CRACKING MODES OF AN EXPANSIVE MISSISSIPPI DELTA SOIL

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ABSTRACT

Modes of cracking in expansive soils of the Mississippi delta and their impact on infiltration were examined. Preliminary laboratory infiltration studies suggested an evolutionary pattern of the crack network. Subsequent studies were conducted to investigate the primary modes of crack formation and their impact on infiltration. Of particular importance in the evolution of the crack morphology, the role of the seal and development of stress within the substrate is discussed. Understanding the developmental aspects of cracked soils permits further development of infiltration relationships that are used to determine the capabilities of cracked soils to transport water and solutes.

INTRODUCTION

Many soils in the Mississippi delta have swelling characteristics due to a high content of expansive clay minerals. The resulting cracks, typical during extended dry periods, appreciably affect infiltration and the movement of agricultural chemicals in watersheds; therefore, information about the crack development is imperative to the understanding and quantification of the hydrologic and chemical mobility status of watersheds with expansive soils.

Several authors (Ritchie et al., 1972; Bouma and Wösten, 1979; Beven and German, 1982) have discussed the impact of crack networks on infiltration. Cracks are a unique feature in soils with high shrink-swell potential. Various chemical, mineralogical, and physical properties such as initial soil water content, soil fabric, type and amount of exchange cations, and desiccation/rewetting cycles influence shrink-swell behavior.

Infiltration in dry clay soils is a function of the size and patterns of the cracks (Bouma and Dekker, 1978). Wilding and Tessier (1988) also noted that the water behavior and shrink/swell potential were related to the change in particle size and arrangement of particles. In shrink-swell soils, infiltration is controlled mainly by the cracks because the water is not influenced by the conductivity of the matrix. The cracks lead to enhanced infiltration and delayed runoff (Prasad et al., 1999). Free water moves to greater depths in relatively short periods of time (Quisenberry and Phillips, 1976). Figure 1 is a graph of the cumulative infiltration at various stages of crack development. A model of cumulative infiltration into cracking soils was discussed by Prasad et al. (1999) and employs the morphological characteristics of width, length, and depth of the existing soil structure.

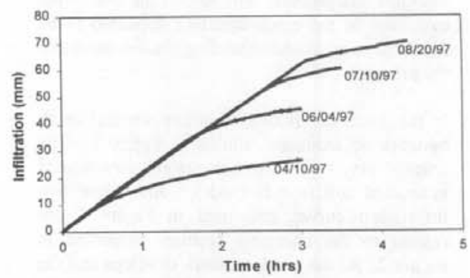

Figure 1. Cumulative infiltration curves.

Seal development is a complex process of detachment, migration, and compaction of the soil surface. Exposed to the energy of the rainstorm, surface aggregates are vulnerable to collapse and slaking. A portion of the detached material is reconstituted into the pores of the larger aggregates or voids between aggregates forming a layer, which clogs surface macropores. The continual process of detachment and

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migration of pore-blocking material, coupled with the inevitable compaction of the layer, creates a thin, semi-flexible surface seal, effectively reducing infiltration. Water movement below the developing seal, hydrates the clay and causes expansion of the soil substrate. The expanding material exerts a compressive upwards pressure on the seal, which eventually leads to a deformation as the force exceeds the tensile strength of the seal as it expands due to the deformation.

The importance of the seal, as a primary contributor in the evolution of the overall structure, warrants considerable review. In preliminary infiltration experiments using a rainfall simulator, carried out in a large box (65cm x 85cm x 15cm), a pronounced surface deformation of uniform structure was observed. During the early stages of the rainstorm, a longitudinal waveform appeared to develop, followed shortly thereafter by a transverse waveform. In short, the surface deformation resembled a checkerboard.

During the post rainfall period, when drying occurred and the cracks had fully developed, we recognized structural similarities between the surface deformation pattern, witnessed early in the rainstorm, and the crack pattern. As the work progressed, we continued to witness this phenomenon and hypothesized how best to interpret this process. The role of the seal in the evolution of the crack structure appeared to be the focal point in understanding the mechanics of the process.

