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Evaluation of the Impact of Climate Variability on the Soil-Water Characteristics Curve

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Abstract

The hydro-mechanical behavior of unsaturated soil, particularly expansive soil, is influenced significantly by cyclic wetting and drying. Understanding the soil parameters is crucial when evaluating the performance of infrastructures constructed on expansive clay. As a result of extreme rainfall events, highway slopes containing highly expansive Yazoo clay in Mississippi, U.S., become vulnerable to volume change. The phenomenon creates perched water zones within the slopes and poses a risk of slope failure. The soil-water characteristic curve (SWCC) defines the relationship between water content and soil suction, which can be obtained from different laboratory procedures. However, conventional laboratory methods have some limitations. To address this, various analytical and predictive models have been developed, but they can only offer estimates based on soil characteristics and lack seasonal variations occurring in field conditions. Studying seasonal SWCC through field measurements can help understand soil responses to changing moisture conditions. The current study utilized field data from six highway slopes in Mississippi and classified the data into different seasons: spring, summer, and fall. After obtaining van Genuchten parameters from the fitted curve for each season, the finite element method was applied to evaluate the parameters for accurate numerical analysis of infrastructures containing expansive clay. The study observed the variations in flow parameters with seasonal change that cannot be achieved when data from only one season is considered. The findings underscore the importance of field instrumentation data for developing SWCC and the significance of seasonal flow parameters in infrastructure design.

Keywords

unsaturated soil, soil-water characteristic, expansive soils, numerical modeling

"Unsaturated" soil refers to the state of the soil where a proportion of the void space between the particles is filled with air. There is lower pressure in the pore water compared with the air, leading to pressure differences that can be significantly larger than atmospheric pressure and can cause volume changes (*1*). The hydro-mechanical behavior of unsaturated soil is significantly affected by cyclic wetting and drying (*2*). The negative pore-water pressure, known as soil suction, can substantially affect infrastructures as it relates to important soil characteristics. There is a risk of rainwater infiltration if the pore-water pressure is neglected. Therefore, it is very important to know the parameters while evaluating the performance of any infrastructure built on unsaturated soil.

Expansive soil is mainly found in semi-arid regions, and, because of the loss of moisture content in the drying period, it faces desiccation drying. This leads to the unsaturated condition of the soil (*3*). Expansive soil is highly plastic in characteristic and goes through volume change with seasonal moisture change (*4*). Climatic conditions and clay mineral present in the soil are important factors affecting the volume change of soil. In addition, the desiccation bond governs the shear strength and, as a result, the volume change behavior of the soil (*5*). During summer, evapotranspiration causes shrinkage of soil, forms desiccation cracks, and increases the void ratio in the soil. Through rainfall events, those voids are filled with rainwater because of the high infiltration rate. It

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increases the moisture content and, eventually, the volume of voids (*6*). In spring, the soil's low permeability causes water to become trapped, leading to the development of a perched water zone (*7*). Rainwater infiltration has an impact on the mechanical properties of soil, particularly on suction and cohesion. Increased moisture reduces the soil matric suction and cohesive strength (*8*).

Various transportation infrastructures, including highway slopes in Mississippi, U.S., contain expansive Yazoo clay because of the lack of any other suitable fill materials. As a consequence of cyclic wetting and drying, the soil reaches up to its fully softened (lower) shear strength from the initial high level of shear strength (*9*, *10*). Montmorillonite, illite, and kaolinite are considered the three most significant groups of clay minerals (*11*). Many studies have found a link between the montmorillonite content and the swelling behavior of expansive soil (*12–14*). Montmorillonite exhibits high plasticity as it possesses a considerably large surface area that attracts a substantial volume of water (*10*). Yazoo clay in Mississippi contains 28% smectite (montmorillonite is a specific type of smectite) that drives the abrupt shrinking and swelling behavior of this type of soil (*15*, *16*). Highway slopes built on Yazoo clay are, therefore, vulnerable to rainfall-induced failure (*17*, *18*).

The volume change behavior of expansive soil comes with the consequence of infrastructural loss. Every year, the cost of damages caused by it exceeds USD 15 billion in the U.S., surpassing the combined damage caused by floods, hurricanes, tornadoes, and earthquakes (*19*). According to the American Society of Civil Engineers, 25% of homes experience damage caused by expansive soils (*20*). Studies observed the trajectories of increased rainfall in southeastern U.S. regions by approximately 20% in the last century as a result of climate change, and this is expected to continue (*21*). During August 2022, six extreme events exceeded the local threshold in Mississippi, qualifying as "1-in-1,000-year" rainfall events according to the classification by the National Weather Service. In a single day, certain regions in Mississippi experienced rainfall of over 8 in. within a span of just 3 h (*22*). A study conducted on six highway slopes in Mississippi found the existence of perched water zone caused by extreme rainfall events (*7*, *15*). The study also observed the increased moisture content and decreased matric suction of the soil after intense precipitation.

