Experimental Study on Mechanical Properties of Soft Clay under Different Stress Paths

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Abstract. In actual engineering, when the soil element is subjected to load, the stress state will change accordingly. In this paper, undrained triaxial stress path tests for Ningbo reshaped saturated soft clay under different confining pressures are carried out. The test uses the GDS bidirectional vibrating triaxial instrument. The stress path dependence of saturated soft clay is studied. The stress-strain relationship and undrained shear strength under different stress paths and consolidation pressures can be expressed in hyperbolic form. The initial stiffness Es basically increases with the increase of the deflection angle of the stress path. The test results have certain reference significance for foundation pit and tunnel engineering.

1. Introduction

As a three-phase material of solid, when the soil is deformed by external force, the spatial position of the particles will change, and the contact force and contact mode between the particles will also change accordingly, which not only change the soil, but also affect the stress-strain response of subsequent loading to a certain extent[1]. In practical engineering, the stress state of soil element will change and undergo different static stress paths in the process of deep excavation and tunnel design[2]. Lambe[3] first proposed the concept of stress path, which provided a reasonable method for in-situ and laboratory study of soil properties, and put forward specific steps on how to consider the influence of stress path in...
engineering practice, Ng [4] described in detail the stress path of the soil unit around the pit wall deep excavation engineering, and compared with the actual results. This paper takes Ningbo's remolded saturated soft clay as the research object, and carries out a triaxial stress path tests under undrained conditions. The stress-strain relationship under different stress path conditions is analyzed emphatically.

2. Properties of soil sample
The test soil samples are taken from Ningbo area, the buried depth is about 28.0-30.0m, and the soil samples are dark gray. The basic physical and mechanical properties are shown in Table 1. It can be seen from Table1 that Ningbo soft clay has the characteristics of large void ratio and high moisture content. The compressibility is 0.81MPa-1, and the sensitivity is 3.5-5.0. It shows that Ningbo clay is a medium-sensitive and highly compressible clay.

| Property                              | Value |
|---------------------------------------|-------|
| Severe γ/kN.m⁻³                       | 17.6  |
| Moisture content w/%                  | 43.9  |
| Liquid limit Wl/%                     | 51.5  |
| Plastic limit Wel.%                   | 23.3  |
| Plasticity Index Ip                    | 28.2  |
| Permeability coefficient K’ (10⁻⁸cm/s)| 5.18  |
| Void ratio e                          | 1.25  |
| Unconfined compressive strength qc/kPa| 50    |
| Sensitivity Sr                         | 3.5~5.0|
| Compression factor αs/MPa-1           | 0.81  |

3. Test scheme
In the three-axis axisymmetric space, the changes of the deviator stress \( q \) and the confining pressure \( \sigma_3 \) are respectively \( \Delta q \) and \( \Delta \sigma_3 \), the change of the average principal stress \( \Delta \sigma \) is:

\[
\Delta \rho = \Delta \sigma_3 + \Delta q / 3
\]

Therefore, the slope of the stress path \( \eta \) can be defined as:

\[
\eta = \frac{\Delta q}{\Delta \rho} = \frac{\Delta q}{\Delta \sigma_3 + \Delta q / 3} = \frac{\Delta \sigma_3 - \Delta q}{\Delta \sigma_3 / 3 + 2 \Delta q / 3}
\]

In order to reflect the generality of the path, this paper develops 7 stress paths. There are paths where confining pressure and axial pressure change separately (or at the same time). Define the direction angle of the stress path \( \theta \) as the angle between the total stress path and the positive semi-axis of the P axis.

The specific stress path test plan is shown in figure 1 and table 2.

![Figure 1 The stress paths in p-q space](image)
Table 2  Test program of isotropic consolidation soft clay under different stress paths

| Consolidation pressure $\sigma_0$/kPa | Slope of stress path $\eta$ | Deflection angle $\theta/\pi$ | Way to control | Shear rate | Clipping path | Drainage conditions |
|--------------------------------------|-----------------------------|-------------------------------|-----------------|------------|---------------|---------------------|
| 50/100/150/200                       | 3.0                         | 0.4                           | Strain control  | 0.1%/min   | $\sigma_3^\downarrow, \sigma_1^\uparrow$ | Undrained            |
|                                      | 3.0                         | 0.4                           | Stress control  | 0.25kPa/min| $\sigma_3^\downarrow, \sigma_1^\uparrow$ |                      |
|                                      | 5.0                         | 0.44                          |                |            | $\sigma_3^\downarrow, \sigma_1^\uparrow$ |                      |
|                                      | $\infty$                    | 0.5                           |                |            | $\sigma_3^\downarrow, \sigma_1^\uparrow$ |                      |
|                                      | -5.0                        | 0.56                          |                |            | $\sigma_3^\downarrow, \sigma_1^\uparrow$ |                      |
|                                      | -1.5                        | 0.69                          |                |            | $\sigma_3^\downarrow, \sigma_1^\uparrow$ |                      |
|                                      | -1.0                        | 0.75                          |                |            | $\sigma_3^\downarrow, \sigma_1^\uparrow$ |                      |

The test instrument used in this paper is the saturated-unsaturated dynamic triaxial test system DYNTTS produced by GDS Company, as shown in Figure 2. Its main components include: axial load driver, three-axis pressure chamber, confining pressure control source, back pressure controller and data collector. The whole test system is controlled by GDSLAB software, which can realize automatic data collection and processing.

