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Coupled Effect of Wet-Dry Cycles and Rainfall on Highway Slope Made of Yazoo Clay

Sadik Khan *, John Ivoke and Masoud Nobahar

Department of Civil and Environmental Engineering, Jackson State University, 1400 J.R. Lynch Street, JSU Box 17068, Jackson, MS 39217-0168, USA

* Correspondence: j00797693@jsums.edu; Tel.: +601-979-6373

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Abstract: Expansive Yazoo clay soil is susceptible to volumetric deformation and is dominant in central Mississippi and other neighboring southern states of the United States. Recurring shrink-swell behavior causes a significant problem to infrastructures in the area. Although Yazoo clay causes a significant problem in the deep southern states, limited study has been conducted on the behavior of Yazoo clay, especially in the presence of rainfall. The objective of this current study is to investigate the coupled effect of changes in void ratio due to wet-dry cycles and rainfall on the stability of highway slopes made of Yazoo clay. The finite element method in Plaxis 2D by Bentley System (<https://www.plaxis.com/>) has been utilized to investigate the coupled effect of changes in mechanical properties and rainfall using flow-deformation and stability analysis. Reconstituted expansive clay soil samples were used for the laboratory experiment. The reconstituted Yazoo clay samples were subjected to 3, 5, and 7 wetting and drying cycles in an enclosed chamber for a 24-h period. The axial deformation of the samples and the change in void ratios at each number of the cycle was closely monitored. The strength change at each wet and dry cycle was also investigated and used for slope stability analysis in the presence of rainfall. The test results indicate that the void ratio increases with the increasing number of wet-dry cycles. A continuous increment in void ratios from 0.99 in an undisturbed state with no wet-dry cycle to 1.49 at the 7th wet-dry cycle, indicating a 48.9% increase, as the wetting and drying cycle increases was recorded; in turn, decreasing the cohesion of the soil by 77%. The factor of safety considering the effect of two total rainfall periods of $R_v = 126.2$ mm (2 h) and $R_v = 271.7$ mm (3 days) reduced from 1.7 to 1.2 and 1.68 to 1.02, considering the effect of the 7th wet-dry cycle at the topsoil. The changes in the void ratio due to the wetting and drying cycle of Yazoo clay soil reduces the shear strength to a fully softened condition, increasing the possibility of slope failure. This condition further worsens in the presence of a perched water condition due to the infiltration of rain water.

Keywords: Yazoo clay; expansive clay soil; wet-dry cycle; slope stability; void ratio

1. Introduction

Expansive soil is highly plastic clay, which makes up approximately 25% of the soil in the United States [1,2]. The highly plastic clay undergoes volume change due to wetting or drying as a result of different seasonal moisture variation. These repeated volume changes can give rise to ground movements, which usually cause structural damages, resulting in the high cost of repair or reconstruction. It is generally accepted that the water content, void ratio and type of clay minerals in the soil are the main factors affecting the volume change potential of the soil [3–5]. On average, expansive soils in the United States incur more financial losses to the nation's infrastructure than earthquakes, floods, hurricanes, and tornadoes combined [6,7].

Yazoo formation contains Yazoo clay, geologically defined within the Jackson Group, which has been identified throughout the southeastern and southwestern United States (Figure 1a). The metropolitan Jackson area is located directly on top of the Yazoo clay outcrop [8]. Yazoo clay has a very high shrink/swell potential, and moisture changes result in swelling and shrinkage behavior due to its high plasticity and percentage of montmorillonite. This shrink/swell behavior causes detrimental effects to the roads, foundations, and related infrastructure in the central Mississippi region [8,9]. The horizontal width of the surface outcrop varies from approximately 35 miles on the west to less than 10 miles on the east, whereas; the metropolitan Jackson area is located directly on top of the Yazoo clay [8]. Yazoo clay is highly plastic and subjected to high volume change [8,9]. The average composition of the Yazoo clay is 28% smectite, 24% kaolinite, 22% quartz, 15% calcite, 8% illite, 2% feldspar, and 1% gypsum based on recent x-ray diffraction results [10]. The Yazoo clay in the Jackson area consists of a weathered upper zone overlying unweathered clays. The weathered portion of the Yazoo clay varies in depth; however, mostly extends to a depth of around 30 feet [10]. In geotechnical engineering practice, the magnitude of the liquid limit and plasticity index reflect the potential to shrink or swell upon changes in the moisture content of clay soil [11]. The weathered Yazoo clay usually has a liquid limit higher than 70% to 100% and plastic limits from 20% to 30%, resulting in a plasticity index greater than 50% [9]. According to Holtz et al. [12], a soil with plasticity index greater than 35 may have a very high degree of expansion (shrink/swell potential) where the probable expansion could be more than 30% when the water content changes from dry to a saturated condition. Based on the plasticity index, Yazoo clay is indicated to have a very high shrink/swell potential. As a result, moisture changes cause swelling, shrinkage, and otherwise destructive behavior, which cause detrimental effect to the roads, foundations, and related infrastructure in the central Mississippi region [8,9]. The change in volume of the Yazoo clay between the liquid limit and oven dry moisture contents ranges from 100 to 235 percent. On the other hand, swell pressures have measured more than 1197 kN/m² [13].

Figure 1. (a) Boundary boxes of the Jackson Formation, including Yazoo clay and its geological equivalents, in Mississippi, Alabama, and Louisiana (after USGS 2010). (b) Slope failure observed in Jackson, MS.

Determination of soil strength parameters for slope stability analysis is the most important task, as the factor of safety reduces significantly with the number of wetting and drying cycles [14]. Wetting and drying (w-d) cycles reduce the expansive nature and increase the collapse tendency of embankment slopes made of high plasticity clay. Rogers and Wright (1986) [15] also reported that wetting and drying could reduce the strength of highly plastic clay, which was reflected by the decrease of cohesion intercepts with only a minor change in friction angle. Reduction of soil strength due to weathering may reduce the factor of safety of a slope with time.

