Research Article

Study on the Effect of Moisture Content and Dry Density on Shear Strength of Silty Clay Based on Direct Shear Test

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Abstract
Silty clay is a kind of clay with more powder group than sand group, and its shear strength is mainly influenced by moisture content, dry density, and particle gradation. In this study, the deformation characteristics of silty clay under different normal pressure conditions were investigated from the perspective of control variables through indoor direct shear experiments. The results of the study show that with the same guaranteed moisture content, it can be seen from the fitted curves that with the increase of dry density, the arrangement of soil particles becomes more compact, the cementation between soil particles is strengthened, the shear strength increases, the occlusal friction increases due to the change of arrangement between soil particles, and the angle of internal friction and cohesion are relatively larger; in addition, when the dry density is the same, with the increase of moisture content, the soil becomes softer, and the form of water in the soil particles changes. In addition, when the dry density is the same, as the moisture content increases, the soil becomes softer, the presence of water between the soil particles changes, resulting in the weakening of the occlusion between the soil particles, the shear strength decreases, and the cohesion and the angle of internal friction relatively decrease.

1. Introduction

Silty clay is a kind of clay that is different from ordinary soil, and its silt group content is greater than that of the sand gravel group. The most direct way to investigate the mechanical properties of soils is the variation of shear strength. The shear strength of silty clay is mainly affected by factors such as dry density, moisture content, matrix suction, and particle gradation.

In terms of exploring the influence of dry density on the shear strength of soil, it has been analyzed by domestic and foreign scholars through different research methods. For example, Gao et al. [1] and Shen et al. [2] used indoor triaxial tests to study the deformation and strength variation laws of remolded soils and conducted triaxial shear tests on soils with different initial dry densities, different suction forces, and different moisture contents, respectively, and integrated the shear strength of remodeled soils. To study the strength characteristics of cured loess, Miao et al. [3] used polymer curing agent cured loess as the material and analyzed the strength variation characteristics of cured loess under different dry densities and moisture content conditions by using the direct shear test. For the same influencing factor, different research perspectives will have different research findings. In order to study the unsaturated nature of silty clay, Huang et al. [4] used an undrained triaxial test method to analyze the strength variation law of loess-like silty clay in the Three Gorges area by conducting triaxial shear tests under different dry density conditions, respectively. The law of intensity changes. From the perspective of the soil-water characteristic curve, Yi et al. [5] investigated the effect of the Van Genuchten model on the soil-water characteristic curves for specimens with different initial dry densities and moisture contents. Regarding the research on the influence of moisture content on the shear strength of soil, due to the
difference of soil properties, the law of change is also not the same. In this regard, domestic and foreign scholars have carried out a lot of research on the influence mechanism of various soil moisture content. For example, Huang et al. [6] used indoor direct shear tests to analyze the strength changes of undisturbed soil and remolded soil under different moisture contents. To analyze the effect of moisture content on the shear strength of unsaturated remodeled loess, Chen et al. [7] used the fast shear test without drainage and consolidation to analyze the variation law of soil shear strength and the damage process. Rui et al. [8] prepared red clay specimens with different water contents to analyze the variation of cohesion and the angle of internal friction characteristics of red clay with uniform and inhomogeneous moisture content distribution under different water loss degrees. The angle of internal friction characteristics changes. In order to study the effect of water content on the landslide zone soil of the Lock’s Head landslide, Song et al. [9] established a landslide hyperbolic stress model using large indoor direct shear experiments and analyzed the stress-deformation mechanism characteristics of the landslide zone soil along the landslide direction during different periods of rapid changes in the moisture content of the landslide. In order to analyze the influencing factors of soil shear strength parameters, Liu et al. and Zhang et al. [10, 11] used direct shear test and triaxial shear test to comprehensively analyze the factors affecting the stability of slide zone soil and the variation characteristics of soil shear strength under the conditions of different moisture content, dry density, and matrix suction of slide zone soil and red clay soil, respectively.

Sorting out the existing research results is not difficult to find that most of the existing research results focus on the analysis of a single influencing factor [12], while the analysis of the coupling effect of multiple factors is relatively small, and the existing research is mainly for general soils. In other words, there is very little research on the dry density and moisture content of silty clay. Coupled with different soil properties, previous research conclusions may not apply to all types of soil. Therefore, to better analyze the strength change characteristics of silty clay, this paper takes the silty clay in the landslide body of Zengcheng, Guangzhou, as the main research object and analyzes the conditions of different dry densities and different moisture contents based on the results of the direct shear test, the strength changes characteristics of the silty clay under different dry density and different moisture content conditions were analyzed to establish the connection between strength change and dry density and moisture content, to understand more deeply the soil changes in shear tests with different dry densities and moisture contents, and to reveal the influence mechanism of dry density and moisture content on the shear strength of silty clay.

