Laboratory Model Test on Moisture-Heat and Deformation Behaviour of Red Clay Slope under Action of Rainfall and Sunlight

Ming Chen¹,²*, Jian Liu¹,², Zhengyong Xie³, Xunjian Hu¹,², Bingyang Li¹,² and Yue Cen¹,²

¹ State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China
² University of Chinese Academy of Sciences, Beijing 100049, China
³ Hubei Road and Bridge Group Tianxia Construction Co., Ltd., Wuhan 430000, China
Email: chenming181@mails.ucas.ac.cn

Abstract. Taking the red clay of Guizhou as the test material, the moisture-heat and deformation behaviour of red clay slope under action of rainfall and illumination were studied by constructing model slopes, observation systems, artificial rainfall systems and sunlight systems. The results showed that the volume moisture content decreased continuously during the sunlight period and decreased slowly after 5 days of sunlight, but it increased sharply during the rainfall period and the increments decreased with the increase in depth. The volume moisture content of the slope crest had almost the same increments after each rainfall; the volume moisture content of the slope surface increased slightly after the first rainfall, and then increased significantly thereafter; and the volume moisture content of the slope toe increased significantly after the first rainfall, and then increased slightly. The migration of water and heat in the soil showed a strong coupling. In other words, the temperature change could indirectly reflect the volume moisture content change, and the volume moisture content change would promote the redistribution of temperature. The depth effected by everyday sunlight and rainfall on temperature were both less than 42cm. Rainfall mainly affected the horizontal displacement of the shallow soil of the slope, and the horizontal displacement of slope toe is the largest, followed by slope surface and the smallest at the slope crest.

Keywords. Red clay slope, rainfall, sunlight, moisture-heat, deformation.

1. Introduction
The influence of weather conditions on the stability of geotechnical structures had attracted the attention of many geotechnical engineers. Under the action of the atmosphere, the phase change of water vapor in the atmosphere would produce clouds and rain, at the same time, the evaporation and transpiration of the ground would change the humidity of the atmosphere, which is the transfer of heat and water. Specifically, the influence of water infiltration on the properties of soil is considered under the action of rainfall, and the influence of evaporation on the properties of the soil under the action of sunlight. Current research mainly focused on the influence of rainfall infiltration on the stability of soil slopes [1-6], while there are few studies that consider both the influence of rainfall and sunlight [7-8]. Studies have shown that the expansion and contraction of red clay is dominated by shrinkage, and the cracks created by the evaporation become a channel for water to enter the soil interior, which
strengthens the interaction between the soil and water [9-11]. The properties of the red clay gradually change under action of moisture-heat, and the strength of the red clay is constantly attenuated, which in turn causes the slope instability and failure. Therefore, it is of practical significance to analyse the moisture-heat and deformation behaviour of red clay slope under action of rainfall and sunlight.

2. Methodology

2.1. Soil Samples and Model Slope
The red clay used in this test was taken from 1.5 to 2.0 m below the surface of a highway section in Guizhou Province. The soil sample at the site was brownish red, hard plastic, and slightly wet. Its basic physical properties were shown in table 1. The main components of clay minerals were kaolinite, chlorite and quartz, and the content of montmorillonite was minimal. From this, it can be seen that the red clay was a high-liquid-limit clay with very weak expansibility.

| Density (g/cm³) | Moisture content % | Specific gravity of solid particles | Liquid limit % | Plastic limit % | Plasticity Index | Optimal moisture content % | Maximum dry density (g/cm³) | Free expansion rate % | Free <5μm Clay content % |
|----------------|--------------------|-------------------------------------|----------------|-----------------|------------------|---------------------------|--------------------------|------------------------|------------------------|
| 1.62           | 39.4               | 2.676                               | 61.1           | 36.8            | 24.3             | 32                        | 1.592                    | 29.5                   | 65                     |

The soil samples were first dried and ground in a natural state, and then mixed with water according to the optimal moisture content of 32%. Considering the loss of water, the actual amount of water added was slightly larger than the optimal moisture content. After mixing the soil sample, cover it with the plastic film and let it stand for 24 hours, and then measure its moisture content. If the moisture content was within the range of about 2% more or less than the optimal moisture content, the soil sample preparation was complete.

Figure 1 showed the model slope with dimensions of 1500 cm in length, 800 cm in width, 800 cm in height in the top of slope, 200 cm in height in the bottom of slope with an inclination of 34 degrees. Because the model slope required the large amount of soil samples, a filling plan with layered preparation of soil samples and layered compaction was adopted and the degree of compaction was 82.2%. The model slope was divided into 5 layers, and the thickness of each layer was 16cm. After the model was filled, let it stand for a week to consolidate under gravity, and then cut it from top to bottom according to the cut slope line. The final generated model slope was shown in figure 2.

