World Journal of Engineering and Technology, 2022, 10, 714-727
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

A Study on the Shear Strength Characteristic of Unsaturated Red Clay

Fei Huang[1,2], Lichun Zhuo[3], Keneng Zhang[4]

[1]CCCC Fourth Harbor Engineering Institute Co., Ltd., Guangzhou, China
[2]Laboratory of Environmental Protection & Safety of Transportation Foundation Engineering, Guangzhou, China
[3]Guangzhou Rising Geotech Ltd., Guangzhou, China
[4]School of Geosciences and Info-Physics, Central South University, Changsha, China
Email: huangfei823@126.com

How to cite this paper: Huang, F., Zhuo, L.C. and Zhang, K.N. (2022) A Study on the Shear Strength Characteristic of Unsaturated Red Clay. *World Journal of Engineering and Technology*, **10**, 714-727.
https://doi.org/10.4236/wjet.2022.104046

Received: August 26, 2022
Accepted: September 24, 2022
Published: September 27, 2022

Abstract

The red clay in Chenzhou, Hunan province is mostly in unsaturated state. Simply applying the mechanical properties that derived from classic saturated soil mechanics often leads to slope failures in this region. In order to study the shear strength characteristic of unsaturated red clay in Chenzhou and to explore a shear strength equation that can be easily applied in engineering practice, a series of triaxial tests of saturated and unsaturated red clay samples were performed using the regular triaxial testing apparatus. The testing results show that the peak strength of red clay drops slightly before the moisture content of 30% but decreases sharply after that. The friction angle of red clay under unsaturated state is basically equal to the effective friction angle under saturated state, while the cohesion of unsaturated red clay is far much bigger than that of saturated one, which indicates that the matric suction makes a great contribution to the cohesion. By fitting the testing results with appropriate curves, the relationships between total strength parameters c_{total} and φ_{total} with moisture content were obtained. The total c_{total} increases logarithmically before the moisture content of 35% then decreases linearly, while φ_{total} decreases cubically with increasing moisture content.

Keywords

Unsaturated Soils, Red Clay, Shear Strength, Triaxial Tests

1. Introduction

Most soils encountered in the engineering practice are unsaturated soils. Due to the existence of gas phase, which usually refers to air, the pore water pressure in unsaturated soils is smaller than pore air pressure. The difference between the two pressures is called matric suction. Matric suction plays a very important role in controlling the mechanical properties of unsaturated soils. Extensive engineering practice and research results show that unsaturated soils and saturated soils have great differences in engineering properties, therefore, unsaturated soils cannot be simply treated as saturated ones. Because of the insufficient understanding of the properties of unsaturated soils, engineering accidents related with suction occur frequently during the implementation of projects, which brings about huge economic loss around the world [1]. Therefore, changes in soil properties caused by changes in moisture content or suction in soils should be considered by applying suitable theory for unsaturated soils. The difficulty of suction measurement makes the theory of unsaturated soil mechanics based on suction basically stay in the stage of laboratory research, and has not been widely used in engineering practice.

In the Lingnan area of Chenzhou, China (**Figure 1**) unsaturated red clay is widely distributed throughout the natural landscape. Slopes in unsaturated red clay can maintain stability at a relative height and steep angle when there is no rainfall, while slopes even with very gentle angles tend to slide after rainfall. Due to the insufficient understanding of the mechanical behavior of unsaturated red clay, slopes comprised of it in Chenzhou often fail after rainfall even if it is reinforced, which causes a great loss to the local economy [2]. Therefore, it is of great theoretical and practical importance to conduct experimental research on the characteristics of unsaturated red clay in Chenzhou and to explore equations that can be easily applied in the analysis of engineering problems such as

Figure 1. Geographical map of the research area (the red star).

slopes and foundation pits.

2. Studies on the Shear Strength of Unsaturated Soils

Since the 1950s, a large number of scholars have been devoted to the study of unsaturated soils, among which Bishop [3] [4], Fredlund [1] [5], Khalili [6] [7], Ning Lu [8] have made outstanding research outcomes.

In 1959, Bishop proposed an effective stress equation for unsaturated soils based on experiments [3].

$$\sigma' = (\sigma - u_a) + \chi (u_a - u_w) \tag{1}$$

where, σ' is the effective stress; u_a is the pore air stress; u_w is the pore water pressure; χ is the effective stress parameter of unsaturated soils that is related to the degree of saturation. χ ranges from 0 - 1.0 (for perfectly dry soil, $\chi = 0$; for saturated soil, $\chi = 1$).

On this basis, and according to the Mohr-Coulomb theory, Bishop *et al.* (1960) put forward a shear strength equation for unsaturated soils [4].

$$\tau_f = c' + (\sigma - u_a)\tan\varphi' + \chi(u_a - u_w)\tan\varphi' \tag{2}$$

where, φ' is the effective friction angle of saturated soils; c' is the effective cohesion.

