



# Study on Shear Strength Tests and Failure Process for Soils Under Different Moisture Content

Gaofeng Chen<sup>1,2,\*</sup>, Xiqi Liu<sup>1,2</sup>, Chenyuan Zhang<sup>3</sup>

<sup>1</sup>Pearl River Water Resources Research Institute, Guangzhou 510611, China;

<sup>2</sup>Key Laboratory of Water Security Guarantee in Guangdong-Hong Kong-Marco Greater Bay Area of Ministry of Water Resources, Foshan 528244, China;

<sup>3</sup>School of Civil Engineering, University of South China, Hengyang 421001, China.

\*863225578@qq.com

**Abstract.** In the field of geotechnical engineering, the relationship between the shear strength and water content of soil has always been regarded as the key and difficult issue in research. This paper investigates unconsolidated undrained rapid shear tests on saturated-unsaturated remolded soil samples, covering a range of moisture content gradients (1.1%, 10.1%, 14.9%, 19.9%, 24.2%, 29.9%, 37.7%) and normal stress levels (50kPa, 100kPa, 200kPa, 300kPa, 400kPa respectively). All tests were completed utilizing a revised SDJ-1 strain-type direct shear device and the NI Lab VIEW data acquisition system from the United States. Analysis of the test data indicates that total cohesion exhibits an initial increasing followed by a decreasing trend with rising moisture content, while the total internal friction angle shows an increasing trend when moisture content decreases. The contribution of anelasticity, cohesion and matrix suction for shear strength under various moisture contents and conventional normal stresses was analysed. The failure process of saturated-unsaturated soils was disclosed.

**Keywords:** soil; shear strength; moisture content; failure process

## 1 Introduction

Extensive engineering practices and experimental results demonstrate that for the same soil type, the influence of moisture content and stress conditions on shear strength is significant. The relationship between soil shear strength and moisture content remains a primary research topic and challenge in geotechnical engineering<sup>[1-11]</sup>. Current studies indicate that this relationship is highly complex, with no consensus yet reached.

Current theories on the shear strength of unsaturated soils all require the measurement of matrix suction. However, such measurements are often complex and difficult to obtain. For practical production units, the lack of adequate equipment and technical expertise, coupled with lengthy testing periods, makes these methods impractical. Consequently, most existing formulas for unsaturated soil strength are of theoretical value

and rarely applied in practice. For this reason, it is practically important for geotechnical engineering to establish a simple and fast approach that can obtain the shear strength parameters of soil at various moisture content levels<sup>[12]</sup>.

In this study, the improved SDJ-1 direct shear apparatus is adopted to perform quick shear experiments on remolded soil samples with varying water contents under different normal stress conditions. After completing the tests, this paper analyzes how frictional strength, cohesion and matrix suction jointly influence soil shear strength under different moisture content and normal stress conditions. In addition, the failure processes of fully dry, unsaturated soils are and saturated discussed from a microscopic perspective.

## 2 Soil Shear Strength Test at Different Moisture Content

### 2.1 Test Materials

The original soil for the experiment was collected from a landslide, exhibiting a yellowish color. It was dried and crushed in the laboratory, then sieved through a 2mm sieve, with the fine particles selected for this study. Through conventional geotechnical tests, the basic physical properties of the soil used in the experiment are presented in Table 1.

**Table 1.** Summary of Soil Physical Indicators

| specimen no-<br>menclature | Proportion<br>(g/cm <sup>3</sup> ) | liquid limit<br>$w_L$ (%) | plastic limit<br>$w_p$ (%) | sand content<br>(%) | Granule con-<br>tent<br>(%) | clay content<br>(%) |
|----------------------------|------------------------------------|---------------------------|----------------------------|---------------------|-----------------------------|---------------------|
| silt                       | 2.727                              | 51.0                      | 26.0                       | 34.7                | 52.5                        | 12.8                |

### 2.2 Test Equipment

The test apparatus adopted in this experiment is the SDJ-1 strain-controlled direct shear device manufactured by Nanjing Soil Instrument Factory. This strain-controlled direct shear device is currently the most commonly utilized direct shear test instrument in geotechnical engineering labs, featuring merits of straightforward operation and consistent performance. Per the geotechnical test standard, the shear rate is set at 0.8mm/min for this experiment, as shows Fig 1 and Fig 2.

