Direct shear test and model prediction analysis of unsaturated silt

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Abstract. In order to study the mechanical properties of Unsaturated Silt in the east of Henan Province, the influence of water content, normal stress, degree of compaction and dry density is studied through direct shear test and model prediction. The results of direct shear test show that with the increase of moisture content and normal stress, the shear deformation of soil gradually changes from softening to hardening, and the higher the dry density is, the more obvious the phenomenon is. In addition, the cohesion decreases with the increase of water content, and the curve is broken line, and the turning point appears near the optimal water content; the influence of water content on the internal friction angle is small, and the internal friction angle increases with the increase of dry density at the same water content. At the same time, the hyperbolic model can well predict the direct shear test results, especially in the case of high normal stress, low density and high moisture content, the more the model prediction value is close to the test value.

1. Introduction
In the eastern part of Henan, there is a large area of silt formed by the Yellow River alluvial deposits, and this soil is often used as a roadbed filler. However, because the soil has poor characteristics such as high powder content, poor water stability, and difficulty in compaction, the study of its water-soil mechanical properties has become a pressing issue in soil mechanics [1]. In classical soil mechanics, the researchers usually assume that this kind of soil is saturated, but most of the soil in actual engineering is in an unsaturated state. Further, the mechanical properties of unsaturated soil must be different from saturated soil [2]. For this reason, many scholars have begun to study the mechanical properties of unsaturated soils.

In addition, most of the research on the shear strength of unsaturated soils has concentrated on theoretical and experimental levels. In theory, there are some classic expressions of shear strength, such as Bishop formula [3], Fredlund formula [4], etc. Subsequently, some scholars modified these formulas according to the test results and put forward more reasonable improved models, such as Huang Runqiu formula [5], Vanapalli empirical formula [6]. At the theoretical level, they also comprehensively considered unsaturated soils and models with dual effects of net normal force, and matrix suction [7]. At an experimental level, the factors affecting the shear strength of unsaturated soil have also been concerned by many scholars. Scholars have studied the influence of moisture content [8], matrix suction [9] and other factors on shear strength for different soil qualities. Furthermore,
some scholars [10] have successively reviewed the current research situation of unsaturated soil and provided ideas for the future research of unsaturated soil. Finally, soil quality is dependent on various regions. Thereby, we will use the silty soil from eastern Henan province in our direct shear test and model prediction to explore the effects of compaction, water content, normal stress and dry density on the hydraulic-mechanical properties of unsaturated silty soil in eastern Henan province.

2. The introduction of the test

2.1. The basic parameters of soil
This article uses the soil in a 6-meter-deep foundation pit in eastern Henan. As shown in Table 1, the basic geotechnical tests identify the basic physical properties of the soil. Figure 1 presents the particle gradation curve. According to the “Road Geotechnical Test Regulations”, the test soil is our study is low-liquid-limit silt soil.

| Parameter                        | Value   |
|----------------------------------|---------|
| Specific gravity, $G_s$          | 2.70    |
| Maximum dry density, $\rho_{\text{dmax}}$ / g/cm$^3$ | 1.72    |
| Optimal water content, $w_{\text{opt}}$ /% | 12.70   |
| Liquid limit, $w_L$ /%           | 24.50   |
| Plastic limit, $w_P$ /%          | 17.30   |
| Plasticity index, $I_p$          | 7.20    |

Table 1. Physical properties of soil

![Particle-size distribution curve](image)

Figure 1. Particle-size distribution curve

2.2. Test method
A conventional geotechnical direct shear instrument is used to test the shear strength of the soil sample. The preparation of the undisturbed silt soil sample is relatively complicated, and the soil sample structure is easily damaged during transportation, so our experiment will first remodel the soil sample and then conduct the test. The specific test plan is as follows: direct shear test has a total of 12 groups, and we selected 1.52 g/cm$^3$ and 1.64 g/cm$^3$, respectively. Each of two kinds of dry density, has six different moisture content, including 6.7%, 8.7%, 10.7%, 12.7%, 14.7%, and 16.7%. We also prepare four soil samples in each group, corresponding to 4 different normal stresses, which are 50 kPa, 100 kPa, 200 kPa and 400 kPa.

