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Direct Shear Test of Unsaturated Soil

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ABSTRACT

The present study focuses on some experimental laboratory tests using a newly-constructed modified direct shear test apparatus. The single-stage and multistage direct shear tests were performed to determine the shear rate and test scheme of the unsaturated shear test. Shear strength parameters of unsaturated soil in different conditions are obtained, and the criteria indicate good agreement with standard theories of unsaturated soil. The nonlinear matric suction failure envelope is determined. Some shear strength equations are also fitted through the experimental results.

Keywords: Unsaturated soil; direct shear test; matric suction

Ensayo de Cizallamiento Directo en Suelos no Saturados

RESUMEN

El presente estudio se basa en varias pruebas de laboratorio montadas en una máquina de experimentos recientemente construida y modificada para este objetivo. Se realizaron las pruebas monofase y multifase de cizallamiento para determinar el punto de corte y el modelo de cizallamiento no saturado. De esta manera se obtuvieron los parámetros de cizallamiento de suelos no saturados bajo diferentes condiciones y los resultados coincidieron con las teorías evaluadas en esta materia. También se determinó la curva de corte para la succión matricial no lineal. Algunas ecuaciones de fuerza de cizallamiento también encajan en los resultados experimentales.

Palabras clave: Suelos no saturados; cizallamiento directo; succión matricial.

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Introduction

Expansive soil mostly spreads in arid, and semi-arid areas, and it has been found in more than 40 countries (Fredlund, 1993), including 20 regions of China. In addition to the unsaturated state most expansive soil always been in practical application, the study on mechanical properties of expansion soil in the unsaturated state is of great significance (Lee, 2010; Abbasi et al., 2017).

Unsaturated soil test features time consuming and expensive in general, mainly due to the low permeability of the unsaturated soil and high air-entry ceramic disc (even though it is permeable but airproof). Test samples in triaxial tests are relatively bigger (39.1 mm diameter, 80 mm thickness; 50 mm diameter, 100 mm thickness and 70 mm diameter, 140 mm thicknesses). Thus, determining the matric suction requires much more time; comparatively time associated with shear strength testing of unsaturated soils is significantly reduced from the smaller size of test samples, generally 61.8 mm diameter, 20 mm thickness (Bishop et al., 1960; Bishop et al., 1963; Ali et al., 2017; Anjum et al., 2017).

Method

Experimental procedures

The newly-constructed modified direct shear test apparatus

The conventional direct shear apparatus has been modified, and now it can control the pore air pressure ua and pore water pressure uw. The direct shear box is placed in a sealed pressure chamber; its internal structure is presented in Figure 1.

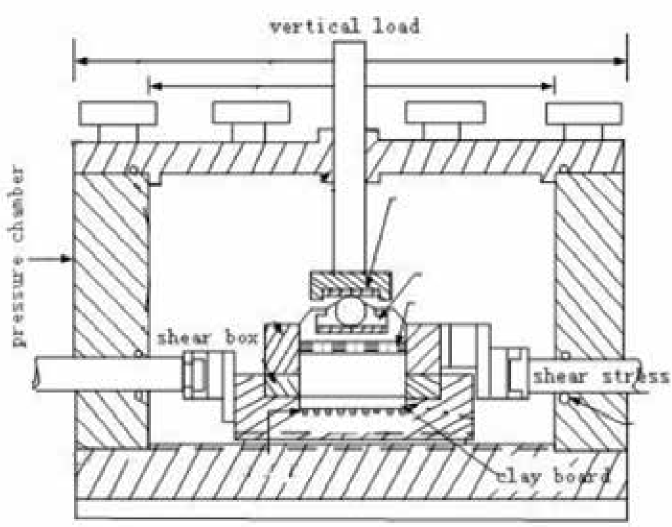


Figure 1. Schematic diagram of the modified direct shear test apparatus.

As shown in Figure 1, the soil specimen is placed in a high air-entry ceramic disc with a porous-permeable stone on top. The pore air pressure ua can be controlled by adjusting the air pressure in the pressure chamber, and the air pressure can be directly added to the porous-permeable stone (Yasin et al., 2017; Shazad et al., 2017). The pore water pressure u_w can be controlled by the high air-entry ceramic disc which is placed at the bottom of the soil specimen to provide continuity of the water phase in the soil specimen and under the ceramic disc (Basarian and Tahir, 2017). Nevertheless, with the test time passed by, the air in soil pore may diffuse into the bottom of the high air-entry ceramic disc with the water flow and generated bubbles. The flushing device is placed at the bottom of the test apparatus to exhaust the air under ceramic disc which can speed up the testing process efficiently. The overall test system is controlled by a computer recording the shear strength, horizontal displacement, vertical displacement and water phase inlet and outlet.

