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Understanding Shallow Slope Failures on Expansive Soil Embankments in North Texas Using Unsaturated Soil Property Framework

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Abstract

Slopes constructed with expansive soils are prone to shallow slope failures when subjected to seasonal wetting-drying. This article presents a field experimental study and corresponding modeling analysis to understand slope failures at shallow depths, typically ranging from 1 to 5 ft (0.3–1.5 m) from the surface. Previous studies (Brand 1981; Cho et al. 2002; Chen et al. 2004) revealed that the major cause of shallow slope failures for earthen dams is due to the formation of surficial cracks due to rapid matric suction change occurring during cyclic wetting-drying from seasonal changes. The purpose of this study is to identify the influential factors such as soil matric suction on the stability of unsaturated soil slopes. In this study, soil from a test section at Joe Pool Lake dam, Texas is considered. Test soil was subjected to basic soil characterization and later studied for their engineering behavior. Unsaturated soil properties for Joe Pool Lake soil are obtained by evaluating the soil water characteristic curve (SWCC) using pressure cell and filter paper technique. Rainfall and temperature data collected at the site were utilized for modeling the unsaturated condition of the slope using VADOSE/W software. Results showed that consistent matric suction variation contributed to the reduction in the stability of the slopes. This analysis also provided valuable insight into the formation of fully softened zones at shallow depths due to the formation of desiccation cracks.

Keywords: shallow slope stability, expansive soils, unsaturated soil framework, desiccation crack

INTRODUCTION

Stability of man-made slopes like highway embankments, cut slopes, earth dams and similar structures is a matter of concern for Geotechnical engineers. Among the different kinds of slope failures, surficial slope failures are often encountered in which a shallow slope failure of about 1-4 feet (0.3 m to 1.2 m) deep is observed (Evans, 1972, Day, 1996 and Minh Le, 2015). Such failures do not instantly affect the functioning of the structures but progressive failures are detrimental to the structural integrity and pose a serious threat to the structure if not repaired in time (USACE, EM-1110-2-1902, 31 Oct 2003).

Embankment slopes having clayey soils are often subjected to seepage, swelling, shrinkage, creep and formation of cracks. These influence the shear strength and hence the integrity of the slope (Duncan et al., 2005). The shear strength of slopes is generally high during summers owing to the contribution of matric suction, which increases the effective stress in the soil system. The phenomenon is reversed during intense rainfalls when the infiltration of water through desiccation cracks increases the degree of saturation leading to reduced soil particle contact, reduced matric suction and hence decrease in strength (Brand, 1981 and Chen et al., 2004). Such loss of strength during a period of prolonged rainfall may lead to failure of slopes (Cho et al., 2002). Besides the reduction in shear strength, the shear stress increases when the cracks are filled with water which acts as a driving force to slide the soil mass.

Surficial failures were observed at Joe Pool Dam in North Texas within two years of its construction possibly due to prolonged rainfall events followed by droughts. Although the failures typically occur between March and July, some failures during the winter period of December and January were also observed. Failures were observed to occur at previous failure sites or in its vicinity (McCleskey et al., 2005 and 2008). Besides rainfall intensity, factors like rainfall characteristics, rainfall pattern, soil characteristics, and slope geometry also affect to the failure of any slope (Churches and Miles, 1987).

Field experiments conducted by Fan and Hsiao (2010) to study the influence of slope terrain on the distribution of matric suction of soil showed the considerable effect of matric suction on the slope stability. Rahardjo et.al. (2010) conducted research on factors contributing to slope failures and found out that the factor of safety (FOS) during rainfall was not affected significantly by the groundwater table near the ground surface.

Ng & Q. Shi (1998) modeled both saturated and unsaturated slope using two-dimensional finite element software SEEP/W. The objectives of the study were to illustrate and clarify the nature of the pore pressure distribution in a typical unsaturated slope and to demonstrate the sensitivity of transient flow systems to various initial hydraulic boundary conditions, rainfall intensities and duration, and in-situ soil permeability. Gofar et al. (2006) examined the mechanism causing the slope failure based on transient analysis for a case of a rainfall-induced landslide in Air Laya, Indonesia. Results showed that the main factor contributing to the landslide is the reduction of shear strength due to increase in soil moisture content impelled by the formation of tension cracks on the ground surface of the slope.

