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Research Article

Study on Strength Attenuation Characteristics of Residual Expansive Soil under Wetting-Drying Cycles and Low Stress and Its Relationship with Shallow Landslide

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The rapid development of expansive soil fissures and the attenuation of strength under the action of repeated atmospheric wetting-drying cycles have a very adverse impact on the shallow stability of expansive soil slope. In this study, shear strength test and fissure observation test were performed on typical residual expansive soil specimens at various wetting-drying cycles and low stress. The results show that the shear strength index of residual expansive soil should be obtained according to the high and low stress sections, respectively. The cohesion of the three residual expansive soils decreased to a similar low value range (0~5 kN) at multiple wetting-drying cycles and low stress; the attenuation of cohesion is the main cause of shallow slope collapse. The fissure rate of the specimen surface increases with the increasing number of wetting-drying cycles, and increasing the dry density can significantly inhibit the development of fissures. The repeated wetting-drying cycles leads to the rapid development of slope fissures from the surface to the inside, destroys the internal natural structure of undisturbed expansive soil, reduces the cementation between soil particles, and leads to the decrease of soil cohesion. For slope stability analysis of residual expansive soil, the strength parameters of the specimens with multiple wetting-drying cycles and internal fissure network should be selected according to the overburden pressure of the slope sliding surface. The research results provide a theoretical basis for the stability analysis of shallow landslide of expansive soil slope and slope protection design.

1. Introduction

Expansive soil is widely distributed in China. More than 300 million people live in expansive soil distribution areas. The geological environment in these areas is fragile, and the economic loss caused by expansive soil landslide disaster exceeds tens of billions of yuan every year [1–3]. Due to the existence of montmorillonite clay minerals with strong hydrophilicity, the expansive soil is extremely sensitive to humidity and heat change. The numerical analyses could be inconsistent with the actual stability of the slope as the uncertainties of its strength contribute to the slope instability in practice [4, 5].

Many researchers almost study the slope stability of expansive soil from the two aspects of shear strength parameters and the development of fissures [6–11]. Li et al. [12] believe that for expansive soil embankment, the influence of wetting-drying cycles on residual strength parameters should be properly considered when selecting strength parameters. Cheng et al. [13] emphasized that the shear strength parameters measured under low stress conditions should be selected to analyze the slope stability in order to obtain reasonable calculation results, but it did not closely link the strength attenuation with the wetting-drying cycle effect. Xiao et al. [14, 15] carried out indoor direct shear and triaxial tests and found that after multiple wetting-drying cycles, the saturated slow shear strength of expansive soil is very small or even tends to zero in the low stress section. Selecting the strength parameters under this condition to analyze the slope stability can get more practical results. There are also some differences in the simulation methods of wetting-drying cycles process in the shear strength test of expansive soil carried out by previous researchers [16–20]. Considering that the actual sliding surface of expansive soil slope is under different overlying pressure conditions, there must be a difference between the deformation of expansive soil after moisture absorption and its expansion without load. Therefore, it is considered that the simulation of moisture absorption conditions in the preparation of expansive soil specimens should be changed to the loaded state. The actual overburden pressure at the shallow sliding surface of expansive soil slope is generally less than 50 kPa, which does not match the overburden pressure that can be applied by the conventional direct shear test, so the shear application conditions in the shear test need to be improved accordingly.

The influence of fissures must be considered in the stability analysis of expansive soil slope [21] .Yin et al. [22] believe that the existence of fissures makes the shear strength of slope soil clear, the fissure depth will be stable at a certain value after repeated wetting-drying cycles, the strength of soil within the fissure development depth will be reduced, while the deeper soil has no fissures and the strength is higher. Therefore, it is proposed that the slope stability analysis should be replaced by corresponding strength parameters in layers to obtain the collapse failure results of expansive soil slope. Secondary fissure refers to the newly generated fissure affected by climate change such as weathering and dry wet cycle, which has a significant impact on the strength of expansive soil. The shallow secondary fissure surface and deep primary fissure surface constitute the unstable sliding surface of expansive soil slope [23] . Moreover, researchers initially treated expansive soil slope as ordinary cohesive soil slope, and the results obtained by limit equilibrium method are quite different from the actual situation. For example, the average slope of Nanyang expansive soil slope in China is 1 : 2, and the calculated stability coefficient is 2.7, but there are still landslides. Some even slow down the slope to 1 : 4, and the landslide phenomenon still exists [24].

This highlights the complexity and uncertainty of the selection of strength parameters in the stability analysis of expansive soil slope. In addition, there are few existing studies to discuss the selection of expansive slope stability analysis parameters combined with the strength attenuation and fissures development of expansive soil under the action of atmospheric wetting-drying cycles. Therefore, studying the strength attenuation and fissures development characteristics of expansive soil under dry wet cycle and low stress conditions are of great significance to clarify the causes of frequent shallow collapse of slope and determine the reasonable value of slope stability analysis parameters and effective engineering treatment measures.