3. Test results and analysis

3.1. Effect of water content, normal stress and dry density on shear stress-shear displacement curve
In order to study the law of shear deformation of silty soil in eastern Henan province, Figure 2 shows the shear stress-shear displacement curves at different water content, normal stress and dry density at
two compaction degrees. To study the shear deformation law of silty soil in eastern Henan, Figure 2 shows two curves, namely, the shear stress-shear displacement curves at different water content, normal stress and dry density at the same compaction degree. Figures 2 (a) and 2 (d) are the shear stress-shear displacement curves of different dry densities below the optimal moisture content. According to the figure, as the normal stress increases, the soil stress-strain relationship gradually shows from softening to hardening, and the dry density increases. In other words, if the dry density of the soil decreases, it is easier to harden at lower normal stresses. Likewise, Figure 2 (b) and 2 (e) are the shear stress-shear. By contrast, the two figures show that when the dry density is large, and the normal stress is small, the stress-strain curve of the soil will soften, but it will gradually become hardening as the normal stress increases. Further, Figures 2 (c) and 2 (f) show that when the soil moisture content is greater than the optimal moisture content, the soil shear stress-displacement curve shows that the soil is hardening. Therefore, it is believed that with the increase of normal stress at the same water content, the internal structure of the soil will also change. For example, Shear shrinkage occurs in the soil [8], so that the stress-strain relationship of the soil gradually changes from softening to hardening. At the same dry density, the larger the water content is, the looser the soil particles are so that the soil is more easily compacted. However, under the condition of low moisture content and high dry density, the normal stress lags significantly when hardening occurs. This is because the internal structure of the soil is relatively stable at this time. Only if the water content exceeds a certain critical value, the internal structure of the soil will change.
3.2 Effect of water content on the shear resistance of silty soil in eastern Henan province

Figure 3 shows the relationship between shear strength and normal stress based on different water contents. For the study of the shear properties of unsaturated sands, our research is similar to that of Cao [8]. Firstly, under the same normal stress, the smaller the water content, the greater the shear strength of the silty soil in eastern Henan. Secondly, at the same dry density, the shear strength increases with the increase of normal stress. Finally, at the same moisture content, the greater the dry density, the greater the shear strength. Figures 4 and 5 show the relationship curves of between water content, and cohesion and internal friction angle. First, Figure 4 shows that the cohesion force is negatively correlated with the increase of water content, and the relationship curve of cohesion force with water content can be fitted as a two-section broken line. More importantly, the turning point of the broken line appears near the optimal moisture content. However, we did not find an obvious law of the influence of dry density on cohesion. It can be clearly seen from Figure 5 that the moisture content has little effect on the internal friction angle at the same dry density. But as the water content increases, the internal friction angle generally decreases. Finally, at the same moisture content, the greater the dry density, the greater the internal friction angle.
3.3. Model prediction

In terms of the previous test results, the shear stress and displacement show the feature of strain hardening. Therefore, the Kondner [10] hyperbolic model in equation (1) is used here to predict the direct shear test results.

$$\tau = \frac{S}{a + bS}$$  \hspace{1cm} (1)

In the formula, $\tau$ is the shear stress and $S$ is the shear displacement; $a$ and $b$ are the coefficients; $E_i = 1/a$ is the initial shear modulus. The value of the hyperbolic asymptote is the final shear stress, which is $\tau_{ult} = 1/b$.

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![Figure 4. Relation curve between water content and cohesion](image1.png)

![Figure 5. Relation curve between water content and internal friction angle](image2.png)

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**Figure 4. Relation curve between water content and cohesion**

**Figure 5. Relation curve between water content and internal friction angle**

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![Experimental data Predictive value](image3.png)

![Experimental data Predictive value](image4.png)

- (a) $\rho_d=1.52g/cm^3$, $w=6.7\%$
- (b) $\rho_d=1.52g/cm^3$, $w=12.7\%$
Figure 6. Comparison of experimental data and prediction values of model under different normal stresses, dry density and water contents

Figure 6 shows the comparison results between the test data and the model predictions at different normal pressures, water contents, and dry densities. The results of Figure 6 (d) show that the predicted value of the hyperbolic model deviates greatly from the test result, but as the normal pressure increases, the predicted value gradually approaches the test result. Although the predicted value of the low normal pressure model also deviates from the test results in Figure 6 (a), it is smaller than that in the case of 6 (d). This is also consistent with the results in Section 3.1. At low water content and high dry density, the hardening phenomenon lags significantly with normal stress. Therefore, under high normal pressure, low density, and large water content, the predicted value of the model is closer to the experimental value.

4. Conclusion

(1) The shear deformation of the soil will gradually change from softening to hardening, with the increase of water content and normal stress. If the dry density increases, this result will be more obvious.

(2) Under the same normal stress, the smaller the water content, the greater the shear strength. In addition, normal stress, dry density, and shear strength have a positive correlation.

(3) The relationship between cohesion and water content changes in a broken line. The turning point may appear near the optimal moisture content. The internal friction angle changes more slightly with the water content, and the greater the dry density, the greater the internal friction angle.

(4) The Kondner hyperbolic model can well predict the results of unsaturated shear silt direct shear tests under different normal pressures, especially under high normal pressure, low density, and large water content. In this case, the model predicted value is closer to the experimental value.
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