![GDS bi-directional cyclic triaxial device](image)

The test in this paper uses saturated reshaped specimens to ensure the uniformity of the specimens. The reshaped soft clay sample was prepared by the kneading method, the sample size was 38mm in diameter and 76mm in height. First, the soft clay sample is saturated by the combined method of vacuum pumping and back pressure saturation. Next, all specimens are consolidated isotropically under a certain confining pressure. When the excess pore water pressure is completely dissipated, the soil sample is considered to be consolidated. At this time, the effective confining pressure applied to the sample is 50, 100, 150, and 200 kPa, respectively. Finally, keep the undrained state and perform undrained shearing according to the set stress path. The test stops when the sample is broken or the confining pressure is unloaded to the back pressure. When the stress-strain curve has a peak, the undrained shear strength is the peak strength. When there is no peak, take the axial deflection stress at the end of the test as the undrained shear strength.

The GDS bi-directional dynamic triaxial test system has two independently controlled variables, that is, the specimen can be loaded by applying confining pressure and axial deflection stress respectively.
Corresponding to the different loading methods of confining pressure $\sigma_3$ and axial stress $\sigma_1$ for different stress paths in Table 2.

4. Analysis of test results

The deformation law of Ningbo reshaping soft clay under the same consolidated confining pressure and different shear stress paths is shown in Figure 3. Some of the curves are relatively close and are marked with red curves. It can be seen from the figure that the soil sample undergoes different shear stress paths after the isotropic consolidation is completed. The deviator stress changes with the axial strain similarly, showing a strain hardening law. It shows that the soil has not entered an obvious failure stage, and the strength of the soil sample will continue to increase with the accumulation of strain after the deformation reaches the yield $^{[221, 226, 227]}$.

When the axial strain $\varepsilon < 2\%$, the deviator stress increases rapidly with the increase of the axial strain, and the shear stress path has little effect on the strength of the specimen. The stress-strain curves corresponding to different $\eta$ basically overlap. When the axial strain $\varepsilon > 2\%$, the stress-strain curves corresponding to different $\eta$ gradually separate. The soil samples under different shear stress paths show different failure strengths.

Figure 3  Relationships between stress and strain under different stress paths

It can be seen from the above figure that the stress-strain curves of saturated remolded soft clay under different stress paths and consolidation pressures are basically the same. The curve can be expressed in hyperbolic form, and the expression is:

$$q = \frac{\varepsilon}{a \varepsilon + b}$$  \hspace{1cm} (3)
In the formula, a and b are fitting parameters. Further analysis shows that the parameters a, b are related to the initial elastic modulus $q_u$ and ultimate strength $E_0$ of the soil, which are specifically

$$q_u = \lim_{\varepsilon \to \infty} \frac{1}{a + b/\varepsilon} = \frac{1}{a}$$  \hspace{1cm} (4)

$$E_0 = \lim_{\varepsilon \to 0} \frac{1}{a \varepsilon + b} = \frac{1}{b}$$  \hspace{1cm} (5)

Fitting the stress-strain curves under different stress paths and consolidation pressures, the values of the stress-strain curve fitting parameters a and b can be obtained, as shown in table 3. It can be seen from table 3 that the correlation coefficient $R^2$ is above 0.95.

Table 3: Fitting parameters under different stress paths and consolidate confining pressure