Nanning, Baise, Shangsi, and other places in Guangxi Zhuang Autonomous Region are typical distribution areas of residual expansive soil in China. The properties of residual expansive soil in these areas are complex and bring many engineering disasters.

In order to study the relationship between strength attenuation and fissure development of residual expansive soil and explore the selection of soil parameters in Shallow Stability Analysis of expansive soil slope, the representative residual expansive soil specimens from Nanning, Baise, and Shangsi in Guangxi Zhuang Autonomous Region are selected for shear strength test under wetting-drying cycles and low stress. Moreover, the Baise residual expansive soil is selected for fissure observation test.

2. Materials and Test Methods

2.1. Soil for Test. Three representative residual expansive soil specimens of Nanning, Baise, and Shangsi in Guangxi Zhuang Autonomous Region were selected for experimental research. The basic soil property test indexes of the three soils are shown in Table 1.

2.2. Specimen Preparation. In this test, remoulded soil was used for specimen preparation. Three types of soil taken from the three selected areas were dried by natural air, crushed, and screened for 2 mm and then mixed into wet soil to achieve a natural moisture content of 17.0%. After 24 hrs of stuffing, the soil specimens were prepared by static pressure method. The dry density of the specimens was maintained at 1.70 g/cm^3, and the test errors of moisture content and dry density were limited within ±0.5% and ±0.02 g/cm^3, respectively, to ensure that the initial state of each soil specimen was basically the same before the implementation of the wetting-drying cycles. In addition, Baise expansive soil specimens with dry densities of 1.5 g/cm^3, 1.6 g/cm^3, and 1.7 g/cm^3 were prepared according to the above methods as fissure observation specimens.

2.3. Wetting-Drying Cycles Methods. The selected numbers of wetting-drying cycles were 0, 2, 4, and 6. Four groups of soil specimens were prepared, and one group of eight specimens was tested with load wetting-drying cycles. A total of 32 specimens were prepared. Filter paper and permeable stone were used to cover the upper and lower sides of each specimen so as to prevent the soil particles on the surface from scattering after water absorption and specimen expansion, respectively. Five specimens from each group were placed in the water tank, and vertical loads of 5, 15, 30, 50, and 75 kPa were applied, as shown in Figure 1. In the moisture absorption process, in order to simulate the critical state that the soil is completely saturated by moisture absorption in the process of rainfall infiltration, the saturated moisture content is controlled above 97%. The tank was filled with water to the same level as the permeable stone on the specimen. The specimen was left standing for 3-4 days for water absorption and saturation. The other three specimens in each group were humidified via vacuum pumping for 24 hrs, and the volume of each specimen was controlled to be constant during the saturation process according to the expansion force of the specimen. The saturations of the specimens obtained by the two methods were basically the same which is equal or more than 97%. Then, the weights of the specimens were determined. In the dehumidification process, in order to simulate the extreme high temperature of the natural environment, the temperature in the control

Table 1: Characteristic Indexes of Residual Expansive Soil.

Expansive soil	Bulk density [g/cm^3]	Liquid limit w_L [%]	Plastic limit w_p [%]	Plasticity index I_P	Particle composition [%] >0.075 mm	Particle composition [%] 0.075–0.005 mm	Particle composition [%] <0.005 mm	Particle composition [%] <0.002 mm	Montmorillonite content [%]	Free expansion rate δ_{ef} [%]	Properties of water-soaked disintegrated material of dry rock mass
Nanning expansive Soil	2.075	46.04	23.77	22.27	0.30	56.14	43.56	42.29	11.78	62	"Slice" muddy
Baise Expansive soil	2.092	56.26	21.37	34.89	0.10	52.02	47.88	45.20	16.58	82	"Clastic" muddy
Shangsi Expansive soil	2.032	55.33	25.19	30.14	0.09	47.87	52.04	48.6	15.05	51	"Debris" muddy

Figure 1: Wetting-drying cycles saturation with loading.

Figure 2: Strain controlled direct shear apparatus.

box is 40 °C, and the sample is taken out for weighing in time during the dehumidification process, and the moisture content of dehumidification is controlled to 13% of the shrinkage limit moisture content of the sample.