2. Test Process

2.1. Main Test Equipment. The soil samples used in the test are mainly silty clay. According to the “Test Methods of Soils for Highway Engineering” [13], a series of laboratory tests were carried out on silty clay and its basic physical properties are shown (see Table 1).

The instrument used for the direct shear test is the ZJ controlled direct shear instrument (quadruple shear) produced by Nanjing Soil Instrument Factory Co. (see Figure 1). The test equipment mainly includes a shear box, a dial indicator, and an automatic control operation platform. The 60 mm³ sample is directly sheared. The shear strength under different normal pressures can be measured by adding or subtracting weights. The maximum vertical pressure of the instrument used is 400 kPa. The area of the tested piece is 30 cm² × 2 cm (H). The strain-controlled direct shear instrument can measure the horizontal shear force when the soil is broken.

2.2. Test Materials. The initial gradation curve is of great significance to study the properties of soil [14]. The sample material used in the test is Guangzhou Zengcheng landslide silty clay with a depth of about 4.8–6.0 m. Due to the small particle size of the silty clay, to ensure the consistency of the test conditions and the reliability of the results, the densitometry method was used for the particle fraction test of the soil samples. When the mass of soil particles with a particle size greater than 2 mm is less than 10% of the total mass, no coarse screening is performed. The grading curve of the soil sample in this experiment is shown in Figure 2, and the basic parameters are shown in Table 2.

2.3. Test Plan. Through the analysis of relevant research data, it is understood that the influencing factors of soil shear strength are mainly related to dry density, moisture content, matrix suction, particle gradation, and temperature. This experiment focuses on verifying the influence of dry density and moisture content on the shear strength of silty clay. The test will be divided into two parts. The first part is to explore the influence of dry density; under the condition that the moisture content of the sample is the same, the soil samples with dry densities of 1.45, 1.52, 1.64, and 1.72 are selected at the normal pressure, respectively, the direct shear test is carried out under the conditions of 100, 200, 300, and 400 kPa. In the second part, in the investigation of the effect of water content, the dry density was controlled to be the same, and soil samples with 10%, 15%, 19%, and 22% water content were selected for indoor direct shear tests under the normal pressure of 100, 200, 300, and 400 kPa, respectively, and the mass of water to be added in the preparation of the target water content soil samples was calculated according to

\[ m_w = 0.01 (w - w_h) \times \frac{m}{1 + 0.01 w_h} (g), \]

where \( m \) is the quality of the soil (g); \( w_h \) is soil moisture content (%); and \( w \) is the moisture content required for sample preparation (%).

2.4. Test Procedure

(1) Material preparation: use an oven to dry the soil samples in batches and keep them for later use.
Sample preparation: the soil used in the experiment is silty clay remolded soil. In the dry density test, a soil sample with a moisture content of 22% is taken, and the soil sample is taken out with a ring knife. The test is divided into 4 groups, taking four different dry density soil samples for testing; each group takes 6 soil samples, 4 are used for the shear test, and 2 are used for measuring soil moisture content. When carrying out the moisture content test, take soil samples with a dry density of 1.56 g·cm\(^{-3}\) for the corresponding test. The test is also divided into 4 groups. Four soil samples with different moisture content are configured by adding water for the test; each group has 6 of the soil samples, 4 were used for the shear test, and 2 were used to determine the dry density.

(3) Install the sample and perform shearing: the installation process is completed by the “Geotechnical Test Method Standard,” the load of this test method is 100, 200, 300, and 400 kPa, and the shear rate is 0.8 mm·min\(^{-1}\).

(4) After cutting, process the data.

### 3. Analysis of Test Results

#### 3.1. The Relationship between Shear Strength and Dry Density

Taking a soil sample with a moisture content of

<table>
<thead>
<tr>
<th>Moisture content (%)</th>
<th>Void ratio</th>
<th>Modulus of compression (MPa)</th>
<th>Gravity (kN·m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.6</td>
<td>0.75</td>
<td>8.33</td>
<td>19.31</td>
</tr>
</tbody>
</table>

Table 1: Basic physical properties of silty clay.

