Comparison of strength of artificially frozen soil in two test modes

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ABSTRACT: Based on triaxial tests on frozen sandy soil under various stress histories of axial loading and radial unloading, it is found that the stress-strain curves have the shape of a hyperbola for both test modes. The yield strength following the FC preparation process (first freezing and then isotropic consolidation) is less than that obtained from preparation via the K₀DCF preparation process (first K₀ drained consolidation and then freezing). The failure strain is greater for the FC preparation mode than for the K₀DCF mode under axial loading and is less than for the K₀DCF mode under radial unloading. The failure envelopes all accord with the Mohr-Coulomb criterion, within the range of confining pressures. Regardless of state of axial loading or radial unloading, the shear strength following the K₀DCF preparation mode is greater than that due to the FC mode, and with increase of normal stress $\sigma$, the difference of the shear strength between axial loading and radial unloading in the K₀DCF mode is less than that in the FC mode.

1 INTRODUCTION

With the extensive use of artificial ground freezing technology in the construction of mines and deepening of sinking shafts, many engineering accidents occur. Many researchers have realized that traditional theories of frozen soil mechanics are not suitable for evaluating the stability of frozen soil structures in deep alluvium (Chamberlain et al. 1972, Sayles 1973, Jones & Parameswaran 1983, Ma et al. 1995, 1999). A study of the mechanical response of frozen deep alluvium deposits must be carried out, and the testing methodology will have to be improved (Cui 1998).

Modelling the response of soil frozen due to artificial ground freezing should allow first for consolidation, followed freezing under this initial consolidation pressure (called the K₀DCF process), and then unloading. This differs from traditional testing methods used for frozen soil, that is the sample is frozen first under zero load, and then testing is carried out after consolidation (called the FC process). The research has shown that the yield strength of frozen soil varies according to these preparation methods (Li et al. 1993, Ma et al. 2000). Many research results have been obtained based on the traditional test methods of frozen soil mechanics, but is there a relationship to be found between the K₀DCF process and the FC process so that research results from the FC process can be applied directly to research of the K₀DCF process? This paper will probe into differences in the yield strength and deformation behaviour following the K₀DCF and the FC preparation processes through triaxial tests on frozen sandy soil under various stress histories of axial loading and radial unloading.

2 PREPARATION OF SPECIMENS AND TEST PROCESS

The material used in these tests was a sandy soil from Lanzhou and the main physical parameters are listed in Table 1. The specimen was cylindrical: 6.18 cm in diameter and 12.5 cm in height. The pre-consolidation water content ($w_0$), bulk density ($\gamma_0$), saturation ratio ($S_s$) and void ratio ($e$) of the specimens were 10.5%, 2000 kg/m³, 0.894, 0.325 respectively.

The pressure chamber contained a loading frame and control system, which was able to consolidate soil under K₀ conditions at high pressure and low temperature. This was developed by our laboratory, with the greatest confining pressure at 15 MPa and the lowest temperature at $-60^{°}$C. Tests were conducted on an MTS-810 triaxial test machine that can control confining pressure and axial stress synchronously with the greatest axial load of 20 T and confining pressure of 40 MPa. The test pattern is axi-symmetric. Test temperature is $-5^{°}$C and the test confining pressure ranges from 1 to 5 MPa.

2.1 K₀ drained consolidation and then freezing (K₀DCF)

The coefficient of lateral earth pressure K₀ = 0.32 for Lanzhou sandy soil was obtained from an earlier test

Table 1. Basic physical properties of sandy soil from Lanzhou.