2.4. Direct Shear Test. After unloading the water saturated specimens with the proposed number of wetting-drying cycles, they were loaded into the shear box. The test instrument was a four-way direct shear instrument produced by Nanjing Soil Instrument Factory (see Figure 2). The corresponding vertical pressure was applied to minimize the impact of the unloading and loading process by conducting the test quickly. The shear strength of each group was measured with slow shearing, with a shearing rate of 0.02 mm/min. For a group of eight specimens, 5, 15, 30, 50, 75, 100, 200, and 300 kPa of corresponding moisture absorption loads were applied. In order to reduce the deviation of test results, three samples are selected as a group for parallel test in this shear strength test. The average value of the test results of the three samples is taken as the final result, and the test results are accurate to 0.01 kpa. The whole test process is carried out in strict accordance with the requirements of Chinese specification highway geotechnical test specification (JTG 3430-2020) [25].

2.5. Fissure Observation Test. After unloading the load on the saturated specimen that has completed the proposed number of wetting-drying cycles, the permeable stone and specimen are put into a 50 °C incubator to continue dehumidification. The specimen is weighed to monitor its humidity change. The fissure changes of different dehumidified specimens were photographed by a camera, and the fissure observation tests of specimens under wetting-drying cycles for 1, 2, 3, 5, and 6 times were completed.

3. Results and Discussion

3.1. Analysis of Shear Strength Test Results

3.1.1. Peak Shear Stress Results. The final shear data of the residual expansive soil measured in slow shear tests are listed in Table 2.

3.1.2. Effect of Vertical Load on Shear Strength. The absolute attenuation rate of the strength of the expansive soil is used as follows to facilitate the quantitative analysis of the attenuation law of the shear strength of soil specimens under different loads relative to the number of wetting-drying cycles:

$$\Delta_{i,\sigma} = \frac{\left|\tau_{i,\sigma} - \tau_{0,\sigma}\right|}{\tau_{0,\sigma}} \times 100. \quad (1)$$

In Equation (1), i is the number of wetting-drying cycles, σ denotes the vertical load, $\tau_{i,\sigma}$ is the shear strength after i wetting-drying cycles (kPa), and $\tau_{0,\sigma}$ is the shear strength of expansive soil without wetting-drying cycles under vertical load σ (kPa).

For the convenience of research, only the measured values of the three groups of soil specimens in Table 2 under the level 4 vertical load of 5, 50, 100, and 300 kPa are selected for analysis. The results calculated by substituting the corresponding data into Equation (1) are listed in Table 3. When the vertical load is fixed, the absolute attenuation rate of the strength of the three types of expansive soil gradually increases with the increasing number of wetting-drying cycles. However, after every two wetting-drying cycles, the attenuation rate gradually decreases, thus indicating the considerable impact of the initial wetting-drying cycles on the strength attenuation. When a number of wetting-drying cycles are the same, the greater the vertical load of the same soil specimen is, the smaller the absolute attenuation rate of the strength is. Therefore, increasing the overburden pressure can reduce the influence of the wetting-drying cycles on the strength attenuation of the expansive soil. It indicates that the load can effectively inhibit the strength attenuation of expansive soil during the wetting-drying cycles [26, 27].

3.1.3. Determination of Shear Strength Parameters. Many experiments have been pointed out that the shear strength line of expansive soil measured under the condition of low stress is nonlinear, which is dominant when the overburden pressure is smaller [28, 29]. The more significant the overburden pressure is, the larger the volume expansion is and the smaller the corresponding maximum shear stress is. However, if the direct shear test is carried out according to the method specified in the code and only the shear force under the condition of high stress is measured and analyzed, then the true value of shear strength at the shallow sliding surface of the expansive soil slope cannot be obtained.

In view of the characteristics of the shallow failure of expansive soil slope, the effective approach is to take the

Table 2: Results of Shear Strength Tests.

Vertical stress during shearing [kPa]	The peak shear stress of Nanning expansive soil [kPa] Number of cycles				The peak shear stress of Baise expansive soil [kPa] Number of cycles				The peak shear stress of Shangsi expansive soil [kPa] Number of cycles			
	0	2	4	6	0	2	4	6	0	2	4	6
5	12.09	7.85	5.46	4.10	12.56	6.32	5.66	5.12	11.27	6.62	5.48	4.86
15	15.84	13.60	13.42	12.74	25.30	17.22	14.63	12.10	15.17	12.05	11.14	10.01
30	26.74	22.12	20.46	19.15	29.05	19.47	18.16	16.43	25.91	21.01	18.65	16.94
50	35.41	31.68	29.80	28.01	42.15	33.01	28.48	26.73	36.72	30.10	27.21	25.29
75	45.14	40.57	37.34	36.65	49.91	45.27	40.24	38.96	48.78	40.42	36.90	34.72
100	55.08	50.29	47.37	47.03	60.35	55.84	53.97	51.83	57.25	47.86	43.32	41.05
200	94.14	89.68	86.13	83.93	99.02	94.69	89.26	84.34	96.09	88.21	83.36	79.35
300	139.28	131.70	128.26	127.40	127.06	118.44	116.72	110.94	130.25	120.33	113.67	110.92

Table 3: Shear strength reduction ratio of expansive soil with different wetting-drying cycles and loadings.

