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Research Progress on Key Issues of Shear Strength Theory and New Testing Technology of Roadway Crossing Unsaturated Soil Layer

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Abstract: By studying the relationship between the shear strength and water content of unsaturated soil, summarizing and analyzing the previous methods of preparing soil samples with different water content, it is found that the test phenomenon of "critical water content" exists in the specific gravity method. The research shows that the shear strength of unsaturated soil is the result of the common action of compactness and water content. Nine widely used shear strength measurement methods of unsaturated soil are sorted out, and their common shear test methods are divided into three categories, namely direct shear test method, compression shear test method and rotary shear test method. The advantages and disadvantages of each method are analyzed. Many shear strength formulas are divided into four categories: combined water-soil characteristic curve, piecewise function, mathematical fitting and total stress index. The characteristics and shortcomings of shear strength of different kinds of unsaturated soil are compared, and some suggestions on the theoretical research direction of shear strength in the future are put forward. Finally, a variety of new ideas and methods for studying the shear strength theory of unsaturated soil are introduced. This paper improves the theoretical basis of unsaturated soil, which is of great significance to speed up the engineering practice of shear strength theory of unsaturated soil.

Keywords: Unsaturated Soil; Matrix Suction; Shear Strength; New Test Technology; Overview.

1. Introduction

The shear strength of soil is widely used in important industries such as water conservancy and hydropower, roadbed engineering, mining engineering, etc. The shear strength of soil determines the bearing capacity and safety performance of geostructures, and has become the focus of research [1]. In nature, most soils are in the unsaturated state, and the properties of unsaturated soils are different from those of saturated soils. Since the 1960s, domestic and foreign scholars have carried out a lot of research work on unsaturated soil, gradually established a theoretical framework for the study of unsaturated soil, designed a large number of shear strength test methods and experimental devices for unsaturated soil, and gradually applied the theoretical and experimental research results to engineering practice.

With the deepening of theoretical research on the shear strength of unsaturated soil, it has been found that there are still many problems difficult to explain in the research framework of unsaturated soil [2], such as: (1) What are the most important factors that lead to the change of shear strength of soil from saturated state to unsaturated state? (2) What is the applicability of various shear test methods and test devices of unsaturated soil and what are the short plates? (3) The theoretical formulas of shear strength have diversified development. Due to the difference in the properties of unsaturated soil, whether the formulas have universal applicability and the necessity of large-scale popularization in engineering? It can be seen that the current shear strength theory of unsaturated soil is not perfect, most of the results are still in the theoretical or laboratory test stage, and some assumptions and existing test methods still have certain limitations.

Domestic and foreign research institutions and scholars have carried out research on the key issues of the shear strength theory of unsaturated soil, and formed a variety of strength theories, sample methods and scientific devices, and achieved a wealth of research results. The author starts from three aspects: the most important factors that change the shear strength of soil from saturated state to unsaturated state, the characteristic relationship between soil and water, the test method of shear strength, and the theory of shear strength. Finally, the author introduces a variety of new ideas and methods for studying the theory of shear strength of unsaturated soil. It is of great significance to accelerate the engineering practice of unsaturated soil shear strength theory.

2. Research Status of Soil-water Characteristic Curve

Experiments show that there are fundamental differences between saturated soil and unsaturated soil in terms of mechanical properties and engineering properties, and the biggest factor determining the difference between the two is soil moisture content, so it is particularly important to study the characteristic curve between soil and water [3][4]. There have been many experimental studies on the relationship between water content and shear strength, among which the majority of them focus on remolded soil. However, due to the different methods of controlling water content in the sample preparation process and the different initial state conditions of the test, the test results are also quite different [5].

The results of the direct shear test show that the shear strength of soil varies with water content because of the different methods of controlling water content. The test of undisturbed soil is conducted using different on-site testing methods. The test of reshaped soil is divided into specific gravity method, drying method and soaking method, and their respective advantages and disadvantages are shown in the table. It can be seen from the research conclusions of the above scholars that no matter which sample preparation

method is used, the shear strength of soil decreases with the increase of water content. The internal friction Angle of soil basically shows a linear decreasing trend.