Research results showed that the effective stress parameter χ is not only related to the degree of saturation, but also to soil types, soil structures, stress history, stress path, hydraulic hysteresis and many other factors.

Fredlund and Morgenstern (1978) proposed a stress analysis procedure for unsaturated soils based on multiphase continuum mechanics which suggests to use two independent stress state variables $(\sigma - u_a)$ and $(u_a - u_w)$ to establish the effective stress equation [5].

$$\tau_f = c' + (\sigma - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi^b \tag{3}$$

where, φ^b is the friction angle of suction, the slope angle that shear strength increases with matric suction $(u_a - u_w)$.

At first proposal of this equation, Fredlund assumed that φ^b is a constant value for a particular type of soil. However, the research results by Gan *et al.* (1988) showed that φ^b is not constant even for the same soil sample [9]. It is a function of matric suction. When the soil sample closes to saturated state, the matric suction is very small and the value of $\tan\varphi^b$ is close to the effective internal friction coefficient of saturated soil $\tan\varphi'$; when the soil saturation decreases and the matric suction increases, the value of $\tan\varphi^b$ decreases gradually and nonlinearly. Therefore, the proper choosing of φ^b in Fredlund's shear strength equation is the key to the popularization and application of this theory.

Ning Lu (2004) pointed out that the most relevant and practical parameter to the physical and mechanical behavior of unsaturated soils is neither the matrix suction nor the effective stress parameter χ, but the product of the two $\chi(u_a - u_w)$ [8].

Due to the difficulty in determining the parameters χ and φ^b, neither Bishop's equation nor Fredlund's equation have been widely used in engineering practice. Therefore, many scholars have proposed a range of total shear strength equations for unsaturated soils that are convenient for engineering application [10]-[18]. Their expressions can be summarized in the following form.

$$\tau_f = c_{total} + \sigma \tan \varphi_{total} \tag{4}$$

where, c_{total} and φ_{total} are the total shear strength parameters which vary with moisture content of soil. The two parameters consider the contribution of matric suction and soil structure to the shear strength, and the exact expression varies with soil types.

However, most of these studies ([10]-[18]) are based on direct shear test, the shear plane and the stress state of which have a huge difference from that of *in-situ* soils. By comparison, the shear strength obtained from triaxial tests are more reliable and more close to the theoretical values. On the other hand, unsaturated triaxial tests are usually both time and labor consuming and industry normally do not have the apparatus to conduct such testing. Therefore, regular triaxial tests were performed to study the relationship between the shear strength and moisture content of unsaturated red clay in Chenzhou, and then equations of total shear strength that are convenient for engineering application were proposed in this paper.

3. Testing Methods

3.1. Sample Preparation and Testing Equipment

The red clay studied in this paper was collected from a foundation pit in Chengzhou. The *in-situ* soil sample has a volumetric moisture content of 16% - 20%, a dry density of 1.6 g/cm^3, a specific gravity of 2.825 and a the void ratio of 0.92. The testing samples were remolded and passed through a 1 mm sieve after drying and rolling and compacted under identical dry density as the natural soil. The soil samples in the consolidated drained tests were all compacted in several layers with a volumetric water content of 20%, and the water content after saturation was 48%. The unconsolidated undrained soil samples were compacted under different moisture contents. All soil samples were 80 mm in height and 39.1 mm in diameter (a slight difference may exists after the sample was made), the typical soil sample is shown in **Figure 2**.

The testing apparatus mainly consists of the TSZ-3 strain-controlled triaxial tester (**Figure 3**) and the corresponding testing system produced by Nanjing Soil Instrument Factory and the BGH vacuum saturator (**Figure 4**).

3.2. Test Plan and Procedures

The triaxial shear tests in the study included two parts: the consolidated drained tests (CD) of saturated soil and the unconsolidated undrained tests (UU) of unsaturated soil. The preparation of soil samples and the testing procedures of CD and UU tests were in accordance with the Standard GB/T 50123-2019 (Ministry of Housing and Urban-Rural Development of the People's Republic of China,

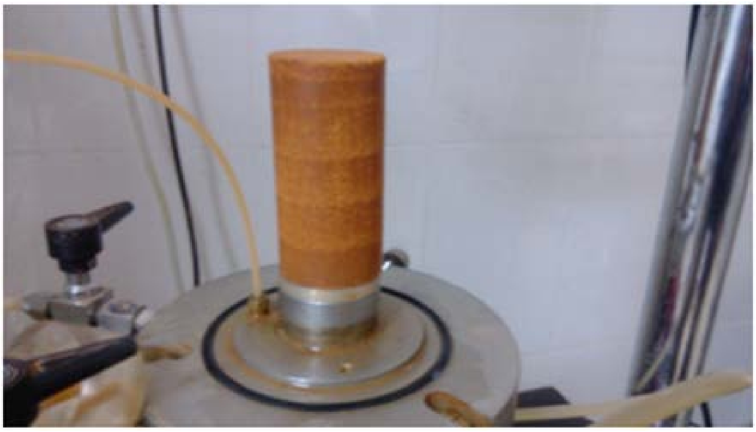

Figure 2. Soil sample of triaxial test.