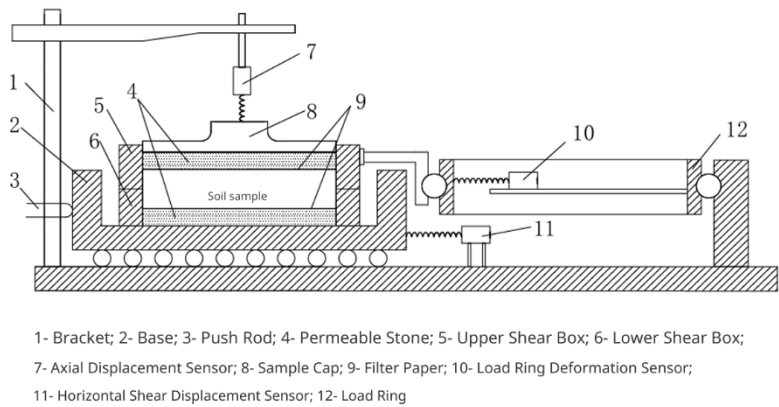


Fig. 1. Schematic diagram of improved direct shear tester

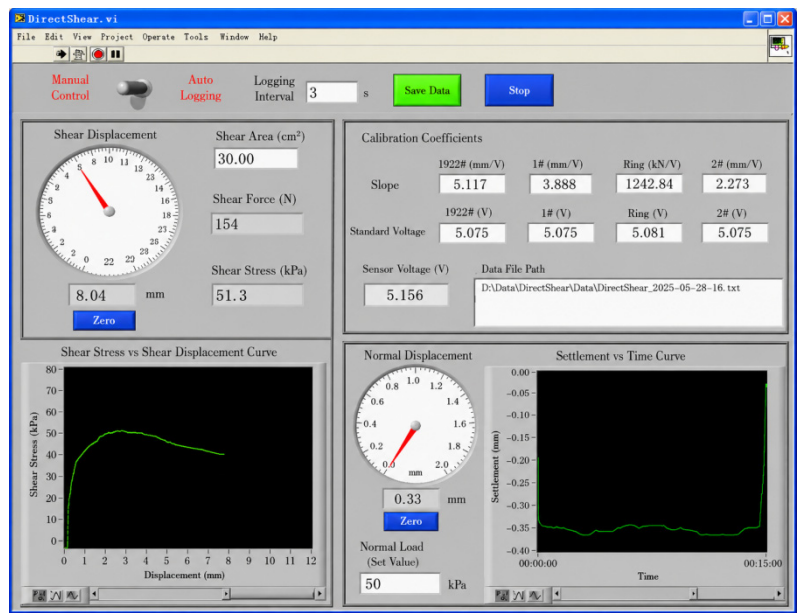


Fig. 2. Control interface of Lab VIEW data acquisition system in the United States

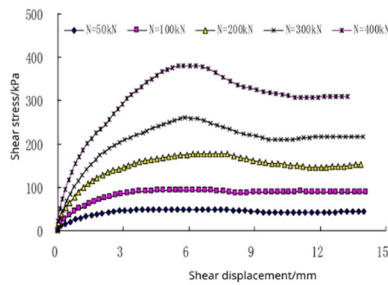
### 2.3 Experimental Design

Seven remolded soil samples with water contents of 0%,10%,15%,20%,25%,30%, and saturated were prepared and subjected to undrained-undrained fast shear tests at various normal stress levels (50kPa, 100kPa, 200kPa, 300kPa, 400kPa). The specimens, measuring 6.18cm in diameter and 2cm in height, were fabricated strictly in accordance with