Test soil samples

The study is conducted using undisturbed expansive soils from Yuzhou, middle of Henan, China, and the clay mineral mainly consists of calcium montmorillonite (Harith and Adnan, 2017). Before testing, soil sample of 25% moisture is dispensed and placed in the moist chamber for 24 hours to permit uniform distribution of water, and then expansive soil specimens in different dry density conditions are created by being extruded from lifting jack and using a cutting ring. The diameter and height of the example are 61.8 mm and 20 mm, respectively. The sample is placed in the moist chamber for spare after being pumped and saturated.

Laboratory test

Shear rate determination

Shear rate determination is a crucial problem that directly affects the time and results associated with the shear strength testing of unsaturated soils. In the consolidated undrained shear test, it takes some time for pore water pressure of the soil transferred to the specimen bottom through the specimen or filter paper (Rahman et al., 2017; Simon et al., 2017). If the shear rate is too high, pore water pressure will not dissipate completely, values of pore water pressure measured at the bottom of the sample will perform lagging, and useful stress parameters cannot be obtained, which apparently makes numerical value measured low. Thus, the shear rate should be determined appropriately according to the soil permeability coefficient (FredLund et al., 1997; Ismail et al., 2017).

Several single-stage direct shear tests were carried out at four shear rates on modified apparatus as experimental tests by maintaining a constant the net normal stress, considering the effect of shear rate on test results. The test detail and results are presented in Table 1 and Figure 2.

Table 1. Tentative experiment scheme for determining test shear rate.

Soil property	Soil type	Shear rate (mm/min))
	S1	0.8
Saturation condition When dry density is 1.6 g/cm³ When the net vertical pressure is 200 kPa	S2	0.15
	S3	0.012
	S4	0.0075

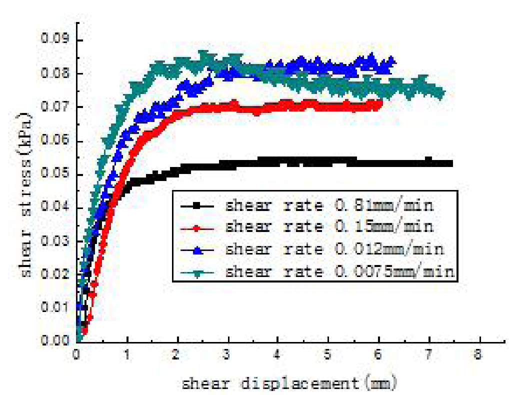


Figure 2. Results of shear displacement and shear stress in different shear rates.

As the test results showed, the ultra pore water pressure can dissipate, peak shear stress can remain stable when the shear rate is controlled by 0.012 mm/min. Thus, 0.012 mm/min is proposed as the standard shear rate in the entire test.

Single-stage shear test of unsaturated soil

The loading steps of the matric suction for the single-stage tests were 0 kPa, 50 kPa, 100 kPa, 200 kPa; under different matrix suctions, the vertical stress measures were 100 kPa, 200 kPa, 300 kPa. Table 2 summarizes the single-stage direct shear test scheme of expansive unsaturated soil.

Table 2. The single-stage direct shear test scheme of expansive unsaturated soil.

Dry density ρ_d (g/cm³)	Pore air pressure (kPa)	Pore water pressure (kPa)	Net vertical pressure (kPa)
		0	100
	0	0	200
		0	300
		0	100
	50	0	200
		0	300
1.40, 1.50, 1.60, 1.70		0	100
	100	0	200
		0	300
		0	100
	200	0	200
		0	300

Twenty samples of same dry density were prepared once a time and placed in the moist chamber after being pumped and saturated to eliminate the effects on test results from sample preparation. Each time the sample was transferred to direct shear apparatus and applied predetermined air pressure until the suction arrived at equilibrium (generally last 12 hours), then the vertical load was applied (maintaining for 12 hours) with keeping the air pressure and vertical stress constant and then be sheared. The shear rate was determined to 0.012 mm/min. Terminated shear displacement was set to 6 mm and 9 - 10 hours. It was needed to guarantee that the peak strength was not surpassed.