Matric suction is one of the most important factors in understanding the behavior and shear strength properties of expansive soil (*23–25*). The relationship between the water content and the soil suction or negative pore water pressure can be presented through the soil-water characteristic curve (SWCC) (*26*). The slope of the SWCC defines the water movement in the soil (*27*). SWCC for a particular soil can be obtained through different laboratory methods. Currently, the available methods are using: a pressure plate apparatus, filter papers, vapor pressure method, evaporation method, Wind-Schindler method (WSM), or humidity cells such as a WP4C dewpoint water potentiometer (*28–32*). However, most of the laboratory methods are subject to several limitations. The pressure plate apparatus requires significant equilibration time, ranging from hours to several days (*33*). Some methods have limitations considering the resolution range of matric suction. While the vapor pressure technique is more effective for measuring suction values below 1,000 kPa, an evaporation technique, such as WSM, performs better in the range of 0–1,000 kPa. Soil properties are altered while handling the samples for laboratory tests (*29*). In addition, the laboratory tests conducted in a controlled environment might not always represent the original field situation.

To reduce the challenges in establishing SWCC from laboratory methods, different analytical and predictive models are developed over time. Leong and Rahardjo evaluated different models and observed that the equations suggested by van Genuchten, McKee and Bomb, and Fredlund and Xing give curves close to sigmoidal, which were compatible with the general shapes of SWCC established by their study (*28*, *34–36*). The fitting parameters corresponding to these equations define the shape of the curve. Different predictive models can predict the parameters based on soil properties such as percent finer, hydraulic conductivity, or void ratio of the soil. However, the predictive models can only give an approximation of SWCC as it involves only soil parameters. The curve attained from these models cannot give the seasonal variations related to real-time changes in matric suction and moisture content. Studying the seasonal SWCC can assist in understanding the soil's response to seasonal moisture variations. The risk of slope failure during wetting and drying periods can also be predicted from field measurements. Also, a study conducted on expansive soil samples exhibited irreversible swelling and shrinkage during wetting and drying cycles being subjected to various surcharge pressures, which cannot be predicted based on the characteristics of soil samples collected in a single season (*6*). Therefore, SWCC obtained from field instrumentations can be a better way to describe the behavior of expansive soil in different climatic variations.

Al-Yahyai et al. adopted the field-sensor-based SWCC formation approach and developed customized calibration curves for particular multi-sensor capacitance and neutron probes installed at the study site consisting of loam soil (*37*). Jabro et al. established field-data-based

Table 1. Locations of the Selected Slopes

Site No.	Site location	Site coordinate	Site No.	Site location	Site coordinate
1	I220N ramp toward I55N	32°24′46.60″N, 90° 8′57.32″W	4	Highland Drive	32°17′21.22″N, 90°14′17.58″W
2	Metro Center	32°17′58.85″N, 90°14′47.00″W	5	Sowell Road	32°32′30.11″N, 90° 5′50.49″W
3	Terry Road	32°16′48.92″N, 90°12′44.03″W	6	McRaven Road	32°17′45.71″N, 90°16′17.17″W

SWCCs for sandy loam and clay loam (*38*). The study found the effectiveness of real-time data in accurately predicting soil water retention behavior. The research conducted by Bordoni et al. considered different hydrological conditions on soil with high silt content to evaluate the performance of field-based instrumentation in successfully depicting SWCC (*33*). Ahmed et al. also developed field-instrumentation-data-based SWCC for highly plastic clay in one of the sites in Texas and compared the parameters with the parameters obtained from five predictive models (*27*). The study also concluded that field measurement has better capability in capturing the variation of SWCC for numerical modeling purposes. However, no previous study has been found that examines the seasonal soil water retention behavior of expansive soil through field instrumentations, specifically on Yazoo clay.

The objective of the current study is to determine the seasonal flow parameters of expansive soil and evaluate the importance of addressing the changes in these parameters with climatic variations. Field-obtained moisture sensor and water potential sensor data from six highway slopes in Mississippi were classified into three different seasons—spring, summer, and fall. Corresponding van Genuchten parameters for three distinct seasons were obtained after fitting the curve with the field data. In addition, the finite element method (FEM) was utilized to further investigate the impact of seasonal flow parameters on soil shear strength. The study found the importance of utilizing field instrumentation data for establishing SWCC and emphasized the significance of seasonal flow parameters for accurate numerical analysis of infrastructures constructed on expansive clay.

Methods

Site Locations

Six highway slopes consisting of highly expansive Yazoo clay and located in the Jackson Metroplex in Mississippi were selected for this study (see Table 1). The selected slopes exhibited early signs of movement or had a history of failure and prior repairs (*18*).

Table 2. Properties of Yazoo Clay

Physical property	Value
Liquid limit	108%
Plasticity index	84%
Dry unit weight	12.88 kN/m^3
Specific gravity	2.68
Natural moisture content	35%

Soil Properties

According to the previous study, the soil was classified as highly plastic clay based on a grain size distribution analysis following “Standard Test Method for Particle-Size Analysis of Soils” (ASTM D422) and “Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis” (ASTM D7928) (*39*). The study identified other parameters of the soil that are presented in Table 2.

Field Instrumentation

Field instrumentation such as GS-1 moisture sensors, Meter Teros 21 soil water potential probes, and ECRN-50 tipping-bucket rain gauge were installed in each site to track the soil moisture content, matric suction, and rainfall intensity, respectively (see Figure 1). The moisture sensors and water potential sensors were placed at the crest, middle, and toe of the slope at 5 ft, 10 ft, and 15 ft depth. Site 3 had additional sensors installed at 6 in. and 18 in. depths. The sensors can produce hourly data, which were collected periodically using the help of data loggers, from 2018 to 2022.

