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Research Article

Field Test Research on Red Clay Slope under Atmospheric Action

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By embedding water content sensors and pore water pressure sensors inside the red clay slope on-site in Guiyang, Guizhou, shear tests were performed on soil samples at different depths of the slope under different weather. The changes of water content, pore water pressure, and shear strength index of the slope inside the slope under the influence of the atmosphere were tracked and tested, and the failure characteristics and evolution of the red clay slope were analyzed. It is believed that the depth of influence of the atmosphere on red clay slopes is about 0.7 m, rainfall is the most direct climatic factor leading to the instability of red clay slopes, and the evaporation effect is an important prerequisite for the catastrophe of red clay slopes. The cohesion and internal friction angle of the slope soil have a good binary quadratic function relationship with the water content and density. The water content and density can be used to calculate the cohesion and internal friction angle. Failure characteristics of red clay slopes: the overall instability failure is less, mainly surface failure represented by gullies and weathering and spalling, and then gradually evolved into shallow instability failure represented by collapse and slump. The damage evolution law is as follows: splash corrosion and surface corrosion stage⟶ fracture development stage⟶ gully formation stage⟶ gully development through stage⟶ local collapse stage⟶ slope foot collapse stage.

1. Introduction

The red clay in China is mainly distributed in the south, such as Guangxi, Guizhou, Yunnan, Guangdong, and Hunan provinces. With the rapid growth of the national economy, numerous infrastructure construction projects such as high-speed railways and highways pass through the red clay soil area, forming lots of red clay slopes. Due to the special engineering properties of red clay, such as high water content, high plasticity, and high void ratio, the failure mode of red clay slopes is different from other soil slopes, and there is insufficient understanding of the dynamic response characteristics of red clay slopes under factors such as evaporation and rainfall. Some slopes suffered damage accidents in the early stage of operation, which brought heavy loses to the lives and properties of local residents and severe social impacts. Therefore, it is urgent to study the dynamic response characteristics of red clay engineering slopes under atmospheric action, which has important practical significance for scientific prevention and control of slope landslide accidents. At present, field test studies on slopes pay more attention to the impact of rainfall infiltration on slope stability [1–8] (Ke and Huang 1995; Zhan and Ng 2003; Gao et al. 2004; Li et al. 2005; Fu et al. 2012; Hung et al. 2020; Sinhang et al. 2020; Yang 2020). For example, Rahardjo et al. [9] analyzed the in situ analysis of residual soil slopes in Singapore under the influence of artificial and natural rainfall on site. The relationship between rainfall infiltration and runoff and the relationship between pore water pressure and water content with rainfall are established; Gasmo et al. [10] obtained changes in soil slope pore water pressure caused by evaporation and infiltration and established the pore pressure observation station of residual soil slope, considering the slope response only pore pressure. In terms of indoor model test research, William et al. [11] developed an atmospheric dry-wet cycle simulation box that can adjust the relative humidity of the model boundary and used a centrifuge to simulate the impact of rainfall infiltration and evapotranspiration on rock and soil structures; Chen et al. [12, 13] (2007) and Kong et al. (2007) established three types of expansive soil slopes in Nanning, including gentle slopes, steep slopes, and grass-growing slopes and tested the laws of slope moisture content, temperature, and deformation with the atmosphere. Yang et al. [14, 15] (2005a, b) studied the influence of different weather on the slope of expansive soil roadbed with different slopes, and tested the relationship between temperature and soil pressure. Ng et al. [16, 17] (2003) and Zhan et al. (2003b) established on-site expansive soil slopes and analyzed the influence of soil-water action on the slope stability under the condition of rainfall infiltration. Sha [18] (2017) established an on-site red clay slope in Guilin, Guangxi, and analyzed the internal water content and temperature response of the slope. Du and Tong [19] (2020) took the loess slope in Yingze District of Taiyuan City as an example, calculated the depth of the infiltration front based on the Mein-Larson modified model, and obtained the weakening law of the shear strength parameters of the loess within the infiltration front through dry-wet cycles and direct shear tests, combining the law of weakening and using the improved strength reduction method to study the stability of loess slopes under different conditions. Pei et al. [20] (2020) conducted field tests on five different slopes of expansive soil slopes under artificial rainfall and calibrated the model. Then, hydraulic analysis was performed on expansive soil slopes with different fracture types to estimate the safety factor of the slope. In order to understand the hydrological process of expansive soil slopes, Lei et al. [21] (2020) conducted a simulated rainfall experiment to study the influence of slope and initial soil water content on runoff and infiltration of expansive soil slopes in the south. Yang et al. [22] (2006) conducted an experimental study on Ningming undisturbed expansive soil under load conditions to simulate the dry-wet cycle process and obtained the law of expansion and contraction deformation and strength change. Miao et al. [23] (2002) conducted a dry-wet cycle test on the soil-water characteristics of Nanyang expansive soil to study its unsaturated state. Estabragh et al. [24] (2015) conducted multiple wetting and drying tests on expansive soil to study the properties of expansive soil. Laboratory tests were carried out on dense samples of expansive clay under different constant charging pressures. The porosity and water content of samples at different stages were measured.

The above-mentioned research results mainly focused on the slope failure characteristics and mechanisms under the conditions of on-site rainfall or indoor model tests. The red clay slope has undergone dry-wet alternation for several years under natural conditions, and there is a time effect in the failure process of the slope. The meteorological factors of the weather are slightly single, and the atmospheric effect is a multi-factor, long-term, and repeated process. Long-term follow-up tests are required to obtain a complete picture of the potential occurrence, development, and extension of red clay slope disasters under the influence of climate process. This paper uses a rain gauge to monitor the weather and rainfall conditions. By embedding water content sensors and pore water pressure sensors inside the red clay slopes in Guiyang, Guizhou, shear tests are performed on soil samples at different depths of the slope under different weather. The changes in the water content, pore water pressure, and shear strength of slopes under the action of the atmosphere deepen the understanding of the catastrophic process of red clay slopes and provide a more scientific basis for the design of red clay slopes.