This paper presents the numerical modeling of unsaturated soil slope with the inclusion of field soil moisture and temperature variation due to local climate variation at Joe Pool dam site. This modeling was undertaken using plane strain model (using VADOSE/W software) that has the atmospheric boundary condition at the top. Mohr-Coulomb model was adopted and the required soil properties were determined from the samples collected from the field and tested in the laboratory. Three cases were adopted for the analysis: (a) No precipitation, (b) with precipitation and (c) precipitation with desiccation cracks.

TEST SITE

The present study is conducted at the Joe Pool Lake dam, Texas, located at Latitude: 32º 38' 39.26" N and Longitude: 97º 00' 6.76" W. This earthen dam was constructed in April 1986 and has a slope of 2.8H: 1V. This dam underwent frequent repairs due to damages caused by the expansive nature of the soil and seasonal fluctuations (McCleskey, 2005). Figures 1(a) and (b) show slope failures occurred due to desiccation cracks formed from seasonal changes.

(a) (b)

Figure 1. (a) and (b) showing the slope failures of Joe Pool Lake Dam, Texas (Mc Clesky, 2005).

LABORATORY CHARACTERIZATION

Table 1 summarizes the basic soil characterization conducted on Joe Pool Lake dam soil. Results of sieve analysis (as per ASTM D6913) and Atterberg limits (as per ASTM D4318) are also included.

Laboratory studies concluded that the soil was high expansive clay which caused the slope failures during seasonal changes. A test section has been selected on the dam site to study the real-time effect of seasonal variations.

Standard Proctor tests were performed on Joe Pool dam soil and the maximum dry unit weight was observed to be 93 pcf (14.6 kN/m^3). The undrained shear strength of the soil sample was obtained by performing unconsolidated undrained (UU) triaxial compression test on three undisturbed samples collected from the dam slope, from a depth of 6 to 8 ft. (1.8 to 2.4m) using Shelby tube. The average in-situ water content of the undisturbed samples was 12%. The average undrained shear strength value was used for the analysis of no rainfall condition (Case 1). The residual shear strength parameter was obtained using Bromhead torsional ring shear (TRS) device and were used for long-term rainfall condition with and without desiccation cracks.

Table 1. Properties of soil from Joe Pool Lake dam (Mc Clesky, 2005).

Property	Joe Pool Dam
% Passing No. 200 sieve	69.4
Liquid limit, %	58
Plastic limit, %	24
Plasticity Index	34
USCS Classification	CH
Activity	Active (3)
% of clay fraction	12

The temperature of the test section and the rainfall data for each month over the period of one year (October 2007- September 2008) from the weather station near Joe Pool Dam is presented in Table 2.

Table 2. Temperature and Rainfall data for Joe Pool Dam test section.

Month	Average Rainfall, inch (mm)	Rainfall intensity, inch/hr (mm/hr)	Average temperature (°F)
October	4.65 (118.1)	1.55 (39.3)	68
November	2.61 (66.3)	0.87 (22.1)	60
December	2.53 (64.3)	0.84 (21.3)	54
January	1.89 (48.0)	0.63 (16.0)	49
February	2.31 (58.7)	0.77 (19.5)	51
March	3.13 (79.5)	1.04 (26.4)	56
April	3.46 (87.9)	1.15 (29.2)	65
May	5.3 (134.6)	1.77 (44.9)	74
June	3.92 (99.6)	1.31 (33.2)	85
July	2.43 (61.7)	0.81 (20.6)	88
August	2.17 (55.1)	0.72 (18.3)	88
September	2.65 (67.3)	0.88 (22.3)	80
Average	2.94 (74.7)	0.98 (24.9)	68

SOIL WATER CHARACTERISTIC CURVE

The soil water characteristic curve (SWCC) obtained using Pressure plate apparatus (as per ASTM C1699) and Schleicher & Schuell No. 589-WH type Filter paper (as per ASTM D 5298) is shown in Figure 2. The specimen was prepared using static compaction method and were compacted at field density conditions (93 pcf (14.6 kN/m^3) maximum dry unit weight at 12% moisture content). The pressure plate apparatus was used to get the SWCC up to 21,000 psf (1005 kN/m^2). The filter paper method was used to complete the remaining part of the SWCC. The air entry value for the given soil was found out to be 650 psf (31 kN/m^2) with a saturated volumetric water content of 0.57 and residual water content of 0.05.