Rainfall-induced slope failures reportedly occur during or immediately following periods of intense or prolonged heavy rainfall onto fine-grained soil [14,16–24]. The unsaturated state of the soil plays a significant role in protecting natural slopes from failure. With even a minimal suction,

the shallow soil deposit often has a high factor of safety, depending on slope morphology, and the triggering of a landslide is not a common phenomenon [25]. Moreover, the soil cover often provides a low hydraulic conductivity at the unsaturated state that usually prevents the soil from approaching saturation even during the high-intensity rainfall period. During the dry periods between rainfall events, the soil loses part of its water content, mainly by evapotranspiration, due in many cases to the presence of vegetation.

Consequently, only intense rainstorms, occurring after prolonged rainy periods, may lead the soil to such wet conditions as to trigger slope instability [25,26]. It is important to note that this condition differs for highly plastic clay soil. Rahimi et al. [22] conducted a study on rainfall-induced slope failure due to antecedent rainfall for high and low conductivity residual soils of Singapore. The authors applied three antecedent rainfall patterns to soil slopes and conducted a transient seepage analysis to investigate the effect of rainfall on the stability of the slope. Results from the study indicated that antecedent rainfall affected the stability of both high-conductivity and low-conductivity soil slopes, with the stability of the low-conductivity soil slopes being more significantly affected. In addition, the stability of the slope was controlled by the amount of rainfall that infiltrated the unsaturated zone of the slope.

Many of the fill slopes in Mississippi are made of Yazoo clay due to the shortage of good engineering fill materials. There are many highway slopes in Mississippi, and some parts of Alabama have similar problems. The highly plastic clay undergoes volume change due to wetting or drying as a result of different seasonal moisture variation. These repeated volume changes can give rise to ground movements, which usually cause structural damages, resulting in the high cost of repair or reconstruction. For instance, moisture redistribution under pavement systems can lead to changes in unbound material stiffness that will affect pavement performance [27]. Each year, landslides (Figure 1) in the expansive Yazoo clay require more than \$10M. It is generally accepted that the water content, void ratio, in-situ stress state and type of clay minerals in the soil are the main factors affecting the volume change potential of the soil [3–5,28]. Although Yazoo clay causes a significant problem in the deep southern states of the US, insufficient research has been conducted on the behavior of this expansive soil.

Slope failure in Yazoo clay is a complex phenomenon that depends on changes in shear strength with different wet-dry cycles and triggered by rainfall. The current study is focused on investigating critical scenarios where slope failure is triggered in slopes made of Yazoo clay. To accomplish this, the specific objective of this study is to investigate (a) the effect of the wet-dry cycle on the void ratio and shear strength of Yazoo clay, (b) the effect of the rainfall on the hydro-mechanical behavior of the slope constructed by Yazoo clay, (c) the associated effect of the changes in shear strength on the factor of safety of slopes with the presence of rainfall. Further investigation was carried out on the effect of the wet-dry cycle on the stability of slopes made with Yazoo clay. Changes in basic soil properties such as moisture content and void ratio can provide valuable insight into the change in soil strength parameters. Consolidated drained direct shear tests in the laboratory were conducted at normal stresses with the soil samples that went through different numbers of wet-dry cycles. The soil test results were utilized in a finite element analysis to investigate the changes in shear strength on the factor of safety of slopes made of Yazoo clay.

2. Methodology

Representative Yazoo clay samples were collected from a borehole in a highway slope site in Jackson, Mississippi. The collected samples were investigated and classified as highly plastic clay (CH) from a grain size distribution analysis according to ASTM D422 and ASTM D7928. A liquid limit and plasticity index of 108% and 84% (Table 1) were determined according to ASTM D4318.

Table 1. Yazoo clay soil properties.

Physical Properties	Values
Unified Classification	CH
Liquid Limit	108%
Plasticity Index	84%
Dry unit weight	12.88 kN/m ³
Specific Gravity	2.68
Natural Moisture Content	35%

Reconstituted Yazoo clay soil samples with a height of 25.4 mm and diameter of 76.2 mm were used to investigate the effect of wet-dry cycles. Collected Yazoo soil samples were first broken down into small pieces and dried in the oven for not less than 24 h. Once the samples were air dried, it was pulverized and passed through a #40 U.S. sieve (0.420 mm). The dry density of 12.88 kN/m³ and initial natural moisture content (35%) were used as “target” values selected from series of test conducted on a state study of Yazoo clay by [8]. The soil samples were transferred into a modified chamber after compaction for the wetting and drying procedure (Figure 2). An acrylic ring with a 63.5 mm inner diameter and 63.5 mm height was used to keep the samples for wetting and drying. First, the soil was compacted at the target unit weight at the acrylic ring, and a porous stone was placed at the top and bottom of the sample for natural drainage of water. To prevent clogging of the porous stone, filter paper was used between the soil and the porous stone. A schematic diagram of the wet-dry cycle mold is shown in Figure 2c. To prevent soil loss, the porous stone at the bottom of the chamber was sealed tight to the acrylic ring. The approximate height of the sample was about 25.4 mm. After preparing the samples, they were placed in an aluminum tray, which was filled with water to soak the samples and let them swell. To measure the volume change of the Yazoo clay, dial gauge was placed at the top of the sample. Once the soil was completely soaked, the water was drained from the aluminum tray, and then, the samples were dried under an incandescent bulb at a constant drying temperature of 48.8–51.6 °C. Once the samples were dried, they were soaked again in water. This procedure was repeated for 3, 5, and 7 cycles to prepare the samples for shear strength, SEM testing, and investigating the variation of volumetric deformation under different wet-dry cycles.