<table>
<thead>
<tr>
<th>Composition of grains/%</th>
<th>Specific gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;0.5 mm</td>
<td>0.5—</td>
</tr>
<tr>
<td>0.05 mm</td>
<td>0.05—</td>
</tr>
<tr>
<td>0.005 mm</td>
<td>&lt;0.005 mm</td>
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<tr>
<td>25.6</td>
<td>54.23</td>
</tr>
<tr>
<td>8.04</td>
<td>12.13</td>
</tr>
<tr>
<td>12.13</td>
<td>2.46</td>
</tr>
</tbody>
</table>
series (Ma & Chang 2001). The prepared unfrozen sample was placed into the pressure chamber and the confining pressure $\sigma_3$ was kept constant, while the axial stress $\sigma_1 = \sigma_3/K_0$ was determined, then the consolidating stress rates were controlled at $10 \times 10^{-5}\text{MPa/s}$ for $\sigma_1$ and $3.2 \times 10^{-5}\text{MPa/s}$ for $\sigma_3$ in order to reach the desired stress at the same time for $\sigma_1$ and $\sigma_3$. When no further drainage was measured, the drainage valve was closed, and then the load was kept constant and the temperature was quickly dropped to $–5^\circ\text{C}$ in order to simulate the consolidating and freezing processes of a foundation. After maintaining the test temperature for 12 h, the shear tests were conducted under undrained conditions with either $\sigma_1$ loading or $\sigma_3$ unloading. The loading and unloading rate is $10^{-5}\text{MPa/s}$ (shown in Figs 1a, b).

2.2 Freezing and then consolidation (FC)

This is the conventional test method in mechanics of frozen soil. The prepared specimen was frozen first to $–5^\circ\text{C}$ under zero load. After maintaining the test temperature for 12 h, the specimen was consolidated under isobaric load (confining pressure). After the deformation ceased changing, the shear tests were conducted under undrained conditions with either $\sigma_1$ loading or $\sigma_3$ unloading. The rate of loading and unloading is $10^{-5}\text{MPa/s}$ (shown in Figs 1c, d).

3 ANALYSES OF RESULTS AND DISCUSSION

3.1 Deviator stress-axial strain curves

The deviator stress $(\sigma_1 - \sigma_3)$-axial strain $(\varepsilon_1)$ curves of frozen soil at different confining pressures and under different test modes are shown in Figure 2. $\varepsilon_1$ is shown negative just on this plot, so that the response can be clearly differentiated from the stress paths. Elsewhere $\varepsilon_1$ is shown positive. It can be seen that, except for an initial set of curves (consolidation set), all of the deviator stress-axial strain curves show more or less similar shapes for the different stress paths, which approximate either to a hyperbola, but their deformation processes are different. For $K_0\text{DCF}$ samples, the deviator stress-axial strain curve is similar to an ideal linear elastic response, when the deviator stress is less than the yield strength. When the deviator stress is greater than the yield strength, the deviator stress remains nearly constant with increase of the axial strain for $\sigma_1$ loading whereas for $\sigma_3$ unloading, they show that the process is a strain hardening one: strain increases with increase of stress and the larger the confining pressure is, the more intense the strain hardening is. The converse appears to be true for the FC

Figure 1. Testing process: stress paths and axial strain versus time ($1-\sigma_1$, $2-\sigma_3$, $3-\varepsilon_1$).
Because of the different initial consolidating processes, the net strain for the K0DCF process is obviously greater than that for the FC process. But the relative density of the sample prior to shearing has shown markedly different responses for initially denser samples (Figs 1a, b) in comparison with the looser samples (Figs 1c, d). This paper is aimed at mainly discussing deformation processes after consolidation, so the following section considers this aspect only.

### 3.2 Yield strength and threshold strain

The point that corresponds to the sudden reduction of stiffness was defined as representing yielding of the frozen soil. The stress corresponding to this point is the yield strength \((\sigma_1 - \sigma_3)_y\) of the frozen soil. The threshold strain is defined as the strain at this point minus the initial strain after consolidation.

The relationship between the yield strength and confining pressures is almost linear under both test preparation modes and for both stress paths (shown in Fig. 3), and the yield strength increases with increasing confining pressure. The yield strength for samples prepared by the FC process is obviously less than for those prepared by the K0DCF process. The yield strength under unloading is less than that under loading for the FC test mode and the difference tends to become larger with increasing confining pressure. Similarly, the relationship between the threshold strain at the beginning of yielding and confining pressures is also linear for both test modes and for both stress paths (shown in Fig. 4) and the failure strain increases with increasing confining pressure, but they show different change processes in comparison with the yield strength. In the K0DCF preparation mode, the threshold strain under both stress paths are approximately the same. In the FC preparation mode, the threshold strain under unloading is greater than that under loading, meanwhile, the threshold strain is greater than that for the K0DCF process under

![Figure 2. Curves of stress-strain in frozen sandy soil during the whole deformation process (1: \(\sigma_1 = 1\) MPa, 2: \(\sigma_3 = 2\) MPa, 3: \(\sigma_3 = 3\) MPa, 4: \(\sigma_3 = 5\) MPa).](image)

![Figure 3. Relationship between yield strength and confining pressures.](image)
unloading and is less than that for the KDCF process under loading.