2.2. Monitoring Equipment
Two kinds of sensors were used in this test, namely TDC220TH soil moisture temperature sensor and JTM-V7000 vibrating wire displacement sensor. The installation location and serial number of sensors were shown in figure 3 below. After the sensors were installed, the automatic collection time interval
was set. Specifically, the displacement sensor was times/5s, the soil moisture temperature sensor was times/10min.

Figure 3. The location and serial number of sensors.

2.3. Experimental Conditions
The purpose of this experiment was to study the influence of the alternate action of rainfall and sunlight on the moisture-heat and deformation characteristics of red clay slopes. Therefore, in order to make the test conditions closer to the local natural climate, the long-arc xenon lamp was used to simulate sunlight, and the JLC-RY2 portable artificial rainfall simulation system was used to simulate natural rainfall. The test experienced five cycles of rainfall and sunlight, and the process goes like this: sunlight for 6 hours per day, the sunlight days in the five cycles were 5, 7, 9, 11, 13 and the sunlight intensity was set to 600w/m². Each rainfall for 2.5h in the five cycles, the rainfall intensity was set to 20.8 mm/h.

3. Experimental Results

3.1. Evolution Law of Slope Volume Moisture Content
Figure 4 are the curves of volume moisture content change in different depths at crest and surface of slope under five cycles of sunlight and rainfall. It can be seen that the curves showed obvious peaks and valleys with the five cycles of sunlight and rainfall. That is, the volume moisture content decreased continuously during the sunlight period, but increased sharply during the rainfall period. After the first rainfall, although the sunlight days in each cycle increased by two days, the volume moisture content was relatively close after each sunlight, indicating that the volume moisture content decreased slowly after 5 days of sunlight.

Figure 4. The curves of volume moisture content change in different depths.

Figure 5 are the curves of volume moisture content change of slope crest along the depth under five cycles of sunlight and rainfall. It can be seen that the volume moisture content decreased only within a
certain depth of the slope in a certain period after rainfall, and continued to increase below this depth. This explained the phenomenon that the instability failure of the red clay slope occurs after rainfall and the failure surface generally penetrates into the interior of the slope. As the moisture content increased, the shear strength of the soil decreased, and the safety factor of the slope decreased, which may cause the slope instability and damage. During the sunlight period, the volume moisture content increased with the increase of depth. After rainfall, the volume moisture content was not much different in depth, indicating that the volume moisture content increment decreased with the increase of depth. Before the first rainfall, the sunlight had a small effect on the volume moisture content, and the volume moisture content decrement decreased with the increase of depth. After the first rainfall, the sunlight had a greater impact on the volume moisture content, and the volume moisture content decrement first decreased and then increased with the increase of depth. It showed that the volume moisture content increased during the rainfall period, which increased the dehumidification rate under the action of sunlight. Moreover, rainfall increased the depth of the impact of light on volume moisture content.

![Figure 5](image1)

**Figure 5.** The curves of volume moisture content change of slope crest along the depth under five cycles of sunlight and rainfall.

Table 2 showed the volume moisture content increment in the depth of 12 cm at crest, surface and toe of slope after each rainfall. It can be seen that the volume moisture content of the slope crest (NO.1) had almost the same increments after each rainfall; the volume moisture content of the slope surface (NO.5) increased slightly after the first rainfall, and then increased significantly thereafter; the volume moisture content of the slope toe (NO.8) increased significantly after the first rainfall, and then increased slightly. Due to the good integrity and the poor permeability, the rainwater on the slope surface cannot infiltrate completely during the first rainfall, and part of rainwater formed runoff on the slope surface and collected at slope toe. Higher pressure made it easier for water to infiltrate downwards. As the number of cycles of rainfall and sunlight increased, the cracks on the slope surface gradually developed to the depth, which accelerated the infiltration of water on the slope surface and decreased the amount of rainwater collected at slope toe.
Table 2. The volume moisture content increment in the depth of 12 cm after each rainfall (%).

|                  | First rainfall | Second rainfall | Third rainfall | Fourth rainfall | Fifth rainfall |
|------------------|----------------|-----------------|---------------|----------------|---------------|
| Crest (NO.1)     | 23.06          | 23.40           | 23.32         | 23.42          | 23.63         |
| Surface (NO.5)   | 22.34          | 30.70           | 29.30         | 28.22          | 27.54         |
| Toe (NO.8)       | 38.88          | 28.33           | 25.69         | 28.20          | 27.92         |

3.2. Evolution Law of Slope Temperature

Figure 6 are the curves of the temperature change in different depths at slope crest and slope surface under five cycles of sunlight and rainfall. It can be seen that the temperature changed in a cliff-like manner during the rainfall period, and the temperature decreased with the increase of depth. The diurnal temperature variation characteristics on slope crest (NO.1 and NO.2) and slope surface (NO.5 and NO.6) were obvious. That is, the temperature was low in the morning and evening, and the temperature was high during the daytime. While the daily temperature fluctuation amplitude of slope crest (NO.3 and NO.4) and slope surface (NO.7) was not significant, indicating that the depth of daily influence of sunlight on temperature was less than 42 cm.

