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Direct Shear Test of Silty Clay Based on Corrected Calculating Model

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Abstract. Direct shear test is one of the common method to study the parameters of shear strength and shear strength of soil. However, the current standard of geotechnical test method does not consider the calculation error caused by the change of shear area during shear process. In this paper, the direct shear test corrected calculation model considering effective shear area is established. This model shows that the test values of shear stress and normal stress are lower than the corrected values with the decrease of effective shear area, and the errors between them will increase with the increase of relative shear displacement. The analysis of the direct shear test results of silty clay shows that the errors between the test and corrected shear stress values are also related to the normal stress. The errors will increase with the increase of the normal stress. The shear strength parameters after correction tends to decrease. The effect of the corrected model on the cohesion is more significant than internal friction angle, and the effect on internal friction angle can be neglected approximately. On the basis of Mohr-Coulomb criterion, a shear strength criterion based on the corrected calculation model is established, which can be used to calculate the true shear strength parameters more accurately.

1. Introduction

In the field of geotechnical engineering, the mechanical properties of soil, such as stress-strain relationship and shear strength parameters, are the important basis of engineering investigation, and also the key to the calculation of bearing capacity of foundation and subgrade. Therefore, how to quickly and accurately determine the mechanical properties of soil is of great significance to geotechnical engineering research.

Nowadays, there are many test methods to study the shear strength parameters of soil, such as triaxial test, unconfined compressive strength test, direct shear test and so on. Among them, the direct shear test



is easy to operate and calculate, and can quickly obtain the shear strength parameters of soil. Therefore, it is widely used in scientific research and engineering practice. However, the direct shear test itself has some shortcomings. For example, the traditional calculation method regards the shear area as a constant value (πr^2). Although it simplifies the calculation process, it ignores the change of shear area in the shear process. However, the calculation of shear stress and shear strength parameters are all related to the change of shear area. Therefore, it can be ascertained that the results calculated by traditional methods will be difficult to accurately reflect the true mechanical properties of materials.

Many scholars have proposed the calculation method of effective shear area and stress [1]. Wang obtained the equation of effective shear area and shear stress by calculating the integral of shear area. It was found that when the shear displacement reached 4 mm, the difference of shear stress before and after correction reached about 10% [2]. Zhan et al. studied the calculation error from the diameter of the circular box and the shear stress, and proposed that the sample box should be made into a small upper box and a large lower box to eliminate the error caused by the reduction of the shear area [3]. Xu et al. established normal stress correction model which is to divide pressure by effective area. They believed that the change of the shear area should be taken into account in the calculation of shear stress, and the shear strength could be neglected in the calculation of shear strength [4]. Considering the change of shear area, Ge et al. studied the variation of stress and strength parameters of rock mass structural plane [5]. Yu et al. summarized the single-point area correction method and the multi-point area correction method. On this basis, a single-point area stress correction method based on area correction and normal stress correction was proposed. It was also found that the increase of shear displacement would make the shear stress greater than the test value [6]. Dong and Wang considered the shear surface fluctuation caused by the eccentricity of normal stress in the shear process. Based on the waveform shear surface calculation model, the effective shear area was corrected. It was pointed out that the calculation results of the model were closer to the true strength values of soil samples, but the fluctuation characteristics of shear surface were difficult to obtain and could not be realized in practical application [7]. Zhang and Wang deduced the equation for calculating effective shear area and processed the data by least square method. It was found that the error of shear strength of soil decreased with the increase of shear area. The results based on shear area correction showed that the true value of shear strength parameters was larger than the test value [8].

In summary, many scholars have basically reached a consensus on the issue that the change of shear area will affect the shear stress and normal stress [9, 10, 11, 12, 13]. However, due to the different simplification of direct shear test calculation model, the calculation models of effective shear area and stress are diverse, and the analysis of shear test results is also different. It is difficult to generalize the results of standard direct shear tests to non-standard (arbitrary radius) tests. Therefore, this paper deduces a direct shear test calculation model considering effective shear area by analytic equation, gives a general corrected model of shear area, shear stress and normal stress. This paper combines the direct shear test data of silty clay under the influence of multiple factors, studies and modifies the shear stress-shear displacement relationship and shear strength of the model. Based on the corrected model of direct shear test and the existing shear strength criterion, the shear strength criterion based on effective shear area calculation is established.