The above are from the macro perspective to analyze the influence between moisture content and shear strength of unsaturated soil, some scholars in view of this phenomenon, from the micro perspective of specific analysis, got a good effect. Higo et al. used electron microscope scanning and CT imaging techniques to study and found that unsaturated soil would form a meniscus water film between soil particles, as shown in Figure 1. When the water content decreases, the water film area decreases, and the shear strength of unsaturated soil increases with the increase of matrix suction.

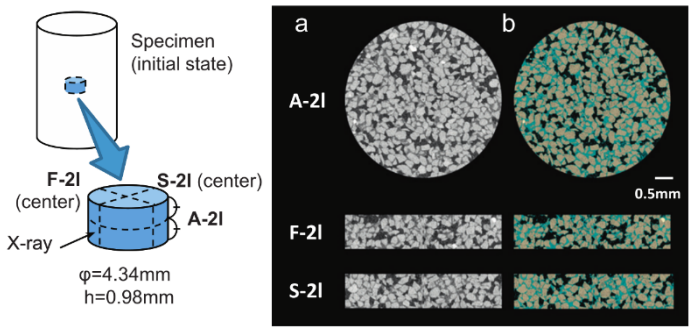


Fig 1. water film distribution of unsaturated soil under micro-CT scanning [13]

Yang Song et al. found that the cohesion is not monotonic with the change of saturation without exhaust shear, and the internal friction Angle decreases with the increase of saturation. With the decrease of water content, the water film bonding force gradually increases, and with the increase of water content, the water film bonding force gradually decreases. When the soil reaches the saturated state, the water film bonding force is completely lost. Zhou et al. [6] believe that when the moisture content of soil reaches a certain value, particle cementation will be lost due to the dissolution of intergranular cements, as shown in Figure 2.

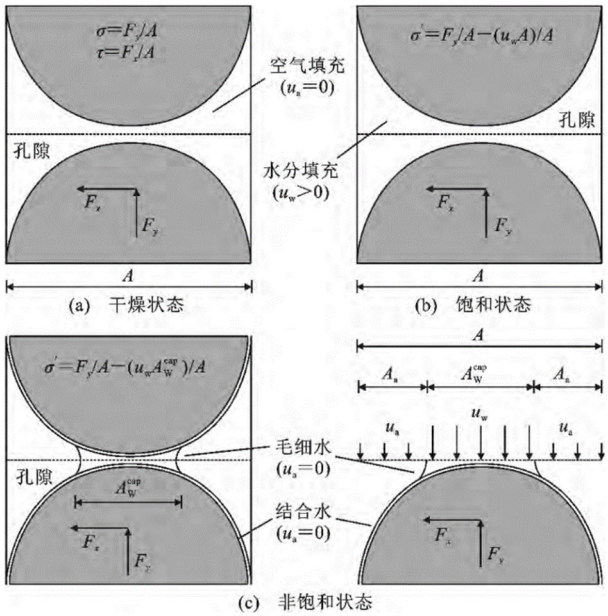


Fig 2. water occurrence form between unsaturated soil particles [15]

Yanlong et al. [7] found that the cohesion of undisturbed soil samples first increased and then decreased with the increase of water content. When the water content is about 7%, the bond strength of some samples is slightly greater than 100 kPa, and when the water content is 20%, the bond strength of almost all samples is very low. In the case of 7% water content, it generally drops to 20% and then stabilizes, as shown in Figure 3. This reflects the reaction of cement materials such as clay minerals, free oxides, carbonates and organic matter to bind the loess particles together. When the soil water content is low (less than 7%), the cementation can not fully function, and the optimal water content is about 7%, the cementation reaches the maximum value, resulting in high cohesion. With the further increase of water content, the bonding effect of clay rapidly weakens, and other cementing materials gradually dissolve, resulting in a continuous decrease in cohesion. There is a critical moisture content in the direct shear test results of controlling the moisture content of the soil sample by controlling the dry density and adding water, while the results of the remolded soil test and the direct shear test results of changing the moisture content by soaking method show that the shear strength decreases with the increase of the moisture content, and there is no critical moisture content.

In summary, with the increase of water content, the cohesion and internal friction Angle of unsaturated soil continue to decrease. When the specific gravity method is used to prepare standard soil samples with different water content, not only the water content of the soil sample is changed, but also the compaction degree of the soil sample is

changed, and the uniqueness of the variables is not guaranteed. Therefore, how to prepare unsaturated soil samples with standard water content is also the key to obtain accurate data.

