Study on the Water Sensitivity Analysis of Red Clay Shear Strength Based on Culon-morper Rule

Lifeng Li1*, Changlu Chen1, Xiaohu Zhang1, Duilin Deng2, Liuping Han1

1School of Architecture and Civil Engineering, Guizhou University of Engineering Science, Bijie, Guizhou, 551700, CHINA
2School of Science, Guizhou University of Engineering Science, Bijie, Guizhou, 551700, CHINA
*Corresponding author’s e-mail: lilifengbj@126.com

Abstract. In this paper, the changing law of the peak and residual cohesive force and internal friction angle for undisturbed soil from three different sampling sites in Bijie area were obtained through the indoor experiment. In the case of natural undisturbed water content, the peak and residual cohesive force decrease with the exponential relationship of water content, while the peak and residual internal friction Angle decrease linearly with the water content range. Based on the traditional Culon-morper shear strength criterion the changes of peak and residual shear strength with water content were obtained. The research in this paper is helpful to understand the change of shear strength with water content in Bijie area and to guide engineering practice.

1. Introduction
The red clay in Guizhou province is a special red clay which is overlying the carbonate strata and formed from the insoluble impurities in the carbonate strata. The red clay in Guizhou province is a special red clay which is overlying the carbonate strata and formed from the insoluble impurities in the carbonate strata. The characteristics of the early formation and material source of red clay are different from those of other types of rocks due to karstification. In the later stage, karst residual deposits underwent lateralization and formed the basic characteristics of red clay [1]. A large number of scholars have conducted extensive research on the unique physical and mechanical properties of red clay. Q. Jiang, C. Liu et al. [2][3] discussed the basic characteristics and influencing factors of the shear strength of red clay based on the triaxial shear test results. The literature [4] analysed the causes of the deviation in view of the unreasonable phenomenon that the current method of calculating soil saturation appears to be too large or even exceed the theoretical maximum value when applied to clay. Z. Huang et al.[5][6] studied the mechanical properties of red clay using different stress paths and CT technology. Literature [7]-[12] studied the water sensitivity of physical and mechanical indexes of red clay in different areas. The results show that the mechanical properties of red clay are not the same due to the differences of soil formation and geological conditions, especially in water sensitivity [7]-[12]. In this paper, the undisturbed red clay in Bijie area is taken as the research object. Based on the traditional molar coulomb shear strength criterion, the variation of peak shear strength and residual shear strength with water content was studied by laboratory test.
2. Theoretical analysis of shear strength water sensitivity based on Culon-morper rule
According to Culon-morper rule, the shear strength of red clay is related to its stress state, cohesion and internal friction Angle, and can be expressed as follows [13].

\[ \tau = c + \sigma \tan \phi \]  

Where \( \tau \) is the soil shear strength (kPa); \( c \) is soil cohesion (kPa); \( \phi \) is the internal friction angle; \( \sigma \) is the stress of d perpendicular to the shear direction.

Normal stress \( \sigma \) perpendicular to the anchor cable is determined by the in-situ stress state of the soil mass, which is related to the depth of burial, the magnitude of external forces, and the constraints around it. The greater the \( \sigma \) value, the greater the shear strength of the soil mass. The cohesive force and internal friction angle of soil have a great relationship, even in the same kind of rock and soil, the size of cohesive force and internal friction angle also varies with the water content of different anchorage sections. The cohesion and internal friction angle of soil can be expressed as the function of water content \( w_g \), as shown in equations (2) and (3).

\[ c = C(w_g) \]  
\[ \phi = \phi(w_g) \]  

Therefore, the shear strength of soil can be expressed as

\[ \tau = C(w_g) + \sigma \tan[\phi(w_g)] \]  

3. Sampling and laboratory testing
Table.1 Basic information of sampling points

| Sampling spot | Dry density (g/cm\(^3\)) | Liquid limit (w\(_L\)) | Plastic limit (w\(_P\)) | Plasticity index (I\(_P\)) |
|---------------|--------------------------|------------------------|------------------------|---------------------------|
| I             | 1.49                     | 36.0                   | 20.6                   | 15.4                      |
| II            | 1.55                     | 27.4                   | 16.3                   | 11.1                      |
| III           | 1.59                     | 29.7                   | 19.2                   | 10.5                      |

In order to make the test representative of red clay in the whole Bijie area, the soil layers of three different engineering sites in Bijie, Guizhou province were studied in this experiment. In order to reflect the changes of cohesion and internal friction angle of undisturbed soil with water content, the natural water content states of different sampling points in different time periods were used in this test. Basic physical properties of soil samples from three sites are shown in table 1. The test instrument is a strain controlled direct shear instrument produced by Nanjing soil instrument factory, with the maximum load of 30kN, table stroke of 70mm, load rate of 0.002 ~ 2.4mm/min, and minimum resolution of 0.1ml. According to the latest geotechnical test standard [14], peak and residual value of the cohesive force and internal friction angle with different water contents were measured. In this test, the natural water content of the undisturbed red clay is used, and the natural water content of the soil sample is between 15% and 28%, which is not as small as that of indoor remolded soil, which can be designed at will.