Vertical load [kPa]	Nanning soil [%]				Baise soil [%]				Shangsi soil [%]			
	Δ_0, σ	Δ_2, σ	Δ_4, σ	Δ_6, σ	Δ_0, σ	Δ_2, σ	Δ_4, σ	Δ_6, σ	Δ_0, σ	Δ_2, σ	Δ_4, σ	Δ_6, σ
5	0	34.70	54.24	65.43	0	49.22	54.38	58.67	0	41.25	51.38	56.88
50	0	10.43	15.69	20.70	0	21.48	32.11	36.22	0	18.03	25.90	31.13
100	0	8.61	13.86	14.48	0	7.41	10.45	13.98	0	16.40	24.33	28.30
300	0	5.39	7.83	8.44	0	6.71	8.05	12.56	0	7.62	12.73	14.84

high-stress and low-stress sections into consideration separately obtain the strength parameters in different sections. Five measuring points of 5, 15, 30, 50, and 75 kPa and four measuring points of 75, 100, 200, and 300 kPa are divided into two sections. As shown in Figure 3(a), straight-line fitting is carried out, and the corresponding c and φ values are shown in Table 4. For the convenience of comparison, a single straight-line strength line is also drawn in Figure 3(b). The correlation coefficient R^2 of each soil specimens fitting segmented strength line is greater than 0.94, which indicates that expressing the shear strength of expansive soil with either a single line or a double line is reasonable and feasible. However, the c value of a single line is much larger than that of a double line for the low-stress section. Therefore, in the stability analysis of expansive soil slope, the c and φ values should be, respectively, varied according to the possible sliding surface depth, and the corresponding index of the stress section can help obtain practical results.

3.1.4. Test Results of c and φ. According to the data in Table 4, regardless of the type of expansive soil and its high-stressor low-stress sections, the cohesion c value decreases continuously with the increasing number of wetting-drying cycles. However, the change range of the internal friction angle φ is relatively small. To further explore the change rule of the cohesion c value, the number of wetting-drying cycles is designated as the abscissa, and the cohesion is designated as the ordinate for curve fitting in the high- and low-stress sections, respectively, and the analysis results are shown in Figure 4.

The attenuation curve of the c value in Figure 4 is fitted numerically, and the attenuation of cohesion of the three types of soil with the increasing number of wetting-drying cycles is an exponential-type relationship. The correlation for the high-stress section is high, and the correlation coefficient is larger than 0.9. The correlation coefficient of the low-stress section of Nanning soil is greater than 0.95, and that of Baise soil is the lowest of 0.91. In summary, the relationship between the strength index c of expansive soil and the number of wetting-drying cycles N can be expressed as $c = ae^{-bN}$ (where a and b are constant).

Under the condition in which the internal friction angle φ does not decrease significantly with the increasing number of wetting-drying cycles, the average values of the four internal friction angles of each group of specimens under several wetting-drying cycles are taken in high-stress and low-stress sections, which are shown in Figure 5. The variation of the measured internal friction angle in five places is relatively small especially in Nanning soil and Baise soil, except for the low-stress section of Shangsi soil (see Figure 5). The deviation of the low-stress section of Shangsi soil is because that the measured internal friction angle of the soil specimen is relatively large when it is not subjected to the wetting-drying cycles. The difference may also be related to the small maximum dry bulk density of the soil. Therefore, within the test error, the value of the internal friction angle of each type of soil under the condition of low stress is replaced by the average value, which should meet the requirements of engineering applications.

3.2. Analysis of Fissure Observation Test Results

3.2.1. Change of Apparent Fissure of Specimen under Wetting-Drying Cycles. Figure 6 shows the photos of apparent fissure development of Baise expansive soil with dry