Seasonal Categorization of Field Data

The temperature data from 2020 to 2022 were acquired from the National Aeronautics and Space Administration (NASA) Power Access Data Viewer website shows that the months from January to May has trend of uprising temperature (see Figure 2) (*40*). The

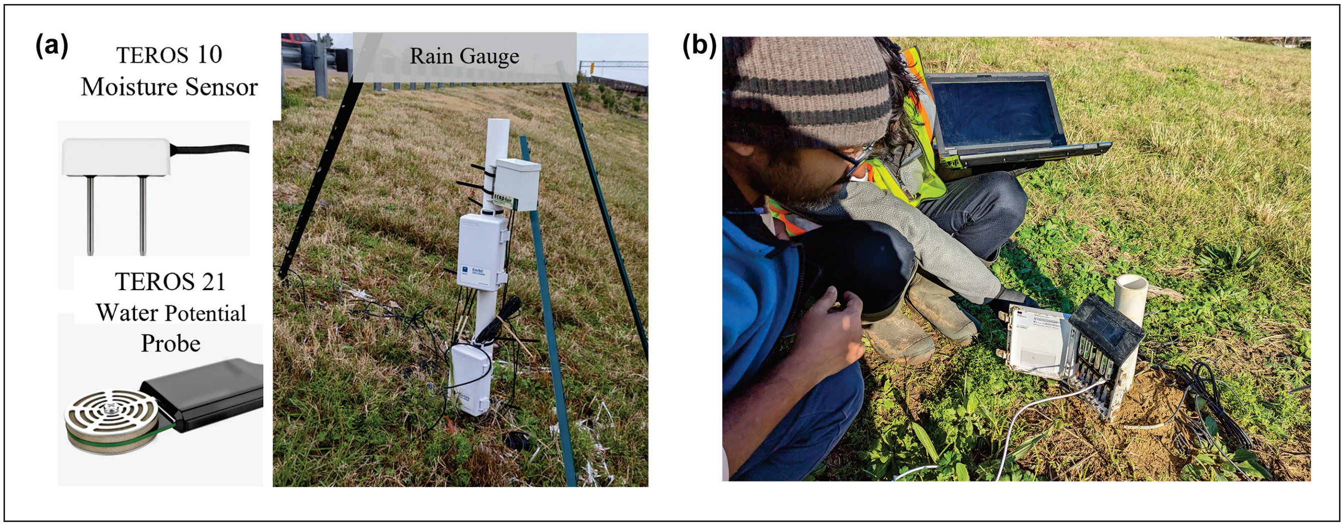

Figure 1. Field instrumentations in the site to track moisture content, pore water pressure and precipitation: (*a*) moisture sensor, water potential probe, and rain gauge installed at the site and (*b*) data collection from data logger at the site.

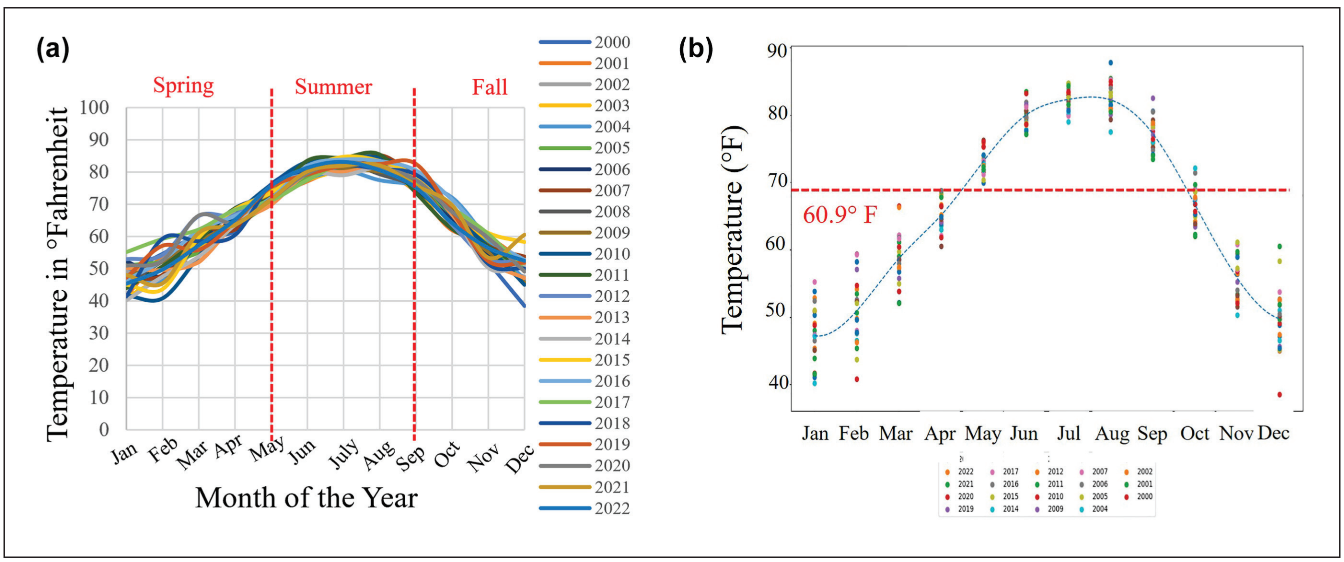

Figure 2. Temperature data in the Jackson area from 2000 to 2022 (National Aeronautics and Space Administration [NASA] Power Data Access Viewer): (*a*) seasonal differentiation on the basis of historical temperature data and (*b*) fitting curve considering 22 years of temperature data.

months from June to September have average temperatures of more than 70°F. Again, the months from October to December have a decreasing trend. The average temperature was found to be 60.9°F. The fitting curve considering 22 years of temperature data showed an increasing trend from January to May, temperature above 60.9°F from May to September, and a decreasing trend from September to December. Therefore, the year has been divided into three seasons: spring (January–May), summer (June–September), and fall (October–December).