Results and discussion

(a) Single-stage direct shear test results of unsaturated soil in dry density of 1.4 g/mm³

The effects of shear displacement and shear stress in different matric suction and vertical pressure are presented in Figure 3.

Table 3. Single-stage direct shear stress parameters of expansive unsaturated soil in the dry density of 1.4 g/mm³.

Matric suction (kPa)	Net vertical pressure (kPa)	Peak shear stress (kPa)	Cohesion (kPa)	Internal friction angle (°)
	100	36		
0	200	73	5.00	Arctan (0.325) = 18.01
	300	101		
	100	52		
50	200	83	18.33	Arctan (0.33) = 18.27
	300	118		
	100	65		
100	200	101	31.00	Arctan (0.345) = 19.04
	300	134		
	100	74		
200	200	118	36.67	Arctan (0.39) = 21.31
	300	152		

It can be summarized from Figure 3 that shear strength of soil sample increased with the rise in vertical pressure and matric suction. Under different matric suctions, the peak shear stress was chosen as failure shear stress if the displacement didn't arrive 4 mm; if exceeded, it should be 4 mm. Shear stress under different matric suctions, and vertical pressure concluded from Figure 3 are presented in Table 3.

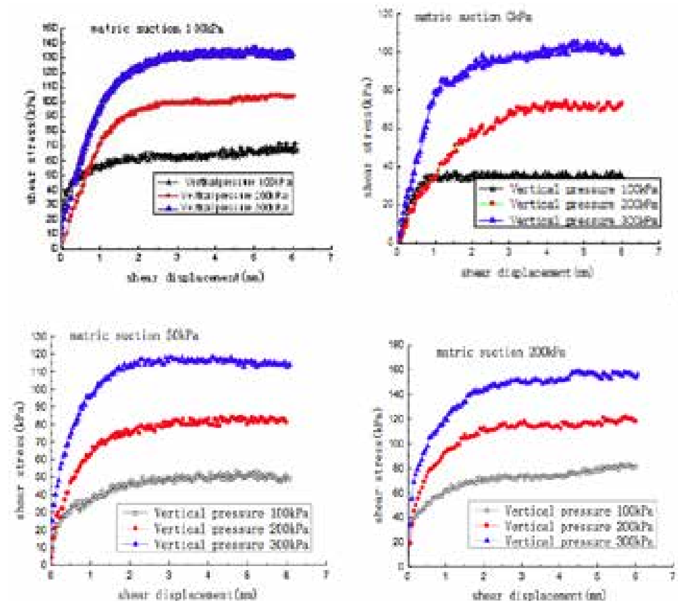


Figure 3. The results of shear displacement and shear stress (ρd = 1.4 g/cm³)

(b) Single-level direct shear test data of unsaturated soil in dry density of 1.5g/mm³

Figure 4 presents relationships between shear displacement and shear stress in different matric suctions and net vertical pressure.

Table 4. Single-stage direct shear test stress parameters of expansive unsaturated soil in a dry density of 1.5 g/mm³

Matric suction (kPa)	Net vertical pressure (kPa)	Peak shear stress (kPa)	Cohesion (kPa)	Internal friction angle (°)
	100	37		
0	200	76	6.00	Arctan (0.33) = 18.27
	300	103		
	100	54		
50	200	86	20.00	Arctan (0.335) = 18.53
	300	121		
	100	67		
100	200	104	32.66	Arctan (0.35) = 19.30
	300	137		
	100	78		
200	200	119	40.67	Arctan (0.395) = 21.56
	300	160		

It can be summarized from Figure 4 that shear stress of soil sample increased with the rising of vertical stress and matric suction. Table 4 shows the single-stage direct shear test strength parameters under different matric suctions.

From Table 4 and Figure 4 it can be summarized that shear stress increase with the rising of net vertical pressure and matric suction. Cohesion value c increased sharply with the rising of net vertical pressure, which can mean that the increase of vertical force has a significant effect on cohesion enhancements; while, the internal friction angle under vertical pressure changed little.