The laboratory program is tabulated in Table 2. At the beginning of the wet-dry cycle testing, the dry soil samples were immersed in water to saturate the sample for at least 24 h. The swelling/shrinkage of the soil specimen was determined by observation of the dial gauge and regarded as complete when no additional expansion or compression was detected. Wetting was followed by a drying period by keeping the sample inside the constructed chamber with inside temperature of (48.8–51.6 °C) for 24 h. This wetting and drying of the samples were repeated with 3, 5, and 7 cycles. The study was further extended to examine the changes in pores (voids) using Scanning Electron Microscopy (SEM). SEM is a popular imaging technique [29] where the change of soil porosity can be visualized and measured by image analysis based on scanning electron microscopy incorporating digital image processing. Once the designated cycles were completed, the samples were extruded into the direct shear box for strength testing using a direct shear test apparatus. The direct shear test was conducted following ASTM D3080 [30]. A 63.5 mm diameter shear box was used for testing with a maximum possible shear displacement of 20 mm. The rate of shearing is 0.0025 mm/min to maintain a drained condition. Direct shear tests were conducted for compacted specimens that underwent 3, 5, and 7 wet-dry cycles with three different normal stresses of 25, 50, and 100 kPa. The shear strength parameters (cohesion and friction angle) of the drying-wetting cycle specimens were determined using a Mohr-Coulomb (M-C) failure envelop. The detail of this study is presented in Khan et al. [31].

Table 2. Laboratory study of the effect of the wet-dry cycle on Yazoo clay.

Number of Samples	No of Wet-Dry Cycles	Investigative Parameters
3	1	Void Ratio, Drained Shear Strength
3	3	
3	5	
3	7

(a)

(b)

Figure 2. *Cont.*

Figure 2. (a) Samples undergoing the wetting cycle; (b) samples undergoing the drying cycle inside the wet-dry cycle chamber; (c) schematics of the wet-dry cycle sample mold.

The Van Genuchten model was used as the hydraulic model. Nobahar et al. [32] developed the Soil Water Retention Curve (SWRC) curve for the Yazoo clay soil in Mississippi, shown in Figure 3. Nobahar et al., 2019 developed the SWRC curve based on the filter paper method proposed by [33]. The Van Genuchten (1980) model is presented in Equations (1) and (2):

$$\theta = \theta_r + (\theta_s - \theta_r) / [1 + (\alpha h)^n]^m \quad (1)$$

$$m = 1 - (1/n) \quad (2)$$

where, h is the pressure head, α , m and n are the Van Genuchten fitting parameters, and θ_s and θ_r are the saturated and residual water content, respectively. The SWRC curve of Yazoo clay soil is presented in Figure 3. The fitting curve was developed through different trials considering the Van Genuchten (1980) model. A simple spreadsheet was developed that plots the SWRC curve with the value of the fitting parameters (α , m and n) and compared with tested results. After several trials, the best fitted SWRC curve with the tested results was considered and the final fitting parameters were set. The spreadsheet is available with the paper as supplementary material in Table S1.

Figure 3. Soil water retention curve of Yazoo clay [32].

The FEM program PLAXIS 2D was used to conduct coupled flow-deformation analysis, which analyzes the simultaneous development of deformations and pore pressures in saturated and partially saturated soils because of time-dependent changes of the hydraulic boundary conditions. The fully coupled flow-deformation analysis directly operates on the total pore water pressure. At the time the total rainfall is applied to the slope, infiltration is generated, and consequently, pore water pressure is measured, and stress profile is formed. As a result, effective stress is measured. Next, this step is a new input to analyses and calculates the shear strength based on the linear Mohr-Coulomb relation, and strain from Hook's Law. The model in PLAXIS makes use of the extended Mohr-Coulomb concept to describe the shear strength behavior of unsaturated soil [4]. Failure envelope is a planar surface in the space of the stress state variables $A-B_a$ and B_a-C and shear stress D_f which may be presented in equation (3), where C' is the cohesion at zero matric suction and zero normal stress, $(A - B_a)_f$ is the net normal stress on the failure plane at failure, ϕ' is the angle of internal friction associated with the net normal stress variable, $(B_a - C_w)_f$ is the matric suction at failure, and ϕ^b is an internal friction angle associated with matric suction, which describes the rate of increase in shear strength relative to matric suction [4].

$$\tau_f = C' + (A - B_a)_f \tan \phi' + (B_a - C_w)_f \tan \phi^b \quad (3)$$

3. Results and Discussions

3.1. Effect of the Wet-Dry Cycle on Vertical Deformation

In the current study, the axial deformation of the Yazoo clay samples at each wet-dry cycle was investigated. The one-dimensional response to wetting can be directly used in making estimates of collapse settlement [34]. The axial deformation of the samples is defined as the difference between the height of the sample after deformation vs. the original height of the samples before any wet-dry cycle. The change in height is relative to the initial height of the sample during the swelling and shrinkage of the soil. The differences in axial deformation compared to the initial height of the samples at 3, 5, and 7 wet-dry cycles are shown in Figure 4. It was observed that at three wet-dry cycles, the axial deformations at shrinkage are greater than deformations during swelling. However, the swelling is lower for 5 and 7 wet-dry cycles compared to the swelling of three wet-dry cycles. Thus, the swelling potential of Yazoo clay is higher at low wet-dry cycles and decreases with the increasing number of wet-dry cycles. These findings are consistent with the results that were reported by [35–37].

Figure 4. Cont.

Figure 4. Vertical deformation curve of Yazoo clay sample at (a) 3 wet-dry cycles, (b) 5 wet-dry cycles, (c) 7 wet-dry cycles.