Figure 3. TSZ-3 strain-controlled triaxial tester.

Figure 4. BGH vacuum saturator.

2019) [19]. All the testing data was collected by the computer-controlled data collector.

3.2.1. Consolidated Drained Tests (CD) of Saturated Soil

The soil samples compacted at 20% volumetric moisture content were saturated in the vacuum saturator for 10 hours, and then three soil samples were subjected to consolidated drained tests under confining pressures of 100 kPa, 200 kPa, and 300 kPa respectively. The shear rate applied in the tests was 0.015 mm/min, and the effective shear strength parameters c' and φ' of saturated red clay were obtained from the testing results.

3.2.2. Unconsolidated Undrained Tests (UU) of Unsaturated Soil

A total of 24 soil samples divided into 8 groups at moisture contents of 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45% were tested under unconsolidated undrained conditions and confining pressures of 100 kPa, 200 kPa, and 300 kPa. The shear rate for the UU tests was 0.4 mm/min, and the total shear strength parameters c_{total} and φ_{total} of unsaturated red clay at different moisture contents were obtained.

3.3. Testing Results and Discussion

3.3.1. Consolidated Drained Tests (CD)

The stress-strain curves of saturated red clay samples under confining pressures of 100, 200, and 300 kPa in the consolidated undrained test are shown in Figure 5.

According to the stress-strain curves, the soil samples did not undergo shear failure when reaching the peak strength or 20% strain, presenting a form of plastic bulging deformation as shown in Figure 6: the greater the confining pressure applied, the greater the peak strength was.

Based on the confining pressure and peak strength, the failure envelope of Mohr's stress circles was plotted for the three soil samples in Figure 7. From the envelope, the effective shear strength parameters of saturated red clay were obtained: $c' = 19.06\text{ kPa}$ and $\varphi' = 28.4^\circ$.

3.3.2. Unconsolidated Undrained Tests (UU)

The stress-strain curves of unsaturated red clay samples at different volumetric moisture contents under confining pressures of 100, 200, and 300 kPa in the unconsolidated undrained tests are shown in Figures 8-15.

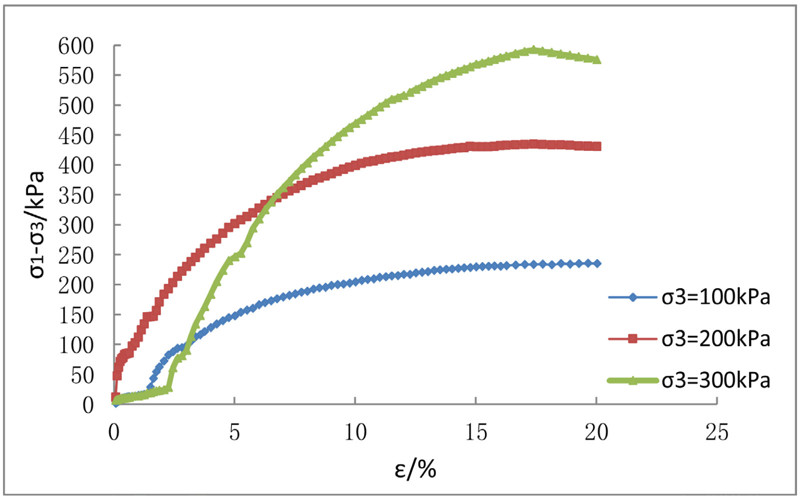

Figure 5. Stress-strain curves of saturated red clay under different confining pressures.

Figure 6. Soil samples of saturated red clay after consolidated drained test.