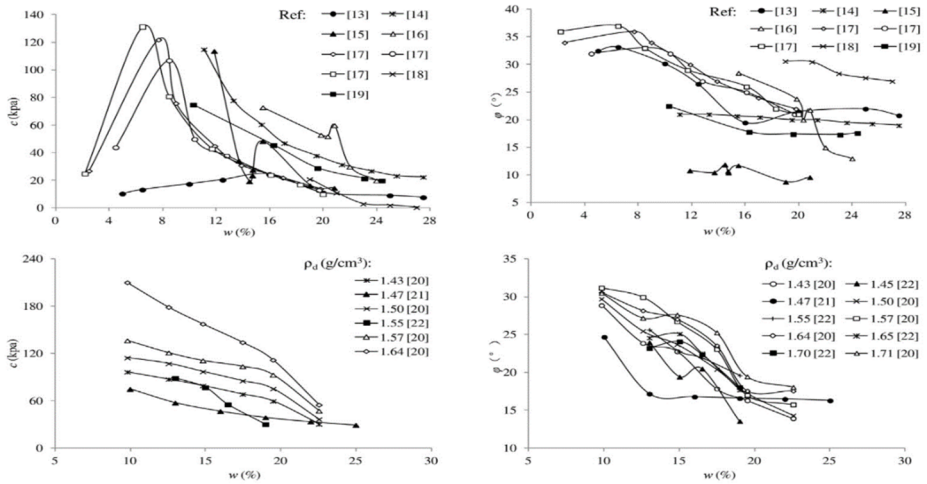


Fig 3. Changes of internal friction angle and cohesion of remolded soil (first row) and undisturbed soil (second row) with the increase of water content [16]

3. Test Method for Shear Strength of Unsaturated Soil

The shear strength of soil mass is widely used in important industries such as water conservancy and hydropower, roadbed engineering, national defense and transportation, and has become the focus of research at present. The shear strength test of soil is to measure the shear strength index of soil through laboratory test or soil in-situ test. Among them, the indoor soil shear test mainly includes single shear test, ring shear test, true triaxial test, hollow cylinder torsion test, unconfined compressive test, slow shear test, etc. The soil field in-situ test mainly includes cross plate shear test and large-scale shear test [8].

Considering the cost error and time and other factors of different kinds of test, the current widely used test methods for soil shear strength are limited uniaxial compression test, triaxial compression test, direct shear test and in-situ cross plate shear test. The author tries to systematically sort out the measurement methods of shear strength of unsaturated soil, and lists 9 different measurement methods, including their basic characteristics, such as size or measurement speed, etc., as shown in Table 1.

In Table 1, the author tries to organize 9 different measurement methods, and tries to divide the commonly used shear test methods into 3 categories, namely, direct shear test method, compression shear test method and rotary shear test method. The formulas of different test methods and test parameters, such as measurement speed and size, are sorted out. Table 3 contains the standard test methods that can be found in the literature, and a comparative review of the literature on different measurement methods found that there are large differences between methods, up to several hundred percent. The cohesion and internal friction angles determined by these methods should not be considered as inherent properties of the soil, as they are affected by many factors.

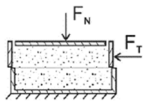
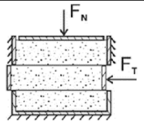
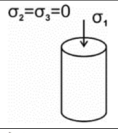
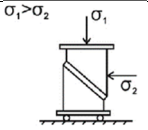
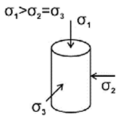
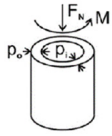
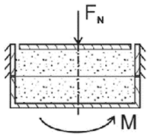
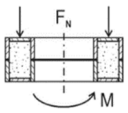
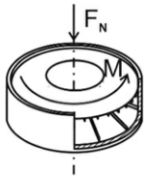
The different effects of scale effect, hole wall effect, strain rate effect, shear kinematics, material type of test equipment and soil properties are considered. Through the comparative analysis of many different direct shear test methods, it is found that the most important parameters in the test methods are geometry, kinematics and velocity. The scale effect is obvious when the shear plane is about 300 cm2. Therefore, for most fine-grained soil samples, it is not necessary to use larger test equipment. The shear speed has a significant effect on cohesive soil, and its cohesive force can be increased by more than 3 times.

