Study on failure mechanism of red clay slope under dry and wet cycles

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Abstract. In order to study the failure characteristics and mechanism of red clay slope under dry-wet cycling conditions, a model slope similar to engineering slope was established. The test slope was monitored by testing elements, and the variation laws of moisture content, temperature, pore water pressure, soil pressure and displacement were analyzed respectively under the alternating conditions of dry-wet cycling. The failure characteristics and mechanism of slope are obtained. With the increase of dry-wet cycles, the overall water content of slope increases, pore water pressure decreases, lateral displacement increases, and vertical displacement remains unchanged to a certain extent. After five dry-wet cycles, the water content of the top and top of the slope is the largest, the water content of the bottom and foot of the slope is the smallest, the horizontal displacement of the slope is the largest, and the horizontal displacement of the top of the slope is the smallest. The range of temperature change increases with the number of dry-wet cycles, and tends to be stable after the third dry-wet cycle. The earth pressure is the largest at the top of the slope, followed by the foot of the slope and the smallest at the slope surface, and the first two dry-wet cycles have the greatest impact on the earth pressure. In the process of dry-wet cycling, the surface cracks of slope undergo the cyclic process of cracking, healing and re-cracking. The width and depth of cracks increase gradually. The surface failure characteristics represented by gully weathering and spalling gradually change into shallow failure characteristics represented by collapse and slump.

1. Introduction
Residual red clay is commonly distributed on the surface of the carbonate rock distribution area in Guizhou province, covering a thickness of 5-7m in general, and the thickest can be more than 20 m. In the construction of roads and railways, it is inevitable to encounter a large number of red clay slopes. Engineering practice has proved that the red clay slope has poor stability and is prone to damage when exposed to natural environment for a long time. Some slopes with slope rates of 1:1 ~ 1:1.5 still suffer from instability failure to varying degrees, and some slopes fail at the construction stage, for which engineers and technicians cannot give a good explanation[1-2]. The reason is that the failure mechanism of red clay slope under wet and dry cycle is not fully understood at present. The failure mode of red clay slope is different from other soils, and the failure mode is different from the traditional sliding arc[3-4]. Aiming at the problem of the stability evaluation of red clay slope, Chen Nan studied the shallow failure mechanisms of slope with the method of field test, and proposed an appropriate stability safety evaluation method[10]. Liu Tianyi discussed and clarified the main types, spatial and temporal distribution, occurrence rules, shape of failure surface and other failure characteristics of the red clay slope, and revealed the failure mechanism of the red clay slope based on the investigation results of the red clay slope failure of several expressways in Guizhou province[1].
Therefore, at present, there are few researches on the failure mechanism of red clay slope under the dry and wet cycles, so it is necessary to study the failure mechanism of red clay engineering slope under long-term natural conditions, and comprehensively grasp the real failure process and failure rules of red clay engineering slope. In this paper, a red clay slope test model similar to the prototype is established in a certain proportion by adopting the research method of similar simulation. Test elements were used to monitor the test slope and analyze its water contents, temperatures, pore water pressures, earth pressures, displacement, failure characteristics and mechanisms under the wet and dry cycles. It provides some references for the research of similar engineering slope failure process.

2. Slope model test scheme

Soil samples are taken from the west campus of Guizhou University. Soil characteristics are brown red, relatively wet, homogeneous, dense structure. According to the method of highway geotechnical test procedure (JTGE40-2007), the basic physical indexes of soil are shown in Table 1.

| Optimum water content/% | Maximum dry density/g/cm³ | Plastic limit/% | Liquid limit/% | Plasticity index |
|-------------------------|---------------------------|----------------|---------------|-----------------|
| 22.98                   | 1.65                      | 26.6           | 56.7          | 30.1            |

The size of the slope model is 300 cm × 150 cm × 140 cm, and the slope rate is 1:1.5. The soil is configured according to the optimal water content of 22.98 %, and the dry density of the slope is controlled at 1.65 g/cm³ during the stacking process. Sensors are embedded in different positions inside the slope, including 14 sets of temperature sensors, 14 sets of pore water pressure sensors, 14 sets of water content sensors, 18 sets of displacement sensors, and 16 sets of earth pressure sensors. Sensors for temperature, pore water pressure, water content, and earth pressure are buried on the left side of the slope; horizontal displacement sensors are buried on the center line of the slope; vertical displacement sensors are buried on the right side of the slope, with water content, pore water pressure, temperature, and earth pressure meters spaced 100 mm in turn.