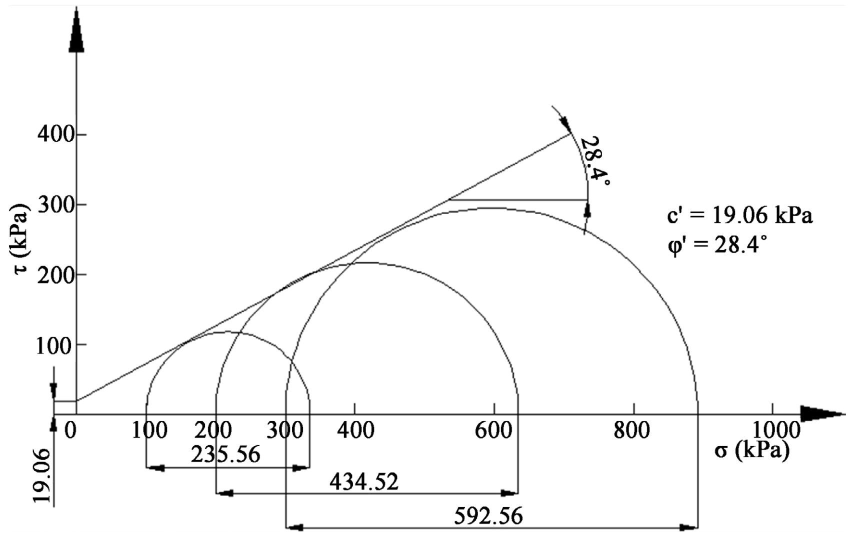

Figure 7. Failure envelope of saturated red clay.

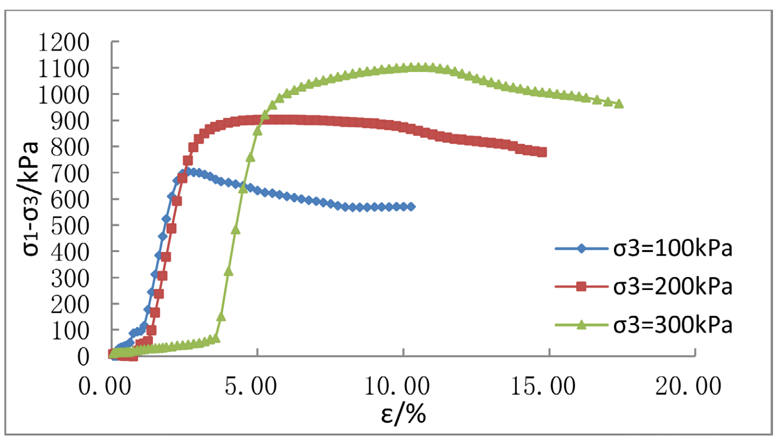

Figure 8. Stress-strain curves of unsaturated red clay at moisture content of 10%.

From these stress-strain curves, it can be observed that:

1) The peak strength of soil samples decreases with the increase of moisture content and the decrease of confining pressure; the peak strength decrease slightly

when the moisture content is between 10% and 30%, but starts to decline significantly after exceeding 30%.

2) The lower the moisture content and confining pressure are, the smaller strain it need to reach the peak strength and the shorter the peak strength is maintained; the higher the moisture content and confining pressure are, the

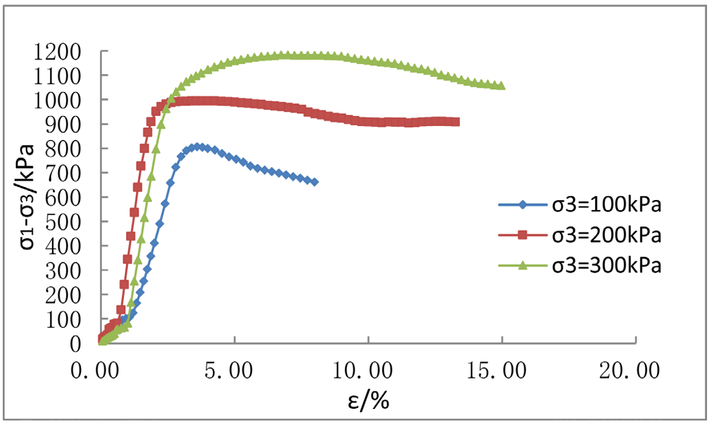

Figure 9. Stress-strain curves of unsaturated red clay at moisture content of 15%.

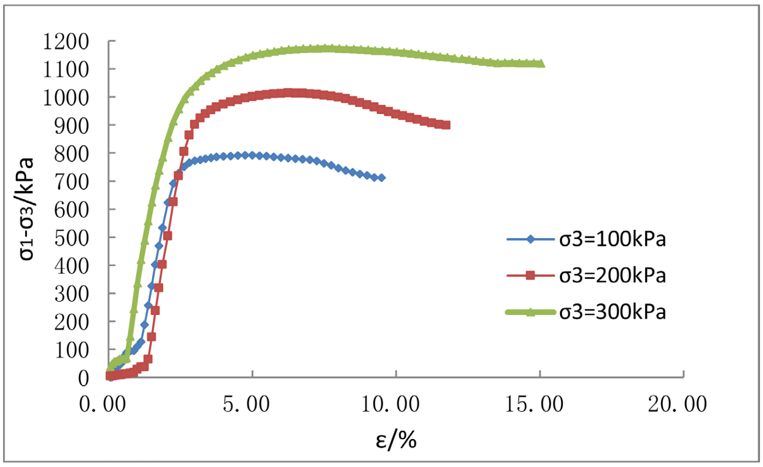

Figure 10. Stress-strain curves of unsaturated red clay at moisture content of 20%.