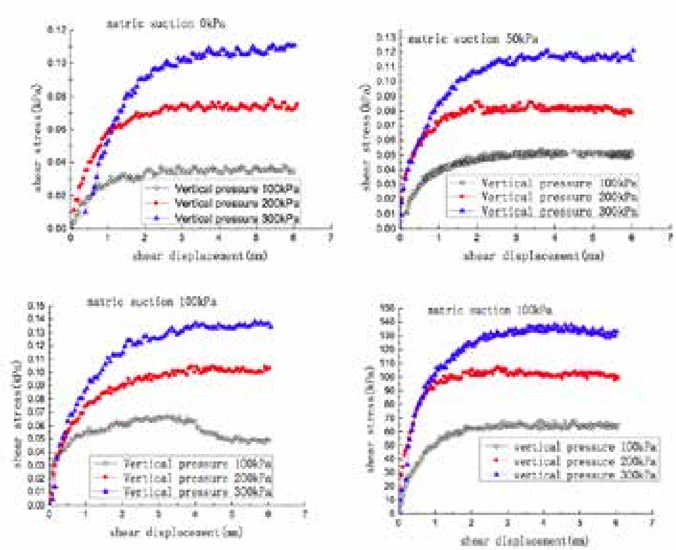


Figure 4. Results of shear displacement and shear stress (ρd = 1.5 g/cm^3)

(c) Single-stage direct shear test results of unsaturated soil in dry density of 1.6 g/mm^3

Figure 5 presents the results of shear displacement and shear stress under different matric suctions and vertical pressure.

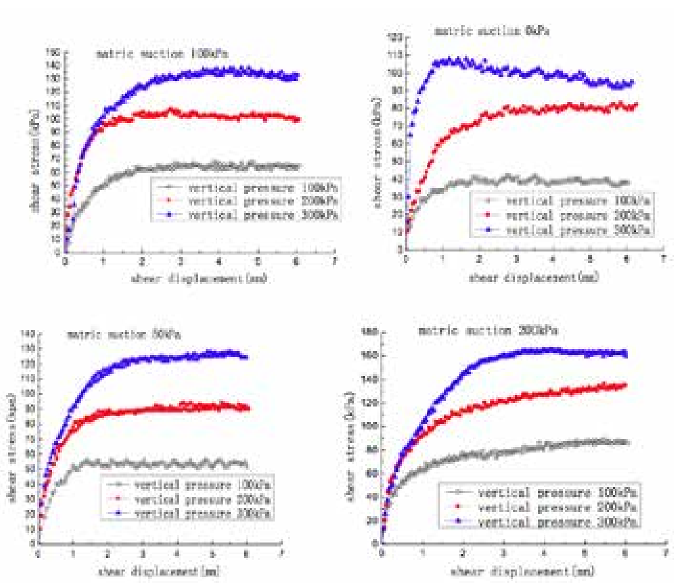


Figure 5. Results of shear displacement and shear stress (ρd = 1.6 g/cm^3).

It can be summarized from Figure 5 that soil shear stress increased with the rising of vertical pressure and matric suction. Under different matric suctions, the peak shear stress was chosen as failure shear stress if the displacement didn't reach 4mm; if exceeded, it should be 4mm. Shear stress under different matric suctions, and vertical pressure concluded from Figure 5 are presented in Table 5.

Table 5. Single-stage direct shear test stress parameters of expansive unsaturated soil in a dry density of 1.6 g/mm^3**.**

Matric suction (kPa)	Net vertical pressure(kPa)	Peak shear strength (kPa)	Cohesion (kPa)	Internal friction angle (°)
	100	42		
0	200	81	11.00	18.27
	300	108		
	100	56		
50	200	92	22.67	18.79
	300	124		
	100	68		
100	200	107	35.00	19.554
	300	139		
	100	83		
200	200	127	43.00	22.30
	300	165		

(d) Single-stage direct shear test results of unsaturated soil in dry density of 1.7 g/mm^3

Figure 6 presents results of shear displacement and shear stress in a dry density of 1.7 g/mm^3 under different matrix suctions and vertical pressure.

Figure 6 allows determining that shear stress of soil samples continuously increased with the rising of matric suction and vertical pressure. Shear strength parameters under different matric suction are presented in Table 6.