Table 2: Soil sample gradation parameter table.

<table>
<thead>
<tr>
<th>Number</th>
<th>Cc</th>
<th>Cu</th>
<th>(d_{10})</th>
<th>(d_{30})</th>
<th>(d_{60})</th>
<th>Gradation evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.77</td>
<td>5.98</td>
<td>0.015</td>
<td>0.061</td>
<td>0.0897</td>
<td>Good</td>
</tr>
</tbody>
</table>

Table 2: Soil sample gradation parameter table.

Figure 1: Experimental flow chart. (a) Straight shear. (b) After direct shear test (moisture content 13%). (c) Before direct shear test (moisture content 13%).

Figure 2: Particle gradation curve.

Figure 2: Particle gradation curve.
22% as an example, its shear strength and strength parameter indexes at different dry densities are shown in Table 3. The variation of shear strength of powdered clay with dry density is shown in Figure 3, and the parameters for fitting the relationship between dry density and shear strength under different normal pressures are shown in Table 4.

Figure 3 plots the relationship curves between dry density and shear strength of silty clay soil samples under different normal pressures. From the figure, it can be seen that the shear strength of the silty clay increases with the increase of dry density under the same moisture content, and it can be seen from the fitted curves of dry density and shear strength in Table 4 that the shear strength increases in an approximately linear manner with the increase of dry density. The higher the normal pressure is, the greater the shear strength is.

The increase of dry density makes the porosity of soil decrease and the arrangement of soil particles tighten [15]. The main forms of soil particle arrangement are cubic and tetrahedral arrangements. When the dry density of the soil sample is small, the arrangement is sparse, and its arrangement is arranged in an approximate cube shape [16]. It is equivalent to that there are 6 particles in contact with 1 soil particle in a cube. For relative movement to occur, the suction force of the 6 particles must be overcome. Therefore, in the macroscopic view, when the dry density is small, its shear strength is also small. When the dry density of the soil sample is high, the arrangement of the soil particles is relatively close, and the friction between the particles is also large. At this time, the soil particles are arranged in an approximate tetrahedral manner, and the relative movement needs to overcome the suction of 12 particles to make the relative movement of the soil more difficult. Macroscopically, as the dry density increases, the shear strength of the soil also increases.

From Figure 4, the relationship between normal pressure and shear strength of silty clay shows that when the moisture content is the same, under the action of different dry densities, the greater the normal pressure, the greater the shear strength of the soil, and the greater the dry density, the greater the shear strength. It can be seen from Table 5 that the relationship between the normal pressure and the shear strength of different dry densities is linearly fitted. As the normal pressure increases, the shear strength increases approximately linearly. It can be seen from the fitting straight line between normal pressure and shear strength that the greater the dry density, the greater the slope of the fitting straight line, indicating that the greater the dry density, the greater the influence of the normal pressure on the shear strength. With the increase of soil density, interlocking effects between soil particles become more obvious. Hence, the dilatancy becomes more significant, the occlusal effect between soils increases.

From the relationship between dry density and cohesion in Figure 5(a), it can be seen that controlling the water content of the soil sample, the cohesion of the pulverized clay increases with the increase of dry density in an approximately convex quadratic function. When the dry density is higher, the pores between the soil particles are smaller and the particles are arranged tightly, which strengthens the occlusion between the soil particles. On the contrary, when the dry density is small, the arrangement of clay particles is relatively loose, the pores are larger, and the occlusion between soil particles is weakened. The cohesion of the soil is mainly related to its arrangement structure. Therefore, the relationship between dry density and cohesion is a positive correlation in the macroscopic view; that is, cohesion $c$ increases with the increase of dry density.

It can be seen from Figure 5(b) that when the moisture content is constant, the angle of internal friction of silty clay shows an approximately linear increase with the increase of dry density. Due to the increase in dry density, the contact of soil particles tends to be closer and closer, and the void ratio is relatively small. At this time, the water stored in the soil particles by strong bound water is relatively stable and not easy to flow. Therefore, the angle of internal friction $\phi$ will increase with the increase of dry density.

### 3.2. The Relationship between Shear Strength and Moisture Content

Taking the dry density of 1.56 g·cm$^{-3}$ soil sample as an example, the values of shear strength and strength index parameters at different moisture contents are shown in Table 6, the curve of the shear strength of the remolded soil with moisture content is shown in Figure 6, and the test data of the shear strength and the moisture content are fitted in Table 7.