2. Project Overview

The test site is located in the new campus of Guizhou University, Huaxi District, Guiyang City, Guizhou Province. The average annual rainfall in this area is 1129.5 mm, and the rainfall period is mostly from June to September each year. The total length of the slope is about 80 m, the slope height is about 9 m, and the slope is about 35°. The slope soil sample is brown-red, with a natural moisture content of 32.1%, a liquid limit of 58.34%, and a plastic limit of 30.11%. The slope is exposed, green turf is paved at the foot of the slope, shrubs are planted on the top of the slope (Figure 1), the slope is intact, and no collapse has occurred.

3. Test Plan

Buried KM30B01 soil moisture sensor and KYJ-32 at the top of slope, slope surface, and slope toe depths of 100 mm, 200 mm, 300 mm, 400 mm, 500 mm, 700 mm, 900 mm, 1100 mm, 1300 mm, and 1500 mm. There are 30 sets of vibrating wire pore water pressure sensors each (Figure 2), which monitor the changes in water content and pore water pressure respectively, use rain gauges to monitor atmospheric rainfall, and shear soil samples at different depths of the slope in different weather test, analyzing the change law of the shear strength index of the soil sample. The monitoring period is from July 22, 2018, to November 10, 2018.

4. Results and Discussion

4.1. Relationship between Water Content Changes

4.1.1. Relationship between Moisture Content and Slope Depth. It can be seen from Figure 3 that when the depth is less than 0.7 m, the water content of the toe and top of the slope increases with the increase of the slope depth, and the water content of the slope does not change much with the increase of the slope depth. The water content of the slope is the largest, between 45% and 55%, followed by the water content of the top of the slope, between 30% and 45%, and the water content of the toe is the smallest, between 24% and 32%. The reason is that the slope has no protective measures. The entire slope is exposed in nature, and the weathering and shedding of the slope surface is serious. Rainwater can easily penetrate into the slope in rainy days, resulting in an increase in the water content of the slope. The foot of the slope is covered with turf, and rainwater cannot easily penetrate the ground, so the water content of the foot of the slope is minimal. When the depth is greater than 0.7 m, the water content of the slope, toe, and top of the slope does not change much with the increase in depth and is basically between 40% and 52%. It can be seen that the depth of atmospheric influence is about 0.7 m.

4.1.2. The Relationship between Moisture Content and Time. It can be seen from Figure 4 that the soil moisture content of the slope increases during the rainfall period, and the rising amplitude has an obvious positive correlation with the amount of rainfall, but the time of the peak moisture content

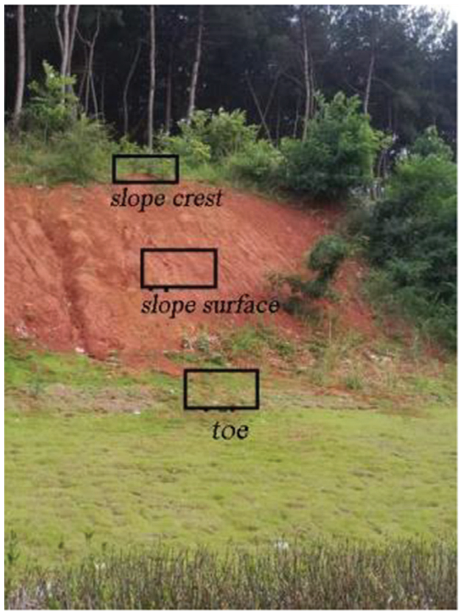

Figure 1: Test slope.

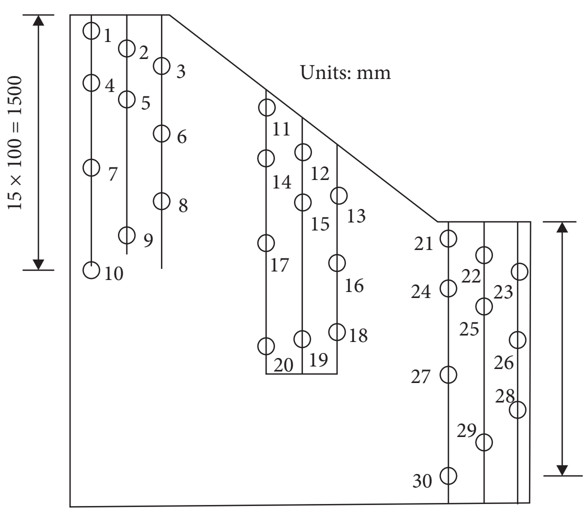

Figure 2: Sensor embedding indication.

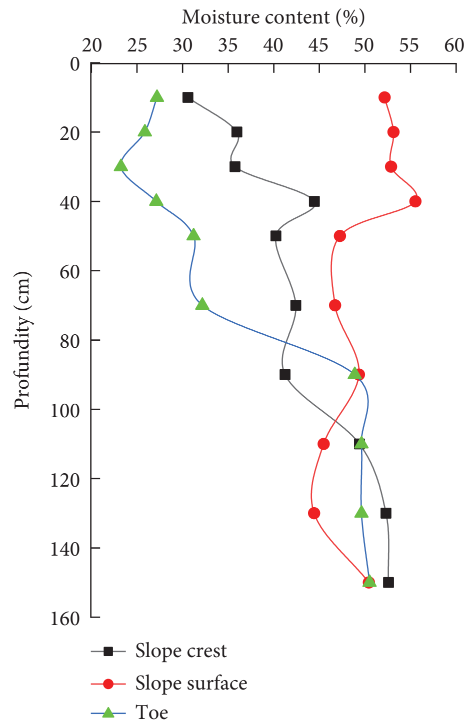

Figure 3: The relationship between water content and depth before monitoring (July 21, 2018).

lags the time of the peak rainfall. The water content of the slope soil decreased in cloudy and sunny days. For example, during the period from September 11 to September 26, the weather is cloudy and rainy, and the rainfall in rainy days is greater than 10 mm. During this period, the increase in water content increases significantly, and the maximum increase in surface water content reaches more than 40%; during the period from August 18 to September 5, except for light rain on the 22nd and 23rd, the rest are sunny. During this period, the moisture content decreases. The hysteresis effect is manifested in the following: from August 1st to August 10th, the maximum rainfall intensity on August 4 was 6.2 mm, and the water content increase at a buried depth of 20 cm did not reach the maximum value of 36.74% until August 9th. From September 11 to September 26, the rainfall intensity was the highest on September 15, reaching 40.9 mm, and the increase in water content at a buried depth of 20 cm did not reach the maximum value of 46.65% until September 22.