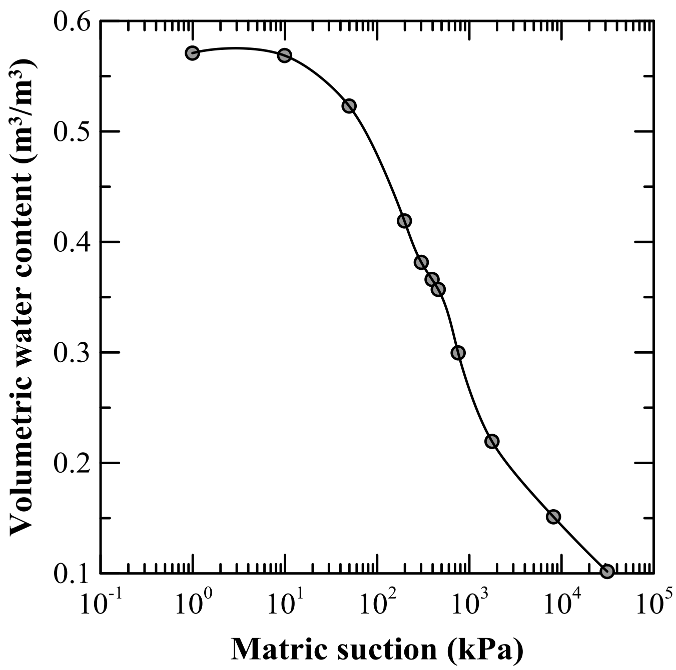

Figure 2. SWCC of Joe Pool dam clay

UNSATURATED SLOPE STABILITY ANALYSIS

Figure 3 shows the geometry of Joe Pool dam slope used in the analysis. Joe Pool dam comprises of three different regions: Pavement, compacted core soil, and topsoil within 5 ft. (1.5 m) from the surface. The surficial failure is most likely to occur in the upper part of the downstream side of the dams it has a steeper slope with a ratio of 2.8 H: 1 V. Mohr-Coulomb material model was adopted in this analysis. The basic soil parameters such as density, cohesion and friction angle are used as input in SLOPE/W.

The plane strain case of Joe Pool dam slope was numerically modeled using finite element software VADOSE/W (GeoStudio 2012) to simulate the variation of field moisture and temperature due to climatic variations. Climatic boundary condition was applied to simulate the interaction of surface layer of slope and the atmosphere. This includes air temperature, relative humidity, wind speed and precipitation data collected using field instrumentation. The average relative humidity and wind speed used in the analysis is 50% and 10 ft./sec (3 m/s) respectively. Seepage analysis was not performed, rather, hydraulic boundary condition was applied by specifying the upstream head at 22 ft. (6.7 m) and downstream head at 4 ft. (1.22 m), to obtain the phreatic surface. Transient analysis was performed using adaptive time stepping that is required for solving climatic boundary condition for a duration of one year (Oct-2007 to Sep-2008). The model was then imported to SLOPE/W to perform stability analysis of the slope. Limit equilibrium approach, which generates all possible slip surfaces and reports the lowest possible factor of safety (FOS) was used for the analysis. The Morgenstern-Price method was adopted to calculate FOS as it satisfies both force and moment equilibrium. Table 3 presents the soil shear strength parameters obtained from TRS and UU test for Joe Pool dam and used in the SLOPE/W analysis. The unsaturated condition of the dam was integrated into the SLOPE/W analysis by importing the volumetric water content function from the VADOSE/W analysis. This step is to calculate unsaturated friction angle (ϕ_b) and unsaturated unit weight of the Joe pool dam clay.

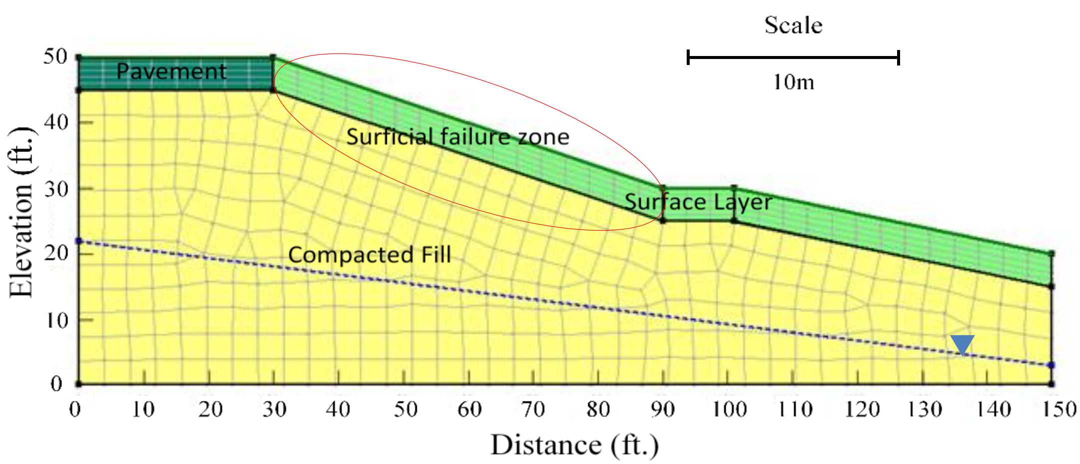

Figure 3. The model geometry of Joe Pool dam.

