The evolution of cracks in red clay under wet and dry cycles and its influence on shear strength

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Abstract. Using computer image processing technology and lots of triaxial experiments, the fracture evolution rules and shear strength indexes of red clay in the wet and dry cycles were analyzed, and the functional relationship between shear strength indexes of red clay and fracture density was established. The parameters in slope stability calculation were also discussed by the strength indexes reduction method. The results show that with the increase of the times of dry and wet cycles, the crack density gradually increases and eventually it remains stable. During the first two wet and dry cycles, the crack development of red clay was the most obvious. After the dry-wet cycle, the stress-strain curve of the red clay is weakly hardened and the failure mode is bulging. The shear strength of red clay is significantly reduced by the influence of dry wet cycle. After the first cycle, the attenuation of strength indexes is obvious, and the final strength indexes trend to be stable. The attenuation amplitude of the cohesive force is significantly larger than the internal friction angle. After the wet-dry cycle, the stable value of its cohesion becomes 54% ~ 57% of the initial value, and the stable value of the internal friction angle becomes 45% ~ 63% of the initial value, so it is recommended to use the value of the long-term strength index and it is more accurate to calculate the slope stability under dry and wet cycles. Under the action of dry and wet cycles, a quadratic polynomial can be used to fit the functional connection between the crack density of red clay and the index of shear strength.

1. Introduction
Red clay is one kind of high plastic clay which is sensitive to the change of environmental humidity and easy to crack. In the dry season, the moisture content in the soil will decrease, causing its volume to shrink, and it will also cause structural damage to its inside to varying degrees, resulting in cracks and destroying its integrity [1-6]. While during the rainy season, the rain water infiltrates into the red clay through fissures, then the strength of the red clay decreases sharply, which leads to the instability of the shallow surface of the slope. With the effect of dry-wet cycle, the soil produces criss-cross cracks, which will cause red clay slopes to often destabilize and collapse during the rainy season. Therefore, it is essential to research evolution of fissures in the action of dry and wet cycles and its influence on the strength of red clay. The studies on the evolution of fissures and its mechanical characteristics of soil under drying-wetting cycles are mainly focus on expansive soil [7-16]. In recent years, with the development of railway and highway construction in central and western China, the engineering performance of laterite has attracted much attention. Its main research focuses on ways to raise the engineering performance of laterite [17-22], but under the action of dry and wet cycles, laterite Little research has been done on the development of cracks and their effect on the attenuation of strength indicators. Based on these considerations, the computerized image processing technology
and lots of triaxial experiments were utilized to analyze the evolutions of fissures and shear strength indexes of red clay under drying-wetting cycles.

2. Laterite sample and its preparation

2.1. Laterite sample
The samples utilized in this test were taken from the No. 12 section of the highway from Yuqing to Kaili in Guizhou Province, China. From Road Geotechnical Test Regulations (JTG E40-2007), the main physical and mechanical properties of red clay are illustrated (Table 1).

| Particle composition | Optimal moisture content (% | Maximum dry density /g/cm³ | Liquid limit (%) | Plastic limit (%) | Uniformity coefficient | Coefficient of curvature |
|----------------------|-----------------------------|-----------------------------|------------------|------------------|-----------------------|------------------------|
| >0.075 (mm (%))      | 0.074~0.002 (mm (%))        | <0.002 (mm (%))             | 19.4             | 64.3             | 16.3                  | 24.8                   | 1.61                   | 53.3                   | 25.2                   | 9.38                   | 1.6                   |

2.2. Sample preparation
The water content of the sample is set near the optimal water content of the tested red soil. that is, the water content is 23%, 25%, 28% and 30%, respectively. The degree of compaction is taken as 80%, 85%, 90% and 96%. The samples were prepared with diameter and height of 39.1mm and 80mm respectively.

2.3. Drying-wetting cycles method
As shown in Figure. 1, in the drying-wetting tests, oven was used for humidification, and syringes were used for humidification. First, the drying temperature in the drying box was set to 105℃, and the sample was put into the drying box until the weight of the sample remained unchanged. Then added water into samples to reach initial water content by using syringe after the temperature of samples changed to room temperature. Finally, put samples into moisturizing cylinder for 24 hours to make water evenly. Thus, the first drying-wetting test was finished. According to this method, the second, third and forth drying-wetting tests were finished.

2.4. Image processing
Under previous study achievements, evolution of cracks of red clay under drying-wetting cycles was characterized by the index named crack density. crack density is defined as follows [23]:

\[ \delta f_A = \sum_{i=1}^{n} \frac{A_i}{A} \]

\( \delta f_A \) is the crack density, %; \( A \) is the acreage of sample in total, mm²; \( A_i \) is the acreage of the ith crack, mm².

A twelve-megapixel digital camera was used to take pictures of samples in their initial state and after each drying-wetting cycle. A shelf which can fix camera and soil samples was made to keep the distance between sample and camera unchangable. At the same time, all the external light sources were blocked and only a constant fluorescent lamp was used to illuminate to make environment of photographing was constant. Images were processed by using MATLAB and binary images were
obtained. The binary image is shown as Figure 2. The area of black pixels regions is the area of fissures. The fissure density can be obtained by calculating the ratio of area of black pixels regions to area of total pixels.

2.5. Triaxial test
Unconsolidated and undrained tests (UU) were conducted on all samples, the shear strain rate was set as 0.08mm per minute. Loading mode was strain control, kept loading up until strain up to 15% of the height of specimens.