At the same depth, the atmospheric effect has a great influence on the water content of the slope. The increase of the water content fluctuates in the range of -5%~40%, and the impact on the top and the toe of the slope is small. The reason is that the toe of the slope is covered with turf, shrubs are planted at the top of the slope, and the weathering degree of the slope toe and slope top is small, so the slope top and slope toe are less affected by the atmosphere. However, the slope has no protective measures, the entire slope is exposed in nature, and the weathering and shedding of the surface of the slope is serious, and rainwater can easily penetrate into the slope in rainy days, resulting in an increase in the water content of the slope. For example, during the rainfall period from August 7th to 10th, the increment of the slope water content increased from 5.13% to 36.74%, while the slope top only rose from 2.12% to 14.33%, and the slope water content change rate was 2.59 times that of the slope top. The root system of the plant has a good water retention effect, and the evaporation of water on the slope in sunny days is greater than that at the foot and top of the slope. For example, during the period from September 27 to October 2, the weather was sunny or cloudy. During this period, the increase in the water content of the slope decreased from 26.83% to 10.94%, a decrease of 15.89%, and the increase in the water content of the slope foot was only 7.99% dropped to 3.44%, a decrease of 4.55%. The drop in water content of the slope is 3.49 times that of the toe.

It can be seen from Figure 5 that as the depth of the slope increases, the degree of influence of the influence of the atmosphere on the water content of the slope gradually

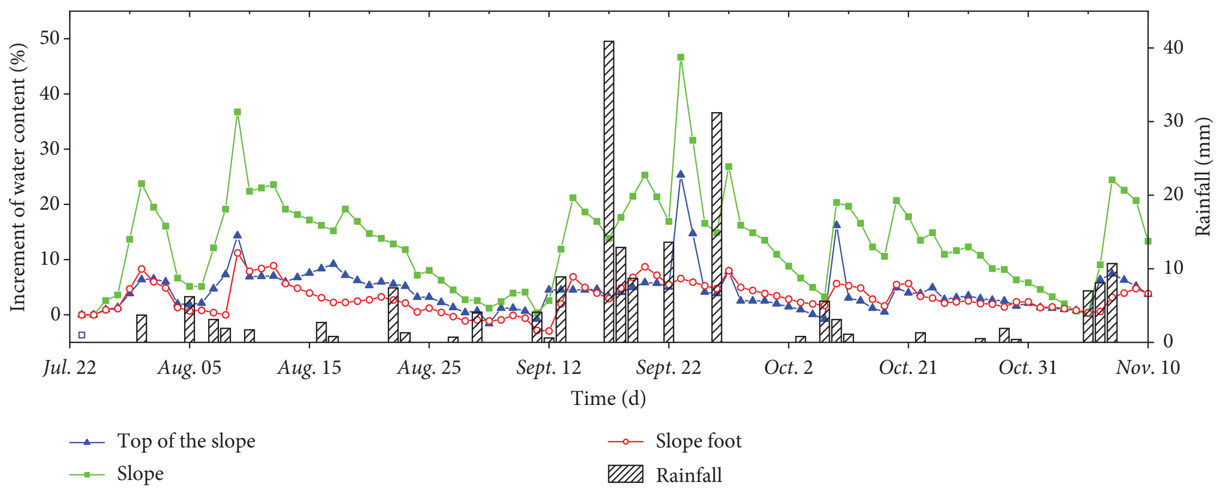

Figure 4: Time history curve of water content at different positions on the slope (buried depth 20 cm).

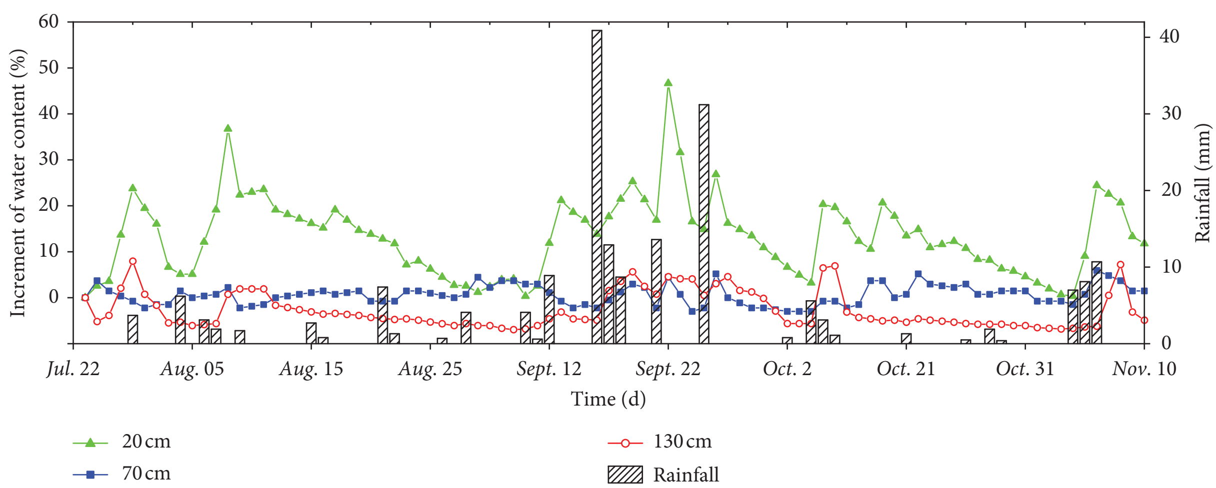

Figure 5: Time history curve of slope depth at different depths (slope surface).

decreases. For example, the increase of water content at a buried depth of 20 cm changes significantly due to atmospheric effects, and the curve fluctuates greatly, while the increase of water content at a buried depth of 70 cm and 130 cm changes smoothly. For example, from August 15 to September 12, sunny days accounted for 2/3 and rainy days accounted for 1/3. The water content at the burial depth of 20 cm of the slope is generally decreasing, while the increase of water content at 70 cm has a slight upward trend, and the water content at 130 cm basically does not change.