Some of the methods proposed so far are not specifically used to determine shear strength; Most of the parameters describing soil behavior under shear load are based on Mohr-Coulomb failure criterion. According to the model, the shear stress on the shear surface depends on the normal stress acting on the shear surface and the two soil parameters of cohesion and internal friction Angle. The purpose of shear strength test is mainly to determine these parameters of soil. However, the measured value is more like an indicator of a specific test process than a material constant that describes the inherent properties of a soil sample. They depend on how the use of standard and custom methods makes a substantial difference in results. Of course, this will depend on the needs of the test execution and the requirements regarding the method (test cost and duration, ease of operation, logistical difficulties, accuracy of measurement, etc.). Each approach has its advantages. For example, penetration tests can provide a quick and rough estimate of soil strength under field conditions. The rotary shear method makes it easy to determine the residual shear strength, that is, the shear strength retained by the soil when subjected to large displacements. Triaxial compression test is generally regarded as the most suitable test method for measuring the shear strength of soil, but it takes a long time and can not be used in the field test of intact soil.

In summary, the methods for measuring the shear strength of unsaturated soil can be divided into two categories :(1) the methods based on direct shear test and triaxial test; (2) Methods based on corresponding tests, such as large direct shear test methods. The first test method can be used in the laboratory to estimate shear strength using the remodeled soil ocean. Such methods tend to be relatively inexpensive, although they are generally considered less reliable because the stress states of remodeled soil samples are different from those of in-situ soil samples. The most authentic method is considered to be more reliable. However, the cost of conducting such tests on the engineering site is moderate and requires instruments that are bulky and inconvenient to

transport.

Table 1. Test methods of shear strength of unsaturated soil in different ways

method			Derivation formula	Mean measurement velocity	Model size	author
type	name	Schematic drawing				
Direct shear test	Direct shear test		$\tau = \frac{F_T}{A}$ $\sigma_N = \frac{F_N}{A}$	0.008-0.016mm/s	100mm*100mm*30mm	Dadakh [18] Liu [19]
	Double-sided direct shear test		$\tau = \frac{F_T}{A}$ $\sigma_N = \frac{F_N}{A}$	N	N	Housel [20] Sowers [21]
Compression shear experiment	Unconfined compression test		$c_u = \frac{1}{2}\sigma_{1\max} for \varphi°$	0.02-0.1mm/s	762mm*1524mm	Tsuchida [22], Elton [23]
	Biaxial compression test		$\tau = \frac{\sigma_1 - \sigma_3}{2}\sin 2\alpha$ $\sigma_N = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2}\cos 2\alpha$	0.05mm/s	200mm*1000mm*600mm	Alabdullah [24] Drescher [25]
	Triaxial compression test		$\tau = \frac{\sigma_1 - \sigma_3}{2}\sin 2\alpha$ $\sigma_N = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2}\cos 2\alpha$	0.08-0.16mm/s	1000mm*1500mm	Hu [26] Bauer [27]
	Hollow cylinder torsion test		$\tau = \frac{3M}{2\pi\left[(\frac{d_0}{2})^3 - (\frac{di}{2})^3\right]}$ $\sigma_{1,3} = \frac{\sigma_z + \sigma_\theta}{2} \pm \sqrt{(\frac{\sigma_z - \sigma_\theta}{2})^2 + \tau^2}$	0.004mm/s	310mm*250mm*180mm	Ampadu [28] Pradhan [29]
Rotary shear experiment	Rotary shear experiment		$\tau = \frac{3M}{2\pi(\frac{d}{2})^3}$ $\sigma_N = \frac{4F_N}{\pi d^2}$	0.05mm/s	60mm*60mm*60mm	Ye [30] Sadrekarimi [31]
	Annular shear experiment		$\tau = \frac{3M}{2\pi\left[(\frac{d_0}{2})^3 - (\frac{d_i}{2})^3\right]}$ $\sigma_N = \frac{4F_N}{\pi(d_0^2 - d_i^2)}$	0.417°/s	600mm*470mm*85mm	Sassea[32] Stark[33]
	Ring shear test		$\tau = \frac{3M}{2\pi\left[(\frac{d_0}{2})^3 - (\frac{d_i}{2})^3\right]}$ $\sigma_N = \frac{4F_N}{\pi(d_0^2 - d_i^2)}$	0.115°/s	100mm*50mm*40mm	Hammerich [34] Schmitt[35]

4. New Technology for Testing Shear Strength of Unsaturated Soil

4.1. Numerical Simulation Technology

With the continuous development of computer numerical simulation technology, numerical simulation technology has opened a door for predicting the shear strength of unsaturated soil and the deformation and instability of soil mass to solve the problem of "parameter assigning" and "modeling". Scholars in the industry have done a lot of research work. The author has tried to analyze the advantages and disadvantages of different numerical simulation methods in simulating soil deformation and failure, as shown in Table 3.