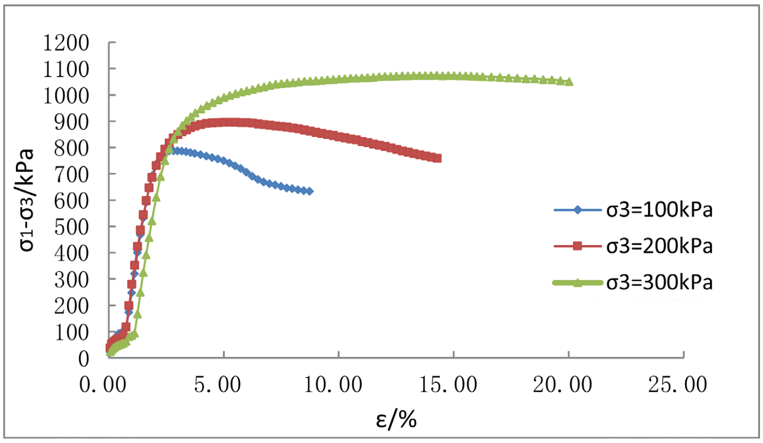

Figure 11. Stress-strain curves of unsaturated red clay at moisture content of 25%.

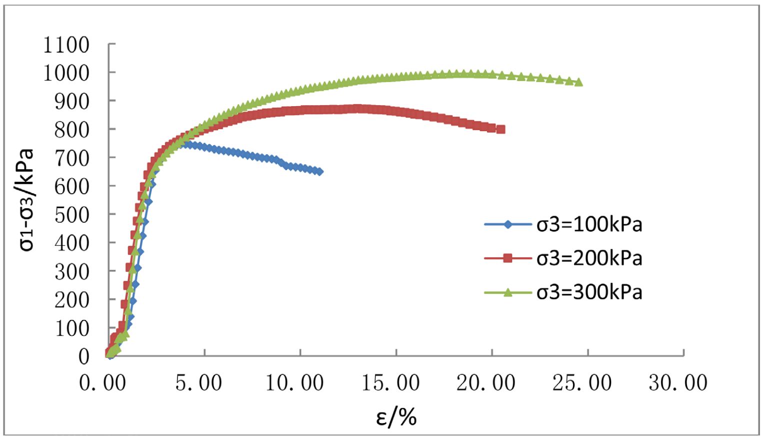

Figure 12. Stress-strain curves of unsaturated red clay at moisture content of 30%.

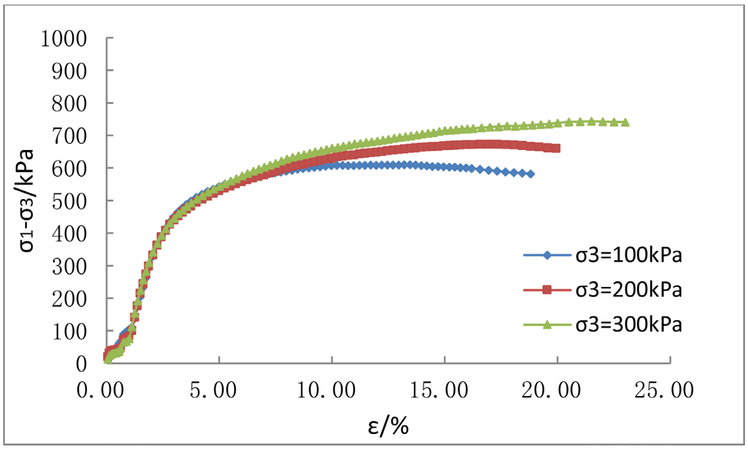

Figure 13. Stress-strain curves of unsaturated red clay at moisture content of 35%.

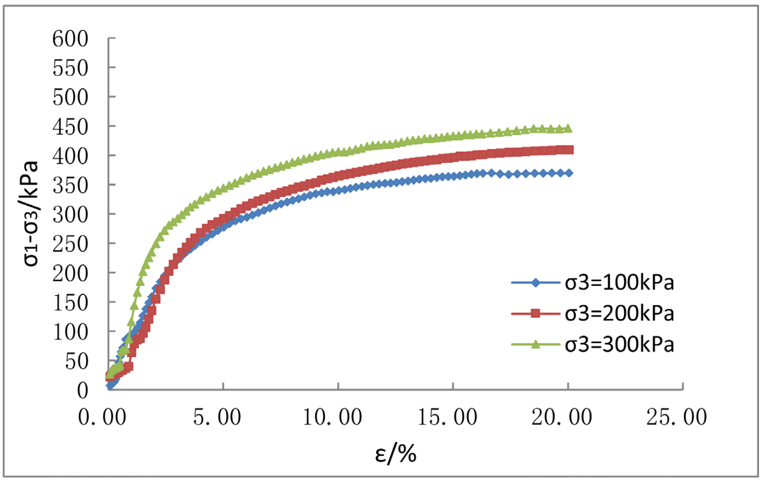

Figure 14. Stress-strain curves of unsaturated red clay at moisture content of 40%.

greater strain it need to reach the peak strength and the longer the peak strength is maintained.