| Consolidation pressure $\sigma'_c$/kPa | Slope of stress path $\eta$ | Fitting parameters $a$ | Fitting parameters $b$ | Initial stiffness $E_0 = 1/b$ (MPa) | Ultimate strength $q_u = 1/a$ (kPa) |
|---------------------------------------|-----------------------------|------------------------|------------------------|--------------------------------------|-------------------------------------|
| 50                                    | -1.0                        | 0.0273                 | 0.0059                 | 0.989                                | 168.21                              | 36.67                               |
|                                       | -1.5                        | 0.0224                 | 0.0107                 | 0.969                                | 93.56                               | 44.72                               |
|                                       | -5.0                        | 0.0160                 | 0.0230                 | 0.957                                | 43.41                               | 62.40                               |
|                                       | $\infty$                    | 0.0156                 | 0.0303                 | 0.957                                | 32.99                               | 63.94                               |
|                                       | 5.0                         | 0.0155                 | 0.0211                 | 0.952                                | 47.30                               | 64.72                               |
|                                       | 3.0                         | 0.0151                 | 0.0271                 | 0.961                                | 36.94                               | 66.03                               |
|                                       | -1.0                        | 0.0127                 | 0.0094                 | 0.997                                | 106.55                              | 78.85                               |
|                                       | -1.5                        | 0.0111                 | 0.0097                 | 0.971                                | 102.69                              | 90.34                               |
|                                       | -5.0                        | 0.0097                 | 0.0126                 | 0.973                                | 79.24                               | 103.27                              |
|                                       | $\infty$                    | 0.0105                 | 0.0118                 | 0.973                                | 84.79                               | 95.62                               |
| 100                                    | 5.0                         | 0.0089                 | 0.0155                 | 0.984                                | 64.42                               | 112.78                              |
|                                       | 3.0                         | 0.0091                 | 0.0155                 | 0.979                                | 64.71                               | 109.82                              |
|                                       | -1.0                        | 0.0090                 | 0.0043                 | 0.992                                | 233.84                              | 111.50                              |
|                                       | -1.5                        | 0.0073                 | 0.0101                 | 0.989                                | 99.41                               | 137.89                              |
|                                       | -5.0                        | 0.0068                 | 0.0092                 | 0.985                                | 109.15                              | 146.84                              |
|                                       | $\infty$                    | 0.0063                 | 0.0093                 | 0.986                                | 107.85                              | 158.16                              |
|                                       | 5.0                         | 0.0061                 | 0.0090                 | 0.987                                | 111.65                              | 163.68                              |
|                                       | 3.0                         | 0.0065                 | 0.0110                 | 0.989                                | 90.91                               | 152.76                              |
|                                       | -1.0                        | 0.0062                 | 0.0057                 | 0.998                                | 173.95                              | 162.47                              |
|                                       | -1.5                        | 0.0058                 | 0.0055                 | 0.984                                | 182.15                              | 173.10                              |
|                                       | -5.0                        | 0.0054                 | 0.0067                 | 0.989                                | 150.21                              | 184.77                              |
|                                       | $\infty$                    | 0.0042                 | 0.0092                 | 0.996                                | 109.09                              | 238.32                              |
|                                       | 5.0                         | 0.0041                 | 0.0060                 | 0.994                                | 167.27                              | 242.17                              |
|                                       | 3.0                         | 0.0051                 | 0.0069                 | 0.989                                | 145.58                              | 195.74                              |

Further analyze the relationship between initial stiffness, ultimate strength, consolidated confining pressure and stress path, as shown in Figures 4 and 5. The stress path deflection angle $\theta/\pi$ is used to characterize the change of the stress path. It can be seen from Figure 4 that the ultimate strengths corresponding to different stress paths are inconsistent under the same consolidated confining pressure. Specifically, in the test range of $0.4 \leq \theta/\pi \leq 0.5$, as the deflection angle of the stress path increases, the ultimate strength $q_u$ also increases, and reaches a peak in this range. When $\theta/\pi \geq 0.5$, the ultimate strength of the soil gradually decreases with the increase of the deflection angle of the stress path. In addition,
under the same stress path deflection angle, the ultimate strength of the soil increases with the increase of the consolidation pressure.

It can be seen from Figure 5 that the initial stiffness corresponding to different stress paths under the same consolidation confining pressure has no obvious law of consistency with the change of the deflection angle of the stress path. But generally speaking, the initial stiffness $E_0$ basically increases with the increase of the deflection angle of the stress path. The greater the deflection angle of the stress path, the greater the difference between the consolidation stress path of the soil and the undrained shear stress path, that is, the greater the anisotropy of the soil due to static loading\(^1\). Therefore, it can be inferred that the main reason for the difference of the initial modulus under different stress paths is the anisotropy caused by the shear loading. In addition, when the deflection angle of the stress path is the same, the initial stiffness of the soil is basically positively correlated with the consolidation stress.

5. Conclusion

This paper conduct static shear tests on the Ningbo saturated remolded soft clay specimens under isotropic consolidation conditions, and the static characteristics of the soil under different stress paths are studied. Get the following conclusions:

The stress-strain relationships of different stress path tests all show obvious nonlinear characteristics, and they are basically strain hardening. The undrained shear strength of the soil obtained under different stress paths is different.

The strength curve of saturated soft clay is related to the stress path. The stress-strain curve of saturated remolded soft clay under different stress paths and consolidation pressures can be expressed in hyperbolic form. In the test range of $0.40 \leq \theta/\pi \leq 0.75$, as the deflection angle of the stress path increases, the ultimate strength $q_u$ first increases and then decreases. On the other hand, in general, the initial stiffness $E_0$ basically increases with the increase of the deflection angle of the stress path, which may be due to the anisotropy caused by shearing along different stress paths.
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