![Figure 1. Buried sections of water content, temperature, pore water pressure and earth pressure sensors.](image1)

![Figure 2. Displacement sensor embedded profile.](image2)

3. Dry and wet cycles test scheme

3.1. Rainfall device

The rainfall system used in this experiment is the portable simulated rainfall device QYJY-501 (502). The equipment is mainly composed of three parts: the water supply system, the rainfall system and the control system. The rainfall intensity is 60 mm/h.

3.2. Drying device

The drying system adopts 6 bath heaters evenly arranged on, in and below the slope model, each of which is 1180w. An electric fan is used at the toe of the slope to increase air flow and speed up slope drying.
3.3. Dry and wet cycles test scheme
The dry and wet cycles simulated such a climate process: rainy day $\rightarrow$ cloudy day $\rightarrow$ sunny day, namely, rain for 1 hour (rainy day) and then static penetration for 24 hours (cloudy day), finally heating bath bar drying and electric fan blowing for 40 hours (sunny day). Follow this step to complete 5 times dry and wet cycles.

4. Analysis of test results

4.1. The water contents

It can be known from figure 6 and figure 7: (1) The water contents increased in the rainfall period; during the resting period, the water contents of surface soil decreased and that of deep soil increased due to the resting of surface water. During the drying period, the water contents gradually decreased and then tended to flatten. In the first and second cycle, the water contents gradually increased. After the third cycle, the varied range of water contents in each cycle gradually stabilized and the overall water contents tended to be stable. (2) As the number of dry and wet cycles increased, the overall water contents of slope increased. The water contents of slope top and slope surface were greatly affected by the wet and dry cycles. After 5 times dry and wet cycles, the water contents of the top and...
the top of the slope were the largest, while that of the bottom and the bottom of the slope were the smallest.

4.2. The temperatures

Figure 8 shows that: In the process of rainfall, the temperatures tended to decrease slowly. During the drying period, the temperatures gradually increased, and the temperatures increased with the increase of the number of dry and wet cycles. After the third cycle, the temperatures increased basically stabilized. The order of temperatures increased in drying period was the slope shoulder, the slope top, the slope toe and the slope surface.

4.3. The pore water contents

Figure 9 and Figure 10: (1) Variation of pore water pressures were caused by dissipation of excess pore water pressure, resting and evaporation of external water. The pore water pressures increased during the rainfall period and the resting period. Due to the dissipation of the excess pore water pressures, the pore water pressures tended to decrease as the number of dry and wet cycles increased. As the depth of the slope increased, the magnitude of the pore water pressures decreased. (2) The pore water pressures in the shallow layer of the slope were larger on the slope surface and the slope shoulder, but smaller on the top and toe of the slope; The pore water pressures in the deep slope reached the maximum at the slope toe, followed by the shoulder and slope surface, and finally the slope top.
4.4. The displacement

Figure 11. The relationship between the lateral displacement and time in different parts of slope (20 cm)

Figure 12. The relationship between the vertical displacement and time in different parts of slope (10 cm)

It can be known from figure 11 and figure 12: (1) With the increased of the number of dry and wet cycles, the horizontal displacement of the slope gradually increased. The horizontal displacement increased rapidly in the rainfall period and the resting period of the first two dry and wet cycles, and remained unchanged in the drying period. After the third cycle, the horizontal displacement increased slowly in the rainfall period and the resting period, decreased slightly in the drying period, and then remained basically unchanged. After 5 times cycles, the horizontal displacement of slope surface was the largest and the top of slope was the smallest. (2) The vertical displacement increased in the process of rainfall and decreased gradually in the process of drying, but eventually returned to the original position basically or remained unchanged. There was no significant vertical displacement of the slope as a whole.