4. Experimental results and analysis

4.1. The influence of water content on peak cohesion and internal friction Angle
According to the experimental results, the experimental data distribution of peak cohesive force and internal friction Angle of soil samples at three sites with different water contents and their relationship curves with water contents are shown in Figure 1 and Figure 2. The experimental data distribution of residual cohesion and internal friction Angle as well as the relationship curve with water content are shown in Figure 3 and Figure 4. The relationship below Figure 1-Figure 4 is the regression equation of corresponding parameters obtained by regression analysis. In Figure 1-4, $\varphi_p$ and $\varphi_r$ are respectively the peak internal friction Angle and the residual internal friction Angle (°); $c_p$ and $c_r$ are peak and residual cohesion (kPa), respectively. $w_g$ is mass water content (%).

From the data distribution and regression analysis curves of peak and residual peak cohesion and internal friction Angle in the figure, the following trend can be obtained. The peak cohesive force of soil samples at the three sampling points, I, II and III, decreases exponentially with the increase of water content. The increase of water content has obvious decreasing effect on cohesion. The peak cohesive force of the three types of soil samples is close when the water content is between 20% and 22%, and all curves intersect in this range. The peak internal friction angle of the three sampling points decreases linearly with the increase of water content, but it fluctuates to some extent. The increase of water content
shows that the angle of internal friction also has obvious subtractive effect. The variation trend of residual cohesion with water content is the same as that of peak cohesion with water content. Different from the peak cohesive force and water content, the peak cohesive force of the three types of soil samples is relatively close when the water content is between 23% and 25%, and all curves intersect in this range. With the increase of water content, the residual cohesion of soil samples at the three sampling points tends to be stable. With the increase of water content, the peak internal friction Angle of soil samples at the three sampling points decreases linearly. The variation of residual internal friction angle with water content is similar to the trend of peak internal friction angle.

4.2. The influence of water content on shear strength

According to the regression equation of peak internal friction angle and peak cohesive force with water content of the three sampling points in this paper, the relationship expression and change trend of peak shear strength and water content are shown in the left column. According to the regression equation of residual internal friction angle and residual cohesion with water content of soil samples from three sampling points in this test, the relationship expression and change trend of residual shear strength and water content are shown in the right column. It can be seen from the figure that the peak shear strength is significantly larger than the residual shear strength, and both the peak and residual shear strength decrease with the increase of water content. The influence degree of water content of different sampling points on shear strength is different. In figure 5-7, $\tau_P$ and $\tau_R$ respectively the peak shear strength of soil and residual shear strength (kPa).

\[
\begin{align*}
\tau_P &= 1568.80e^{-0.2w} + 11.29 + \sigma \tan(50.71-1.57w) \\
\tau_R &= 716.88e^{-0.21w} + 6.37 + \sigma \tan(30.15-0.86w)
\end{align*}
\]

(a) Peak shear strength  
(b) Residual shear strength

Figure 5. The changing law with water content of peak shear strength and residual shear strength for the sampling point
\[ \tau_p = 350.67e^{-0.12w_g} + 5.56 + \sigma \tan(43.62 - 1.25w_g) \]

(a) Peak shear strength

\[ \tau_R = 1508.64e^{-0.25w_g} + 8.7 + \sigma \tan(39.78 - 1.21w_g) \]

(b) Peak shear strength

Figure 6. The changing law with water content of peak shear strength and residual shear strength for the II sampling point.

\[ \tau_p = 341.12e^{-0.06w_g} - 56.67 + \sigma \tan(55.58 - 1.85w_g) \]

(a) Peak shear strength

\[ \tau_R = 16109.78e^{-0.34w_g} + 6.85 + \sigma \tan(36.98 - 1.23w_g) \]

(b) Peak shear strength

Figure 7. The changing law with water content of peak shear strength and residual shear strength for the III sampling point.

5. Conclusion
With the increase of water content, the peak and residual cohesive forces of red clay show a first-order negative exponential decay relationship, and both have a stable trend. The curves of peak cohesion and residual cohesion of red clay intersect in a certain water content range. The peak internal friction Angle and the residual internal friction Angle of the red clay decreased linearly. The variation trend of peak internal friction Angle and cohesive force, residual internal friction Angle and cohesive force with water content of red clay is similar, but the values are different. The peak value and residual shear strength decrease with the increase of water content. The influence degree of water content of different sampling points on shear strength is different.

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