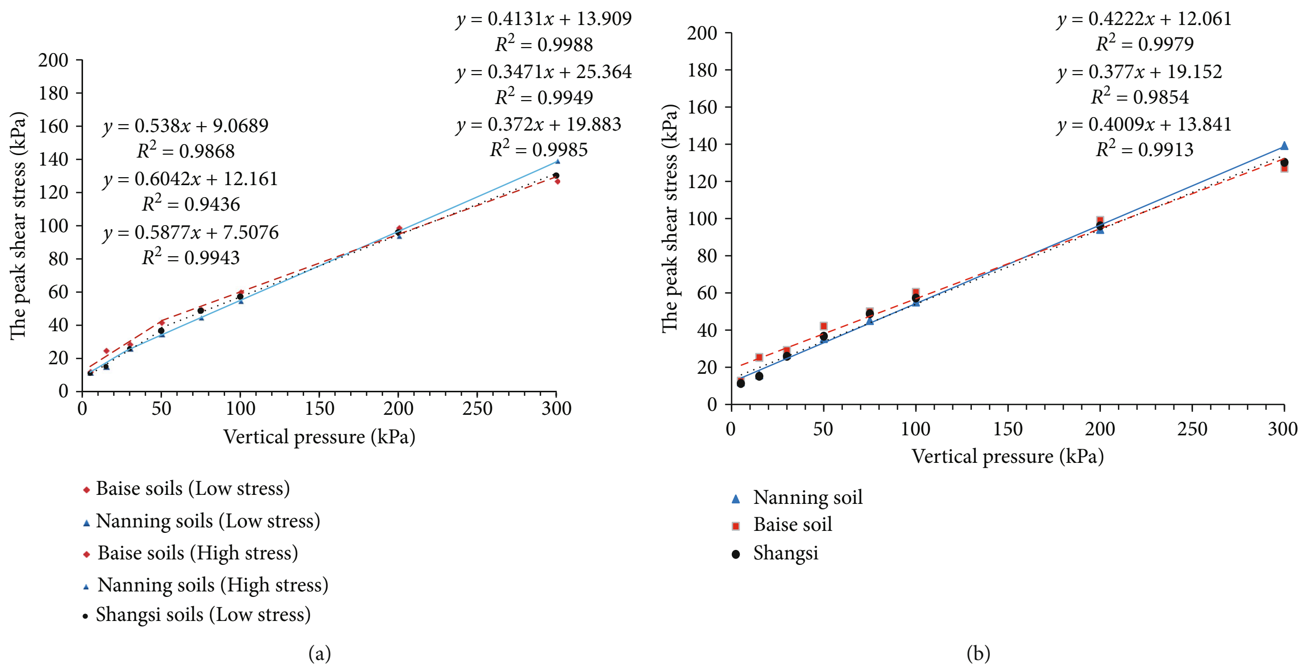

Figure 3: Line of shear strength of expansive soil with 0 wetting-drying cycles.

Table 4: Shear strength parameters of high and low stresses.

Stress interval	Parameters of strength	Nanning soil specimen under dry-wet conditions Number of cycles				Baise soil specimen under dry-wet conditions Number of cycles				Shangsi soil specimen under dry-wet conditions Number of cycles			
		0	2	4	6	0	2	4	6	0	2	4	6
High stress	φ [°]	22.58	22.00	21.90	21.76	19.02	18.18	18.51	17.46	20.07	19.88	19.26	19.07
	c [kP]	13.17	9.82	6.97	6.32	22.30	14.33	10.71	9.83	21.44	13.18	10.33	8.19
Low stress	φ [°]	25.78	25.13	24.03	24.13	26.90	27.96	25.20	25.16	28.79	25.81	24.02	23.01
	c [kP]	10.12	6.72	5.67	4.44	14.02	5.64	4.95	3.41	8.34	5.11	4.28	3.50

density of 1.5 g/cm^3, 1.6 g/cm^3, and 1.7 g/cm^3 under the action of wetting-drying cycles ($n = 2$, 3, 4, 5, and 6).

According to the Figure 6, under the same dry density, the apparent fissure development of the specimen becomes more intense with the increase of the number of wet dry cycles, and the depth of fissure development also gradually increases. The above findings are broadly consistent with the previous results reported in the literature (e.g., Luo et al. [30] and Xu et al. [31]).

This is because when the tensile force generated under the wetting-drying cycles exceeds the tensile force of the soil, the specimen surface will crack. Even if the fissure heals with water, the tensile strength of the soil cannot be fully restored with the healing of the fissure, so this place becomes the weak place of the soil. In the next dehumidification process, the weak place is easy to produce stress concentration and small tension, resulting in cracking. Therefore, with the increasing number of wetting-drying cycles, the fissure of the specimen continues to expand in the original weak position, gradually forming a fissure with larger area and deeper fissure depth until it is connected. However, the larger the dry density of the specimen, the slower the development of the apparent fissure under the same wetting-drying cycles conditions, which shows that increasing the dry density can significantly inhibit the development of the specimen fissure [32] .The dry density of the actual expansive soil slope soil increases gradually with the increase of soil depth, and the development of the apparent fissure also slows down from the surface to the inside under the action of atmospheric wetting-drying cycles, which is just consistent with the conclusion of the test.