Figure 13. Relationship between earth pressures and time at different depth of slope shoulder

Figure 14. The relationship between earth pressures and time at different parts of slope
It can be known from figure 13 and figure 14: (1) The earth pressures rose in the rainfall period, and decreased in the period of resting and drying. With the increased of slope depth, the earth pressures decreased less in the resting period and drying period. With the increase of the number of dry and wet cycles, the earth pressures increased gradually. The first two cycles had great influence on earth pressures. (2) the earth pressures reached the maximum at the slope top, followed by the slope toe, and the earth pressures on the slope surface were the minimum. The reasons were as follows: during the period of rainfall, water accumulated at the slope top, and the water penetrated down sufficiently. At the slope toe, it was supplemented by free water inside the slope, and its water contents were relatively large. However, the rainwater falling on the slope surface was mainly transformed into runoff, with less resting and less water contents.

5. Analysis of slope failure evolution law and mechanism under dry and wet cycles

![Image of slope failure evolution](image)

During the first rainfall, there was an obvious wetting front. The wetting front reached 7 cm at the slope surface and 14 cm at the slope top. At the slope toe, part of soil fell off, local collapse and lateral cracks appeared under the action of gravity. The end of rainfall, the soil mass expanded slightly, splash erosion appears in many places, and surface erosion appears in the middle of slope. During the first drying period, a transverse crack, about 15.6 cm deep, appeared about 40 cm away from the slope shoulder. The slope shrank and produced cracks, which developed completely in about 15 h. The depth and width of cracks at the slope toe were much larger than those at the slope top and the slope surface. The deepest is about 3 cm. The crack of the second rainfall closed gradually, the splash erosion expanded gradually and developed into surface erosion. During the second drying period, the crack extended and the deepest part of the slope toe reached 3.9 cm. The cracks closed gradually in the third rainfall, but some of them were not closed completely. The erosion areas on the upper slope surface were further enlarged. In the process of rainfall, there were small mud flowing and whole blocks collapse at the slope toe. The cracks closed gradually in the third rainfall, but some of them
were not closed completely. The erosion areas on the slope were further enlarged. In the process of rainfall, there were small mud flowing and whole blocks collapse at the slope toe. After the third drying, the cracks cut through the soil, and the crack width decreased slightly. In the fourth rainfall, cracks closed slowly, and new surface erosion tended to form along the completely closed cracks. The existing surface erosion developed further, and the area gradually expanded. After the fourth drying, the crack width tended to be stable and the crack depth reached the maximum cyclic value of about 6.5 cm. In the fifth rainfall, the surface erosion developed further along the incomplete closed fracture, and the surface erosion in different areas gradually connected. The fifth time of drying, crack width tended to be stable. The crack depth decreased slightly compared with the previous drying. Therefore, with the increase of dry-wet cycles, through the cracks in the slope surface soil cracking and healing, and cracking cycle, cracks will develop along the slope surface to the deep, and its width and depth also increased gradually, eventually will surface water along the direction of crack depth into the inside of soil slope, the slope failure represented by gully weathering flake gradually transforms the surface destruction features represented by collapse, slip fall shallow instability destruction features[5-6].

The deformation and failure mechanism of red clay slope is closely related to the dry-wet cycle. The wet and dry cycle leads to red clay cracking and changes in water content. The wet and dry cycle leads to red clay cracking and changes in water content. The void ratio of red clay is large and the natural moisture content is high. The dry and wet cycle causes the soil to shrink and swell. When artificial excavation slope formation, the red clays lose their original cover protection, natural red clay directly exposed to the air, soil surface near the international airport will continue to reduce surface water content decreased, the soil particle peripheral water film thinning, soil water loss contraction, tensile stress increases between the soil particles, formed a reticular crack development, appeared the initial crack, the formation of the initial cracks will provide deeper range of moisture transfer outward channel conditions.International airport this recurring process will make the soil surface crack further development, the increasing deepening of the broadening, shearing strength is reduced, causing the direction of the soil mass deforming toward surface morphology, once precipitation caused soil fissure filling water for a long time, the soil fissure hydrostatic pressure and internal pore water pressure increase, at this time will occur a wider range of red clay slope instability of collapse. It can be seen that the internal relaxation, water saturation and collapse of red clay are the internal cause of slope deformation and cracking, while rainfall and evaporation are the external factors promoting the rapid development of this process[7-8].