4.1.3. Changes in Slope Soil Moisture Content after Rainfall. In order to explore the variation law of soil moisture content of slope soil after rain, the relationship of moisture content change within 6 hours after rain was recorded after the three days of rainfall ended on August 30, September 5, and September 22. Among them, August 30 the daily rainfall intensity is 1.7 mm, the rain pattern is showers, and the duration is 0.5 h; on September 5, the rainfall intensity was 4.1 mm and the duration was 3 h; on September 22, the rainfall intensity was 13.6 mm. During the raining process, the rainfall gradually decreased until the rain stopped, and the entire rainfall duration lasted 12 h.

It can be seen from Figure 6(a) that after the rain stopped on August 30, the water content of the soil at 10 cm of the slope reached peak within 2 hours, and then the water content decreased with time. The water content at 30 cm reached its peak within 4 h, and then the water content gradually decreased with time. The greater the buried depth, the water content gradually increases, and the water content increment curve becomes more and more gentle. The reason is that this time the rainfall was short, the rainfall was small, and the rainwater only penetrated into the range of 0–20 cm. Therefore, as the rainwater penetrates into the deep layer after the rain, the moisture content of the surface soil gradually decreases while the moisture content of the deep soil gradually increases; due to the smaller permeability coefficient of red clay, the time required for rainwater to penetrate into the interior also increases with the increase of depth.

It can be seen from Figure 6(b) that the increase in water content at a depth of 50 cm shows a negative value, indicating that the rainwater penetrates into the deep layer after

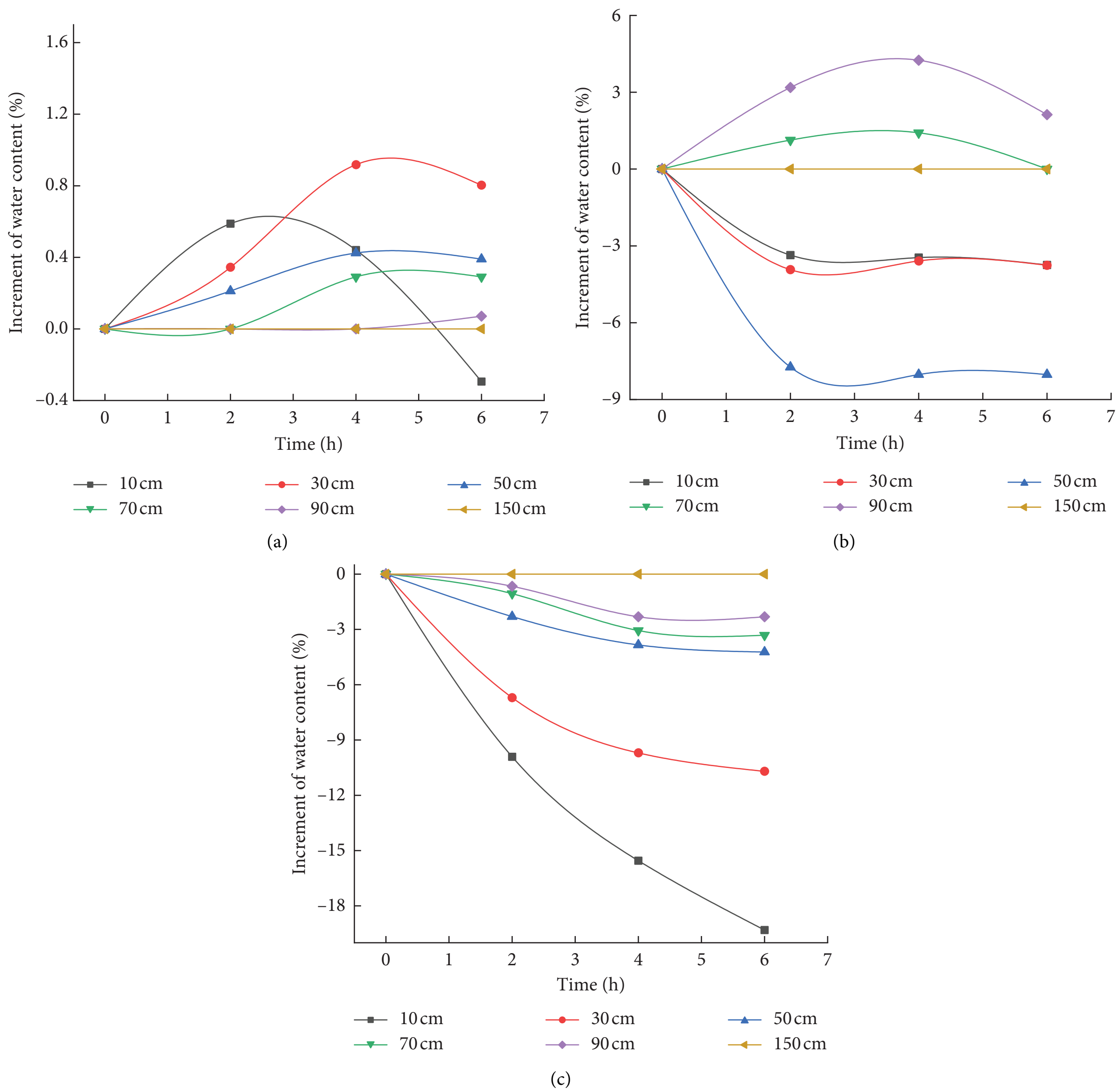

Figure 6: Relationship between water content of slope surface and time after rain: (a) August 30; (b) September 5; (c) September 22.

the end of the rainfall, which causes the water content to decrease, and the water content gradually tends to decrease after 2 h after rainfall. After the depth is greater than 50 cm, the upper layer rainwater seepage continues to increase 4 hours after the rainfall. After 4 hours, the upper layer rainwater recharge is less than the layer infiltration amount, so the water content gradually decreases.