Table 3. Shear strength parameters for Joe Pool Dam clay

Case	Test Method	c (psf) (kPa)	ϕ (degrees)
Case 1	UU Triaxial Test	1309.5 (62.7)	0
Case 2 and Case 3	TRS Test	0	22

For evaluating the short term and long term stability of the Joe Pool dam slope, numerical analysis was performed for three different scenarios: (a) Case 1: which represents the short-term post-construction condition of the slope, (b) Case 2: which consider the maximum water table level obtained from the VADOSE/W analysis and (c) Case 3: represents the worst case scenario in which desiccation cracks are formed at the surface layer along with the maximum water table level obtained from the VADOSE/W analysis. Soil properties were assigned to the regions with respect to the three scenarios and their corresponding strength parameters.

Case 1: Numerical simulation was performed to evaluate the stability of Joe Pool dam slope under short-term condition. The dam was constructed by compacting borrow soils at optimum moisture content and it was assumed that there is no change in moisture content. Undrained shear strength was used for this analysis. The slip surface developed is shown in Figure 4.

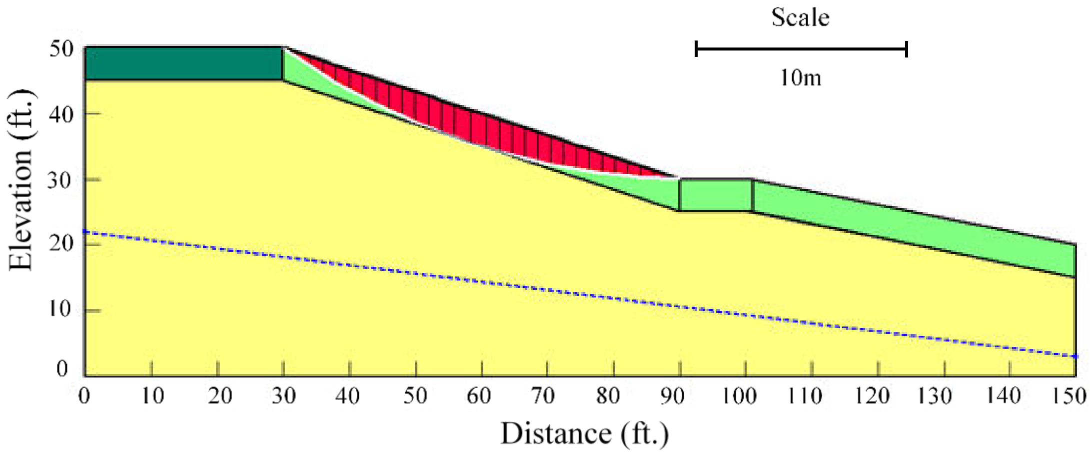

Figure 4. Slip surface for the case 1 under short-term condition.

Case 2: Numerical simulation was performed to evaluate the effect of precipitation on the stability of the unsaturated slope by including precipitation and temperature data using VADOSE/W. The average rainfall data was considered and used for a given month. The surface layer was modeled and the climatic boundary condition was applied. The simulation was then carried out for 365 days and the maximum water table level was observed after 104 days. Stability analysis was performed at this stage to determine the factor of safety (FOS) of the slope. The slip surface developed due to sudden rainfall is shown in Figure 5. The depth of the slip surface is observed to be 0.3 inches (7.6 mm). Contour plot of matric suction developed in the Joe pool dam after 104 days and 365 days are shown in Figure 6a and 6b respectively.