It can be seen from Figure 6 that the shear strength and moisture content change curve, the influence of moisture content on the shear strength of silty clay is very significant. The main manifestation is that as the moisture content increases, the shear strength continues to weaken. It can be seen from the fitting curve of the test data in Table 7 that the curve of shear strength and moisture content is fitted by a quadratic polynomial curve, and its shape is mainly concave; that is, the shear strength decreases with increasing moisture content in an approximate second-order curve.

During the shear test, when the moisture content of the soil sample is at a low level, On the one hand, it is necessary to overcome the work done by the cementation force between soil particles, and on the other hand, it is necessary to overcome the additional work done by the rearrangement of the particles due to the breaking of shear. At the same time, it is necessary to overcome the work done by matrix suction. With the increase of shear displacement, the cementation between soil particles is destroyed, and when the shear stress reaches the peak, the change of shear displacement becomes smaller and smaller, and the cementation between soil particles becomes weaker and weaker. There is a phenomenon of less water and more gas in the soil. The main factors that play a leading role in the soil are its sliding friction and occlusal friction. At this time, the shear strength between soil particles mainly comes from the sliding friction between the soil particles and the matrix suction. Therefore, macroscopically, when the moisture content is low, its shear strength is relatively large. With the increase of moisture content, the suction force between soil particles becomes smaller and smaller, the distance between soil particles
becomes larger and larger, the cementing force between soil particles weakens, and part of the organic matter is dissolved after chemical action occurs, making the cemented material between the soil particles softer, and the friction coefficient is significantly reduced during the shear test. At this time, the pore water pressure bears part of its pressure. Therefore, the shear resistance of the soil will also be weakened, and the shear strength of the soil will decrease rapidly.

As can be seen from the relationship between moisture content and shear strength of silty clay in Figure 7, at the same dry density and moisture content, the shear strength of silty clay always increases approximately linearly with the increase of normal pressure. But as the moisture content continues to increase, its shear strength will also decrease. According to Table 8 under different soil moisture content conditions, the relationship between shear strength and normal pressure is fitted to the curve. The results show that due to the continuous increase of moisture content, the intercept of the straight line is significantly reduced. The Mohr–Coulomb strength formula shows that the intercept on the $\tau - \sigma$ line represents cohesion. That is, as the moisture content of silty clay increases, its cohesion decreases significantly. The test shows that the moisture content has a significant weakening effect on the shear strength of silty clay.

From Figure 8(a), the relationship between water content and cohesion of pulverized clay, it can be seen that the cohesion decreases with the increase of water content in an approximate quadratic parabolic manner for the same dry density, and the greater the moisture content, the slower the reduction of cohesion, and the overall nonlinear change. This situation occurs mainly because the increase in moisture content makes the soil soft and the soil particles are loosely arranged. Because the cohesion of remolded soil is not only related to the gravitational force between soil particles but also related to its repulsive force [17, 18].
Therefore, from the microscopic analysis, the phenomenon that the cohesion weakens with the increase of moisture content is mainly analyzed from two aspects: on the one hand, the water between soil particles mainly exists in the form of free water and bound water. As the rate changes, the form of water also changes. When the soil sample has a low moisture content, water molecules mainly exist in the form of bound water, and the main source of its cohesion is the content of bound water in the soil. Therefore, when the soil moisture content is low, its cohesion is relatively higher. According to the extended Mohr–Coulomb theory, Abd et al. [19] think that it is known that the shear strength of soil is mainly related to the cohesive force, the angle of internal friction, and the matrix suction. Therefore, as the moisture content continues to increase, the cementing force of the soil becomes smaller and smaller, and the matrix suction force is gradually weakened. The pore water pressure assumes part of the compressive stress, which leads to the hydrolysis of some
Table 6: Values of shear strength and strength index parameters at different moisture contents.

<table>
<thead>
<tr>
<th>Moisture content (%)</th>
<th>100 kPa</th>
<th>200 kPa</th>
<th>300 kPa</th>
<th>400 kPa</th>
<th>Cohesion (kPa)</th>
<th>Angle of internal friction φ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>99.52</td>
<td>133.48</td>
<td>134.79</td>
<td>197.71</td>
<td>67.401</td>
<td>16.5</td>
</tr>
<tr>
<td>15</td>
<td>54.5</td>
<td>57.66</td>
<td>95.94</td>
<td>110.72</td>
<td>27.967</td>
<td>11.4</td>
</tr>
<tr>
<td>19</td>
<td>23.69</td>
<td>38.7</td>
<td>39.64</td>
<td>58.64</td>
<td>13.784</td>
<td>6</td>
</tr>
<tr>
<td>22</td>
<td>11.85</td>
<td>16.59</td>
<td>18.24</td>
<td>33.21</td>
<td>3.5327</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Figure 6: Relationship between shear strength and moisture content of silty clay.