It can be seen from Figure 6(c) that the water content increments of all curves are negative, and the smaller the buried depth, the greater the decrease. It shows that, after the rainfall, the rainwater has been infiltrating into the deep layer, resulting in a decrease in the water content, and the rainwater infiltration rate of the surface layer of the slope is faster. For example, the water content at the buried depth of 20 cm has been decreasing. The water content of the buried depth of 30 cm decreased significantly in the first 2 hours, and then the water content remained basically unchanged due to the infiltration of rainwater in the upper soil. The water content at 130 cm decreased slightly, and the water content at 150 cm remained basically unchanged. The reason is that this time the rainfall was longer and the rainfall was also large. The later rainfall gradually decreased until the rain stopped. Therefore, at the end of the rainfall, the rainwater has penetrated into the slope. The moisture content of the surface layer of the slope cannot be greatly supplemented; that is, the amount of water infiltration of this layer of soil is much greater than the amount of water supplement, so the increase in moisture content is negative.

It can be seen that the moisture content of slope soil after rainfall is related to rainfall, rain pattern, and duration. The rainfall is small and the duration is short. After the rainfall ends, the water content of the slope surface increases and reaches its peak within 2–4 hours. As the rainfall increases, the longer the duration, the water content of the slope soil decreases after the rainfall ends, the rainwater has been infiltrated into the deep layer, and the rainwater infiltration rate of the slope surface layer is faster.

4.2. Relationship between Pore Water Pressure Changes. It can be seen from Figure 7 that rainfall infiltration and evaporative drying are the main causes of changes in the pore water pressure of the site slope. The surface pore water pressure is obviously affected by the atmosphere. The pore water pressure increase at a depth of 10 cm reaches a maximum of 0.6 kPa during the rainfall period, while the pore water pressure increment at the depth of 40 cm and 110 cm only fluctuates in the range of $0{\sim}1.5 \times 10 - 2$ kPa. The pore water pressure of the slope surface has obvious synchronization with the rainfall infiltration reaction. The pore water pressure rises rapidly in rainy days and decreases in cloudy and sunny days. Pore water pressure and rainfall also have a good positive correlation. The greater the rainfall, the greater the pore water pressure. For example, the maximum rainfall on September 15 was 40.9 mm, at which time the pore water pressure increment reached the maximum value of 0.584 kPa.

It can be seen from Figure 8 that the pore water pressure of the slope is more affected by the atmosphere than the toe and top of the slope, and the pore water pressure of the slope is more affected by the atmosphere than the toe. The reason is that the slope exposed to the atmosphere is obviously affected by the atmosphere. The water infiltration of the slope during the rainfall period and the evaporation of water vapor in the dry period are easier, so the pore water pressure changes significantly; at the same time, the rainwater flows along the slope top to the slope surface during the rainfall period. Converging to the foot of the slope, the actual water volume at the foot of the slope increases, so the pore water pressure at the foot of the slope is greater than the pore water pressure at the top of the slope.

4.3. Relationship between Shear Strength Changes. In rainy weather (August 16, August 23, and September 7) and sunny weather (August 15, August 21, and September 5), the drilling depth is 20 cm and 50 cm, respectively. In rainy weather (August 16, August 23, and September 7) and sunny weather (August 15, August 21, and September 5), drill soil samples at four depths of 20 cm, 50 cm, 80 cm, and 100 cm were drilled to conduct water content, density, and shear tests. The relationship between water content, density, cohesion, and internal friction angle with slope depth were obtained as shown in Figure 9 moisture content and density, Figures 10 and 11 are obtained.

It can be seen from Figures 10 and 11 that the slope soil cohesion and internal friction angle have a good binary quadratic function relationship with water content and density. The expression is

$$y = A\omega^2 + B\rho^2 + C\omega + D\rho, \tag{1}$$

where y is cohesion c or φ, ω is water content, ρ is density, and A, B, C, D, are test constants. According to formula (1), the water content and density can be used to calculate the cohesion and internal friction angle.

4.4. Failure Characteristics and Evolution Law of Red Clay Slope. Through one-year on-site monitoring, the failure characteristics and evolution of red clay slopes were summarized (Figures 12 and 13).

From Figures 12 and 13, it can be seen that the red clay slope failure characteristics: mainly surface failure represented by gullies and weathering spalling, and then gradually evolved into shallow instability failure represented by collapse and slumping, and overall failure less damage. The evolution law of red clay slope failure under the dry-wet cycle is splash corrosion and surface corrosion stage⟶ fracture development stage⟶ gully formation stage⟶ gully development through stage⟶ local collapse stage⟶ slope foot collapse stage.

(a) Sputter erosion and surface erosion stages (Figure 13(a)): when the newly built slope rains for the first time, the free fall of rainwater impacts the small particles of the surface soil of the slope, causing splash erosion and surface erosion. At the beginning of the test, the soil on the complete slope surface has a high degree of compaction, and the permeability of red clay is low. There was less rainwater infiltrating into the slope. The rainwater on the top of the slope collects towards the slope shoulder, and the water on the slope collects towards the toe of the slope. The rain at the shoulder and the toe of the slope increases, and eventually surface erosion and microgully are formed on the shoulder and toe of the slope.

(b) Fracture development stage (Figure 13(b)): during the drying period, the soil loses water and shrinks, and cracks begin to appear on the top of the slope. The cracks are usually in the shape of an "eight" and develop in and around the slope. The crack divides the entire slope into several relatively independent soil blocks, and part of the soil falls on the surface of the slope.