In order to quantitatively analyze the influence of dry cycle action on the fissure development of Baise expansive soil specimen, the image pro plus image processing software is used to obtain the characteristic parameters of the apparent fissure of Baise expansive soil specimen, and the variation curve of the fissure area ratio of the specimen with the number of wetting-drying cycles is drawn (see Figure 7). The formula for calculating the fissure area ratio of the specimen is written as

$$S = \sum_{i=1}^{k} A_i / A_w, \tag{2}$$

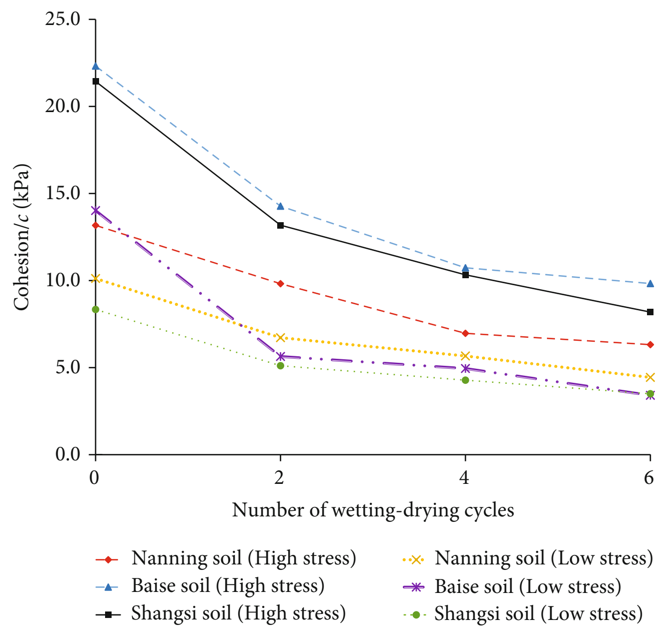

Figure 4: Curve fitting of c reduction with three types of expansive soil.

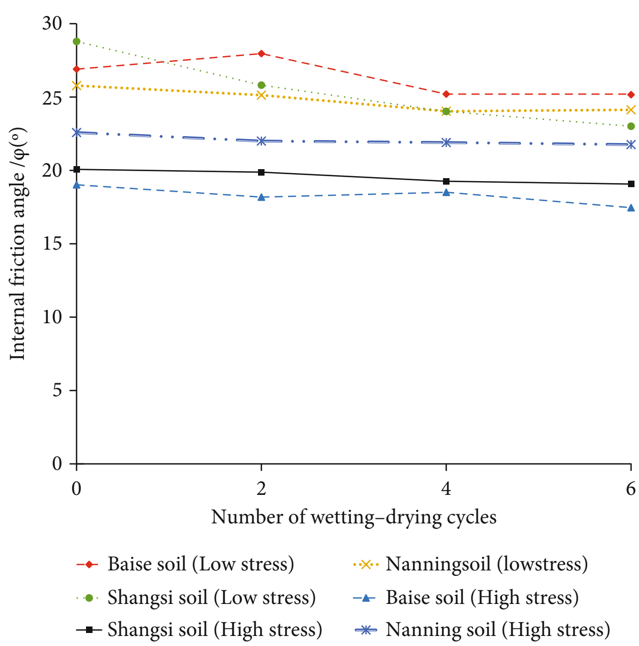

Figure 5: φ range of three types of expansive soil.

where S is the fissure area ratio; A_w is the area of the specimen when the humidity is w; A_i is the area of the i fissure; and k is the total number of fissures in the specimen.

It can be seen from Figure 7 that the fissure area ratio of the specimen increases with the increase of the number of wetting-drying cycles and finally tends to be stable. When the dry density is 1.5 g/cm3 and $N = 1 \sim 6$ times, the fissure area ratio are 0.00%, 0.26%, 3.38%, 4.43%, 5.50%, and 5.88%, respectively. The largest increase in the fissure area ratio of the specimen occurs in $n = 3$, which is 12 times that of $n = 2$. The fissure area ratio of $n = 6$ is only 6.9% higher than that of $n = 5$. The increase of specimens with higher dry density is more gentle than those with lower dry density, and the fissure area ratio is also smaller after six wetting-drying cycles. When $n = 6$, the fissure area ratio of the specimen with dry density of 1.7 g/cm^3 is 1.68%, which is only 29% of that of the specimen with dry density of 1.5 g/cm^3.

4. Discussion

4.1. The Relationship between Strength Attenuation of Expansive Soil and Fissure Development. Expansive soil is a typical clayey soil with many fissures. One of its typical characteristics is that the swelling shrinkage deformation is much larger than that of ordinary clayey soil. The swelling and shrinkage deformation of newly excavated expansive soil slope occurs continuously under the action of dry and wet cycle. The wetting-drying cycles leads to the generation and development of fissures in the slope and finally forms a chaotic fissure network after repeated times, especially in the high-temperature, humid, and hot areas in the south. The internal natural structure and initial integrity of undisturbed expansive soil are damaged due to the development of fissures, which immediately has a significant impact on the shear strength of soil. Therefore, the fissure factor in expansive soil cannot be ignored when analyzing the causes of shear strength attenuation.