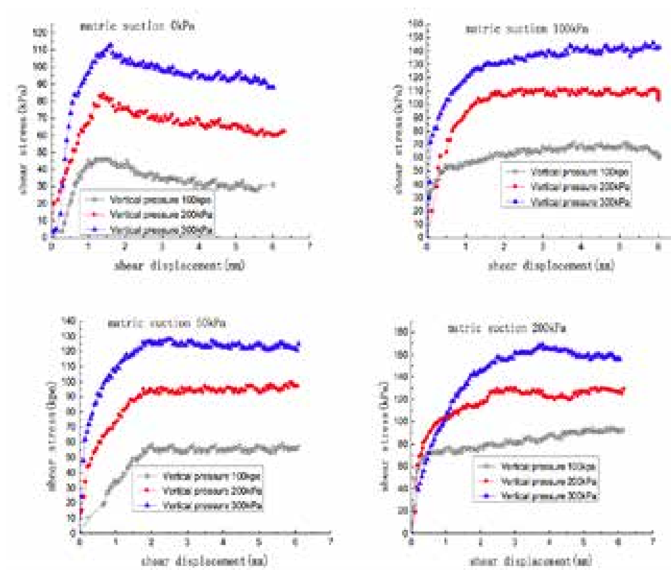


Figure 6. Results of shear displacement and shear stress (ρd=1.7g/cm^3).

Table 6. Single-stage direct shear test stress parameters of expansive unsaturated soil in a dry density of 1.7 g/mm^3**.**

Matric suction (kPa)	Net vertical pressure (kPa)	Peak shear strength (kPa)	Cohesion (kPa)	Internal friction angle (°)
	100	46		
0	200	84	14.00	18.53
	300	113		
	100	58		
50	200	97	24.33	19.30
	300	128		
	100	70		
100	200	111	35.00	20.00
	300	143		
	100	87		
200	200	131	45.00	23.06
	300	172		

Results analysis

Shear strength parameters of four dry density specimens under different matric suction and vertical pressure are listed in Table 7

Table 7. Direct shear test stress parameters of unsaturated soil.

(a) Effects on shear strength parameters from matric suction

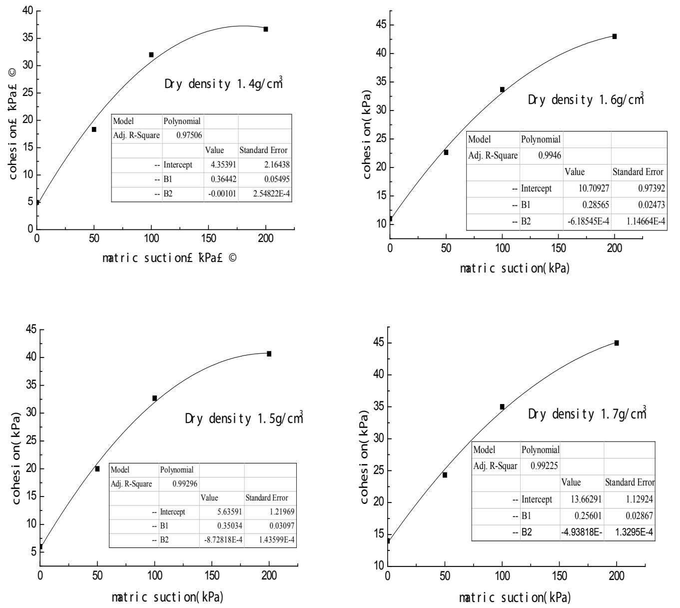


Figure 7. Results of cohesion and matric suction in different dry density conditions.

The experimental results are represented by a equation including cohesion, internal friction angle and matric suction

$$c = a_1 + a_2 * S + a_3 * S^2 \quad (1)$$

$$\varnothing = \exp(b_1 + b_2 * S + b_3 * S^2) \quad (2)$$

Where $S =$ matric suction, $c =$ cohesion and $\varnothing =$ internal friction angle, $a_1, a_2, b_1, b_2, b_3 =$ fitting parameters. Fitting curves in different dry density conditions are presented in Figure 7 and 8; parameters are listed in Table 8.