2. Calculating models

2.1. Shear area correction model

In the process of shearing, the relative displacement of the upper and lower shear box is produced, and the shear area decreases gradually. The calculation sketch is shown in Figure 1. When the shear displacement is s , according to the symmetry, a quarter of the shear area can be calculated first.

Sector area:

$$dA_s = \frac{1}{2}r^2 d\theta \quad (1)$$

$$A_s = \int_{\theta_0}^{\pi/2} \frac{1}{2} r \cdot r d\theta = \frac{1}{2} r^2 \left(\frac{\pi}{2} - \theta_0 \right) \quad (2)$$

$$\theta_0 = \arcsin \frac{s}{2r} \quad (3)$$

Triangular area:

$$A_T = \frac{1}{2} r \cos \theta_0 \cdot r \sin \theta_0 = \frac{1}{4} r^2 \sin 2\theta_0 \quad (4)$$

Corrected shear area:

$$A = 4(A_s - A_T) = \pi r^2 - 2r^2 \theta_0 - r^2 \sin 2\theta_0 \quad (5)$$

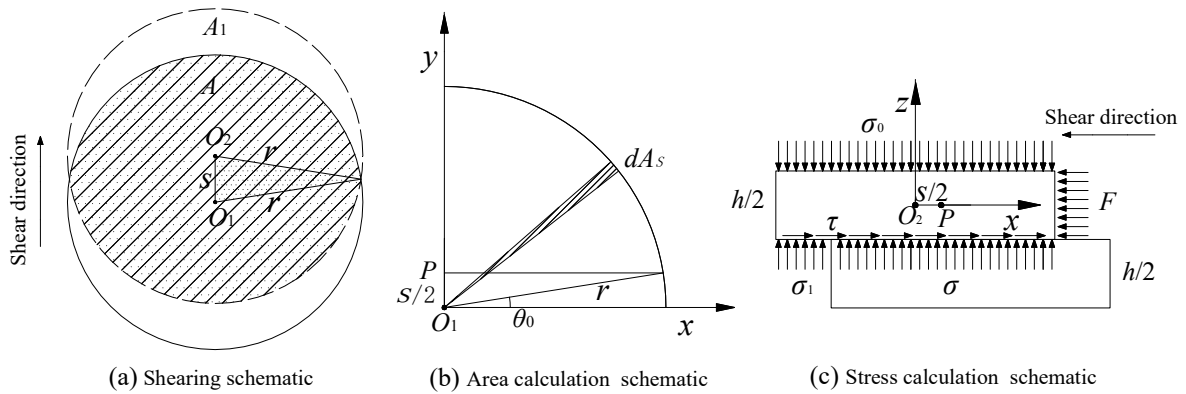


Figure 1. Calculation model of direct shear test.

The absolute error e_A and relative error e_A' of the corrected shear area are respectively:

$$e_A = A - A_0 = (-2\theta_0 - \sin 2\theta_0)r^2 \quad (6)$$

$$e_A' = \frac{A - A_0}{A_0} = \frac{-2\theta_0 - \sin 2\theta_0}{\pi} \quad (7)$$

$$A = A_0(1 + e_A') \quad (8)$$

In equation (8), its e_A' can also be called shear area correction factor. Fig. 2 shows the relationship between the relative error of shear area before and after correction and relative shear displacement after normalization. Fig. 2a is a integral curve, in which the relationship between relative error and relative shear displacement is non-linear, and the relative error is always negative. This indicated that the effective shear area decreases with the increase of shear displacement during shear process. For standard direct shear test, the diameter of shear box is 61.8 mm, and the shear displacement is generally in the range of 0-6 mm. Therefore, we should focus on the relationship between e_A' and relative shear displacement in the range of 0-0.1. As shown in Fig. 2b, in the range of 0-0.1 relative shear displacement, e_A' has a good linear relationship with relative shear displacement, and its linear fitting equation is as follows:

$$y = -1.27x \quad (9)$$

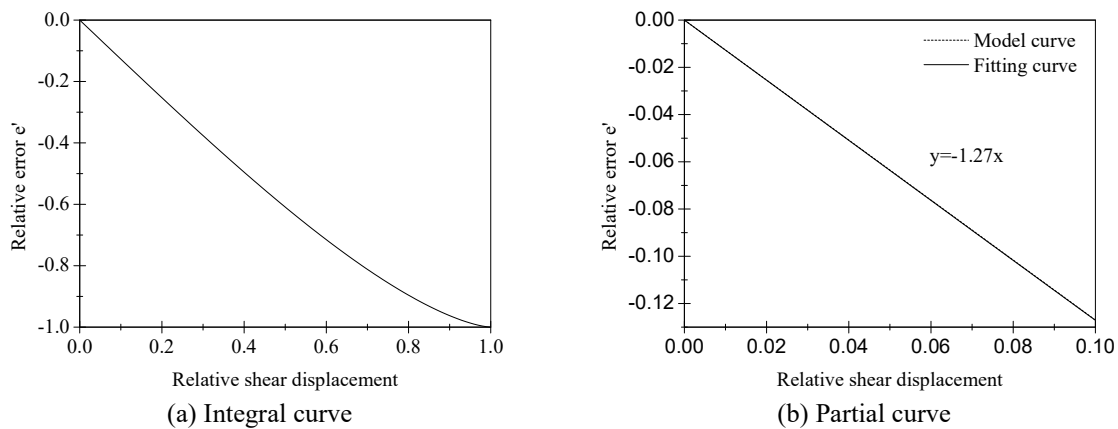


Figure 2. Relative error of shear area vs. relative shear displacement.

2.2. Shear stress correction model

The traditional method is to multiply the shear displacement and the stiffness coefficient of the force ring to represent the shear stress, which is essentially the stress of the effective shear plane rather than the true value. From above equations, it can be seen that the effective shear area is a function of shear displacement, which decreases continuously during the shear process. Therefore, the shear stress calculated according to the traditional method is smaller than the true value, so the original calculation model needs to be corrected. The corrected shear stress value is τ , and the test shear stress value calculated by the traditional method is τ_0 . The following relationship is established:

$$\tau_0 = CR \quad (10)$$

$$\tau A = \tau_0 A_0 \quad (11)$$

Corrected shear stress:

$$\tau = \left(1 + \frac{2\theta_0 + \sin 2\theta_0}{\pi - 2\theta_0 - \sin 2\theta_0}\right) CR = (1 + \beta_1) CR \quad (12)$$

$$\beta_1 = \frac{2\theta_0 + \sin 2\theta_0}{\pi - 2\theta_0 - \sin 2\theta_0} \quad (13)$$

Among them, C is the stiffness coefficient of the measuring ring, R is the displacement value of the dial indicator, CR is the product of the stiffness coefficient of the measuring ring and the indication, which is called the test value of shear stress. Among them, β_1 is the shear stress correction factor. From equation (13) and (5), it can be seen that β_1 is a function of shear displacement and the size of the direct shear box. Therefore, it is not universally applicable to study only the relationship between shear displacement and β_1 . We also normalize the shear displacement. It can be seen from Fig.3a that the relationship between β_1 and relative shear displacement is non-linear, and increases with the increase of relative shear displacement, and the growth rate increases synchronously. From Fig.3b, it can be seen that the increment of β_1 is proportional to the increment of relative shear displacement in the range of 0-0.1. When the relative shear displacement reaches 10%, the error of shear stress increases to 14.6%. Through linear fitting of the original curve, the fitting linear equation is as follows:

$$y = 1.4x \quad (14)$$

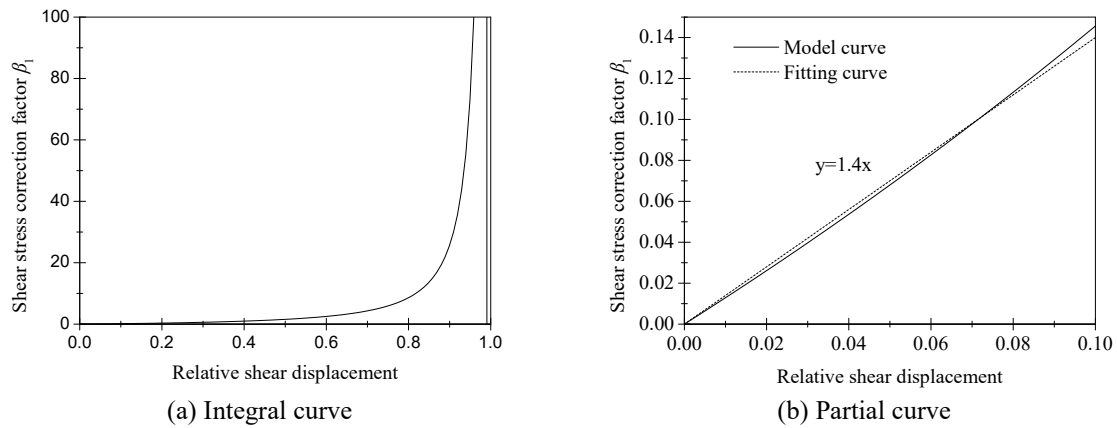


Figure 3. Shear stress correction coefficient vs. relative shear displacement.

2.3. Normal stress correction model

During shearing process, the effective shear area decreases and the normal pressure keeps unchanged, so the normal stress distribution on the shear plane will inevitably change. Therefore, it is necessary to correct the normal stress calculation model. The forces acting on the shear process are shown in Figure 1, where σ_0 is the normal stress applied, σ_1 is the stress applied to the lower shear box, σ is the true normal stress on the shear plane, and h is the thickness of the direct shear specimen. For strain-controlled direct shear tests, the shear process can be regarded as uniform motion, which conforms to Newton's second law. Static analysis of upper shear specimens was carried out:

$$\begin{cases} \sum F_x = 0, & \tau A = F \\ \sum F_z = 0, & \sigma_0 A_0 = \sigma_1 A_1 + \sigma A \\ \sum M_{0_1} = 0, & M_{\sigma_0} = M_{\sigma_1} + M_\tau \end{cases} \quad (15)$$

$$\begin{cases} M_\tau = \tau A \times h / 4 \\ M_{\sigma_0} = \sigma_0 A_0 \times \frac{s}{2} \\ M_{\sigma_1} = \sigma_1 A_1 \times x_P \end{cases} \quad (16)$$

Among them, A_0 is the area of the circle, x_P is the distance between the equivalent force of σ_1 and P , which can be calculated by following equation:

$$\begin{cases} x_{\sigma_1 \sigma_2} = |x| + \frac{s}{2} \\ x = \frac{A_0 \times 0 - A \times \frac{s}{2}}{A_0 - A} \end{cases} \quad (17)$$

The corrected normal stress equation can be obtained from the simultaneous equation (15-17):

$$\sigma = \sigma_0 + \frac{CRh(2\theta + \sin 2\theta)}{2s(\pi - 2\theta - \sin 2\theta)} = \sigma_0 + CR\beta_2 \quad (18)$$

$$\beta_2 = \frac{h(2\theta + \sin 2\theta)}{2s(\pi - 2\theta - \sin 2\theta)} \quad (19)$$

In the above equations, β_2 is a normal stress correction factor, and β_2 is also a function of shear displacement and shear box size. Similarly, it is normalized and the relationship between β_2 and relative shear displacement is obtained as shown in Fig. 4. Comparing with FIG. 3, it can be found that β_2 and