Flow Parameters Estimation

Van Genuchten described a simple equation to form SWCC related to some fitting parameters (*34*). The proposed equation is:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + \left(\frac{\psi}{a}\right)^n\right]^m} \qquad (1)$$

where

θ = volumetric moisture content corresponding to a specific level of suction ψ,

Table 3. General van Genuchten Parameters for Sand, Loam, Clay, and Laboratory Sand (*41*)

Parameter	Sand	Loam	Clay	Laboratory sand
θ_s	0.26	0.37	0.47	0.32
θ_r	0.01	0.05	0.16	0.05
α, 1/cm	−0.0324	−0.0161	−0.0066	−0.0630
n	6.6600	2.6632	1.8601	4.4545

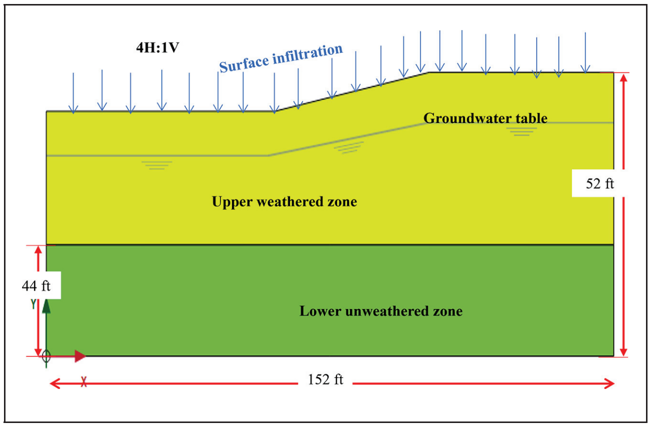

Figure 3. Finite element method soil model considered for analysis.

θ_s = saturated volumetric moisture content,
θ_r = residual volumetric moisture content, and
a, n, and m = fitting parameters ($m = 1- \frac{1}{n}$).

The general values of the van Genuchten parameters for different soils are presented in Table 3.

Ghada established a spreadsheet in Microsoft Excel program where the users can input the field data, and it generates the van Genuchten parameters for the fitted curve (*42*). The current study adopted the van Genuchten model and used the spreadsheet to generate the seasonal flow parameters. The field data for covering four consecutive years (2018–2022) were categorized into three seasons: January–May as spring, June–September as summer, and October–December as fall. Matric suction and moisture content data were used for curve generation. Since the installed sensors were closely spaced and all the sites were built on Yazoo clay, a single curve integrating data from all six sites for each season was generated. Alam, and Ahmed et al. adopted the lower-bound and upper-bound approaches for determining the flow parameters (*27*, *43*). The current study also implemented the same technique and determined average, lower-bound, and upper-bound parameters for each season.

Finite Element Method (FEM)

To get a better understanding of the impact of seasonal variations on van Genuchten parameters, finite element analysis was performed. The soil layer was divided into two segments, the upper weathered and lower unweathered layer. The slope design of Site 6 with a 4H:1V slope was considered for the model (see Figure 3). The model adapted the Mohr-Coulomb approach and 15-node triangular elements. The top layer of soil was considered for the infiltration of rainwater. Three distinct sets of seasonal rainfall data in Jackson for the year 2021 were obtained from the National Oceanic and Atmospheric Administration (NOAA) website. These datasets were utilized as input for periodic rainfall simulation in three separate models.

The unsaturated parameters obtained from the average fitted curves of three different seasons were utilized as the input parameters in PLAXIS 2D program. Vertical permeability was considered higher in summer than in the other seasons because of the development of desiccation cracks during this time (*39*). Other required parameters (see Table 4) were used considering the soil properties from previous studies on Yazoo clay. The FEM model was calibrated by incorporating parameters obtained from a previous study, ensuring that the numerical representation accurately reflected the physical properties of the monitored sites (*15*).

Table 4. Soil Parameters Used for Finite Element Method Analysis

Parameter		Upper weathered layer	Lower unweathered layer
Bulk unit weight (lb/ft^3)		128.5	126.6
Saturated unit weight (lb/ft^3)		134.3	127.3
Horizontal permeability (ft/day) (cm/s)		0.6236×10^{-3} (2.2×10^{-7})	0.6236×10^{-3} (2.2×10^{-7})
Vertical permeability (ft/day) (cm/s)	Summer	0.06236 (2.2×10^{-5})	0.06236 (2.2×10^{-5})
	Spring and fall	0.6236×10^{-3} (2.2×10^{-7})	0.6236×10^{-3} (2.2×10^{-7})
Cohesion (psf)		30	200
Friction angle (degrees)		8°	15°

Note: psf = pounds per square foot.