(c) Gully formation stage (Figure 13(c)): after rainfall, rainwater enters the cracks, and after the cracks are filled, the rainwater on the top of the slope flows along the vertical cracks at the slope shoulder to the slope surface, washing the cracks, making the cracks wider and deeper, and then forming a gully.

(d) The development of the gully through stage (Figure 13(d)): after the soil at the gully is washed by rain, the strength of the soil decreases sharply. In the dry period, the soil body loses water and cracks more severely, the crack density is greater, and the number of "eight"-shaped soil blocks is higher. In the dry period, the soil body loses water and cracks more severely, the crack density is greater, and the number of "eight"-shaped soil blocks is higher. The partially penetrating gullies made the slope surface become several relatively independent soil strips.

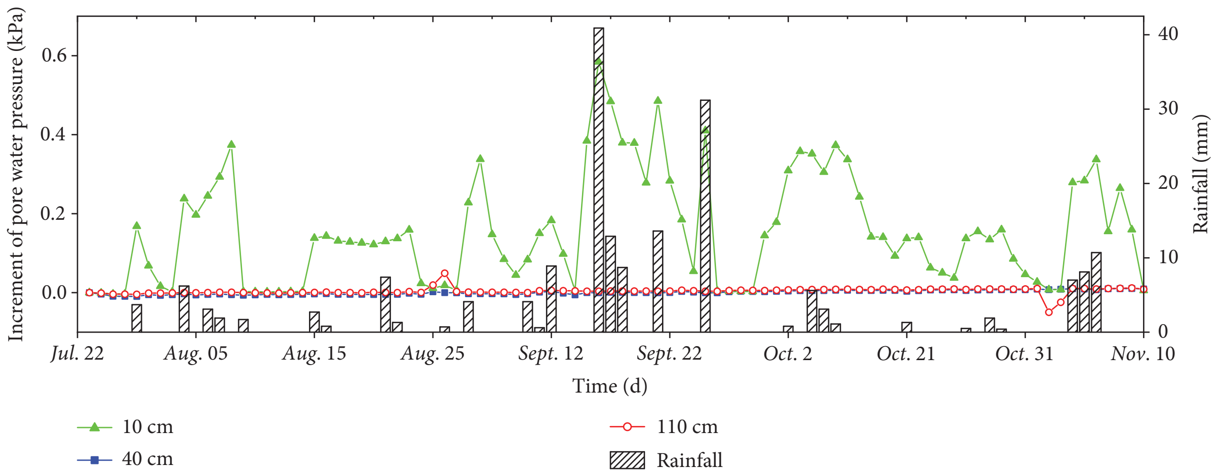

FIGURE 7: Time history curve of pore water pressure at different depths of slope (slope surface).

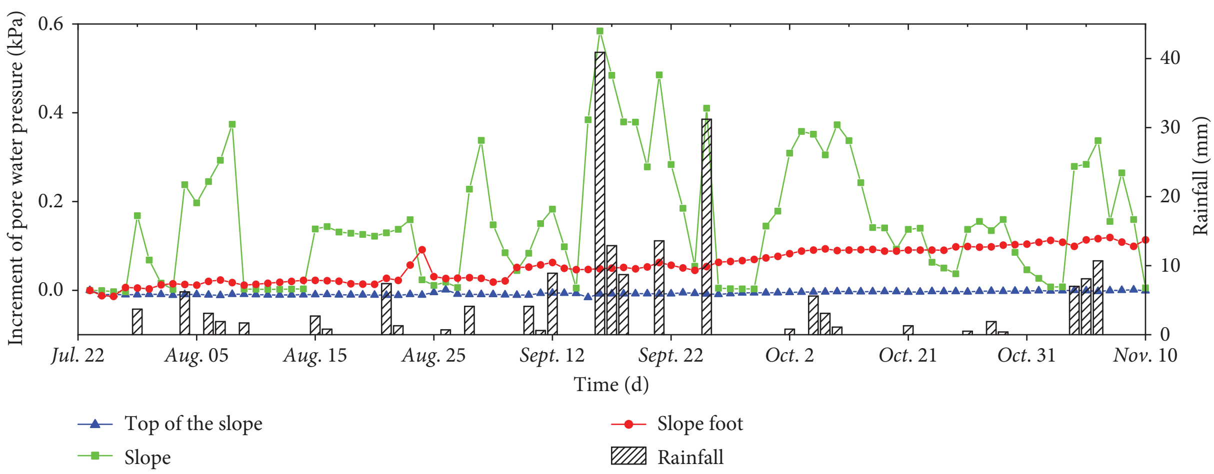

FIGURE 8: Time history curve of pore water pressure at different positions on the slope (40 cm).

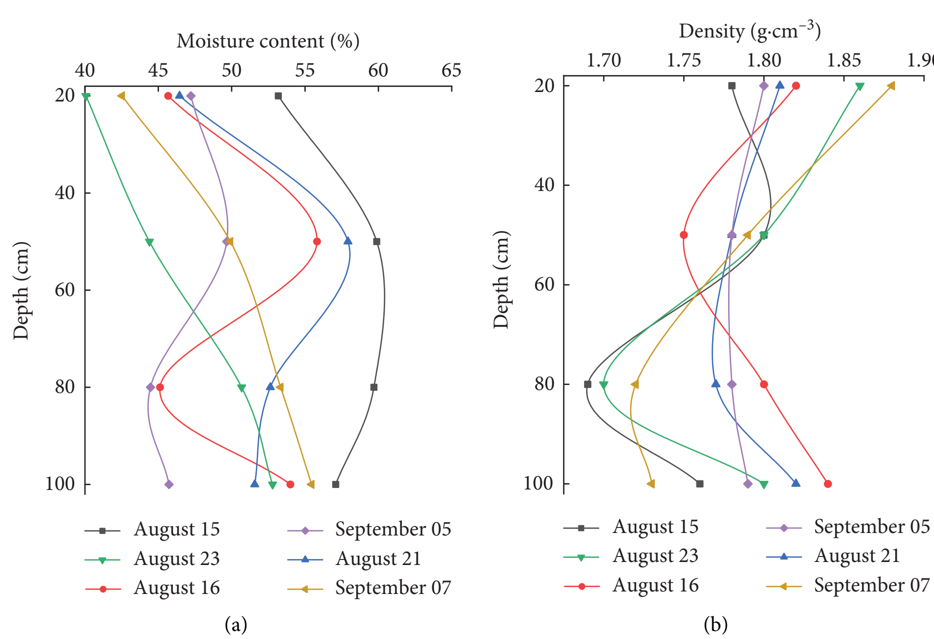

FIGURE 9: Continued.