β_1 have similar change rules, both increase with the increase of relative shear displacement, and the increasing rate is accelerating. In the range of 0-0.1, the increment of β_2 is also positively correlated with the increment of relative shear displacement. When the relative shear displacement reaches 10%, the correction coefficient of normal stress will reach 23.55%. The same is true, the product of β_2 and shear stress will also be enlarged, reflecting that the difference between the true value of normal stress and the test value of direct shear will gradually increase with the increase of shear displacement.

$$y = 0.3x + 0.205 \quad (20)$$

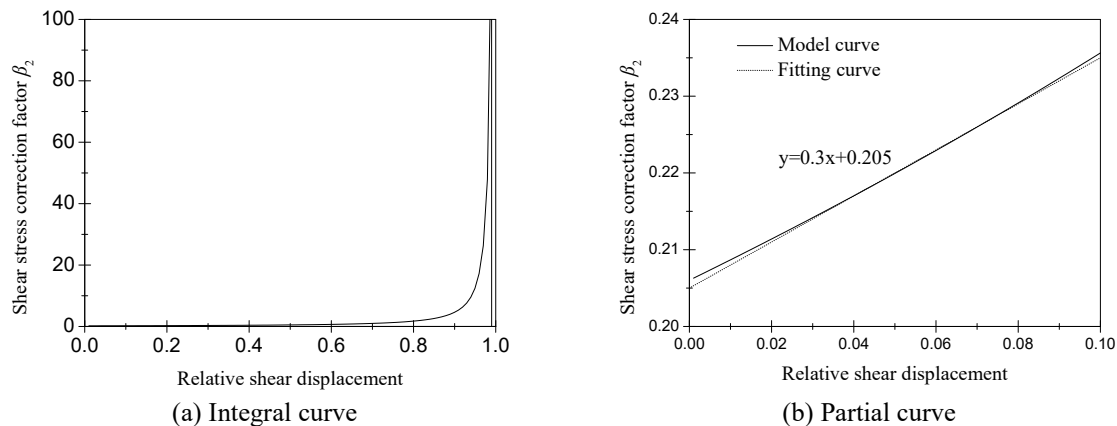


Figure 4. Normal stress correction coefficient vs. relative shear displacement.

3. Test introduction

The soil samples were taken from Weishan Irrigation District, Shandong Province. According to the Standard of Geotechnical Test Method (GB/T 2023-1999), particle size analysis test and liquid-plastic limit test were carried out. The test results show that the maximum dry density of silty clay is 1.67 g/cm^3 , the optimum water content is 16.7%, the plastic limit W_P is 21.38%, the liquid limit W_L is 33.53%, and the plastic index I_P is 12.15. The test process is as follows: firstly, the soil sample is dried after 2 mm sieve, secondly, it is prepared according to the water content of the test design and treated overnight. Thirdly, direct shear specimens with diameter of 61.8 mm and height of 20 mm are pressed by a die press. In the process of sample preparation, the water content is controlled by spraying the deionized water through the sprayer, the dry density is controlled by weighing soil samples quantitatively and pressing moulding machine, the freeze-thaw cycle uses freezer constant temperature freezing (-15°C) and freezer constant temperature thawing (-20°C). The minimum cycle of freeze-thaw cycle is 24 hours, freezing and thawing are 12 hours each. In order to avoid the loss of water during freezing and thawing, all the samples were wrapped with fresh-keeping film. The shear rate of the test was 2.4 mm/min . The specific test scheme is shown in Table 1.

Table 1. Direct shear test scheme.