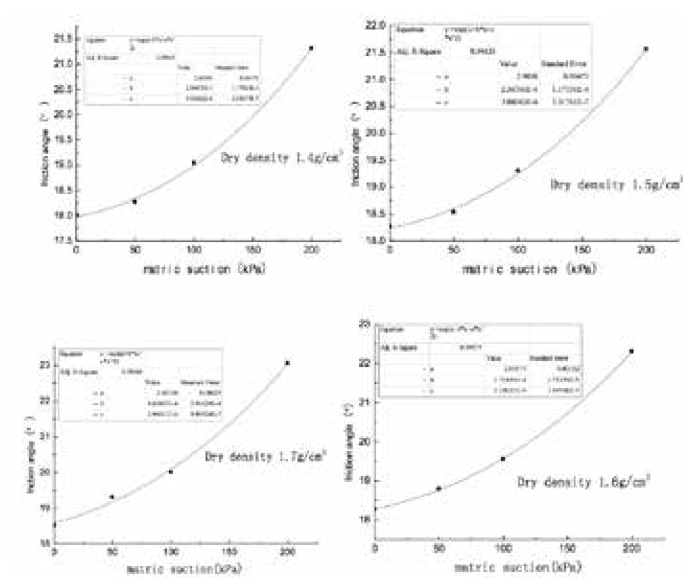


Figure 8. Results of internal friction angle and matric suction in different dry density conditions.

Table 8. Fitting parameters.

Dry density (g/cm³)	fitting parameters related to cohesion				fitting parameters related to internal friction angle			
	a_1	a_2	a_3 (10^{-4})	R	b_1	b_2 (10^{-4})	b_3 (10^{-4})	R
1.4	4.3539	0.3644	-10	0.985	2.8894	2.3867	3.0583	0.996
1.5	5.6359	0.3503	-8.7281	0.9929	2.9038	2.3676	3.0008	0.9963
1.6	10.7092	0.2856	-6.1854	0.9946	2.9057	3.7245	3.1063	0.9997
1.7	13.6629	0.2560	-4.9381	0.9922	2.9219	4.8580	2.9601	0.9934

(b). Effects of cohesion and internal friction angle from dry density

Values of fitting parameters in Table 9 are known parameters. Consider the effect on fitting parameters from dry density, fitting curves and parameters are presented in Figure 9.

Table 9. Parameters fitted by polynomials.

	Related to a_1	Related to a_2	Related to a_3	Related to b_1	Related to b_2
first parameter	i_1 = 57.3204	j_1 = 0.0112	k_1 = - 0.0043	l_1 = 2.8645	m_1 = 0.0058
Second parameter	i_2 = - 96.5517	j_2 = 0.8160	k_2 = 0.0028	l_2 = - 0.0477	m_2 = - 0.0080
Third parameter	i_3 = 41.791	j_3 = - 0.389	k_3 = - 0.00031	l_3 = 0.0475	m_3 = 0.0029
The fitting coefficient R	0.9079	0.8629	0.9449	0.7988	0.9109

Fitting formulas (3) ~ (7) are presented below; fitting coefficients are listed in Table 9.

$$a_1 = i_1 + i_2 * \rho_d + i_3 * \rho_d^2 \quad (3)$$

$$a_2 = j_1 + j_2 * \rho_d + j_3 * \rho_d^2 \quad (4)$$

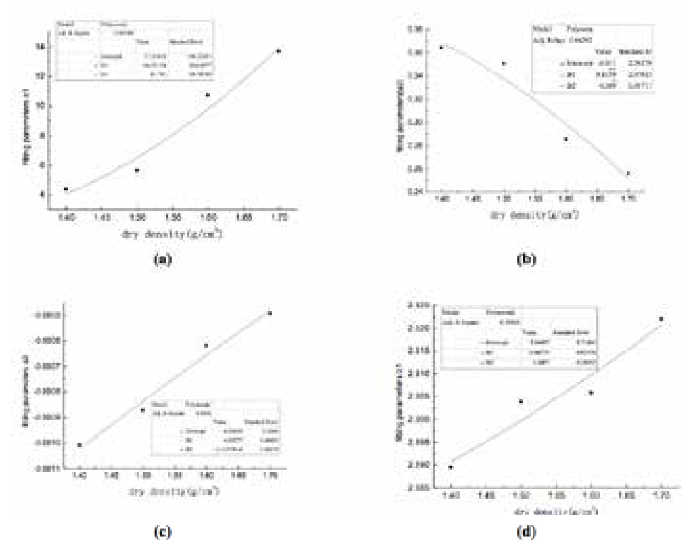
$$a_3 = k_1 + k_2 * \rho_d + k_3 * \rho_d^2 \quad (5)$$