In the field, dry periods promote vertical crack network development, similar to Figure 2. The cracked clay soils form a polygonal structure of individual soil islands (peds). The cumulative infiltration curves presented in Figure 1 are related to the changing features presented in Figure 2. As the crack network develops and the cracks increase in size, the infiltration capacity of the sample is increased.

The developmental picture for the formation of this structure is composed of two prominent features: seal formation and swelling stress. In as much as the entire matrix is composed of highly expansive materials, each rainstorm provides the energy required for the material to rebound, pass through equilibrium into stress, and then evolve into a reduced state. The modes of cracking evolve as the seal matures and the stress history increases. This is not to say that the matrix reformulates itself after each rainstorm. The initial stress regime continually manifests itself in the structure as the dominant feature of the network (Wells, 1995; White, 1972). Individual peds develop similar structural features through stress induced cracking. The process is a continual struggle of stress balance through fracture relief.

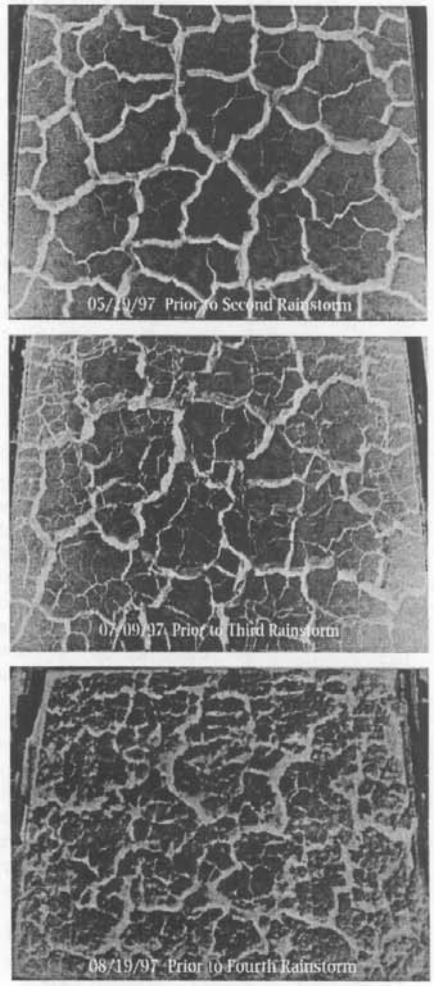

Figure 2. Evolution of crack network.

A series of experiments were conducted to investigate the evolution of the crack network. Based on the patterns observed in our preliminary infiltration experiments on the large sample with many cracks, we decided to reduce the sample width and focus on one longitudinal deformation/crack. Our objective was to investigate the role of the seal in the evolution of the crack network. If the seal is the determining factor in the crack pattern, then we needed to determine the cracking pattern that would develop in the absence of a seal, which can be done by protecting the surface from the impact energy of the rainstorm. This was accomplished by placing a rainfall energy-absorbing filter just above the surface.

MATERIALS AND METHODS

A sample from 0-30cm depth of a Sharkey silty clay (Vertic Haplaquepts) from the Hester farm in Bolivar County, MS (Grid 87, 1958 USDA Soil Survey, MSEA site), was brought to the laboratory, air-dried, and crushed to pass through a 2-mm sieve. Soil texture was 65% clay, 32% silt, and 3% sand. An X-ray analysis of the soil revealed smectite as the dominant clay mineral.

Soil samples were packed in a rectangular box (20cm x 94.3cm x 20cm), fitted with a subsurface drainage system. The soil was packed to a depth of 16cm, over a 4cm layer of fine sand. The packing density varied from $1.4 g/cm^3$ to $1.5 g/cm^3$. The box was fitted with a center divider, parallel to the sidewalls, providing two identical test surfaces during each rainstorm. Three experiments were conducted to observe crack development. During the experiments, one side of the test sample was protected from raindrop impact by an energy-absorbing filter, minimizing seal development. The other side was left unprotected to allow seal development. All samples were subjected to 15mm/hr simulated rainstorms for a duration of 6 hours, allowing 9cm of water to be applied to each sample.