Water content /%	Dry density / $\text{g}\cdot\text{cm}^{-3}$	Number of freeze-thaw cycles	Normal stress /kPa
12.7	1.47, 1.57, 1.67	0, 1, 2, 3	0, 50, 100, 200
16.7	1.47, 1.57, 1.67	0, 1, 2, 3	0, 50, 100, 200
20.7	1.47, 1.57, 1.67	0, 1, 2, 3	0, 50, 100, 200

4. Results

Based on the above calculation model, the second development of EXCEL is carried out by using VBA (Visual Basic for Applications), and a set of data correction program is established. The program can complete the correction of the test data, automatically generate shear stress-displacement diagram and shear strength envelope diagram, etc., which greatly improves the speed and authenticity of data processing. It can be popularized in future research

4.1. Shear stress-displacement relationship

Taking the direct shear test results of silty clay with the optimum water content of 16.7%, maximum dry density of 1.67 g/cm^3 and freeze-thaw cycles of 0 times as an example, the corrected shear stress-shear displacement relationship (hereinafter referred to as τ - μ curve) is shown in Fig. 5. When the normal stress is 0 kPa, 50 kPa and 100 kPa, the peak shear stress of τ - μ curves are strain-softening. When the normal stress is 200 kPa, the τ - μ curve has no peak stress and is strain-hardening. It can be found that the type of τ - μ curve will not be changed before and after correction. When the normal stress is 0 kPa, the τ - μ curve almost coincide before and after the correction. When the normal stress is 50 kPa, 100 kPa and 200 kPa, the corresponding maximum shear stress errors are - 5.567 kPa, - 9.948 kPa and - 17.97 kPa, respectively. It is confirmed again that the test shear stress is less than the true value, and the error between them is related to the normal stress. The greater the normal force, the greater the error.

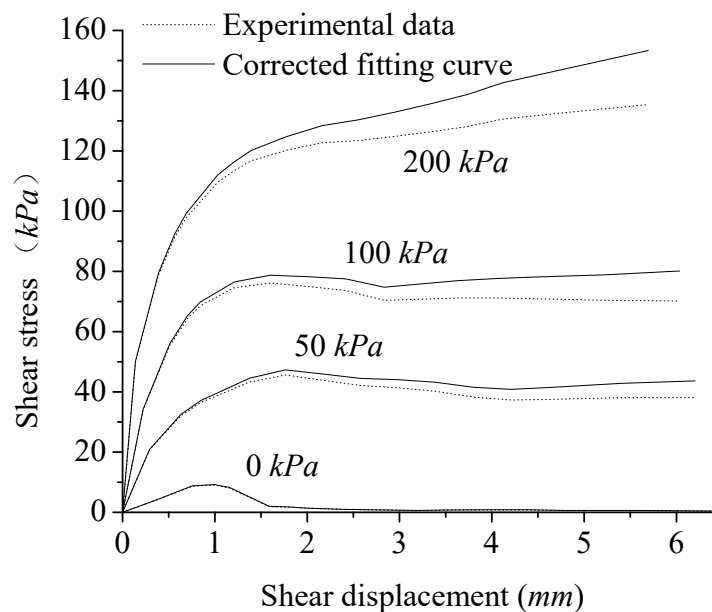


Figure 5. Shear stress vs. shear displacement.

4.2. Shear stress-displacement relationship

According to the shear stress-displacement relationship, the corrected τ - μ curves can be divided into strain softening and strain hardening. For strain softening, the peak shear stress is shear strength, and for strain hardening curve, the shear stress corresponding to 6 mm shear displacement is shear strength. At present, Mohr-Coulomb criterion is commonly used in solving shear strength parameters. The equation for calculating shear strength is as follows.