3.2. Effect of the Wet-Dry Cycle on Void Ratio

Basma et al. (1996) [38], suggested that swelling is associated with a decrease and an increase in the apparent voids in soils due to partial and full shrinkage. A decrease in the swelling ability of the clays, corresponding to a reduced water absorption capability, was observed when the soils were alternately wetted and partially shrunk. This reduction decreases the ability of soil to attain further water upon rewetting and this, in turn, reduces the potential expansiveness of the clay with the progression of the wet-dry cycle. The current study also indicates that most of the free water will evaporate during full shrinkage, and this causes an overall reduction in the apparent voids. This, in turn, creates more pores to be filled with water when the samples are rewetted. Consequently, the potential swelling increases. This is consistent with observations made in this study for Yazoo clay. The swelling potential and rate of shrinkage increases as the number of wet-dry cycles increases although the latter rate dominates, as shown in Figure 5.

Figure 5. Change in void ratio with different wet-dry cycles.

With the increase in the number of drying-wetting cycles, the compaction segment of the curve grows significantly; mainly because the sample grain skeleton structure under the action of a cycle is changing. Microcracks evolve, which continuously increases the voids. As indicated in Figure 4, the initial void ratio of the Yazoo clay was 0.94, which increases to 1.2 after the end of the third wet-dry cycle, which further increased to 1.4 after the end of the seventh wet-dry cycle. These values agree with an initial to final void ratio of 0.75 to 1.12 for three wet-dry cycles reported by [14], while investigating

the effect of wetting and drying for long-term shear parameters for compacted Beaumont clay. It should be mentioned that at the end of each wetting and drying phase, the void ratio increases, which may make the samples lose over time.

The study was further extended to examine the chemical composition of Yazoo clay sample (Table 3) and changes in pores (voids) using Scanning Electron Microscopy (SEM). As indicated in Table 3, Yazoo clay has a high percentage of oxygen (54.14%), silicon (25.21%) and aluminum (10.90%), which indicates that most of Yazoo clay is montmorillonite [39].

Table 3. Yazoo clay sample chemical composition based on SEM data.

Mineral Composition of Yazoo Clay Sample	Weight (%)	Weight % Error (+/−1 Sigma)	Normalized Weight (%)	Normalized Weight % Error (+/− Sigma)	Atom %
Carbon	1.36	±0.11	1.36	±0.11	2.26
Oxygen	54.14	±0.40	54.14	±0.40	67.67
Flourine	0.00	—	0.00	—	0.00
Magnesium	1.22	±0.08	1.22	±0.08	1.00
Alluminium	10.90	±0.13	10.90	±0.13	8.08
Silicon	25.21	±0.18	25.21	±0.18	17.95
Potassium	1.44	±0.08	1.44	±0.08	0.74
Calcium	1.53	±0.09	1.53	±0.09	0.77
Titanum	0.46	±0.05	0.46	±0.05	0.19
Iron	3.74	±0.21	3.74	±0.21	1.34

Figure 6 shows the changes of Yazoo clay voids/porosity after the 3rd, 5th, and 7th wet-dry cycles. The ultimate available resolution with SEM is of the order of 0.2 μm (0.66 μft). This order was used during the examination of Yazoo clay because of the sample's high cohesion and very tiny particles compared to silt or sand that can be examined on the order of 0.5 μm (1.64 μft). Conclusively, from the SEM image shown below, the increase in void ratio will reduce to fully soften shear strength.

Figure 6. Cont.

Figure 6. Change in pore space of Yazoo clay using SEM imaging after the sample subjected to (a) 3 wet-dry cycles (b) 5 wet-dry cycles (c) 7 wet-dry cycles.

3.3. Effect of the Wet-Dry Cycle on Shear Strength

Results obtained from the direct shear tests on wet-dry samples prepared from high plastic clay are presented in Figure 7. As the soil strength parameters decrease with the increasing number of wet-dry cycles, the position of M-C failure surface shifts downward. This indicates the dependency of the failure envelope on changes in void ratio. Increase in some wet-dry cycles increases the void ratio and reduces the shear strength envelope.

Figure 7. Mohr-coulomb failure envelopes of the samples subjected to different wet-dry cycles.

Based on the direct shear test of results of Yazoo clay soil samples, the variation in cohesion and friction angle was calculated based on the test results of wetting and drying cycles of 0, 3, 5, and 7, respectively. The results indicated that with the increase of drying-wetting cycles, the cohesive force is significantly reduced. In the 7th wetting and drying cycle, the cohesive force was reduced to a minimum of 4.31 kPa from 18.44 kPa for zero wetting and drying cycle, which is a 77% drop in cohesion. On the other hand, there was a drop in friction angles, which was not significant, as it was observed in the cohesion. For example, the frictional angle for 0 wet-dry cycles was 20.34, which

dropped to 18.42 deg—with 7 wet-dry cycles, resulting only in a drop of 10%. This result is in good agreement with an observation made by [14,40].

The fully softened shear strength corresponds to the average strength mobilized along observed failure surface in case histories that [41,42] investigated while developing recommendations for shear strengths that should be used in stability analyses of slope that had not undergone prior landslide. These slopes are referred to as first-time slides [41,42]. Based on the test results from this study, it can be concluded that the first-time slide of the slope will occur in the 7th wet-dry cycle (4.31 kPa and frictional angle of 18.42 deg).

3.4. Effect of Rainfall on Slope Failure

Slope failures have been a recurring phenomenon in Jackson, Mississippi, because of the existence of the highly plastic Yazoo clay soil. Most of the failure occurs after prolonged rainfall, around 5–7 years after construction. Therefore, the current study also investigated the effect of the rainfall on the hydro-mechanical behavior of the slope constructed by Yazoo clay. The analysis was conducted using 2D Finite Element Analysis using coupled flow deformation and stability analysis in Plaxis 2D.