Experiment I

A sample was prepared with an initially flat surface. The surface was lightly brushed to provide an initial surface roughness. The surface of the sample was profiled using an infrared laser on a 0.5mm by 0.5mm grid. During the rainstorm, point gauge measurements, cumulative infiltration measurements, and surface runoff measurements were taken. At the cessation of the rainstorm, point gauge measurements were taken and the surface profile was mapped with the laser. Laser profile measurements were taken every 12 hours for two days following the rainstorm. Figure 3 is a plot of the surface profile of the unprotected surface prior to the rainstorm, immediately after the rainstorm, and after crack development following drying.

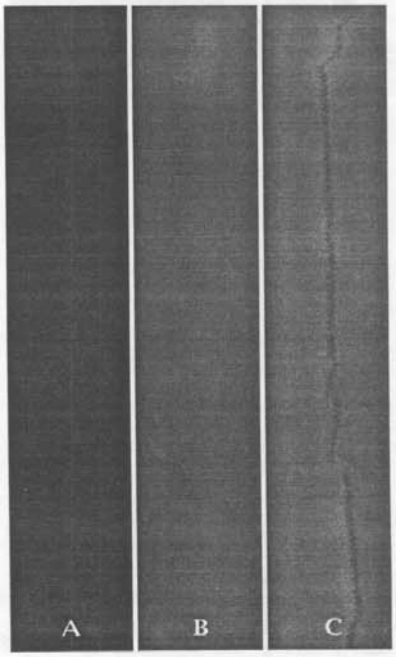

Figure 3. Laser profile of the unprotected soil surface (A)before, (B)immediately after, and (C)following drying.

Experiment II

The entire experiment was similar to Experiment I, except that grease was used on the sidewalls, front, and rear of the sample. The measurement scheme was identical to Experiment I. Figure 4 is a plot of the surface profile prior to the rainstorm, immediately after the rainstorm, and after crack development. The grease film was thought to reduce soil adhesion to the wall during expansion and shrinkage.

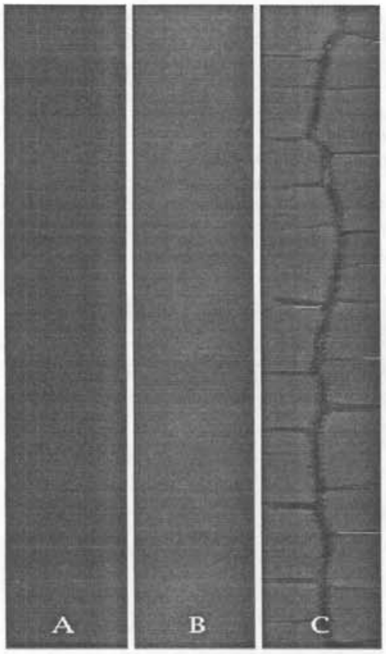

Figure 4. Laser profile of the soil surface with grease sidewalls (A)before, (B)immediately after, and (C)following drying.

Experiment III

The entire experiment was similar to Experiment I, except that the surface was prepared with a concave profile with a radius of 6cm. The measurement scheme was identical to Experiment I. Figure 5 is a plot of the surface profile prior to the rainstorm, after the rainstorm, and after crack development. Figure 6 is a picture of the experimental setup. The curvature was created to initiate a change in the wet front profile and possibly develop a new crack pattern.

RESULTS AND DISCUSSION

Unprotected Surface Experiments

We begin our discussion of the unprotected experimental samples by focusing on the soil water regime. During the rainstorm, the wet

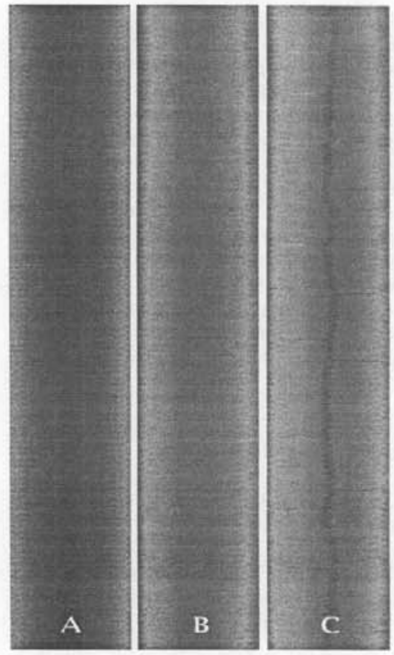

Figure 5. Laser profile of the soil surface (A)before, (B)immediately after, and (C)following drying.