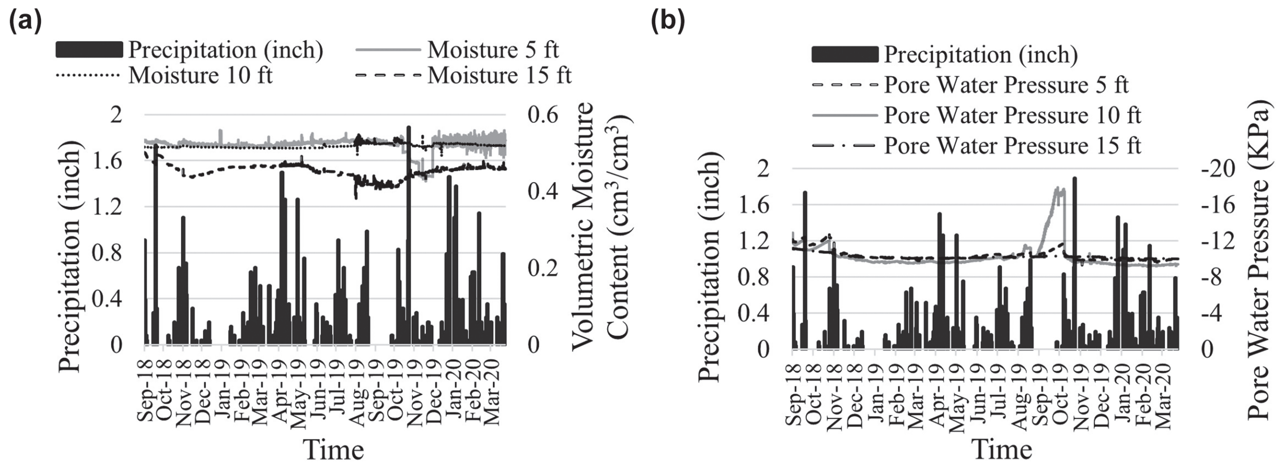

Figure 4. Instrumentation data collected from the field (Site 1): (*a*) moisture content variations with rainfall and (*b*) pore water pressure variations with rainfall.

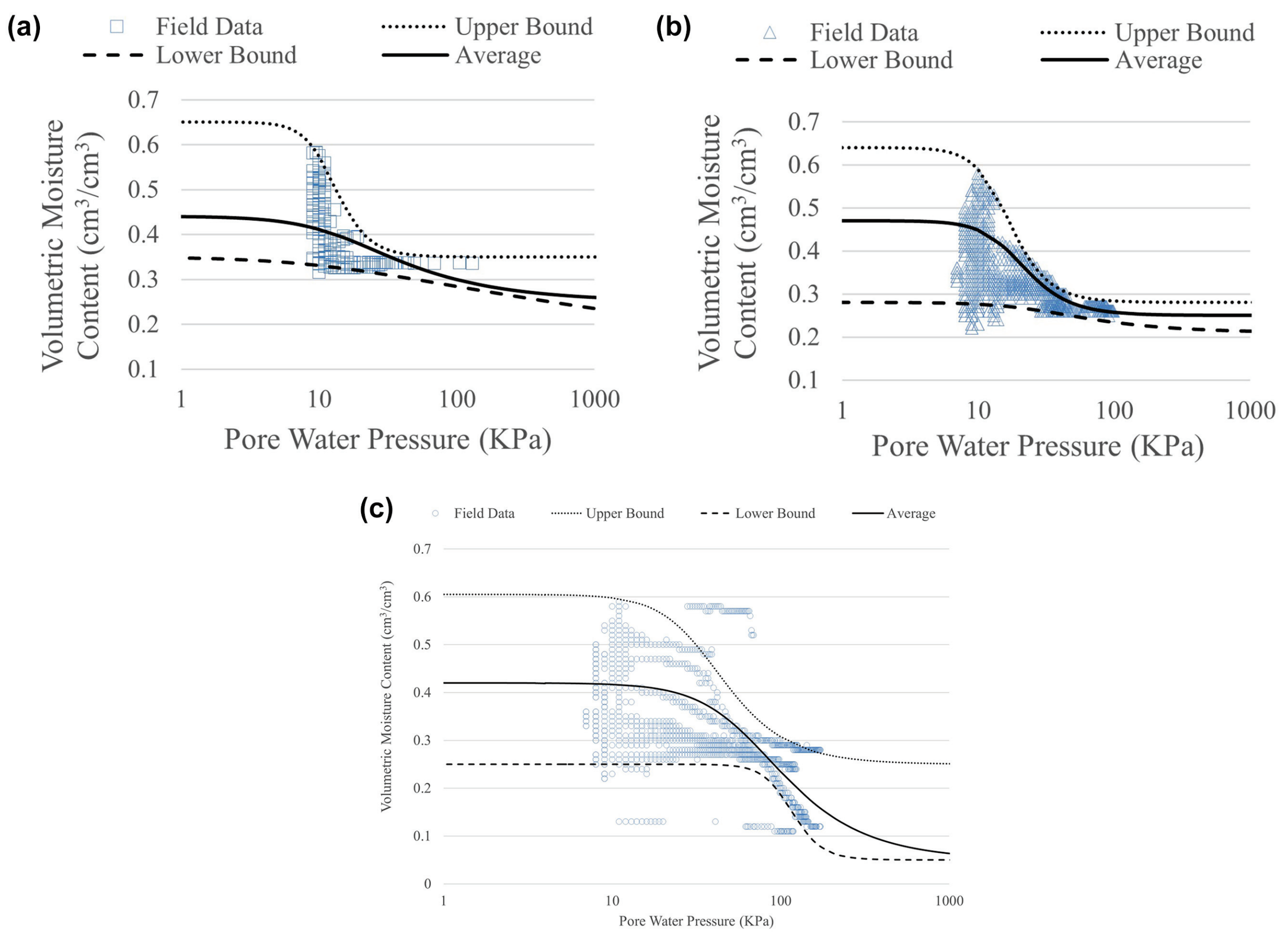

Figure 5. Seasonal soil-water characteristic curve obtained from field instrumentation and fitted with van Genuchten equation: (*a*) spring, (*b*) summer, and (*c*) fall.