The PDS-based intensity duration frequency (IDF) curve of precipitation with a 100-year return period, based on NOAA Atlas 2014 of Jackson, Mississippi, was utilized. Based on the NOAA database, different volumes of rainfall (70.86 mm and 271.78 mm) with different duration of rainfall (2 h and 3-days) are selected, based on IDF curve of Jackson, MS, as presented in Table 4.

Table 4. Selected Precipitation pattern for FEM analysis.

Rainfall Duration (h)	Rainfall Intensity (mm/h)	Total Rainfall Volume (RV, mm)
0.5	141.73	70.86
1	98.55	98.55
2	63.12	126.2
6	29.80	178.81
12	17.29	207.51
24	9.76	234.18
72	3.77	271.78

A fill slope constructed of Yazoo clay soil, with slope ratio of 3H (Horizontal): 1V (Vertical) was selected. The fully-coupled flow-deformation analysis in Plaxis 2D was performed using a 15-node triangular element, which provides a fourth order interpolation for displacements.

The unimodal Van Genuchten fitting parameters of Yazoo clay ($\alpha = 0.0031$, $m = 0.1$ and $n = 2.75$) is utilized during this study. The soil parameters, shown in Table 5 below, were used in the numerical analysis using PLAXIS 2D. In the numerical analysis, soil layer one is defined as the active zone of the Yazoo clay, which tends to degrade over time with repeated wet-dry cycles. In this numerical analysis, four different cases (Case I, Case II, Case III, and Case IV), were considered for the values of shear strength, which soften over time with wet-dry cycles presented in Table 6. For Case, I, the peak shear strength values were assigned to the topsoil strength. Also, for Case II, Case III and Case IV, the shear strength values related to the 3, 5, and seven wet and dry cycles were assigned as topsoil strength. The soil parameters, as presented in Table 5, were used in the numerical analysis in PLAXIS 2D. The values of strength parameters selected for soil types 2–4 were established from existing soil test reports [43].

Table 5. Soil parameters for FEM analysis.

Parameter	Name	Unit	Soil 1	Soil 2	Soil 3
Bulk unit weight	γ_{unsat}	kN/m ³	20	20	22
Saturated unit weight	γ_{sat}	kN/m ³	21	21	22
Vertical Permeability	k_v	cm/s	0.034	-	-
Horizontal Permeability	k_h	cm/s	3.06×10^{-6}	-	-
Poisson's Ratio	ν	-	0.3	0.3	0.3
Young's Modulus	E	kN/m ²	4.788	4.788	4.788
Cohesion	C	kPa	Presented in Table 6	18.4	3000
Friction angle	Φ	degree		20.2	35

Table 6. Wet-Dry Cycle Shear Strength Values for Yazoo Clay (Soil 1 in Table 5).

Case	Wet-Dry Cycles	Cohesion (kPa)	Friction Angle (deg.)
I	0N	18.44	20.34
II	3N	5.98	21.99
III	5N	4.79	20.87
IV	7N	4.31	18.42

Precipitation with different intensities was applied to the soil model to assess the coupled flow-deformation behavior during rainfall. The flow through the topsoil was determined for each of the intensities assuming rainfall durations lasted 30 min, 60 min, 2 h, 6 h, 12 h, one day, and three days. The representative soil model is presented in Figure 2b. The boundary condition, as outlined in the mentioned figure, shows the infiltration of the topsoil, which simulates water ponding at the topsoil layer. During the dry period, the highly plastic clay soil developed desiccation cracks, which might have significantly increased the permeability vertically at the active zone. However, due to the desiccation crack, the permeability in the horizontal direction might not have any effect and could have remained unchanged [44–46]. The Yazoo clay usually has significant cracks, which have been observed in the laboratory as well as in the field. The diameter of the cracks varies from 3 mm (laboratory) to 304.8 mm (field), where the boundary plays a significant role in defining the size of the cracks. The desiccation cracks of Yazoo clay are shown in Figure 8. Therefore, a high vertical permeability value of $k_v = 0.034$ cm/s was used for the part mentioned above for each of the slopes to simulate the effect of the desiccation crack. It should be noted that with the changes in the wet-dry cycles, the horizontal permeability of the clay soil also gets impacted. However, due to lack of available data and literature on the change in the k_h of Yazoo clay, a constant value of the k_h is considered, which also showed good agreement with the existing scenario of the slopes in Mississippi. The value of horizontal permeability was selected as $k_h = 3.06 \times 10^{-6}$ cm/s. In other clay layers, the permeability for both the horizontal and vertical directions was selected as 3.06×10^{-6} cm/s, respectively. The water table was placed at 3 m below the surface layer from field observation.

Figure 8. Desiccation cracks on Yazoo clay soil observed at the laboratory.

Flow Analyses Results

The variations in suction at the 3H:1V slope for the initial phase, 30 min, 60 min, 12 h, and 3 days rainfall volumes are presented in Figure 9c–g. As indicated, the suction immediately dropped at the toe of the slope after rainfall and continued to drop during rainfall, representing the accumulation of water at the corresponding depth. It was also observed that the suction increase continued for a few hours even after the rainfall. It was also noticed that after a few days of rainfall, the suction increased, and the soil almost regained its original profile for the layer. This trend of suction profile is similar for other cases that have different shear strength with 3, 5, and 7 wet-dry cycles.

It should be noted that during the FEM analysis, infiltration behavior was assigned to the topsoil layer, which allowed the ponding of water to simulate realistic behavior. From FEM analysis results, ponding exists in almost all surficial soil for the toe of the slope with different rainfall intensities. However, for the 12-hour and three-day rainfall intensities, ponding hardly can be found on the slope, due to low intensity. Ponding decreased the amount of suction for the topsoil layer at the toe. Ponding of water is commonly visible in the failed slope sites in Mississippi.