To solve the shear failure problem of unsaturated soil, particle flow numerical simulation of PFC can simulate its failure characteristics from a microscopic point of view, and accurately determine its macro parameters through the microscopic parameters of the parallel bond model, which can truly realize the soil failure analysis, and is of great significance to solve the practical problems of unsaturated soil engineering.

Shi et al. [9] constructed a hollow cylinder torsion device (HCA) by using discrete element method (DEM). As shown in Figure 4. In the test, the hollow cylindrical specimen is subjected to axial force, torque, internal pressure and external pressure. By independently controlling these four loads, the

testing machine can change four stress components, namely axial normal stress, circumferential normal stress, radial normal stress and shear stress. Conventional triaxial compression tests and complex stress path tests with torsion were carried out under different confining pressures. The results of numerical calculation are in agreement with those of laboratory and theoretical studies, which shows that the microscopic parameters of DEM pattern are correct and reasonable.

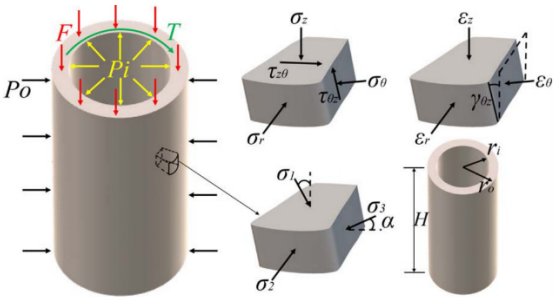


Fig 4. Distribution of load, stress and strain state of hollow cylinder [67]

Based on HCA DEM samples, macro and micro mechanical responses of soil samples under four typical unloading stress paths were studied, and the variation laws of strain energy density, strain energy and dissipated energy of soil samples were obtained, as shown in Figure 5. The research results can provide reference for the study of mechanical properties of unloaded sandstone in geotechnical engineering.

4.2. Unsaturated Ring Shear Test Device

In the shear test measurement of unsaturated soil, it can be seen from Section 2 that the shear strength of unsaturated soil can be measured by direct shear test or triaxial test, but for some soil slopes with obvious internal damage, certain failure surface has been formed inside, and the stability of slope can be ensured by residual strength [68]. Most studies on the residual strength focus on the direct shear test of saturated soil and the ring shear test of Bromhead et al. [69], while there are few domestic studies on the residual strength of unsaturated soil.

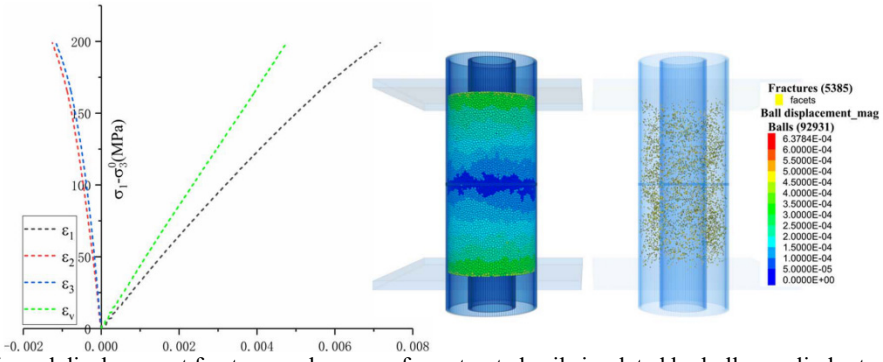


Fig 5. stress-strain and displacement fracture nephogram of unsaturated soil simulated by hollow cylinder torsion device [67]