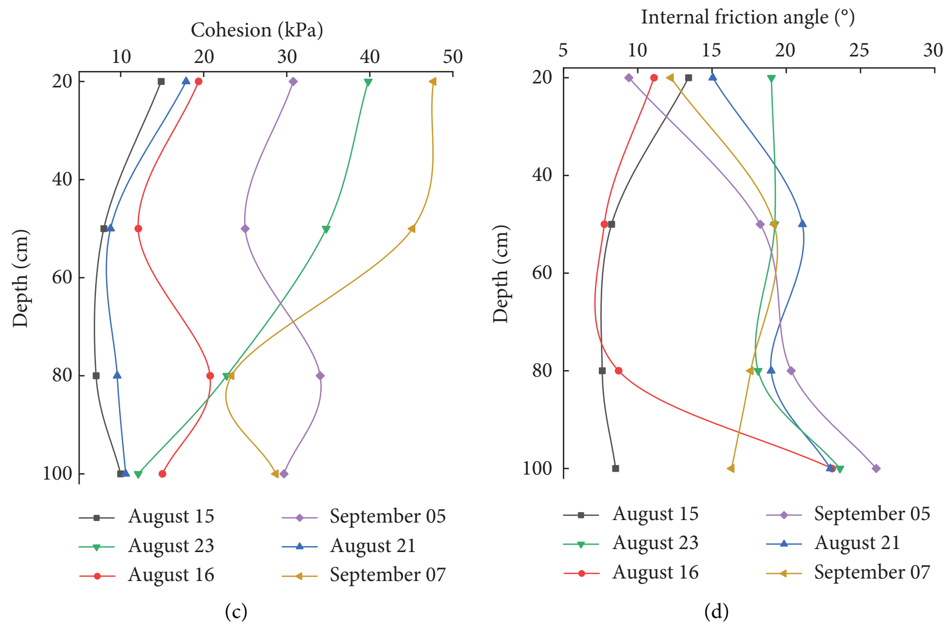

Figure 9: The relationship between various factors and the depth of the slope. (a) Moisture content. (b) Density. (c) Cohesion. (d) Internal friction angle.

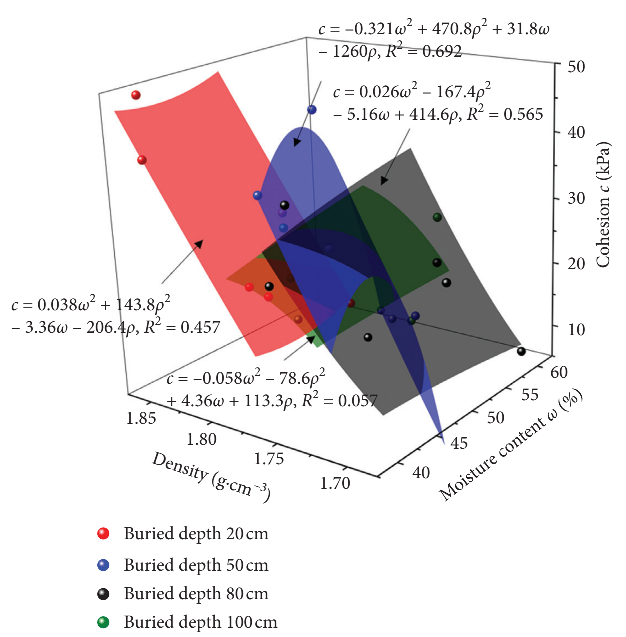

Figure 10: Relationship between cohesion at different depths and density and water content.

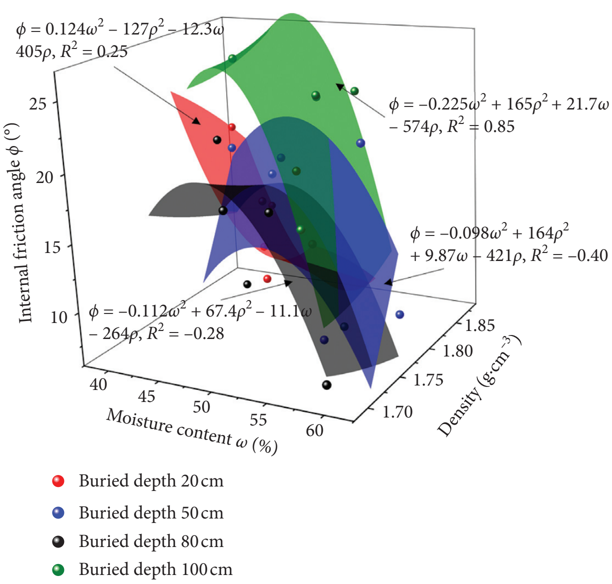

Figure 11: Relationship between internal friction angle and density and water content in different depths.

(e) Partial collapse stage (Figure 13(e)): with the continuation of evaporation-rainfall, the width, length, number, and depth of the cracks in the evaporation stage are further developed, extending the gully to the middle and lower part of the fracture surface. During the rainfall phase, the rainwater flows down the original gullies and runs through to the foot of the slope. When the rainfall intensity is high, when the original slope shoulder gully cannot bear the flow, rainwater will flow down along other vertical cracks of the slope shoulder to form a new gully. At the same time, the soil blocks and soil striped with the word “eight” on the slope surface fall off and collapse locally due to rain erosion.