3.5. Stability Analysis Results

In shear strength reduction method, the factor of safety of a slope is defined as the factor in which the original shear strength parameters can be reduced to bring the slope to the point of failure [47]. During this study, stability analysis was conducted considering the unsaturated moisture and matric suction variation of the soil, as investigated by the fully-coupled flow analysis. Time-dependent hydro-mechanical behavior of the soil is described in a coupled format, taking both deformation and groundwater flow into account, in which mixed equations of displacement and pore pressure are solved simultaneously.

Based on the material stiffness, Poisson's ratio and Young's Modulus were 0.3 and 4.788 kN/m². In this study, different shear strength values for the topsoil layer were utilized, considering three different cases in the active zone.

Figure 9. Suction profile variation of 3H:1V slope made of Yazoo clay: (a) Flow functions to simulate rainfall in FEM analysis, (b) the boundary condition for the soil model, (c) suction profile before rainfall, (d) suction profile after rainfall-30 min, (e) suction profile after rainfall-60 min, (f) suction profile after rainfall-12 h (g) and suction profile after rainfall-3 days.

The factor of safety of slope was determined using the phi-c reduction method in Plaxis 2D, which is alternately known as the shear strength reduction analysis. In the shear strength reduction method, the factor of safety of the slope is defined as the number by which the original shear strength parameters must be divided in order to bring the slope to the point of failure. In Plaxis 2D, the shear strength parameters $\tan \phi$ and c of the soil are successively reduced until failure of the slope occurs to determine failure shear strength. The reduced strength parameters c'_f and ϕ'_f is defined in Equations (4) and (5), as suggested by [47]:

$$c'_f = \frac{c'}{FS} \quad (4)$$

$$\varphi'_f = \arctan\left(\frac{\tan \varphi'}{FS}\right) \quad (5)$$

where,

c' = Available cohesion of soil

c'_f = Cohesion at failure

φ' = Available friction angle

φ'_f = Friction angle at failure

FS = Factor of Safety

In this study, stability analysis was conducted using the unsaturated moisture and matric suction profile of the soil, as investigated by the fully-coupled flow analysis. The slip surface for the 126.2 mm rainfall volume of the 3H: 1V slope within four cases are presented in Figure 10. As presented in Figure 10, the deformation contours are presented. During the phi-c reduction analysis in Plaxis 2D, at the failure strength, the factor of safety of the soil is determined. Beside the determination of the soil strength, the FEM package calculates displacement at the soil body. The displaced area represents the failure area (deformation contour) and the edge of displaced soil presents the slip surface of the slope. Based on the FEM results, it can also be observed that the factor of safety changed with different rainfall durations.

Figure 10. Phi-C reduction analysis results for 126.2 mm rainfall volume for one-day rainfall duration for 3H:1V slope ratio: (a) before rainfall (b) Case I (c) Case II (d) Case III (e) Case IV.

Figure 11 shows the change in slip failure surface for Case IV (7 wet-dry cycles). In this portion, the soil shear strength is with seven wet and dry cycles, and the factor of safety varied from 1.28 to 1.2. As shown, the soil strength in the top layer with seven cycles of wet and dry decreased and was susceptible to failure. Therefore, the slope failure took place due to the reduction in shear strength with an increased number of wet and dry cycles at the steep part of the slope.

Figure 11. Case IV; changes in slip surface for 126.2 mm/h rainfall volume for 3H:1V slope ratio: (a) prior to rainfall, (b) 2-h rainfall duration, (c) 1-day rainfall duration, (d) 3-day rainfall duration.

The factor of safety for the 3H:1V slope with consideration of the mentioned four cases is presented in Figure 12. The figure mentioned above shows the progressive variation of the factor of safety for Case I to Case IV. The failure surface was observed to be deep-seated in Case I and shallow in Cases II to IV, which is due to the progressive change in the shear strength due to the repeated wet-dry cycles. As the rainfall influenced the matric suction value at the topsoil, a significant change in the factor of safety occurred, leading to shallow slip surface failure. The factor of safety considering the effect of two total rainfall periods of $R_v = 126.2$ mm (2 h) and $R_v = 271.7$ mm (3 days) reduced from 1.7 to 1.2 and 1.68 to 1.02, respectively, considering the effect of the 7th wet-dry cycles at the topsoil. Consequently, it can be observed that the factor of safety reached a critical value after the topsoil layer shear strength was replaced with the seventh wet and dry cycle's value with higher total rainfall. It is also observed that in a dry state with 7 wet-dry cycles, the slopes are stable ($FS = 1.4$). However, the slope will fail in the presence of three days of consistent rainfall after seven wet-dry cycles. This study shows the growing need of incorporating the effect of seasonal changes in civil engineering design, as also emphasized by [48] on how Enhanced Integrated Climatic Model (EICM) incorporates the changes in temperature and moisture of unbound materials into the design process.

Figure 12. Change in the factor of safety.

4. Conclusions

The objective of this current study is to investigate the coupled effect of changes in void ratio due to wet-dry cycles and rainfall on the stability of highway slopes made of Yazoo clay. The major findings are summarized as:

- It is evident that the variation in numbers of wet-dry cycles increases the void ratio of Yazoo clay. With changes in the void ratio of Yazoo clay, the shear strength of the soil, especially cohesion, dropped significantly. With seven wet-dry cycles, a 77% drop in cohesion was observed.
- The stability analysis of slopes made of Yazoo clay with a different number of wet-dry cycle shear strengths on the topsoil decreased from 2.7 to 1.4 as the number of wet-dry cycle increased.
- Considering the effect of two rainfall periods of $R_v = 126.2$ mm (2 h) and $R_v = 271.7$ mm at three days, the factor of safety reduced from 1.7 to 1.2 and 1.68 to 1.02, respectively, considering the effect of 3, 5 and 7 wet-dry cycles in the topsoil. It is clearly observed that the factor of safety reached a critical value, which is a coupled effect of the changes in shear strength due to 7 wet-dry cycles and saturation due to sustained rainfall for three days.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2076-3263/9/8/341/s1>, Table S1: Determination of van Genuchten (1980) fitting parameters.