Table 5. Van Genuchten Parameters Obtained from Field-Based Soil-Water Characteristic Curve

Parameter	Spring			Summer			Fall		
	Upper bound	Lower bound	Average	Upper bound	Lower bound	Average	Upper bound	Lower bound	Average
θ_r (cm^3/cm^3)	0.35	0.05	0.25	0.28	0.21	0.25	0.25	0.05	0.05
θ_s (cm^3/cm^3)	0.65	0.33	0.44	0.64	0.28	0.47	0.605	0.25	0.42
a (kPa)	12	20	15	15	28	18	35	110	65
n	4	1.1	1.7	3.5	1.8	3	2.7	5.2	2.2
m	0.75	0.09	0.417	0.71	0.44	0.67	0.63	0.81	0.54

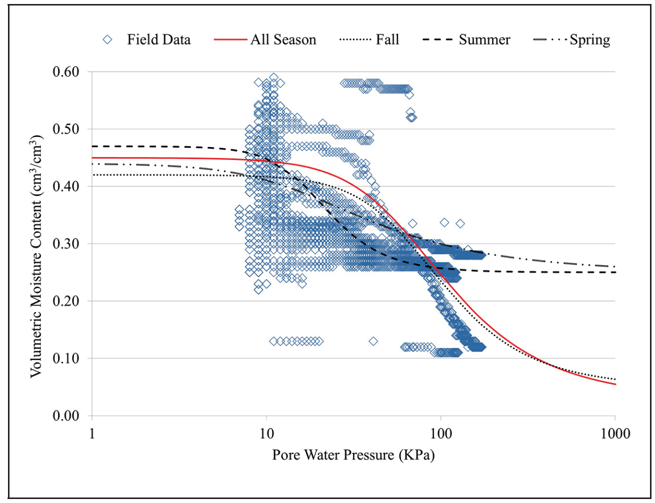

Figure 6. Soil-water characteristic curve obtained from field data of all seasons.

Results

Field Monitoring

The moisture content and pore water pressure data were plotted against the rainfall data from sensors. The diagrams showed that the changes in moisture content and matric suction were quite low with time. Charts obtained from Site 1 are presented in Figure 4 to show the variations in moisture content and suction. The constant moisture content (0.45–0.55 cm^3/cm^3) and constant low water potential (close to 10 kPa) values show the existence of a perched water zone within the slope. Increased values of pore water pressure (up to 18 kPa) were observed during the period when there was little-to-no precipitation. The subsurface temperature was monitored, and no frozen condition was observed in the sites.

Estimation of van Genuchten Parameters

Plots established based on the collected field data show that the real-time data do not demonstrate a linear or a particular trend. The plot was rather scattered between a certain range (see Figure 5). The average residual moisture contents (θ_r) varied from 0.05 to 0.35. Higher values were obtained in some cases as expansive clay has a higher affinity for water, and significant water remains even after it is in the dry state. Higher saturated moisture content (θ_s), ranging between 0.42 and 0.45, also explains the water retention capability of expansive clay because of its mineral contents and large surface area of particles. Most rainfall events occurred during the summer. As a result, the residual and saturated moisture contents were higher in this season.

Table 5 summarizes the parameters found for the fitted curves.