(f) The collapse stage of the slope toe (Figure 13(f)): because all the rainwater of the slope is collected to the toe of the slope, the runoff of the toe increases, the moisture content of the soil at the toe

Figure 12: Failure characteristics of red clay slope.

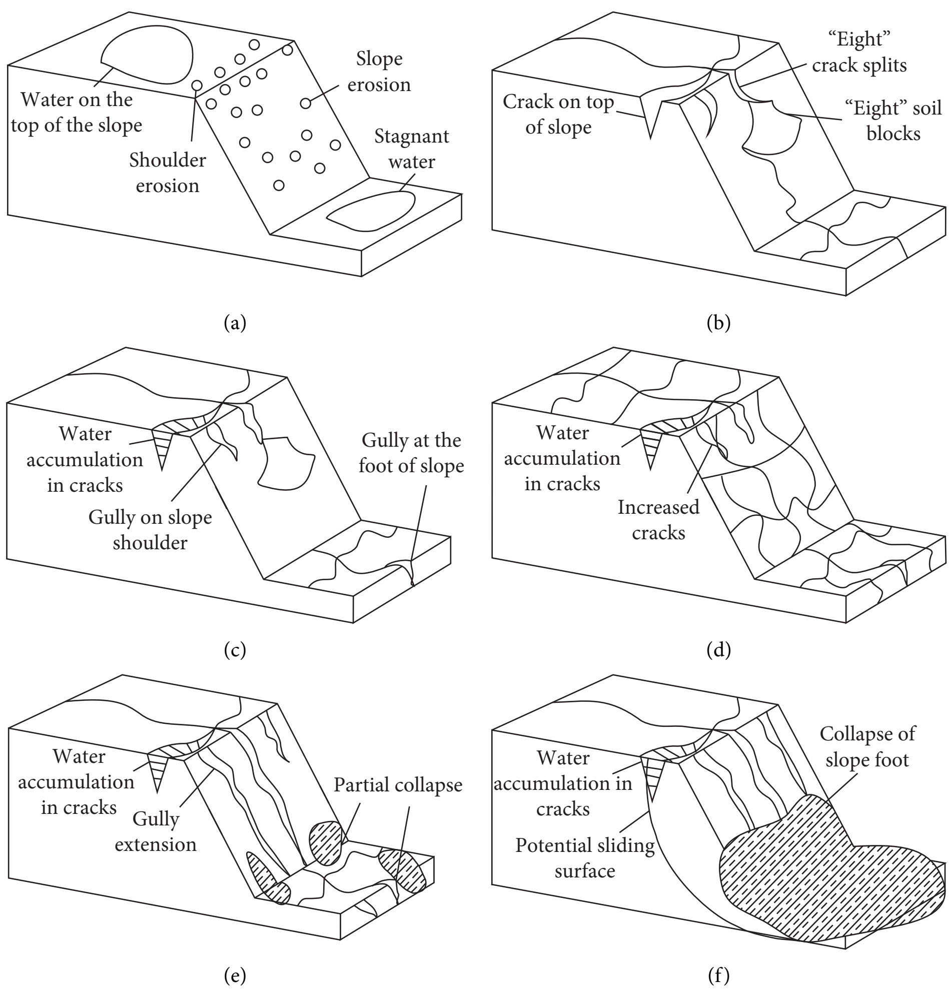

Figure 13: Slope failure evolution law under dry-wet cycle. (a) Sputter erosion and surface erosion stages. (b) Fracture development stage. (c) Gully formation stage. (d) The development of the gully through stage. (e) Partial collapse stage. (f) The collapse stage of the slope toe.

increases, the pore water pressure also increases, the shear stress of the slope toe increases, the shear strength decreases, and the toe shows first collapse.

5. Conclusion

(1) The atmospheric influence depth of the red clay slope is about 0.7 m. When the depth is greater than 0.7 m, the water content of the slope, toe, and top of the slope is between 40 and 52%. The red clay slopes with or without vegetation cover respond to different degrees under the same climate influence. The atmospheric effect has a great influence on the moisture content of the bare slope, and it has a small influence on the top of the slope with shrubs and the toe covered with turf.

(2) Rainfall is the most direct climatic factor leading to the instability of red clay soil slopes. During the rainfall period, the water content of the slope soil increases. The greater the rainfall, the greater the increase, but the time of the peak water content lags the time of the peak rainfall. Evaporation leads to the loss of water in the red clay soil, cracks in the soil, and also provides a channel for rainfall infiltration, which causes the strength of the soil to attenuate and progressive destruction. This also shows that the evaporation effect is an important prerequisite for the catastrophe of the red clay soil slope.

(3) The water content of slope soil after rainfall is related to rainfall, rain pattern, and duration. The smaller the rainfall, the shorter the duration, and the water content of the slope surface increases after the rainfall ends, reaching a peak in 2–4 h. The greater the rainfall, the longer the duration. After the rainfall ends, the moisture content of the shallow soil of the slope decreases, and the rainwater permeates to the deep layer.

(4) Rainfall infiltration and evaporation are the main causes of changes in the pore water pressure of the site slope. Surface pore water pressure and rainfall infiltration have obvious synchronization. The greater the rainfall, the greater the pore water pressure.

(5) The cohesion and internal friction angle of slope soil have a good binary quadratic function relationship with water content and density; the expression is

$$y = A\omega^2 + B\rho^2 + C\omega + D\rho. \tag{2}$$

(6) The failure characteristics of red clay slopes are mainly caused by the ravines formed by water flow and exfoliation caused by weathering which then gradually evolve into collapsed shallow instability failures. The overall failure of slopes is rare. The evolution law of red clay slope failure under the dry-wet cycle is splash corrosion and surface corrosion stage⟶ fracture development stage⟶ gully formation stage⟶ gully development through stage⟶ local collapse stage⟶ slope foot collapse stage.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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