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References

1. Nelson, J.; Miller, J.D. *Expansive Soils: Problems and Practice in Foundation and Pavement Engineering*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 1992.
2. Buhler, R.L.; Cerato, A.B. Stabilization of Oklahoma Expansive Soils using Lime and Class C Fly Ash. In Proceedings of the Geo-Denver 2007, Denver, CO, USA, 18–21 February 2007; pp. 1–10.
3. El-Sohby, M.A.; El-Sayed, A.R. Some factors are affecting swelling of clayey soils. *J. Geotech. Eng.* **1981**, *12*, 19–39.
4. Fredlund, D.G.; Rahardjo, H. *Soil Mechanics for Unsaturated Soils*; John and Wiley and Sons, Inc.: Hoboken, NJ, USA, 1993.
5. Hanafy, E.; Knodel, P. Swelling/Shrinkage Characteristic Curve of Desiccated Expansive Clays. *Geotech. Test. J.* **1991**, *14*, 206.

6. Puppala, A.J.; Manosuthkij, T.; Nazarian, S.; Hoyos, L.R. Threshold moisture content and matric suction potentials in expansive clays prior to initiation of cracking in pavements. *Can. Geotech. J.* **2011**, *48*, 519–531. [[CrossRef](#)]
7. Ahmed, A.; Hossain, S.; Khan, M.S.; Shishani, A. Data-Based Real-Time Moisture Modeling in Unsaturated Expansive Subgrade in Texas. *Transp. Res. Rec. J. Transp. Res. Board* **2018**, 2672, 86–95. [[CrossRef](#)]
8. Landris, T.; Lee, P.E., Jr. *State Study 151 and 236: Yazoo Clay Investigation*; MDOT State Study 236; US Army Corps of Engineers: Washington, DC, USA, 2012.
9. Douglas, S.C.; Dunlap, G.T. Light commercial construction on Yazoo clay. In Proceedings of the Second Forensic Engineering Congress, San Juan, Puerto Rico, USA, 21–23 May 2000; pp. 607–616.
10. Taylor, A.C. Mineralogy and engineering properties of the Yazoo clay formation. Jackson Group. Master's Thesis, Mississippi State University, Mississippi State, MS, USA, 2005.
11. Das, B.M.; Sobhan, K. *Principles of Geotechnical Engineering*, 8th ed.; Cengage Learning: Boston, MA, USA, 2013; ISBN-13 978-1133108665.
12. Holtz, R.D.; Kovacs, W.D.; Sheahan, T.C. *An Introduction to Geotechnical Engineering*; Pearson: Upper Saddle River, NJ, USA, 2011.
13. Johnson, L.D. *Properties of expansive clay soils, Jackson field test section study*; U.S. Army Engineer Waterways Experiment Station: Vicksburg, MI, USA, Report 1, Misc. Paper S73-28; 1973.
14. Rogers, L.E.; Wright, S.G. *The Effects of Wetting and Drying on the Long-Term Shear Strength Parameters for Compacted Beaumont Clay*; FHWA/TX-87/40+436-2F; Center for Transportation Research, University of Texas at Austin: Austin, TX, USA, 1986.
15. Day, R.W.; Axten, G.W. Surficial Stability of Compacted Clay Slopes. *J. Geotech. Eng.* **1989**, *115*, 577–580. [[CrossRef](#)]
16. Baum, R.L.; Chleborad, A.F. *Landslides Triggered by Pacific Northwest Storms in the Puget Lowland, Washington*; Information Reports; Washington State Department of Natural Resources: Washington, DC, USA, 1998.
17. Cai, F.; Ugai, K. Numerical Analysis of Rainfall Effects on Slope Stability. *Int. J. Géoméch.* **2004**, *4*, 69–78. [[CrossRef](#)]
18. Collins, B.D.; Znidarcic, D. Stability Analyses of Rainfall Induced Landslides. *J. Geotech. Geoenviron. Eng.* **2004**, *130*, 362–372. [[CrossRef](#)]
19. Pando, M.A.; Ruiz, M.E.; Larsen, M.C. Rainfall-Induced Landslides in Puerto Rico: An Overview. In Proceedings of the Geo-Frontiers 2005, Austin, TX, USA, 24–26 January 2005.
20. Tohari, A.; Nishigaki, M.; Komatsu, M. Laboratory Rainfall-Induced Slope Failure with Moisture Content Measurement. *J. Geotech. Geoenviron. Eng.* **2007**, *133*, 575–587. [[CrossRef](#)]
21. Cascini, L.; Cuomo, S.; Pastor, M.; Sorbino, G. Modeling of rainfall-induced shallow landslides of the flow-type. *J. Geotech. Geoenviron. Eng.* **2009**, *136*, 85–98. [[CrossRef](#)]
22. Rahimi, A.; Rahardjo, H.; Leong, E.-C. Effect of hydraulic properties of soil on rainfall-induced slope failure. *Eng. Geol.* **2010**, *114*, 135–143. [[CrossRef](#)]
23. Conte, E.; Troncone, A. Simplified approach for the analysis of rainfall-induced shallow landslides. *J. Geotech. Geoenviron. Eng.* **2011**, *138*, 398–406. [[CrossRef](#)]
24. Tiwari, B.; Upadhyaya, S. Influence of Antecedent Rainfall on Stability of Slopes. In Proceedings of the Geo-Congress 2014, Atlanta, GA, USA, 23–26 February 2014; pp. 3243–3251.
25. Damiano, E.; Mercogliano, P. Potential Effects of Climate Change on Slope Stability in Unsaturated Pyroclastic Soils. *Landslide Sci. Pract.* **2013**, 15–25. [[CrossRef](#)]
26. Hossain, J. Geohazard Potential of Rainfall Induced Slope Failure on Expansive Clay. Ph.D. Thesis, University of Texas at Arlington, Arlington, TX, USA, 2013.
27. Lu, Y.; Zapata, C.E. Temperature effects on the unsaturated hydraulic properties of two fine grained soils and their influence on moisture movement under an airfield test facility. In Proceedings of the Geotechnical and Structural Engineering Congress 2016, Phoenix, AZ, USA, 14–17 February 2016.
28. Pino, A.; Pedaria, A.; Puppala, A.; Hoyos, L.R. Evaluation of swell behavior of expansive clays from specific moisture capacity. In Proceedings of the E3S Web of Conferences, Paris, France, 12–14 September 2016; p. 14011.
29. Lawrence, M.; Jiang, Y. Porosity, Pore Size Distribution, Micro-structure. In *Bio-Aggregates Based Building Materials*; RILEM State-of-the-Art Reports; Amziane, S., Collet, F., Eds.; Springer: Berlin/Heidelberg, Germany, 2017.