In the KDCF preparation mode, the relationship between the yield strength \( \sigma_{1y} \), the threshold strain \( \varepsilon_{1y} \) and confining pressures \( \sigma_3 \) can be given by following equations respectively:

\[
(\sigma_1 - \sigma_3)_y = k_1 \sigma_3 + c_1 \tag{1}
\]

\[
\varepsilon_{1y} = k_2 \sigma_3 + c_2 \tag{2}
\]

where \( k_1 \), \( k_2 \), \( c_1 \) and \( c_2 \) are test coefficients, respectively, which become for unloading, \( k_1 = 2.41 \), \( c_1 = 0.87 \) and for loading \( k_1 = 1.88 \), \( c_1 = 0.78 \). The values for Equation 2 become \( k_2 = 0.21 \), \( c_2 = 0.57 \) for both loading and unloading.

In the FC preparation mode, the relationship between the yield strength \( (\sigma_1 - \sigma_3)_y \), the threshold strain \( \varepsilon_{1y} \) and confining pressures \( \sigma_3 \) can be given by the following equations respectively:

\[
(\sigma_1 - \sigma_3)_y = k_3 \sigma_3 + c_3 \tag{3}
\]

\[
\varepsilon_{1y} = k_4 \sigma_3 + c_4 \tag{4}
\]

where \( k_3 \), \( k_4 \), \( c_3 \) and \( c_4 \) are test coefficients, respectively. For loading, \( k_3 = 1.337 \), \( k_4 = 0.42 \), \( c_3 = 1.22 \), \( c_4 = 1.22 \) and for unloading \( k_3 = 0.69 \), \( k_4 = 0.15 \), \( c_3 = 0.064 \), \( c_4 = 0.43 \).

Let \( \Delta(\sigma_1 - \sigma_3)_y \) and \( \Delta \varepsilon_{1y} \) express the difference respectively between the yielding strength and the threshold strain for both preparation modes. According to Equations 1, 2, 3 and 4, we can obtain:

\[
\Delta(\sigma_1 - \sigma_3)_y = k_5 \sigma_3 + c_5 \tag{5}
\]

\[
\Delta \varepsilon_{1y} = k_6 \sigma_3 + c_6 \tag{6}
\]

where, for loading, \( k_5 = 1.07 \), \( k_6 = -0.21 \), \( c_5 = -0.35 \), \( c_6 = -0.65 \) and for unloading, \( k_5 = 1.19 \), \( k_6 = 0.06 \), \( c_5 = 0.716 \), \( c_6 = 0.14 \).

3.3 Yield criterion

The failure envelopes for the frozen soil for both preparation modes and various stress states are shown in Figure 5. The failure envelopes all accord with Mohr-Coulomb’s failure criterion within the range of confining pressure in these tests, namely:

\[
\tau = c + \sigma \tan \phi \tag{7}
\]

where, \( \tau \) is the shear strength (MPa), \( \sigma \) is the normal stress (MPa), \( c \) is the cohesion (MPa), \( \phi \) is the angle of internal friction (°). These are expressed here in terms of total stresses since it is impossible to determine the pore pressures.