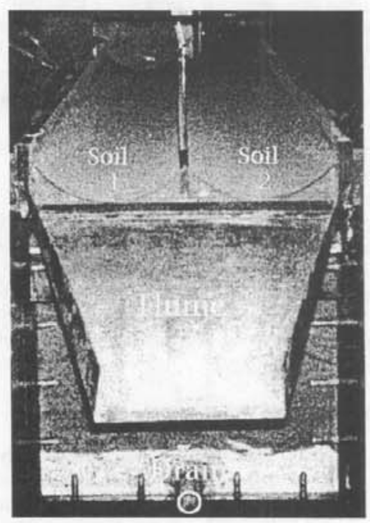

Figure 6. Picture of curvature setup.

front penetrated to a depth of 3.5cm. In the preliminary experiment, the wetted portion of the sample was dug up to determine the wetting front profile. The shape of the wetted profile was convex, with the center approximately 0.5cm higher than that at the edges. In the experiments that followed, the wetted portion was dug up after crack formation. This revealed a linear wet front profile, suggesting that the primary mode of redistribution was horizontal.

The surface profiles presented in Figures 2, 3, and 4 contain several features worthy of discussion. First, we point to the role of the seal. Point gauge measurements, taken during the rainstorm, show an increasing trend leading to a pronounced surface deformation 0.8cm in height in the center and 0.6cm in height near the sidewalls. The seal develops in the first 15 to 30 minutes of the rainstorm as particles are redistributed and compacted by raindrop impact. As the seal matures, the clay in the substrate begins to expand from the infiltrating water and a compressive upwards stress develops beneath the seal. As more water infiltrates, the seal deforms to accommodate the increasing volume/pressure of the substrate. The grease experiments were implemented to allow the material on the sidewalls to move with the central material, but point gauge measurements revealed that the seal continued to deform in the same fashion. The difference in results between the two experiments was an overall height increase of the deflected shape in the samples with grease. At this point, one might suggest that the sides of the sample were zones of continuous deposition of material from runoff. The concave experiments were implemented to address this issue. Point gauge measurements, taken after cessation of the rainstorm, revealed that the center was continuing to move vertically more than the sidewalls.

Experiments I-III point to the compressive stress, developed within the material, as a major factor contributing to the deformation of the seal. Micro-cracking occurs as the compressive stress builds and the material comprising the seal is no longer able to maintain integrity. After the rainstorm has ceased, a longitudinal crack appears, followed by transverse cracks as the soil drys and consolidates. The width of the longitudinal and transverse cracks was 1cm and the depth was a function of the wet front depth, typically 3cm to 3.5cm. The spacing of the transverse cracks was approximately 10cm.

Protected Surface Experiments

The primary goal of the protective filter was to dissipate the energy of the raindrop, prevent seal formation, and thus allow maximum infiltration. During the rainstorm, the wet front penetrated to a depth of 6.5cm, almost twice the depth recorded from the unprotected samples. Similar to the unprotected samples, protected samples were dug up at the cessation of rainfall and after crack formation. A linear wetted profile was observed in each case.

The filter was not always effective in disrupting seal formation and localized seals did form. However, point gauge measurements of the surface, taken after the rainstorm, showed a similar deformation profile, with the center at 1.4cm and 1.2cm near the sidewalls. Without the seal to retard the movement of water into the sample, the material expanded an additional 0.6cm. After the rainstorm had ceased, transverse cracks appeared at regularly spaced intervals, followed by longitudinal cracks, if localized seals were formed.