3. Experiment results

3.1. Evolution rules of fissures of red clay under dry and wet cycles
Figure 3 indicates that the surface of the samples in the initial state was smooth. there was no fissure in the surface after the first process of drying, but the samples lost water and shrunk, and space appeared between the samples and ring-knives. After first water addition process, a large number of micro fissures began appearing in the middle of the surface. After the second process of drying, the fine and micro fissures developed from the middle to the edge, and the large fissures appeared. After the second water addition process, some of the small and micro fissures began disappearing. After the third process of drying, large fissures began appearing on the surface of the sample. After the third water addition process, the small and micro fissures disappeared and the large fissures developed. After the fourth process of drying, the large fissures continued developing, and after the fourth water addition process, all the fissures continued to decreasing. In a word, as the times of dry and wet cycles increased, a large number of small and micro fissures first appeared in the middle of surface on samples, then the lager fissures appeared, and surface appeared loose and shedding. After that, a part of small and micro fissures disappeared and the large ones developed from middle to edge of samples. The number of all the fissures first increased and then decreased. The number reached maximum after first drying-wetting cycles.

The Figure. 4 shows the relationship between fissure density and times of dry and wet cycles. As the times of dry and wet cycles increases, the crack density increases and finally tends to a stable state. The first two wet and dry cycles had strongest influences on the development of fissures of red clay. The reason may be in the first and second processes of drying, the samples shrank because of loss of water. The cementation between soil particles weakened and fissures appeared on the surface of samples. In the water addition process, some micro fissures closed because of water filling and swelling of red clay, so the fissure density became small. However, with the increasing number of dry and wet cycles, the cracks in the soil tend to expand to a stable state, and the internal structure of the red clay reaches a certain degree of equilibrium. [24-26].
3.2. The Change Law of Shear Strength Index of Red Clay and Its Relationship with Cracks under Dry-wet Cycle

Due to the limit of the paper volume, the test results of specimens with compactness and moisture content are 96% and 25% are taken as examples. The stress-strain curves and failure mode of samples are demonstrated in Figure. 5 and Figure. 6.

Figure. 5. Strain-stress relationship curve of soil samples after different wet-dry cycles (K = 96%, ω = 25%)

Figure. 6. Failure mode of samples

Figure. 5 shows that the stress-strain curves of samples in the initial state were steep, the type of stress-strain curves was strong strain hardening. With the increasing times of dry and wet cycles, the stress-strain relationship curve becomes gentle, and its type is weak strain hardening. From Figure. 6, the failure mode of samples is bulging, and no obvious shear failure surface was observed.
Figure 7 demonstrates the connection between shear strength indexes of red clay and times of dry and wet cycles. As the times of dry and wet cycles continue to increase, cohesion decreases, and angle of internal friction decreases. The shear strength indexes tended to be stable after certain times of dry and wet cycles. The largest reduction of cohesive force and internal friction angle was happened after first drying-wetting cycle. This phenomenon can be explained as follows: with water content of sample increased, the shear strength decreased due to the increase of pore ratio and the attenuation of matrix suction. As the moisture content decreases during the drying process, pores between the particles are compressed, and the suction power of the matrix increases, so the shear strength increases. The reversed cyclic actions led to irreversible changes of soil structure, destroyed the internal connection between clay particles, and eventually led to strength degradation [27]. The relation between norm of shear strength and fissure density are demonstrated in Figure 8. and Figure 9. The relation between shear strength indexes and fissure density of red clay under drying-wetting cycles can be fitted by quadratic polynomial. The from of formula is , are the parameters can fit by experimental data.

Figure. 7. Relation between indexes of shear strength of red clay and times of dry and wet cycle

Figure. 8. Relation between cohesive force and fissure density
Figure. 9. Relation between internal friction angle and fissure density
3.3. Application of strength index reduction method in slope stability calculation

Obviously, under the action of dry and wet cycles, shear strength of red clay will be significantly reduced. In order to make the calculation result of slope stability more scientific and reasonable, instead of the initial value, the value of long-term strength indexes should be used in the slope stability calculation. According to the results of tests, after the three times of drying-wetting cycles, the shear strength indexes trended to be stable. Therefore, the ratio of average value of the shear strength indexes after first, second and third drying-wetting cycles to the initial shear strength indexes are defined as the reduction coefficient, and the average value of the reduction coefficient with different degrees of compaction is defined as the final reduction coefficient.

It can be seen from the above that the reduction coefficient of the value of $c$ is about 54% ~ 57%, and the reduction coefficient of the value of $\phi$ is about 45% ~ 63%. Therefore, the parameters of slope stability calculation under drying-wetting cycles are as follows: the stable value of cohesive force is about 54% ~ 57% of the initial value. The stable value of internal friction angle is about 45% ~ 63% of the initial value.

4. Conclusion

- As the times of dry and wet cycles continues to increase, the crack density gradually increases and finally tends to a stable state. Among them, the first and second dry and wet cycles have the greatest influence on the development of crack. The crack develops from the middle of the sample to the edge, and the surface appears to be loose and peeled to varying degrees.
- The stress-strain curves of red clay in the initial state were steep, the type of stress-strain curves was strong strain hardening. As times of dry and wet cycles plused, stress-strain curves became gentle, the type was weak strain hardening. The failure mode of samples is bulging, and no obvious shear failure surface was observed.
- As the times of dry and wet cycles continues to increase, the cohesive force decreases and the internal friction angle decreases. The strength indexes trended to be stable after certain times of dry and wet cycles. The attenuation of the internal friction angle is smaller than the attenuation of the cohesion.
- Instead of the initial value, the value of long-term strength indexes should be used in the slope stability calculation. The stable value of cohesive force is about 54% ~ 57% of the initial value. The stable value of internal friction angle is about 45% ~ 63% of the initial value.
- The relation between indexes of shear strength and crack density of red clay under drying-wetting cycles can be fitted by quadratic polynomial. The from of formula is, is the test parameter.
- To maintain the stability of the roadbed using red clay as filler, the slope should be blocked out to reduce influence of dry and wet cycle.

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