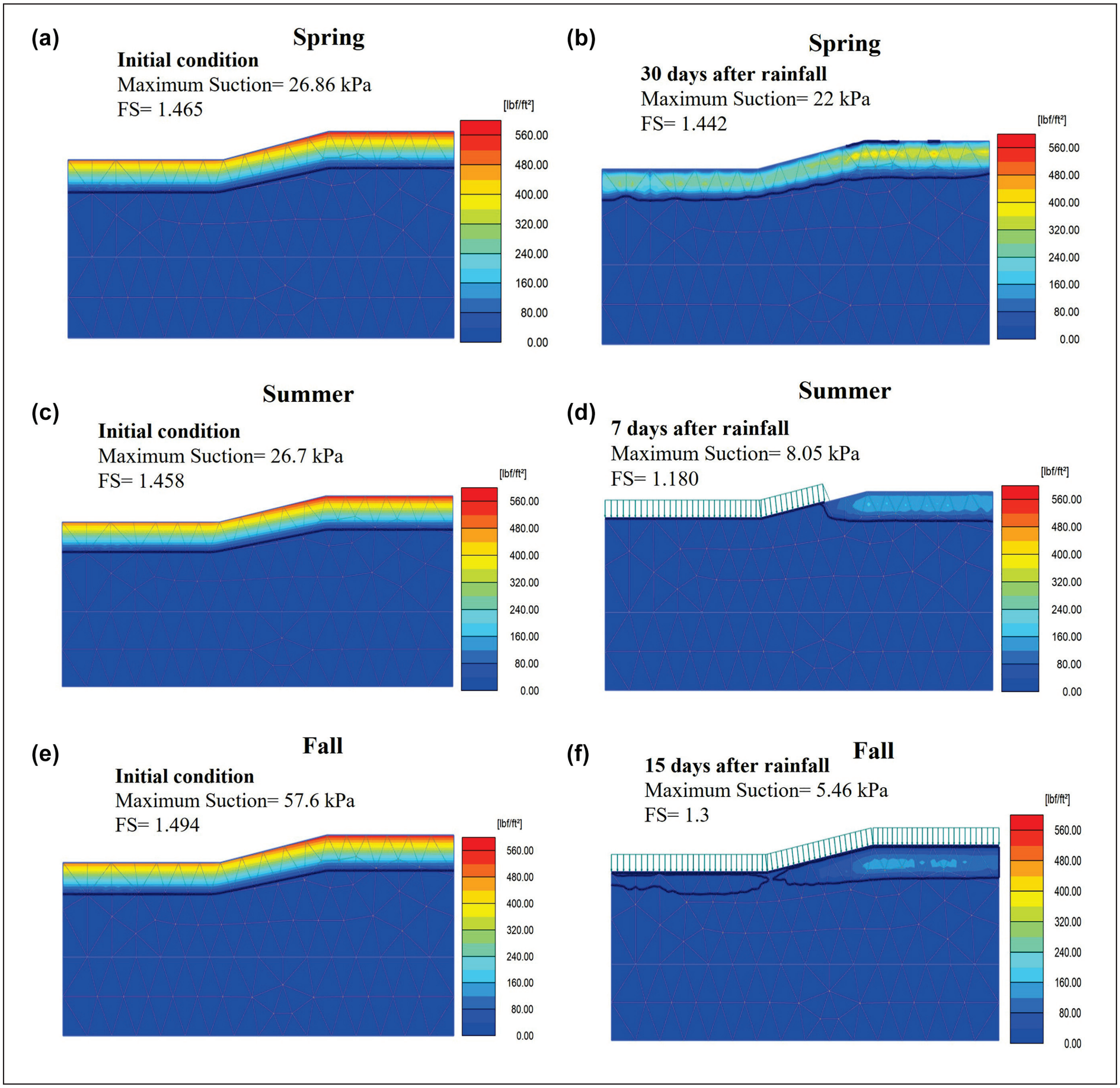

Figure 7. Finite element method flow analysis results for matric suction for three different seasons: (*a*) spring initial condition, (*b*) spring 30 days after rainfall, (*c*) summer initial condition, (*d*) summer 7 days after rainfall, (*e*) fall initial condition, and (*f*) fall 15 days after rainfall.
Note: FS = Factor of Safety.

SWCC was established using field data of all seasons. From Figure 6, it is observed that the SWCC established for the summer season falls above the SWCC established considering all seasons. The curve can be considered as the curve for the drying period as it represents the upper bound. SWCCs drawn for the fall and spring seasons remain under the curve for all seasons, depicting the lower bound or the wetting period.

Finite Element Method (FEM) Flow Analysis Results

The variation of matric suction and factor of safety was obtained at intervals of 3 h, 6 h, 12 h, 24 h, 3 days, 15 days, and 30 days. The numerical analyses in PLAXIS 2D show the changes in matric suction because of rainfall infiltration occurred mostly in the shallower depth. In all the seasons, the initial factor of safety was close to 1.4. The factor of safety was higher after 30 days of

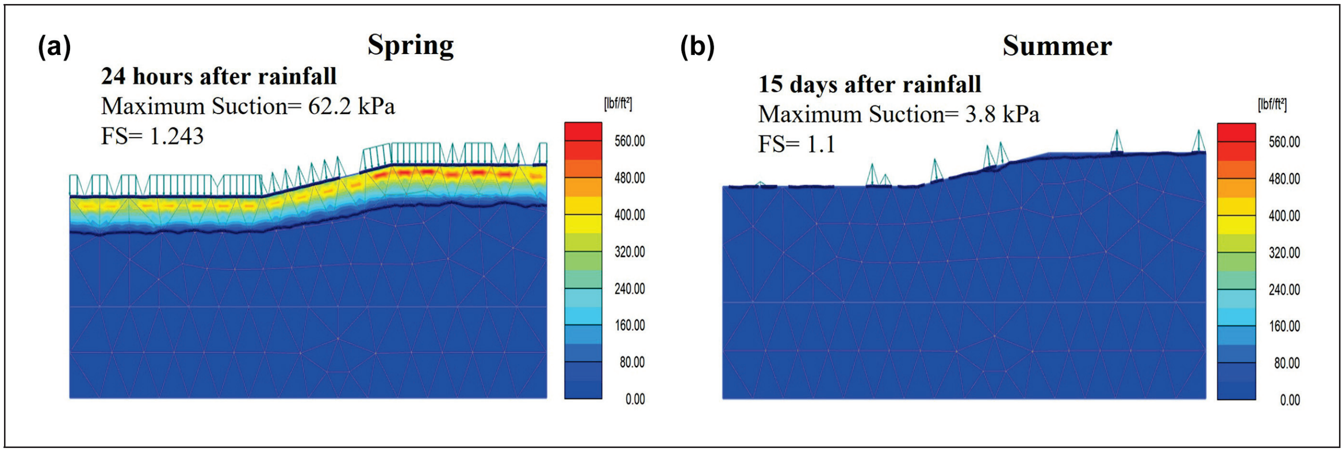

Figure 8. Highest and lowest matric suction observed: (*a*) highest maximum suction in spring (24 h after rainfall) and (*b*) lowest matric suction observed in summer (15 days after rainfall).
Note: FS =Factor of Safety.