From the perspective of fissure, the reason for strength attenuation is mainly the repeated expansion and contraction of soil specimens under the action of wetting-drying cycles. When the tensile force exceeds the tensile force of soil, the soil surface will crack [33]. However, the tensile strength of soil is a function of effective cohesion and matrix suction. The cohesion of soil will gradually decrease with the progress of wet dry cycle and finally tend to be stable. At this time, the tensile strength of soil is a function of matrix suction. In

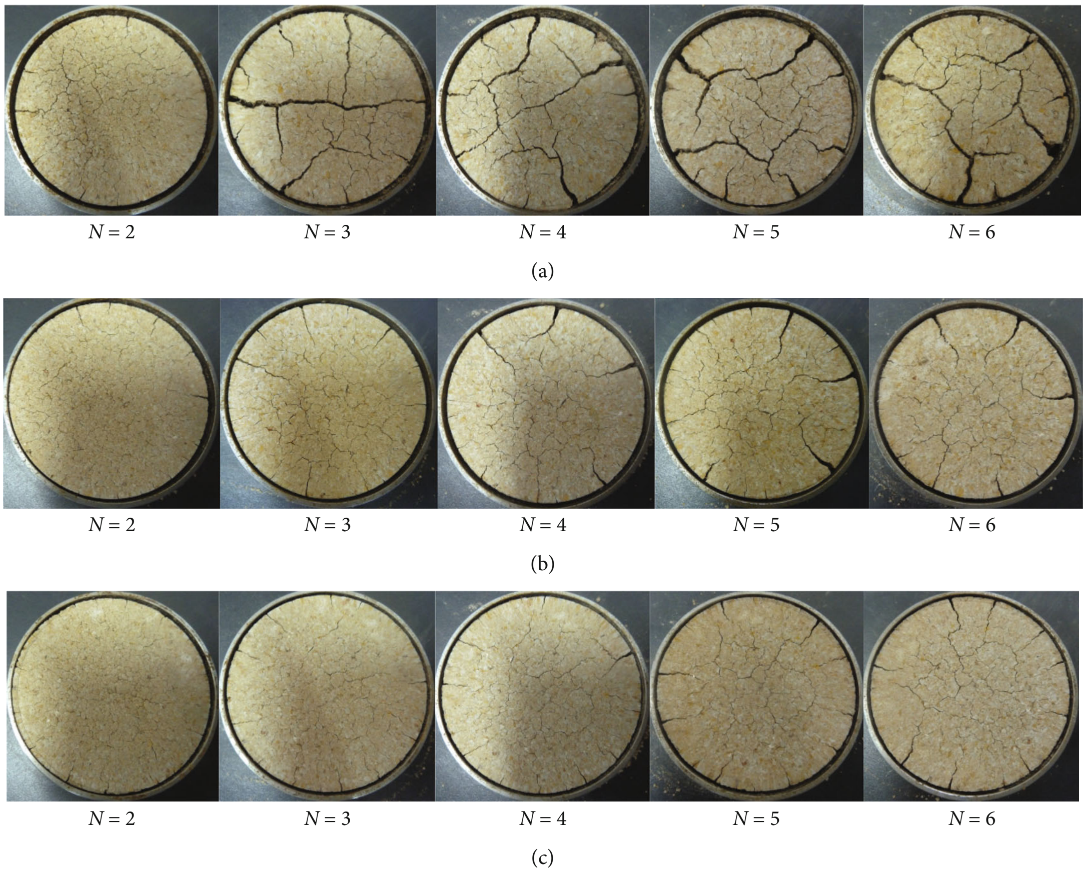

FIGURE 6: Apparent fissure images of Baise expansive soil specimens with different dry densities (*N* represents the number of wetting-drying cycles).

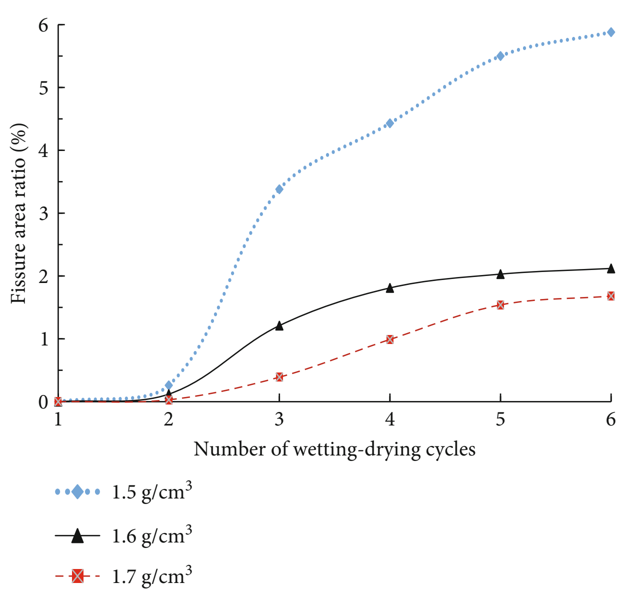

FIGURE 7: The fissure area ratio of specimen under wetting-drying cycles.