Table 7: Curve fitting parameters of the relationship between moisture content and shear strength under different normal pressure.

<table>
<thead>
<tr>
<th>Normal pressure (kPa)</th>
<th>Fitting curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>$\tau = 0.2819\omega^2 - 16.429\omega + 236$, $R^2 = 0.9985$</td>
</tr>
<tr>
<td>200</td>
<td>$\tau = 0.6209\omega^2 - 29.211\omega + 361.98$, $R^2 = 0.9864$</td>
</tr>
<tr>
<td>300</td>
<td>$\tau = 0.1077\omega^2 - 6.7033\omega + 214.27$, $R^2 = 0.9849$</td>
</tr>
<tr>
<td>400</td>
<td>$\tau = 0.5434\omega^2 - 31.139\omega + 454.93$, $R^2 = 0.9999$</td>
</tr>
</tbody>
</table>

Figure 7: Relationship between moisture content and shear strength of silty clay.
of the salt and cement in the soil, and the cementing effect is weakened, and the cohesive force is reduced.

It can be seen from Figure 8(b) that the angle of internal friction of the soil has a negative correlation with the moisture content. From the results of this experiment, the change of the angle of internal friction is relatively small. The size of the angle of internal friction is generally related to the arrangement of soil particles, the size of the particles, and the degree of soil compaction. This is because when the moisture content is at a low level, the cohesion is relatively large due to the existence of bound water between soil particles. Therefore, the occlusal friction between the soil particles is also very large, and the angle of internal friction also increases. With the increase of soil moisture content, the water molecules between the soil particles change their morphology, and the cement in the soil is gradually dissolved by water, which leads to the relative reduction of the occlusal friction between the soil particles and the reduction of the angle of internal friction.

4. Conclusion

(1) Because the shear strength of soil is mainly related to the particle size distribution, moisture content, dry density, and matrix suction of the soil, therefore, in order to ensure the accuracy of the test results, it is feasible to use the control variable method as the basic criterion of the experiment.

(2) This paper takes silty clay remolded soil as the research object, based on the results of the direct shear test, and analyzes the change law of the shear strength of the soil when the dry density and moisture content change. The results show that when the moisture content is controlled for a certain amount, the relationship between dry density and shear strength is generally linear. The dry density increases, the arrangement of soil particles become tighter, and the occlusal friction area is larger, which makes the shear strength of the soil relatively larger. The relationship curves of dry density and $\phi$, $c$ are fitted with exponential and quadratic polynomials, respectively, and then it is concluded that the higher the dry density, the larger the angle of internal friction and the cohesion.

(3) When the dry density of the controlled test soil sample is constant, the analysis test results show that the relationship between the moisture content and the shear strength is approximately concave quadratic curve fitting. When the moisture content increases, the structure of the soil is looser; the existing form of the water between the soil particles changes from bound water to free water. Therefore, the cementing force of the soil becomes smaller and smaller, and the matrix suction force is gradually weakened. The pore water pressure assumes part of

Table 8: Fitting lines of the relationship between shear strength and normal pressure under different moisture contents.

<table>
<thead>
<tr>
<th>Moisture content $\omega$ (%)</th>
<th>Fitting curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$\tau = 0.2959\sigma + 67.401$, $R^2 = 0.87$</td>
</tr>
<tr>
<td>15</td>
<td>$\tau = 0.2069\sigma + 27.967$, $R^2 = 0.9124$</td>
</tr>
<tr>
<td>19</td>
<td>$\tau = 0.1054\sigma + 13.784$, $R^2 = 0.91$</td>
</tr>
<tr>
<td>22</td>
<td>$\tau = 0.0658\sigma + 3.5327$, $R^2 = 0.8449$</td>
</tr>
</tbody>
</table>

Figure 8: (a) Relationship between moisture content and cohesion of silty clay. (b) Relationship between moisture content and angle of internal friction.
the compressive stress, and the cohesion and angle of internal friction show a decreasing trend.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Conflicts of Interest**

No potential conflicts of interest were reported by the authors regarding the publication of this paper.

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