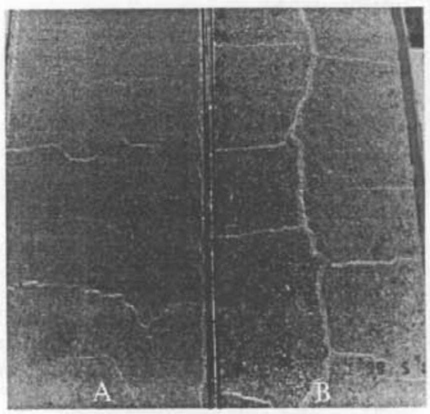

Figure 7. Picture of sample. (A)LHS is protected and (B)RHS is unprotected.

MODAL PROCESS

The unprotected experiments and the protected experiments exhibited two modes of cracking. Figure 7 is a picture of a sample where the right hand side (RHS) was unprotected and the left hand side (LHS) was protected. The first mode is most pronounced in the unprotected samples where the seal is allowed to develop. The seal develops as a function of the rainstorm and continues to evolve throughout the rainstorm. Internal stress develops as the expanding clay beneath the seal causes a deformation/bending of the structure. The energy is released with a fracture of the seal, creating a longitudinal fracture plane in the center of the sample. This mode is a structural failure of the seal.

The secondary features of the unprotected samples, appearing as primary features in the protected samples, comprise the second mode of the system. Transverse cracks are the primary energy release mode for the expanding substrate. This pattern can also be seen in samples where the wet material is removed and the remaining portion allowed to stand for a few weeks. Transverse cracks appear in the matrix of a material that at most has been subjected to vapor transport. The increasing compressive stress creates an energy release mode for the material. Both the structural failure mode and the energy release mode give rise to ped formation we observe in the field.

CONCLUSIONS

The observations presented herein are intended to expand upon the mechanical aspects of crack network formation and its fundamental modes. A modal system was presented as a simplistic view of the structure formation we find in the field. Experiments on large samples provided key information in the development of a composite system of mechanical behavior. A model is currently being developed which simulates the unprotected system as a composite beam subjected to axial loading conditions. The model accounts for the deformation of the seal and predicts the zone of rupture. Predicting structural deformations related to cracking networks may prove to be a valuable tool for infiltration and solute transport problems.

REFERENCES

Beven, K., and P. German. 1982. Macropores and water flow in soils. Water Resources Research 18:1311-1323.

Bouma, J. and L.W. Dekker. 1978. A case study on infiltration into dry clay soil, I. Morphological Observations. Geoderma 20:27-40.

Bouma, J., and J.H.M. Wösten. 1979. Flow patterns during extended saturated flow in two, undisturbed swelling clay soils with different macropores. Soil Sci. Soc. Am. J. 43:16-21.

Ritchie, J.T., D.E. Kissel, and Earl Burnett. 1972. Water movement in undisturbed swelling clay soil. Soil Sci. Soc. Am. Proc. 36:874-879.

Quisenberry, V.L., and R.E. Phillips. 1976. Percolation of surface applied water in the field. Soil Sci. Soc. Am. J. 40:484-489.

Prasad, S.N., M.J.M. Römkens, R.R. Wells, and R. Neely. 1999. Predicting incipient ponding and infiltration into cracking soil. In Proceedings of the 19th Annual American Geophysical Union Hydrology Days, August 16-20, 1999, edited by Hubert J. Morel-Seytoux, 343-356. Colorado State University, Fort Collins, CO.

Wells, R.R. 1995. "Effect of cracks on rain infiltration in a Mississippi Delta clay soil." Master Thesis, University of Mississippi.

White, E.M. 1972.Soil-Dessication features in South Dakota depressions. Journal of Geology 80:106-111.

Wilding, L.P. and D. Tessier. 1988. Genesis of Vertisols: Shrink-swell phenomenon. Vertisols: Their distribution, properties, classification, and management. L.P. Wilding and R. Puentes, (eds.). Texas A&M Printing Center, College Station, TX. pp 83-96.