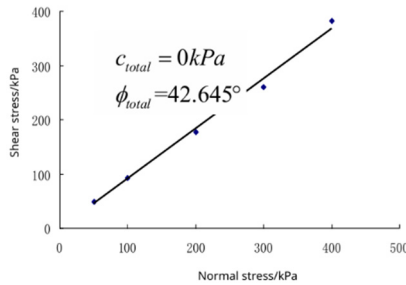
the "Geotechnical Test Specification SL237-1999". To ensure comparability across different moisture contents, all specimens were uniformly controlled at a dry density of  $1.34 \text{ g/cm}^3$  during preparation. After mixing, the samples were sealed in double-layer plastic bags and left undisturbed for 24 hours. Prior to sample preparation, the measured water contents were: 1.1%, 10.1%, 14.9%, 19.9%, 24.2%, 29.9%, and 37.7% respectively, which closely matched the originally designed moisture content.

## 2.4 Test Results

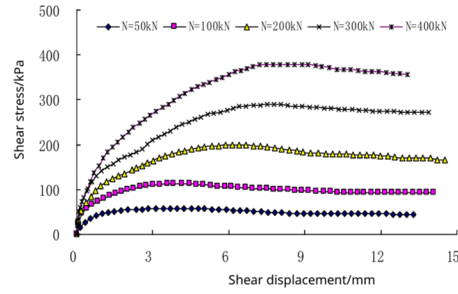
Plots of the shear stress versus shear displacement, along with the corresponding shear strength envelopes from representative shear strength tests, are presented in Fig. 3 to Fig. 12.



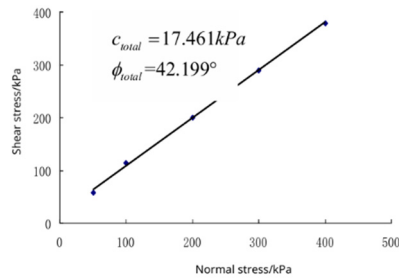
**Fig. 3.** Shear stress-displacement curve( $w=1.1\%$ )



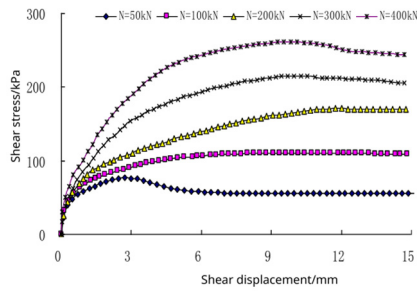
**Fig. 4.** Shear strength envelope( $w=1.1\%$ )



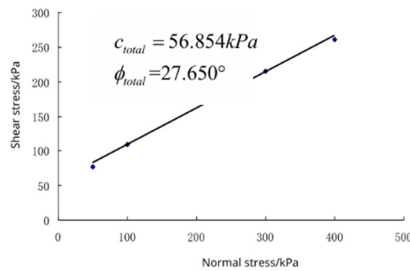
**Fig. 5.** Shear stress-displacement curve ( $w=10.1\%$ )



**Fig. 6.** Shear strength envelope ( $w=10.1\%$ )



**Fig. 7.** Shear stress-displacement curve ( $w=19.9\%$ )



**Fig. 8.** Shear strength envelope ( $w=19.9\%$ )

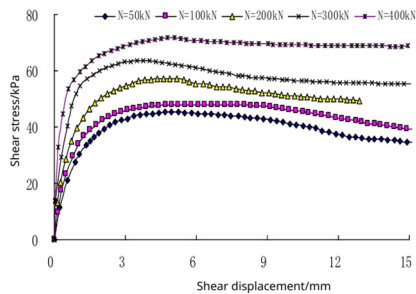


Fig. 9. Shear stress-displacement curve (w=29.9%)

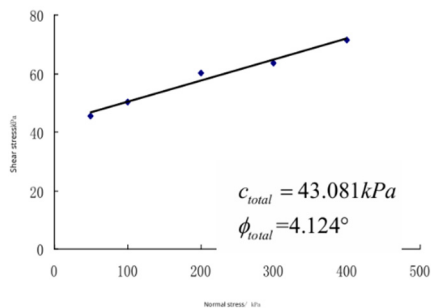


Fig. 10. Shear strength envelope line (w=29.9%)