30. ASTM D3080/D3080M-11, *Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions*; ASTM International: West Conshohocken, PA, USA, 2011.
31. Khan, M.S.; Ivoke, J.; Nobahar, M.; Kibria, G. Effect of Wet-Dry Cycles on the Void Ratio of Expansive Yazoo Clay Soil. In *Proceedings of the Eighth International Conference on Case Histories in Geotechnical Engineering*, Philadelphia, PA, USA, 24–27 March 2019.
32. Nobahar, M.; Khan, M.; Ivoke, J.; Amini, F. Impact of Rainfall Variation on Slope Made of Expansive Yazoo Clay Soil in Mississippi. *Transp. Infrastruct. Geotechnol.* **2019**. [[CrossRef](#)]
33. Bulut, R.; Wray, W.K. Free energy of water suction in filter papers. *Geotechnical Testing J.* **2005**, *28*, 355–364.
34. Houston, S.L.; Houston, W.N.; Zapata, C.E.; Lawrence, C. Geotechnical engineering practice for collapsible soils. *Geotech. Geol. Eng.* **2001**, *19*, 333–355. [[CrossRef](#)]
35. Alonso, E.; Romero, E.; Hoffmann, C.; Garcia-Escudero, E. Expansive bentonite-sand mixtures in cyclic controlled-suction drying and wetting. *Eng. Geol.* **2005**, *81*, 213–226. [[CrossRef](#)]
36. Rosenbalm, D.; Zapata, C.E. Effect of Wetting and Drying Cycles on the Behavior of Compacted Expansive Soils. *J. Mater. Civ. Eng.* **2017**, *29*, 4016191. [[CrossRef](#)]
37. Tripathy, S.; Rao, K.S.; Fredlund, D.G. Water content—Void ratio swell-shrink paths of compacted expansive soils. *Can. Geotech. J.* **2002**, *39*, 938–959. [[CrossRef](#)]
38. Basma, A.A.; Al-Homoud, A.S.; Malkawi, A.I.H.; AlBashabsheh, M.A. Swelling shrinkage behavior of expansive natural clays. *Appl. Clay Sci.* **1996**, *11*, 211–227. [[CrossRef](#)]
39. Barton, C.D. Clay minerals. In *Encyclopedia of Soil Science*; Marcel Dekker: New York, NY, USA, 2002; pp. 187–192.
40. Zornberg, J.G.; Kuhn, J.; Wright, S. *Determination of Field Suction Values, Hydraulic Properties and Shear Strength in High PI Clays*; Research Report 0-5202-1; Center for Transportation Research, University of Texas at Austin: Austin, TX, USA, 2007.
41. Skempton, A.W. First-Time Slides in Over-Consolidated Clays. *Géotechnique* **1970**, *20*, 320–324. [[CrossRef](#)]
42. Skempton, A.W. Residual strength of clays in landslides, folded strata and 2493 the laboratory. *Géotechnique* **1985**, *35*, 3–18. [[CrossRef](#)]
43. Khan, M.S.; Nobahar, M.; Ivoke, J. *Development of Design Protocol: Sustainable Stabilization of Slope Using Recycled Plastic Pin in Mississippi*; Maritime Transportation Research and Education Center: Fayetteville, NC, USA, 2017.
44. Khan, M.S.; Hossain, S.; Ahmed, A.; Faysal, M. Investigation of a shallow slope failure on expansive clay in Texas. *Eng. Geol.* **2017**, *219*, 118–129. [[CrossRef](#)]
45. Khan, M.S.; Nobahar, M.; Ivoke, J.; Amini, F. Effect of Rainfall on Slope made of Yazoo Clay Soil in Mississippi. In *Proceedings of the Transportation Research Board (TRB) 97th Annual Meeting*, Washington, DC, USA, 7–11 January 2018.
46. Khan, M.S.; Ivoke, J.; Nobahar, M. *Effect of Swell-Shrink Characteristics on Landslides in Yazoo Clay*; Maritime Transportation Research and Education Center: Fayetteville, NC, USA, 2018.
47. Griffiths, D.V.; Lane, P.A. Slope stability analysis by finite elements. *Géotechnique* **1999**, *49*, 387–403. [[CrossRef](#)]
48. Zapata, C.E.; Andrei, D.; Witczak, M.W.; Houston, W.N. Incorporation of Environmental Effects in Pavement Design. *Road Mater. Pavement Des.* **2007**, *8*, 667–693. [[CrossRef](#)]

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