6. Conclusion

- The water contents of the slope increased during the rainfall period. There was a hysteresis in the water loss during the drying period. The water contents increased first and then decreased, and the surface water contents decreased more than the inside of the slope. As the number of dry and wet cycles increased, the water contents of the slope increased. After 5 times cycles, the water contents of the slope top and the upper surface of the slope were greater than the water contents of the lower part of the slope and the slope toe.
- The temperatures during the rainfall period and the resting period were relatively stable, and the temperatures of the slope top and the shoulder of the slope during the drying period fluctuated greatly.
- The pore water pressures of the slope increased during the rainfall period and the resting period, and decreased during the drying period. Due to the dissipation of the excess pore water pressures, the overall effect of the dry and wet cycle was as the pore water pressures decreased slightly as the number of dry and wet cycles increased.
- The earth pressures rose during the rainfall period and decreased during the resting and drying periods. As the number of dry and wet cycles increased, the earth pressures generally increased, and the first two cycles had a greater impact on the earth pressures. The earth pressures were maximum at the slope top and minimum at the slope surface.
As the number of dry and wet cycles increased, the horizontal displacement of the slope increased gradually. Horizontal displacement increased rapidly during the rainfall and resting periods of the first two dry and wet cycles. After 5 times wet and dry cycles, the horizontal displacement of the slope surface was the largest and the slope top was the smallest. The wet and dry cycles had little effect on the vertical displacement of the slope.

With the increased of the number of dry and wet cycles, the slope surface cracks experienced the cycle process of cracking, healing and re-cracking, and their width and depth also gradually increased. The surface failure characteristics represented by erosion and exfoliation of gully gradually changed into the shallow instability failure characteristics represented by collapse and slide collapse.

In the protection design of the red clay slope, the waterproof and moisturizing measures for the soil layer should be fully considered. After the slope is excavated, rapid construction should be adopted, and the rapid sealing should be carried out to keep the red clay from losing water. The construction in the rainy season should be avoided as much as possible. The red clay is prone to cracks under the action of dry and wet circulation. After the slope is excavated, the completion protection measures can be arranged on the slope to avoid the free development or penetration of the crack and improve the stability of the slope.

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References
[1] LIU, T.Y., WANG, J.Z., WU, L.J. (2015) Study on failure mechanism and stability calculation method of red clay slope. Journal of Highway and Transportation Research and Development, 8: 47-49.
[2] ZHANG, L.Y., HUANG, H.H., ZHENG, J.J. (2014) Stability analysis of red clay slope in Guizhou expressway. Journal of Guizhou University, 31: 105-110.
[3] FANG, W. (2011) Research on stability analysis method of cutting slope of residual red clay. Central South University.
[4] QIAN, Z.Y. (2007) The main technical problems and the countermeasures of railway projects in red clay area. Chinese Railways: 41-45.
[5] CHEN, K.S. (2015) Experimental study on rainfall flushing of red clay slope. Highway Engineering, 40: 18-22.
[6] LUO, L. (2018) Study on stability of red clay slope in Western Shanxi. Journal of Highway and Transportation Research and Development, 14: 133-135.
[7] CHEN, N., WU, L.J., ZHOU, Y., et al. (2016) Failure mechanism of shallow layer of red clay slope and stability evaluation method. Journal of Highway and Transportation Research and Development, 33: 37-42+88.
[8] NONG, C.S, MO W.Y. (2017) Analysis of deformation and failure mechanism of red clay slope in a highway in Guangxi. Western China Communications Science & Technology: 24-27.