$$b_1 = l_1 + l_2 * \rho_d + l_3 * \rho_d^2 \quad (6)$$

$$b_2 = m_1 + m_2 * \rho_d + m_3 * \rho_d^2 \quad (7)$$

$$c = i_1 + i_2 * \rho_d + i_3 * \rho_d^2 + (j_1 + j_2 * \rho_d + j_3 * \rho_d^2) * S + (k_1 + k_2 * \rho_d + k_3 * \rho_d^2) * S^2 \quad (8)$$

$$\varphi = \exp[l_1 + l_2 * \rho_d + l_3 * \rho_d^2 + (m_1 + m_2 * \rho_d + m_3 * \rho_d^2) * S + b_3 * S^2] \quad (9)$$



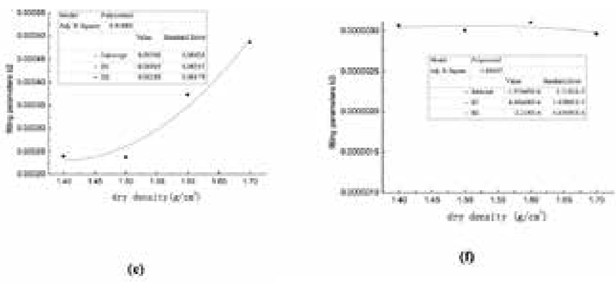


Figure 9. Relationship between dry density and fitting parameters
(a): a_1; (b): a_2; (c): a_3; (d): b_1; (e): b_2; (f): b_3.

Matric suction conditions can be calculated substituting (3) - (7) to (8) and (9), cohesion and internal friction angle in any dry density.

$$c = 57.32043 - 96.55174 * \rho_d + 41.791 * \rho_d^2 + (-0.01123 + 0.81598 * \rho_d - 0.389 * \rho_d^2) * S + [-0.00429 + 0.00277 * \rho_d - (3.11375E-4) * \rho_d^2] * S^2 \tag{10}$$

$$\phi = \exp[2.86455 - 0.04775 * \rho_d + 0.0475 * \rho_d^2 + (0.00586 - 0.00805 * \rho_d + 0.00288 * \rho_d^2) * S + (3.0E-6) * S^2] \tag{11}$$

Conclusions

Methods for unsaturated shear testing are more complicated, more time consuming and more expensive when compared to conventional test methods for saturated soils. An extensive investigation was carried out to study the validity of rapid procedures in obtaining shear strength parameters of saturated and unsaturated soils using the single-stage direct shear test. In this paper, the tests used a newly-constructed modified direct shear test apparatus that uses smaller samples and allows independent control of pore air pressure u_a and pore water pressure u_w. The shear strength was established using single-stage loading over a range of net normal stresses and matric suction values. The study was carried out using soil samples from the middle route of South-to-North Water Transfer Project in YuZhou section. The main conclusions from the study are presented as below:

(1) The tests to determine appropriate shear displacement rate was successfully applied before unsaturated direct shear tests. The results of experimental tests showed that 0.012 mm/min is the most suitable shear rate for the samples of Yuzhou.

(2) It was shown that efficiency of the direct shear test of unsaturated soil is higher compared with the conventional analysis. Because of this time-saving test method, it cost less time to get shear strength parameters of unsaturated soil under different conditions.

(3) Numerous parameters can be controlled in modified tests, from which we got shear strength parameters of unsaturated soil under different conditions; some classical theories about unsaturated soil are also verified. Also, the nonlinear failure envelope of matric suction was obtained.

(4) The test results confirmed the nonlinear interrelationship among the cohesion, internal friction and dry density, which can be used in some practical engineering about unsaturated soil as a kind of empirical formula.

(5) It was shown that the shear rate must be controlled within 0.012 mm/min to get reliable shear strengths parameters for unsaturated soil samples of Yuzhou. Thus, the test of determining appropriate shear displacement rate before the shear test is necessary. Thus, the recommendations are given excessively, it is essential to shear the soil sample beyond the peak shear stress to the strain softening region, and make sure that the samples are wholly consolidated at every new effective normal stress-stage.

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