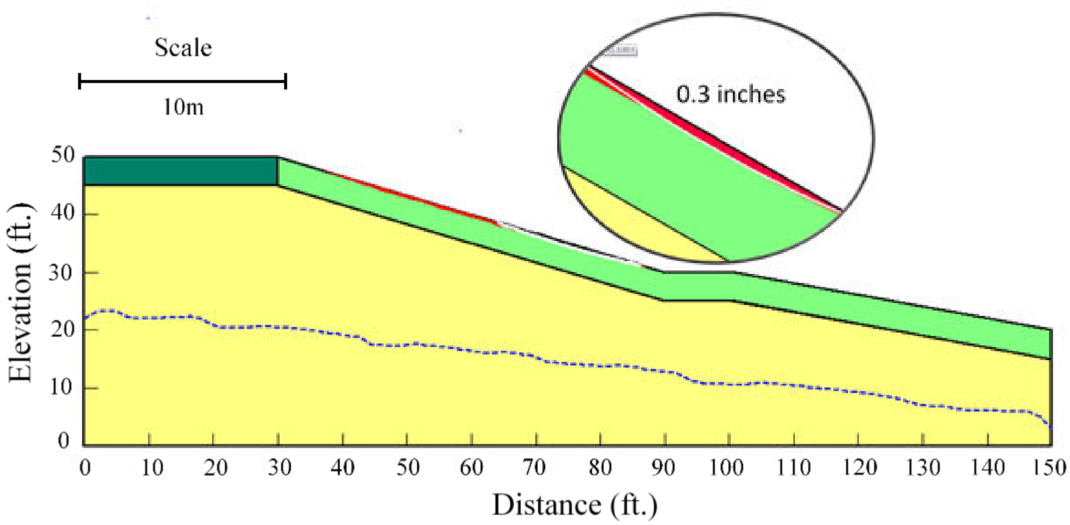

Figure 5. Slip surface for the case 2 with maximum water table level from VADOSE/W.

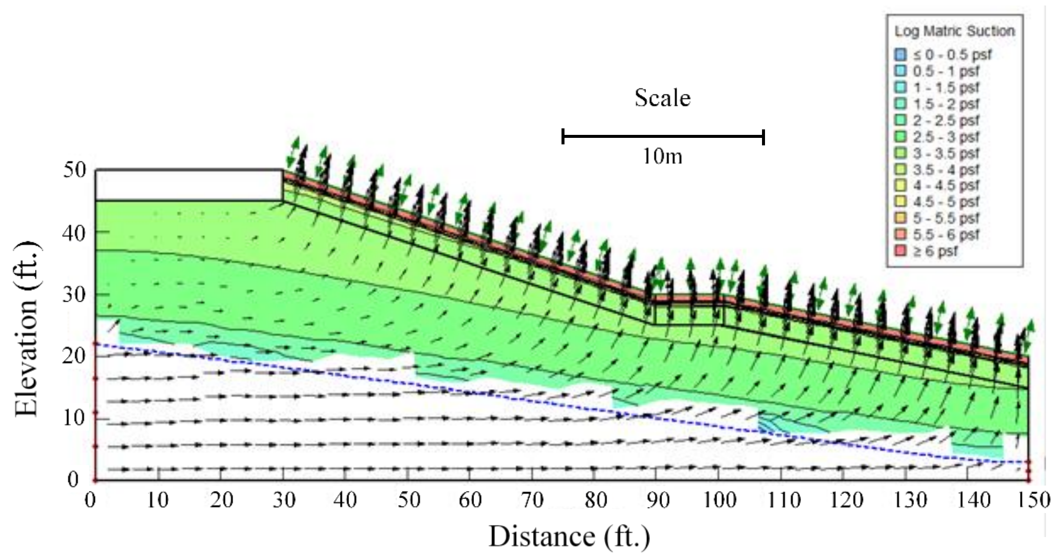

Figure 6a. Matric suction profile for the case 2 with maximum water table level (after 104 days) from VADOSE/W.