Table 2. Summary of characteristics of unsaturated soil simulated by numerical simulation method

category	Numerical method	software	Damage treatment	Failure analysis	Block motion	Seepage analysis
Continuity method	FDM	$FLAC^{2D}$	√	√		√
		$FLAC^{3D}$	√	√		√
	FEM	ABAQUS	√			√
		RFPA		√		
Discontinuous method	DEM	PFC	√	√	√	√
		3DEC			√	
	FDEM	Y-GEO	√	√		

In foreign countries, Vaunat et al. and Suits et al added a suction control device to the traditional Bromhead ring shear apparatus to achieve the purpose of controlling the suction of unsaturated soil matrix through axial translation technology. Hoyos et al. developed an unsaturated soil ring shear instrument with automatic suction, which mainly consisted of suction control system, ring shear head, and data recording equipment, as shown in Figure 7. Hoyos et al. obtained the conclusion that the residual stress of SM soil sample increased linearly with the increase of matric suction, as shown in FIG. 8a, while that of SC-SM soil sample showed a nonlinear change, as shown in FIG. 8b. The multi-stage ring shear test proves that the residual strength of soil is independent of the pre-shear process and suction history.

4.3. Large In-situ Unsaturated Soil Shear Test Device

Lv et al. proposed a new method for testing the shear strength of unsaturated soil -- in-situ borehole compression shear test method, aiming at the problems and limitations of conventional methods for testing the shear strength of unsaturated soil. The test method is fast, simple and accurate. According to the principle of drilling and shearing technology, the mechanical model and mathematical model are established. This method and the in-situ direct shear method are applied to test the shear strength of similar soil-rock mixtures, and the test results are compared and analyzed. The results of this study help enable a simple and inexpensive test to determine the shear strength of unsaturated soils.

The test equipment includes probe, hydraulic jack, steel barrel, steel frame, pressure sensor, displacement sensor, dynamic data display device, data storage device and computer, as shown in Figure 6. The specially developed probe is the main equipment and consists of drill pipe, shear plate and airbag. The drill pipe is 50 mm in diameter and 1500 mm in length. The shear plate is 250mm in diameter and 50mm in height. The airbag has a height of 150mm and a diameter of 300mm. The maximum atmospheric pressure provided by the airbag is 2 MPa. The drum has a diameter of 650 mm and a height of 800 mm. Use Tanton hydraulic jack

to lift probe.

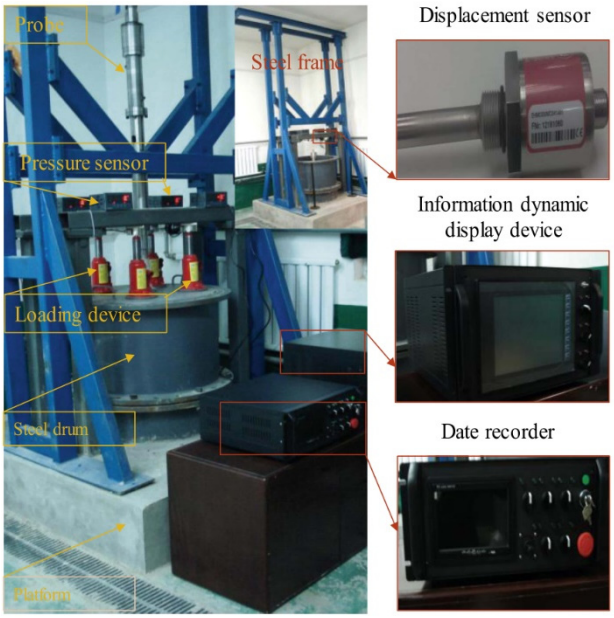


Fig 6. Main instruments of in-situ borehole pressure shear test [75]

5. Conclusion

(1) By studying the relationship between shear strength and moisture content of unsaturated soil, summarizing and analyzing the previous methods for preparing soil samples with different moisture content, it is found that there is a test phenomenon of "critical moisture content" in the specific gravity method, and the research shows that the shear strength of unsaturated soil is the result of the joint action of compaction degree and moisture content.

(2) A variety of new ideas and methods for studying the shear strength theory of unsaturated soil are introduced, and it is pointed out that the research of unsaturated soil ring shear instrument is still in the development stage in China, and numerical simulation technology will be the development trend of unsaturated soil research in the future. This paper improves the theoretical basis of unsaturated soil and is of great significance for accelerating the engineering practice of the shear strength theory of unsaturated soil.

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