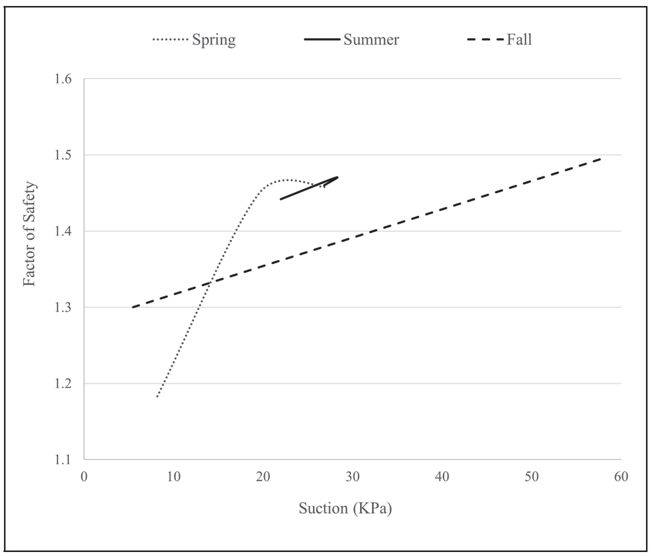

Figure 9. Factor of safety versus matric suction.

rainfall during spring; that might be because of the lower precipitation in the first half of spring. Because of the higher rainfall in the summer, the factor of safety was reduced to 1.180 after only 7 days of rainfall. The soil body collapsed in the model after 15 days of rainfall simulation for summer. The factor of safety was 1.3 after 15 days of rainfall for the fall season. The reason behind the lower factor of safety can be related to the higher residual moisture content and the perched water condition resulting from the precipitation during the summer. Figure 7 represents the results of the FEM analysis conducted for the three distinct seasons.

The highest maximum suction of 62.2 kPa (1,299 psf) after 24 hours of rainfall was observed during spring, and the lowest maximum suction of 3.8 kPa (79.80 psf) was found after 15 days of rainfall simulation during the summer (see Figure 8).

Discussion

The variations in van Genuchten flow parameters showed the behavior of highly expansive Yazoo clay during different seasons. The higher residual moisture content in spring and summer occurred because of more rainfall events in late spring and summer. For all three seasons, saturated moisture contents were higher, depicting the high affinity of expansive Yazoo clay for water. Reduced shear strength was also confirmed from FEM analysis, where the suction was lower during the summer. With the given conditions, the soil body collapsed after 7 days of rainfall during the simulation. The changes in the factor of safety also exhibit the condition of lower shear strength during the time of heavy rainfall. The safety factor was reduced by 19% after 7 days of rainfall for summer and 12% after 30 days of rainfall for fall. On the other hand, in spring, the factor of safety was reduced by only 1.56% from 1 day of rainfall to 30 days of rainfall. A graph with the factor of safety against suction of initial and failure phase for three different seasons was constructed. It shows that the factor of safety increased with the increase of suction (see Figure 9).

However, the values of horizontal and vertical permeability for the numerical analysis were obtained from previous studies, where the researchers focused on expansive clay soil. Therefore, comprehensive investigation of parametric factors using hydraulic conductivity functions is needed that consider the diverse vertical permeabilities present in different soil types.

Conclusions

The study determines the van Genuchten flow parameters for fitted SWCC of expansive clay soil. Six highway slopes in Jackson, Mississippi, containing Yazoo clay, were instrumented to monitor rainfall, moisture content, and matric suction of the soil. The data were collected and categorized into three different seasons—spring, summer, and fall—based on the precipitation trend. Most rainfall events occurred during the summer. There were peaks in moisture content and a drop in matric suction after events of heavy rainfall. The constant values of two of these parameters exhibit the perched water conditions within the slope. From the fitted curve of moisture content versus the pore water pressure plotted against the van Genuchten equation, it was observed that the flow parameters such as saturated moisture content values were quite high (more than 40% in all seasons). Considering the high plasticity of expansive clay, the values were found to be reasonable. The obtained parameters were applied to the numerical analysis tool PLAXIS 2D to further explain the changes in parameters during different seasons. The analysis also exhibited reduced matric suction and factor of safety in summer, indicating the reduced shear strength caused by increased precipitation.

The research found that the unsaturated flow parameters of expansive clay change with seasonal changes. This is important to understand the water infiltration and shear strength behavior of the soil. Relying on laboratory tests conducted on soil samples collected during a single season could mislead the design considerations for highway slopes. Also, the factor of safety generated through numerical analysis can be higher than the original condition if seasonal variations are not considered during the design process. Therefore, developing SWCC based on real-time field data may more accurately describe the soil's behavior. The current model considered only 1 year of rainfall data. Future research can integrate more extreme weather events, such as data of 100- and 500-year storm intensity-duration-frequency to evaluate the future behavior of soil with changed climatic conditions. The findings of the study can help transportation agencies in designing more resilient infrastructures on expansive clay.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: S. Khan, F. Amini, F. Rahman; data collection: F. Rahman, M. Khan; analysis and interpretation of results: F. Rahman, M. Khan, A. Nahian; draft manuscript preparation: S. Khan, F. Rahman. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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