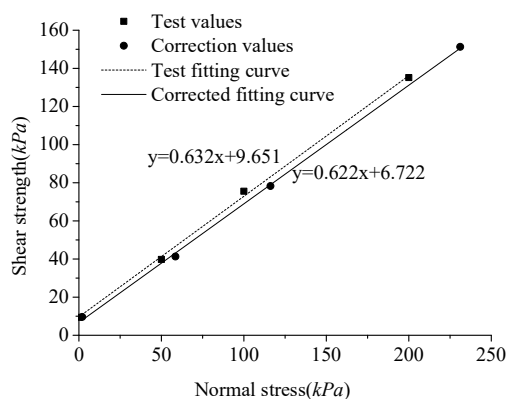
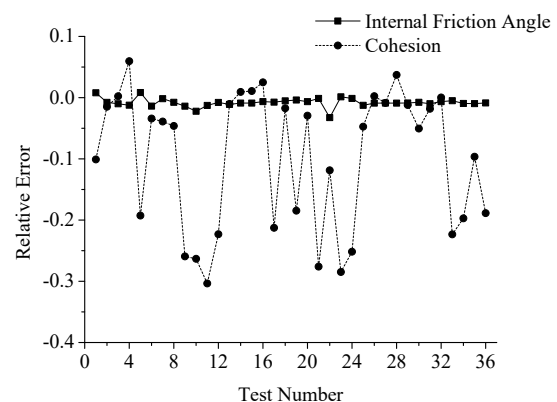
$$\tau = \sigma \tan \varphi + C \quad (21)$$

In the above equation, τ is shear stress, σ is normal stress, φ is internal friction angle, and C is cohesive force. It is used to fit the relationship between shear strength and normal stress linearly, as shown in Fig.6. The fitting results show that the Mohr-Coulomb criterion has good applicability for both test and corrected values. Therefore, the Mohr-Coulomb criterion is selected to describe the shear strength in this paper. The shear strength parameters of silty clay are calculated according to the traditional method and the model modification algorithm respectively. The results of internal friction angle and cohesion C are obtained as shown in Table 2.

Table 2. Calculation results of shear strength parameters.

Number	Test values		Correction value		Number	Test values		Correction value	
	$\varphi_0/^\circ$	C_0/kPa	$\varphi/^\circ$	C/kPa		$\varphi_0/^\circ$	C_0/kPa	$\varphi/^\circ$	C/kPa
1	31.467	5.23	31.716	4.702	19	32.005	4.999	31.881	4.076
2	32.005	4.422	31.758	4.356	20	31.675	4.616	31.467	4.48
3	32.579	3.499	32.252	3.507	21	32.005	11.8	31.964	8.543
4	32.943	2.115	32.538	2.241	22	31.964	10.15	30.922	8.945
5	30.541	9.576	30.795	7.731	23	31.675	9.653	31.716	6.904
6	32.538	6.769	32.088	6.538	24	32.005	7.268	31.964	5.439
7	31.142	6.499	31.088	6.245	25	32.66	4.115	32.252	3.92
8	32.293	5.384	32.047	5.135	26	32.293	3.846	32.005	3.855
9	32.456	12.15	32.005	8.999	27	32.375	3.615	32.088	3.584
10	31.84	10.73	31.132	7.905	28	32.334	3.422	32.046	3.549
11	32.293	9.651	31.882	6.722	29	32.619	5.653	32.334	5.585
12	31.84	8.768	31.592	6.812	30	32.375	5.461	32.129	5.185
13	33.024	4.346	32.66	4.301	31	32.782	4.884	32.456	4.795
14	32.375	3.422	32.088	3.454	32	31.758	3.999	31.55	4
15	32.334	3.23	32.047	3.265	33	32.782	8.422	32.619	6.541
16	31.84	2.999	31.633	3.074	34	33.544	6.269	33.225	5.033
17	32.86	5.615	32.619	4.421	35	33.064	6.115	32.741	5.525
18	31.592	5.192	31.425	5.102	36	32.822	5.969	32.538	4.843

The relationship of the relative error between the corrected shear strength parameters and the test values is shown in Fig.7, and the calculation equation is equation (22). In the picture, it can be seen that the calculated results of the corrected shear strength parameters are mostly negative, that is, the test shear strength parameters are larger than the true values. The maximum relative error of internal friction angle is 0.008317, the minimum value is -0.0326, and the average value is -0.00808. The maximum relative error of cohesion is 0.059574, the minimum value is -0.30349 and the average value is -0.09885. Thus it can be seen that the influence of the corrected model on the calculation results of internal friction angle and cohesion is different. Among them, the relative error of internal friction angle has good constancy. The change of internal friction angle before and after the correction is about 1%, reflecting that the change of shear area has little effect on the internal friction angle. The relative error of cohesion is higher discreteness, the maximum error is more than 30%, which reflects that the change of shear area has a significant impact on cohesion.