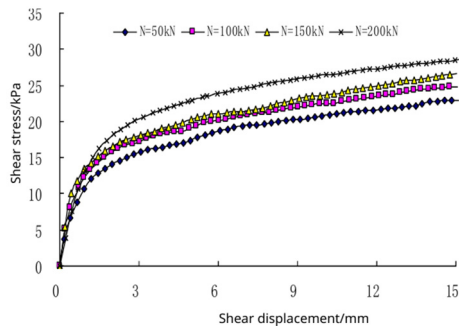


Fig. 11. Shear stress-displacement curve (w=37.7%)

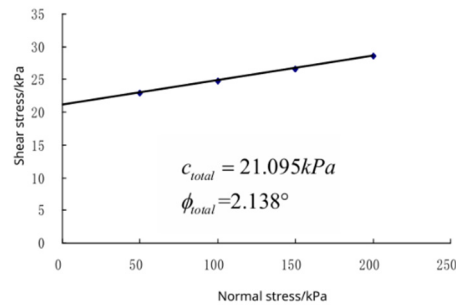


Fig. 12. Shear strength envelope (w=37.7%)

3 Analysis of Test Results

3.1 Shear Strength Parameter

Following the framework of Mohr-Coulomb theory, if the suction strength term is not included in the derivation, the shear strength equation takes the form:

$$\tau_f = c_{total} + \sigma \tan \phi_{total} \tag{1}$$

In the formula,  $c_{total}$  denotes the total cohesive force, while  $\phi_{total}$  represents the total friction angle.

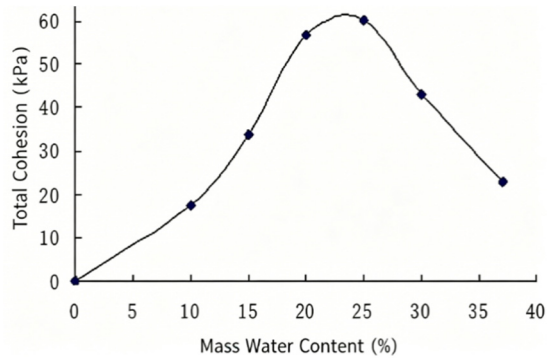
Table 2 lists the shear strength parameters obtained from soil samples with different moisture contents.

Table 2. Summary of Shear Strength Parameters

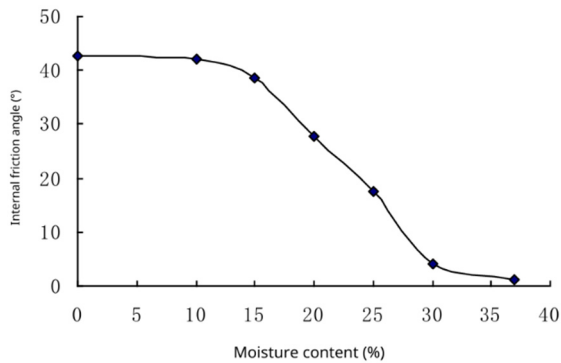
| rate of water content (%) | 1.1  | 10.1 | 14.9 | 19.9 | 24.2 | 29.9 | 37.7 |
|---------------------------|------|------|------|------|------|------|------|
| $C_{total}(\text{kPa})$   | 0.0  | 17.5 | 33.7 | 56.9 | 60.3 | 43.1 | 21.1 |
| $\phi_{total}(^\circ)$    | 42.6 | 42.2 | 38.5 | 27.7 | 17.5 | 4.1  | 2.1  |

3.2 Relationship between shear strength parameters and moisture content

The correlations between total cohesion, total internal friction angle and water content can be found in Fig. 13 and Fig. 14.