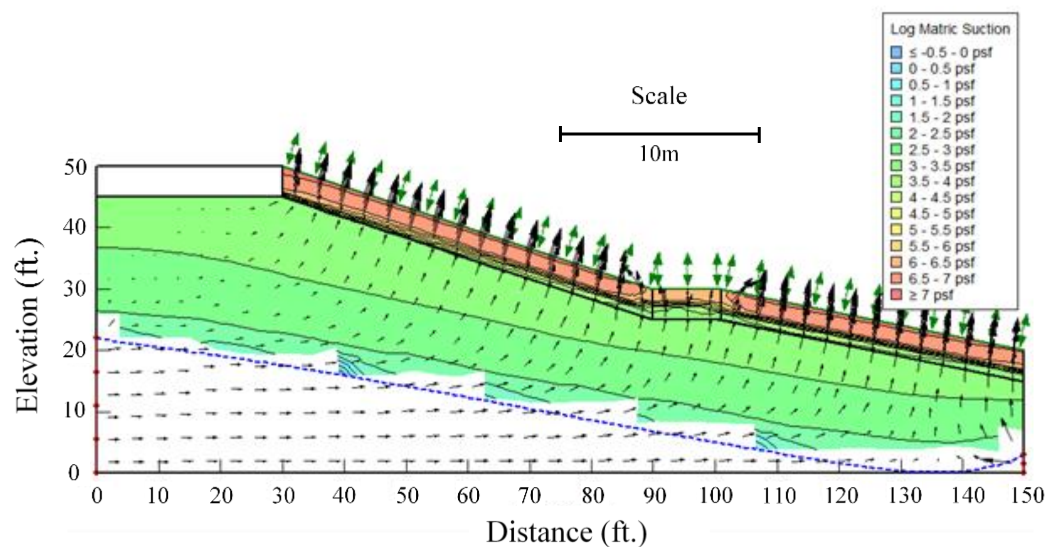

Figure 6b. Matric suction profile after 365 days from VADOSE/W.

Case 3: Desiccation cracks are very common in expansive clay slopes. These cracks are mainly formed parallel to the alignment direction of the dams. Le (2013) and Acharya (2015) reported a desiccation crack almost 8 m long in the Joe Pool dam slope. To analyze the effect of these cracks on the stability of unsaturated slopes, simulations were performed on the Joe Pool dam model with tension cracks. These cracks were assumed to be infinite in the direction along the axis of the dam. Two cracks were considered at a spacing of 7 ft. (2.13 m) and the stability analysis was performed using SLOPE/W. Surficial failure surface is observed at a lower Factor of Safety and is shown in Figure 7.

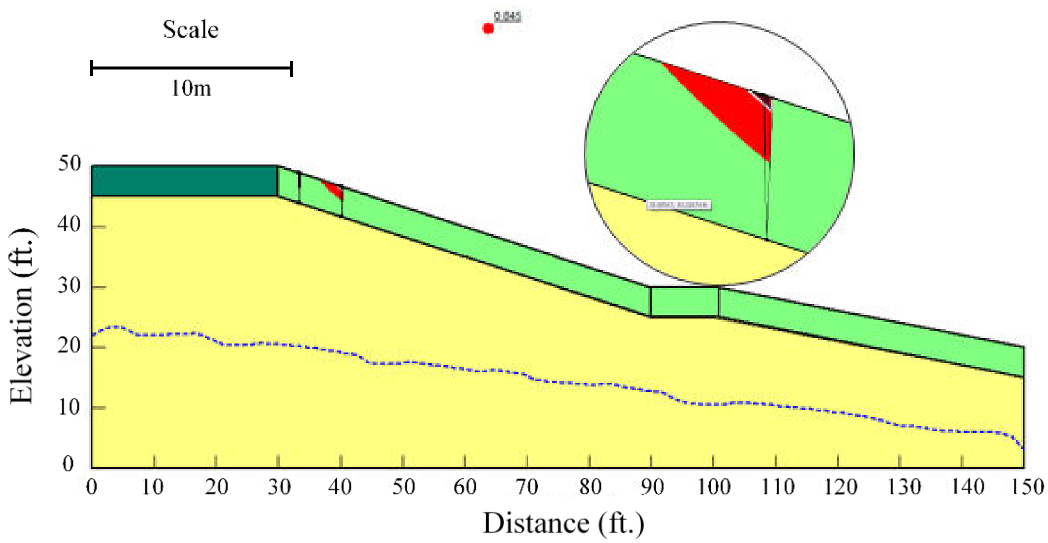

Figure 7. Slip surface for the case 3 with maximum water table level from VADOSE/W along with desiccation cracks.

The FOS obtained for the above cases are listed in Table 4. Generally, a minimum FOS for the embankment to prevent surficial failure is 1.5. A sudden drop in the minimum factor of safety from 17.123 to 1.213 is observed when the precipitation is considered in the analysis. This is due to the reduction in shear strength of the soil because of a sudden increase in pore water pressure. The presence of desiccation cracks further reduced the FOS to 0.847.

Table 4. The factor of safety obtained from the analysis.

Case	Factor of safety
Case 1	17.123
Case 2	1.213
Case 3	0.847

SUMMARY AND CONCLUSIONS

This study evaluates the effect of precipitation and desiccation cracks on the stability of unsaturated soil expansive slopes. Laboratory tests are conducted on the soil samples to