**Figure 6.** Shear strength vs. normal stress.**Figure 7.** Relative error of shear strength parameters.

$$\begin{cases} e_{\varphi}' = \frac{\varphi - \varphi_0}{\varphi_0} \\ e_C' = \frac{C - C_0}{C_0} \end{cases} \quad (22)$$

4.3. Shear strength criterion

The linear regression equation of the standard Mohr-Coulomb criterion is:

$$\begin{bmatrix} \sigma_1 & 1 \\ \sigma_2 & 1 \\ M & M \\ \sigma_i & 1 \end{bmatrix} \begin{bmatrix} \tan \varphi \\ C \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \\ M \\ \tau_i \end{bmatrix} \quad (23)$$

According to the calculation equation of shear stress and normal stress correction model, equation (23) is corrected:

$$\begin{bmatrix} \sigma_1 + CR_1\beta_{21} & 1 \\ \sigma_2 + CR_2\beta_{22} & 1 \\ M & M \\ \sigma_i + CR_i\beta_{2i} & 1 \end{bmatrix} \begin{bmatrix} \tan \varphi \\ C \end{bmatrix} = \begin{bmatrix} \tau_1(1 + \beta_{11}) \\ \tau_2(1 + \beta_{12}) \\ M \\ \tau_i(1 + \beta_{1i}) \end{bmatrix} \quad (24)$$

When the normal stress is σ_i , the normal stress correction coefficients, shear stress correction coefficients and percentile displacement meters are represented by β_{1i} , β_{2i} and R_i respectively. The corrected shear strength criterion is obtained from the simultaneous equation (14) and equation (20):

$$\begin{bmatrix} \sigma_1 + (0.3x_1 + 0.205)\tau_1 & 1 \\ \sigma_2 + (0.3x_2 + 0.205)\tau_2 & 1 \\ M & M \\ \sigma_i + (0.3x_i + 0.205)\tau_i & 1 \end{bmatrix} \begin{bmatrix} \tan \varphi \\ C \end{bmatrix} = \begin{bmatrix} \tau_1(1 + 1.4x_1) \\ \tau_2(1 + 1.4x_2) \\ M \\ \tau_i(1 + 1.4x_i) \end{bmatrix} \quad (25)$$

In the above equation, σ_i and τ_i represent the test values of normal stress and shear strength respectively. When the normal stress is σ_i , x_i is a relative shear displacement which is dimensionless. The relative shear displacement x_i is added to the equation, so that the corrected shear strength criterion can effectively calculate the true internal friction angle and cohesion.

5. Conclusion

On the basis of previous studies, this paper theoretically deduces corrected models suitable for (non) standard circular box direct shear test, develops a set of data correction program, and analyses the data of silty clay direct shear test. The main conclusions are as follows:

1. According to the corrected calculation model, it is concluded that the test values of shear stress and normal stress are lower than the corrected true values due to the decrease of shear area in shear process. The error of true value increases with the increase of relative shear displacement.

2. The characteristics of shear stress-displacement curve of silty clay are related to normal stress: under low normal stress, the strain softening type is the dominant one, while under high normal stress, the strain hardening type is the dominant one. In addition, the error between the test shear stress and the true value is also related to the normal stress, which will increase with the increase of the normal stress.

3. Mohr-Coulomb criterion has good applicability to the corrected direct shear test data. After correction, the change of internal friction angle is small and can be neglected approximately, but the change of cohesion is discrete and the corrected model has a significant influence on cohesion.

4. The corrected model of shear stress and normal stress are substituted into the Mohr-Coulomb linear regression equation, in which the relative shear displacement is added. The corrected shear strength criterion can calculate the true shear strength parameters more accurately according to the test

shear strength, shear displacement and normal stress.

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