![Figure 6](image)

(a) Slope crest
(b) Slope surface

Figure 6. The curves of the temperature change in different depths.

Table 3 showed the temperature change in different depths at slope crest after each rainfall. It can be seen that as the depth increased, the temperature change decreased. At the depth of 42 cm, the temperature change was very small, almost close to zero, indicating that the depth of the influence of rainfall on temperature was less than 42 cm.

Table 3. The temperature change in different depths at slope crest after each rainfall (℃) (Negative number means decrease, positive number means increase).

|                  | First rainfall | Second rainfall | Third rainfall | Fourth rainfall | Fifth rainfall |
|------------------|----------------|-----------------|---------------|----------------|---------------|
| NO.1 (depth 12cm)| -2.69          | -4.58           | -3.30         | -2.97          | -2.36         |
| NO.2 (depth 24cm)| -0.65          | -3.08           | -1.51         | -2.53          | -1.71         |
| NO.3 (depth 42cm)| 0.14           | -0.29           | -0.01         | 0.39           | 0.51          |
| NO.4 (depth 60cm)| 0              | 0.12            | 0.15          | 0.20           | 0.26          |

Figure 7 are the curves of the temperature change in the depth of 12 cm at crest, surface and toe of slope under five cycles of sunlight and rainfall. It can be seen that the temperature at slope crest was relatively close to that at slope surface, and the temperature was the lowest at slope toe. Comparing the
volume moisture content in the depth of 12 cm, it was found that the volume moisture content at slope toe was the highest. This showed that there was a clear correspondence between temperature and volume moisture content. The heat transfer mainly depended on the thermal conductivity of the heat-conducting medium. In comparison, the thermal conductivity of water was larger than that of soil particles. Therefore, the higher the volume moisture content, the greater the thermal conductivity, and the faster the soil transfers heat. The migration of water and heat in the soil showed a strong coupling. The change of temperature can indirectly reflect the change of volume moisture content in the soil, and the change of volume moisture content will promote the redistribution of temperature.

Figure 7. The curves of the temperature change in the depth of 12 cm.

3.3. Evolution Law of Slope Horizontal Displacement

Figure 8 are the curves of horizontal displacement change in different depths at slope crest under five cycles of sunlight and rainfall. It can be seen that there was almost no horizontal displacement in NO.5 (depth 36 cm) and NO.6 (depth 60 cm) during the whole test process, and only NO.4 (depth 12 cm) had a large horizontal displacement during the rainfall period, reached the maximum value of 4.25 mm during the first rainfall period. This indicated that rainfall mainly affected the horizontal displacement of the shallow soil of the slope, and the first rainfall had the greatest impact.

Figure 8. The curves of the horizontal displacement change in different depths.  

Figure 9. The curves of the horizontal displacement in the depth of 12 cm.

Figure 9 are the curves of the horizontal displacement change in the depth of 12 cm at crest, surface and toe of slope under five cycles of sunlight and rainfall. It can be seen that the NO.2 (depth 12 cm) had a large horizontal displacement only during the second and fourth rainfall periods, which were about 25 mm and 35 mm respectively. The NO.1 (depth 12 cm) had a large horizontal displacement only during the fourth and fifth rainfall periods, which were about 43 mm and 5 mm respectively. This
indicated that the horizontal displacement of slope toe was the largest, followed by slope surface and the smallest at the slope crest.

4. Conclusion
Through artificial simulation of rainfall and sunlight, the evolution laws of volume moisture content, temperature, and horizontal displacement of model slope were studies. The main conclusions are as follows:

(1) The volume moisture content decreased continuously during the sunlight period and decreases slowly after 5 days of sunlight, but it increases sharply during the rainfall and the increments decreased with the increase in depth. Rainfall increased the depth of the impact of light on volume moisture content. The volume moisture content of the slope crest had almost the same increments after each rainfall; the volume moisture content of the slope surface increased slightly after the first rainfall, and then increased significantly thereafter; the volume moisture content of the slope toe increased significantly after the first rainfall, and then increased slightly.

(2) The depth of daily influence of sunlight on temperature was less than 42cm, while the depth of influence of rainfall on temperature was less than 42cm. The temperature at slope crest was relatively close to that at slope surface, and the temperature at slope toe was the lowest. The migration of water and heat in the soil showed a strong coupling. The change of temperature can indirectly reflect the change of volume moisture content in the soil, and the change of volume moisture content will promote the redistribution of temperature.

(3) Rainfall mainly affected the horizontal displacement of the shallow soil of the slope, and the first rainfall had the greatest impact. The horizontal displacement of slope toe was the largest, followed by slope surface and the smallest at the slope crest.

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