**Fig. 13.** Relationship between total cohesion and moisture content



**Fig. 14.** Variation of shear strength parameters with moisture content

As moisture content climbs, the value of  $C_{total}$  first goes up before starting to decline. In contrast, the total friction coefficient ( $\phi_{total}$ ) shows a steady downward trend as moisture content grows, while the total friction coefficient ( $\phi_{total}$ ) decreases with increasing moisture. When the soil sample is dry,  $C_{total}$  equals zero, and  $\phi_{total}$  reaches its maximum value of 42.6. At this stage, the soil exhibits shear mechanical properties similar to sandy soil, with strength entirely derived from friction between particles at the shear plane. When the soil is fully saturated,  $\phi_{total}$  approaches zero, and shear strength is primarily attributed to  $C_{total}$ . At approximately 25% moisture content,  $C_{total}$  peaks, which further indicates an inflection point on the correlation curve between internal friction angle and water content. Thus, 25% is considered the characteristic moisture content for the test soil sample.

#### 4 Analysis of Soil Mass Destruction Process

The shear failure process of soil can be analyzed as follows:

#### **4.1 Analysis of the Disintegration Process of the Fully Dry Soil Sample (Sand Sample)**

When a soil sample is fully dried (sand), its shear strength primarily derives from frictional forces, specifically the sliding and interlocking friction between solid particles. As shear displacement increases, soil particles undergo rolling, sliding, and reorientation. Some particles fracture and yield due to excessive contact stress. These processes of particle fragmentation and reorientation require additional external work, thereby increasing shear strength and elevating the soil's internal friction angle, ultimately reaching peak shear stress. With further shear displacement, particle fragmentation and reorientation become nearly complete, eliminating the need for additional external work, and shear stress gradually decreases to a constant value. The shear failure process under different normal stresses is fundamentally similar, with the key difference being that higher normal stresses lead to greater particle fragmentation and reorientation, requiring more external work and consequently resulting in higher peak shear stress. For sand, the effective area of matrix suction is minimal, resulting in negligible equivalent matrix suction and insignificant suction intensity.

#### **4.2 Analysis of the failure process of unsaturated soil samples**

When the soil is in the state of non-saturation (not completely dry), the cementation body is formed between the soil particles. The strength of the soil is composed of cohesion, internal friction angle and equivalent matrix suction.

(1) During soil sample shearing, when the moisture content is low, the system must perform work to overcome two key forces: the cohesive force of inter-particle bonds and the additional work required for particle fragmentation and reorientation. Simultaneously, it must also overcome the matrix suction caused by capillary action. As the shear displacement increases, the inter-particle bonds gradually break down, and the fragmentation and reorientation of particles stabilize, reaching maximum shear stress. With further displacement, the cohesive force becomes increasingly ineffective, and the shear strength primarily derives from the sliding friction between solid particles and the matrix suction.

(2) As the moisture content increases, both the effective area of the cemented mass and the matrix suction area expand. When sufficient pressure is applied, some coarse soil particles undergo interlocking, at which point the shear strength provided by cohesion reaches its maximum value (corresponding to the total cohesion at 25% moisture content in Figure 13). Prior to the shear stress peak, cohesion dominates the shear strength.

(3) With the increase of water content, the cementation force of cementation body is smaller and smaller, the matrix suction is smaller, some organic matter meets with water to have chemical reaction (such as dissolution hydration), the pore water pressure bears part of the compressive stress, and the shear strength is reduced rapidly.

### 4.3 Analysis of the failure process of saturated soil sample

When the soil sample is fully saturated, the pressure is almost entirely borne by the pore water pressure, and the effective stress in the friction strength  $\sigma \tan \phi_{total}$  is nearly zero. Consequently, the internal friction angle in the shear strength index becomes minimal. Meanwhile, the matrix suction also drops to zero, and the dissolution hydration process reaches its peak. At this stage, the shear strength is primarily provided by cohesion.

## 5 Conclusion

(1) Using an improved SDJ-1 strain-controlled direct shear apparatus alongside the Lab VIEW data acquisition system, the shear stress-displacement curves for unconsolidated undrained quick shear tests were acquired.

(2) The total cohesion and total internal friction angle of the soil sample were obtained based on Mohr-Coulomb strength theory. The total cohesion increased first and then decreased with the increase of water content, and the total internal friction angle decreased with the increase of water content.

(3) This paper analyzes the different contributions of frictional strength, cohesive force and matrix suction to shear strength under different stress conditions and normal moisture content, and explores the shear failure process of soil samples with different moisture content from a micro perspective.

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