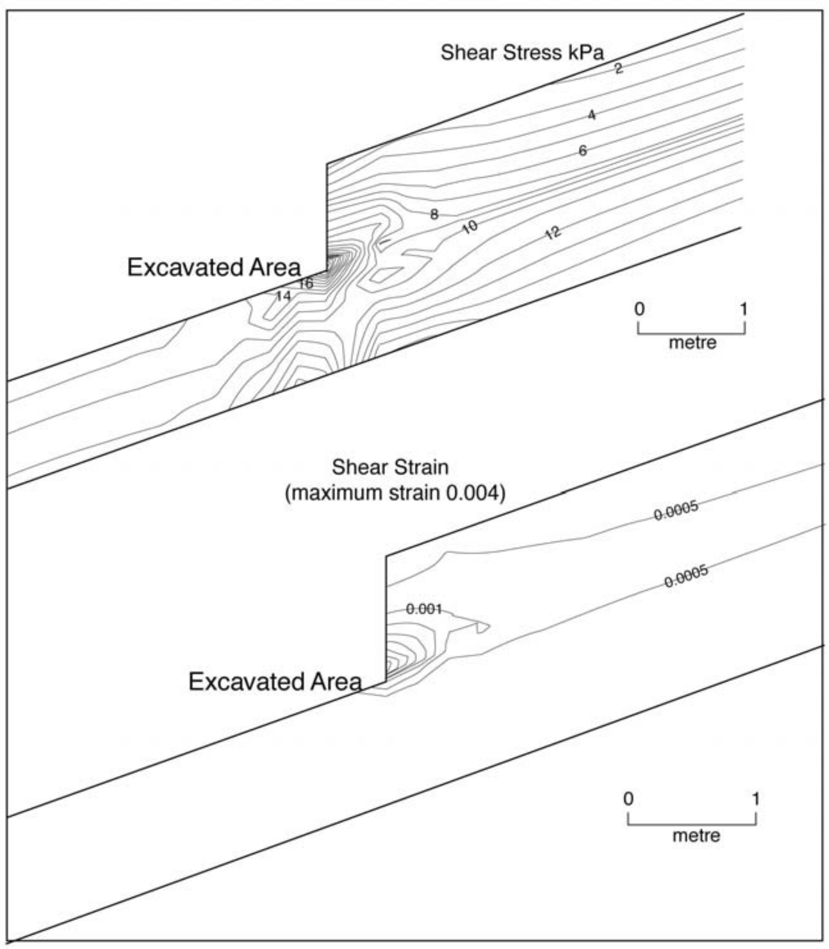

Figure 8 Distribution of shear stress and strain for a 1 m-high headcut in loess-derived materials. From Collison and Simon (2001).

These opposing tendencies are illustrated in Figure 9 but must be combined with a treatment of infiltration via macropores and stress-strain relations to better understand and predict this complex interaction of processes. The timing and magnitude of headcut migration by mass failure of the face (failure-block width) is at least partially controlled by the juxtaposition of these processes; where wetting causes preferential weakening of the soil matrix and lateral seepage, combined with stress-strain deformation that can determine the dimensions of the block.

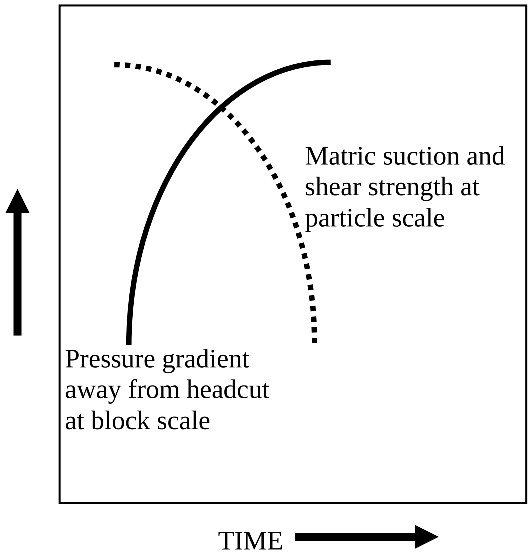

Figure 9 Conceptual illustration of opposing tendencies of seepage and geotechnical process domains during storms.

SUMMARY

Results of this study point to the interaction of hydraulic, geotechnical and seepage forces in controlling migration of an edge of field gully. Stability analysis has verified the need for undercutting to create conditions where mass failure of the gully headwall can occur with partial saturation of the face. These conditions were identified on several occasions at the Goodwin Creek EFG. The importance of cracks and infiltration via macropores remains to be further investigated using finite-element seepage and stress-deformation modeling. Measurements made in this study were not able to identify seepage forces moving towards the gully head (within the proximal 0.6 m) that would lead to pop-out failures although mass failures of this type were observed. However, previous simulations (Collison and Simon, 2001) of typical deposits do provide a mechanism for development of preferential zones of saturation and weakness that could explain undercutting by pop-out failures.

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