3) When the moisture contents of soil samples are ranging from 10% to 35%, shear failure occurs after reaching the peak strength as shown in **Figure 16**. After

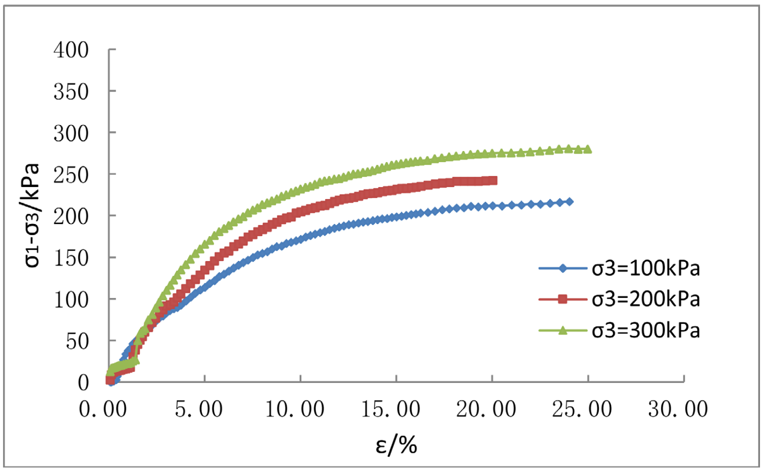

Figure 15. Stress-strain curves of unsaturated red clay at moisture content of 45%.

Figure 16. Shear failure of soil samples with moisture content below 35%.

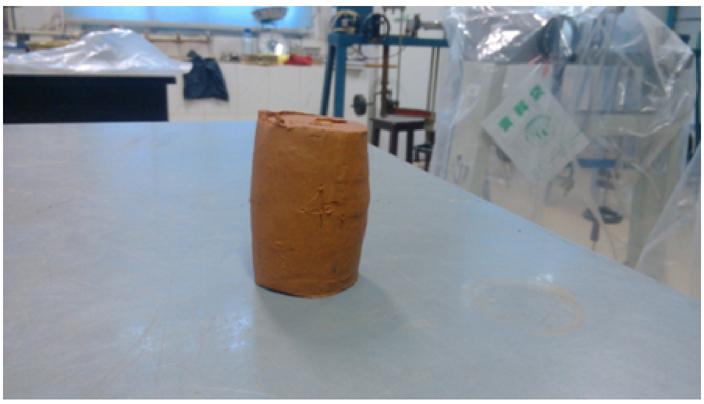

Figure 17. Bulging deformation of soil samples with moisture higher than 35%.

reaching the moisture content of 35% (300 kPa confining pressure), a form of plastic bulging deformation (**Figure 17**) is observed instead of shear failure, which is similar to the saturated soil samples in CD tests.

Based on the confining pressure and peak strength, the failure envelopes of Mohr's stress circles were plotted for the unsaturated soil samples. The total shear strength parameters c_{total} and φ_{total} of unsaturated red clay at different moisture contents were obtained and shown in Table 1.

By fitting the testing data of c_{total} and φ_{total}, the corresponding curves for the two parameters were obtained and shown in Figure 18 and Figure 19.

Table 1. Shear strength of unsaturated red clay at different moisture contents.

Volumetric moisture content θ (%)	c_{total} (kPa)	φ_{total} (kPa)
10	144.65	30
15	181.94	29
20	180.65	29.2
25	200.25	24.7
30	207.39	22.5
35	210.63	14.5
40	141.06	9.2
45	82.12	7.4

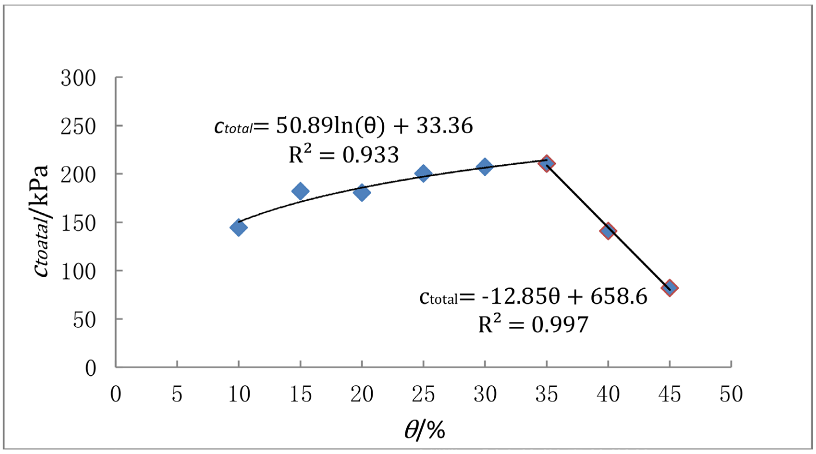

Figure 18. Relationship between total strength parameter c_{total} and moisture content.