Following the KDCF preparation mode, for which consolidation pressure has been applied to the specimen before freezing, the sample has experienced a stress history with higher initial density than for the FC preparation mode and the tangent to the Mohr’s Circle is defined by \( c = 0 \) MPa, \( \phi = 31.4^\circ \). For the \( \sigma_1 \) loading state at failure, \( c = 0.2 \) MPa, \( \phi = 31.7^\circ \) and for the \( \sigma_3 \) unloading state, at failure \( c = 0.4 \) MPa, \( \phi = 33.7^\circ \). For the same initial stress state, \( c \) and \( \phi \) failure on the unloading stress path are obviously larger than those for the loading stress path. Compared with the initial stress state, \( c \) is larger and \( \phi \) does not vary

![Figure 4](image1.png)

Figure 4. Relationship between threshold strain at the beginning of yielding and confining pressures.

![Figure 5](image2.png)

Figure 5. Mohr’s envelopes for the frozen soil.
much for the $\sigma_1$ loading state, $c$ and $\phi$ are notably larger than for the initial stress state for the $\sigma_3$ unloading stress path.

For specimens frozen under zero load in the FC preparation mode, an isotropic initial stress state exists so that the deviator stresses are zero. In the $\sigma_3$ unloading state, $c = 0$ MPa, $\phi = 14.6^\circ$ and in the $\sigma_1$ loading state, $c = 0.5$ MPa, $\phi = 22.7^\circ$. The $c$, $\phi$ at loading is greater than that at unloading and with increasing $\sigma$, the difference of $\tau$ at loading and unloading increases gradually.

In comparison with both test modes, it can be found that regardless of whether the stress path follows $\sigma_1$ loading or $\sigma_3$ unloading, $\tau$ for the K$_0$DCF preparation process is always greater that for the FC preparation process and the difference between $\tau$ at loading and unloading for the K$_0$DCF preparation process is less than that for the FC preparation process. Maybe this is the result caused by the initial deviatoric stress state, which has been “locked in” during the K$_0$ consolidation prior to freezing, together with the initially dense state of the sample. Let $\Delta \tau$ express the difference in the shear strength $\tau$ between both preparation modes, so:

$$\Delta \tau = \Delta c + \sigma \Delta \tan \phi$$

(8)

Here, $\Delta c$ and $\Delta \tan \phi$ are the difference between the cohesion and the coefficient of internal friction for both preparation modes, respectively. For the $\sigma_1$ loading state, $\Delta c = -0.1$ MPa, $\Delta \tan \phi = 0.25$ and for the $\sigma_1$ unloading state $\Delta c = 0.2$ MPa, $\Delta \tan \phi = 0.36$. So, the shear strength in both preparation modes can be linked together by Equation 8.

4 CONCLUSIONS

1) Except for the initial set of curves (consolidation), all the deviator stress-axial strain curves show more or less similar shapes, either of a hyperbola or a bi-linear plot, but their deformation processes are different. In some cases, the deviator stress-axial strain curve is similar to an ideal linear elastic response, otherwise the process is a strain hardening one.

2) The relationship between the yield strength and confining pressures is linear. The yield strength for the FC preparation process is less than that for the K$_0$DCF process. For both preparation modes, the yield strength under $\sigma_3$ unloading is less than that under $\sigma_1$ loading and the difference becomes larger with increasing confining pressure.

3) The relationship between the threshold strain and confining pressures is also linear under both test modes and for both stress paths. In the K$_0$DCF preparation mode, the threshold strain is the same for both stress paths. In the FC preparation mode, the threshold strain under $\sigma_1$ loading is obviously greater than that under $\sigma_3$ unloading, meanwhile, the threshold strain is greater than that for the K$_0$DCF process under $\sigma_1$ loading and is less than that for the K$_0$DCF process under $\sigma_3$ unloading.

4) The failure envelopes all accord with Mohr-Coulomb’s failure criterion within the range of confining pressures applied here. The $c$ and $\phi$ mobilised at failure for the $\sigma_1$ loading path are larger than those for the $\sigma_3$ unloading path. The $\tau$ for the K$_0$DCF preparation process is always greater than that for the FC preparation process and the difference between $\tau$ for $\sigma_1$ loading and for $\sigma_3$ unloading for the K$_0$DCF preparation process is less than that for the FC preparation process.

5) If the yield strength, the threshold strain and the shear strength are known for one of the test modes, we can obtain the yield strength, the failure strain and the shear strength for another test mode by using Equations 5, 6 and 8.

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