addition, matrix suction is mainly affected by water content [34] .With the increase of fissure depth, the distance between soil particles increases and the viscosity decreases after wet dry cycle. As a result, the moisture in the lower part is easier to evaporate, the moisture content gradient of the shallow surface soil of the specimen gradually decreases, the tensile strength decreases, and the fissures continue to develop and form a network inside. The continuously expanding and penetrating fissures reduce the cementation ability between soil particles, greatly reduce the cohesion, and aggravate the damage to the integrity of soil specimens, resulting in the reduction of its shear strength.

4.2. Suggestions on Strength Value during Stability Analysis of Expansive Soil Slope. Shallow collapse is a common geological problem faced by exposed expansive soil slopes in Southwest China, especially in Guangxi Zhuang Autonomous Region. Practice has shown that it has a certain relationship with the types and causes of expansive soil, but the severity of its damage is more closely related to the local atmospheric dry and wet cycle. In order to explore the main cause of shallow collapse of slope, the final shear strength of expansive soil must be determined.

Due to the remarkable characteristics of high peak strength and low residual strength of expansive soil, some scholars believe that the change process of expansive soil slope from stability to failure is from the peak of shear strength to the attenuation of residual strength [35]. The residual strength value of expansive soil is recommended for slope stability checking calculation. However, residual strength is the stress drop after reaching the peak value. It is proposed for ordinary cohesive soil slope, which is suitable for analyzing the progressive failure of slope. Expansive soil is a special clay which is particularly sensitive to the external water temperature. Its strength variation characteristics are mainly determined by its own expansion and contraction properties, and its actual attenuation reason is not directly related to the residual strength. Liu et al. [36] concluded that the residual strength of expansive soil is not equal to the strength after wetting-drying cycles by using the specific data obtained from the test. The repeated change of the volume of expansive soil reduces the compactness of the soil, and the fissure development affects the initial integrity of the soil. The existence of small fissures leads to the reduction of strength, and large fissures directly disconnect the soil without strength.

The three soil specimens selected in this study are typical and representative expansive soils in Guangxi. After six wetting-drying cycles, the cohesion of residual expansive soil specimens in Nanning, Baise, and Shangsi in the low stress section (representing the shallow layer of the slope) is 4.48 kpa, 3.44 kpa, and 1.60 kpa, respectively. According to the rapid development of apparent fissures of the specimen with dry density of 1.5 g/cm^3 (representing the shallow soil of the slope) under the action of six wetting-drying cycles, it is not difficult to find that the strength of the sliding surface is also in the extremely low strength range of 0 ~ 5 kpa when the shallow soil of the expansive soil slope is damaged. Therefore, according to the actual environment, the strength index value of specimens with fissure network after many wetting-drying cycles should be used in the stability calculation of expansive soil slope.

In the construction of slope in expansive soil area, the shallow protection of expansive soil slope should be strengthened. In particular, for some cutting slopes disturbed by excavation, timely covering and water sealing measures should be taken to delay the development of secondary fissures on the slope, so as to avoid shallow damage of exposed expansive soil on the excavated expansive soil slope caused by atmospheric dry wet cycle for a long time.

5. Conclusion

(1) The shear strength parameters (cohesion) of the soil in the shallow layer (less than 50 kPa) and deep layer (100~200 KPa) of the expansive soil slope are very different. Generally, the slope stability analysis based on the deep soil strength parameters obtained from the conventional shear test will overestimate the stability of the actual expansive soil slope

(2) Although the expansion and shrinkage grades of expansive soil are different, as long as they are placed under the same climatic environment and load conditions (less than 50 kPa), the final shear strength will fall to a similar low value range (0~5 kN) after multiple wetting-drying cycles and low stress, which is also the key reason for the shallow collapse of slope in expansive soil area

(3) The strength decline of expansive soil under wetting-drying cycles is closely related to the development of fissures in the soil. The continuous development of fissures reduces the cementation ability between soil particles, greatly reduces the cohesion, and intensifies the damage to the integrity of soil specimens, resulting in the reduction of its shear strength. The strength index value of specimens with fissure network after many wetting-drying cycles should be used in the stability calculation and protection design of expansive soil slope

(4) The object of this study is the residual expansive soil in Guangxi Zhuang Autonomous Region of China. The general adaptability of its conclusion needs to be further verified by relevant tests of different expansive soils in other regions

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Jin Chang contributed to the methodology and writing-original draft. Jieling Ma contributed to the conceptualization and revision. Xianyuan Tang contributed to the data curation and language editing.

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