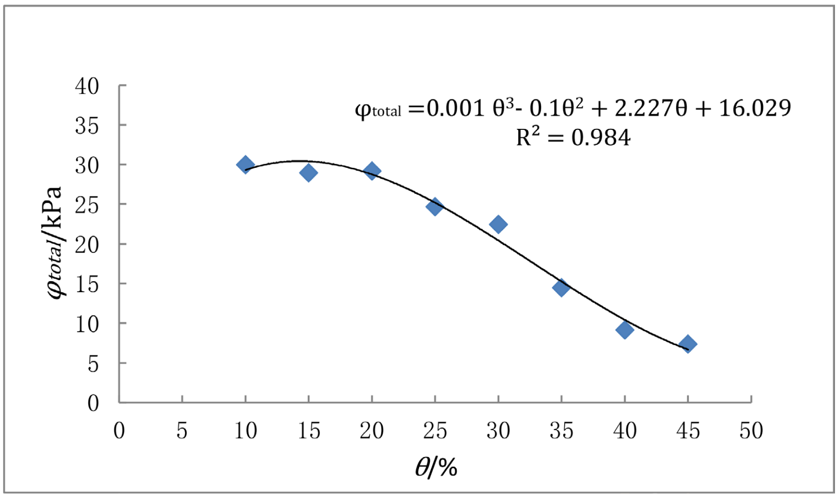

Figure 19. Relationship between total strength parameter φ_{total} and moisture content.

Observations form **Table 1**, **Figure 18** and **Figure 19** show that:

1) The total cohesion c_{total} is between 82.12 kPa and 210.63 kPa when the moisture content is 10% to 45%, much larger than the effective cohesion (19.06 kPa), which indicates that the matric suction makes a great contribution to the total cohesion. Besides, the total cohesion first increases and then decreases with increasing moisture content, which is consistent with the research results of Shengming Luo [15] and Gaofeng Chen [16]. To be specific, c_{total} increases slowly before moisture content of 35%, while decreases rapidly after that point. The reason for this behavior can be explained as follows: the water in red clay is mainly bound water at a low moisture content, and the increasing bound water improves the cohesion of soil to a great extent; when the moisture content rises, the water in red clay becomes free water, the cohesion between soil particles is weakened, and the matric suction also decreases with increasing moisture content, so the total cohesion decreases. The varying trend of c_{total} can be fitted by the function (4a) and (4b).

$$c_{total} = 50.89 \ln \theta + 33.36 \quad \left(0 \le w \le 35\%\right) \tag{4a}$$

$$c_{total} = -12.85\theta + 658.6 \quad \left(35\% \le w \le 48\%\right) \tag{4b}$$

2) The total strength parameter φ_{total} of unsaturated red clay remain stable (29˚ to 30˚) before the moisture content of 20%, closing to the effective friction angle φ' (28.4˚), which indicates that in this range of moisture content, the gas in soil is in a connected state. Because the volumetric deformation is small in this stage, the air pressure does not increase significantly during the shearing process in this stage, therefore it has little effect on the value of φ_{total}. On the other hand, φ_{total} decreases significantly after the moisture content of 20%, indicating that the gas in the soil is in a partially-connected state after that point. The pore water begins to connect and pore water pressure is generated during the shearing process so that the total friction angle is substantially reduced. The varying trend of φ_{total} can be fitted by function (5).

$$\varphi_{total} = 0.001\theta^3 - 0.1\theta^2 + 2.227\theta + 16.029 \tag{5}$$

4. Conclusions

In this paper, the shear strength characteristics of unsaturated red clay were investigated by performing regular triaxial tests on the saturated and unsaturated soils. By analyzing the testing results, following conclusions can be drawn.

1) The peak shear strength of unsaturated red clay decreases with increasing volumetric moisture content, especially after moisture content of 30%. This explains why properly reinforced slopes in the red clay could fail after heavy rainfall.

2) Due to the existence of matric suction, The total cohesion of unsaturated red clay is significantly larger than effective cohesion c'. This explains why unsaturated soil slopes can maintain stability at a relative steep angle. c_{total} can be perfectly fitted by an increasing logarithmic function and a decreasing linear

function.

3) The total friction angle φ_{total} decreases with the increasing moisture content. The stable value before moisture content of 20% means that the red clay is in an air connection state. In other words, it mainly reflects the characteristic of unsaturated soils. The varying trend can be fitted by a cubic polynomial function.

4) By simply measuring or calculating the moisture content of soils in different depth, the proposed shear strength equations can be easily applied in engineering practice, which may help to reduce the possibility of engineering accidents like slope failures in Chenzhou.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Fredlund, D.G. and Rahardjo, H. (1993) Introduction of Soil Mechanics. *Soil Mechanics for Unsaturated Soils*. John Wiley and Sons, Inc., New York, 1-16. https://doi.org/10.1002/9780470172759

[2] Ma, W.H. (2012) Research on Geological Hazards Mechanism and Comprehensive Prevention Disaster in Hunan Province. Ph.D. Thesis, Central South University Changsha. (In Chinese)

[3] Bishop, A.W. (1959) The Principle of Effective Stress. *Teknisk Ukebldad*, **106**, 859-863.

[4] Bishop, A.W., Alpan, I., Blight, G.E. and Donald, I.B. (1960) Factors Controlling the Strength of Partly Saturated Cohesive Soils. *Research Conference on Shear Strength of Cohesive Soils*, ASCE, Boulder, 503-532.

[5] Fredlund, D.G., Morgenstern, N.R. and Widger, R.A. (1978) The Shear Strength of Unsaturated Soils. *Canadian Geotechnical Journal*, **15**, 313-321. https://doi.org/10.1139/t78-029

[6] Khalili, N. and Khabbaz, M.H. (1998) A Unique Relationship for χ for the Determination of the Shear Strength of Unsaturated Soils. *Geotechnique,* **48**, 681-687. https://doi.org/10.1680/geot.1998.48.5.681

[7] Khalili, N., Geiser, F. and Blight, G.E. (2004) Effective Stress in Unsaturated Soils: Review with New Evidence. *International Journal of Geomechanics*, **4**, 115-126. https://doi.org/10.1061/(ASCE)1532-3641(2004)4:2(115)

[8] Lu, N. and William, J.L. (2004) State of Stress. *Unsaturated Soil Mechanics*, John Wiley and Sons, Inc., Hoboken, 173-218.

[9] Gan, J., Fredlund, D.G. and Rahardjo, H. (1988) Determination of the Shear Strength Parameters of an Unsaturated Soil Using the Direct Shear Test. *Canadian Geotechnical Journal*, **25**, 500-510. https://doi.org/10.1139/t88-055

[10] Chen, H.M., Ban, Q.F. and Liu, X.W. (2006) Relationship Between Water Content ω and Unsaturated Soil Shear Strength Indices c and φ. *Journal of Hefei University of Technology*, **29**, 736-739. (In Chinese)

[11] Lin, H. and Yin, Z.Z. (2007) Variation of Unsaturated Soil Strength with Water Content. *Chinese Journal of Rock Mechanics and Engineering*, **26**, 1499-1503.

[12] Chen, B. (2010) Research on Chenzhou Colluvial and Residual Soil Slope's Process Stability and Process Control. Ph.D. Thesis, Central South University, Changsha. (In Chinese)

[13] Bian, J.M. and Wang, B.T. (2011) Research on Influence of Water Content on the Shear Strength Behavior of Unsaturated Soils. *Chinese Journal of Underground Space and Engineering*, **7**, 17-21.

[14] Wang, Z.W., Hong, B.N., Liu, X. and Zhou, Q. (2011) Water-Sensitive Properties of Shear Strength of Red Clay. *Journal of Sichuan University* (*Engineering Science Edition*), **43**, 17-22. (In Chinese)

[15] Luo, S.M. (2012) Experimental Study of Unsaturated Silty Clay Shear Strength and Its Impact on Slope Stability Analysis. Master's Thesis, Zhejiang University of Technology, Hangzhou. (In Chinese)

[16] Chen, G. F., Shi, B. F., Huang, H. Z., Zhang, J. J. and Shi, M. (2012) Study on the Influence of Moisture Content to Shear Strength for Unsaturated Soils. *Journal of Engineering Geology*, 20, 127-131. (In Chinese)

[17] Yan, Q., Li, Y.H. and Xu, Y.H. (2020) Experimental Study of Moisture Content on Shear Strength of Unsaturated Soil. *Journal of Henan University of Urban Construction*, 29, 48-52. (In Chinese)

[18] He, Y., Yu, Z.P., Zhang, Z., Chen, B. and Zhang, K.N. (2022) Effects of Rainfall on Mechanical Behaviors of Residual-Soil Landslide. *Frontiers in Earth Science*, **10**, s925636. https://doi.org/10.3389/feart.2022.925636

[19] Ministry of Housing and Urban-Rural Development of the People's Republic of China (2019) Standard for Geotechnical Testing Method. GB/T 50123-2019. China Architecture & Building Press, Beijing. (In Chinese)