Experimental Study on Deformation and Strength Characteristics of Undisturbed Loess Foundation under High Fill

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ABSTRACT: Based on consolidation compression, creep and tri-axial tests on undisturbed loess, the paper studies its deformation and strength characteristics at high pressure and mainly draws the following conclusions: reduction of load increment or increase of moisture content may improve the compressibility of soil; creep deformation of undisturbed loess has a constant-speed growth trend at high pressure; a stress-strain-time formula in the exponential function form is put forward; the stress-strain relationships of saturated loess and unsaturated loess at high pressure are respectively softening and hardening, and along with increase of confining pressure, the softening or hardening degree is increasing; and the strength of undisturbed loess at high confining pressure shows obvious non-linearity; the breakage mechanism of undisturbed loess at high confining pressure is analyzed under the frame of breakage mechanics for geological materials.

KEYWORDS: High pressure; Undisturbed Loess; Deformation; Strength

INTRODUCTION

Northern Shaanxi is a main part of Loess Plateau of China, dominated by hills and gullies. With great emergence of high fill projects in this region in recent years, however, during project construction, undisturbed loess under high fill substantially finishes primary consolidation deformation in the construction stage, but much post-construction creep deformation caused by high gravity stress after completion of project construction will last for years or even decades, directly affecting the use of structures above; and meanwhile, as most high fill bodies are about dozens or hundreds of meters in height, undisturbed loess under high fill is at a high-stress level, and the stress-strain and strength characteristics of soils in high stress and low stress are obviously different.

The paper launched a high-pressure consolidation compression test of undisturbed loess under different load increments and moisture contents to study its consolidation compression characteristic and also to study its high-pressure creep characteristic. Meanwhile, a consolidation undrainage test
on high-stress saturated undisturbed loess and a tri-axial shear test on unsaturated loess are conducted to study the stress-strain relationship and the strength characteristic of undisturbed loess at high pressure.

1. Compressive Deformation Characteristic

1.1 Sample Property and Test Scheme

The test takes undisturbed loess of Yan’an New District, Shanxi as the soil sample. The basic physical indexes of the loess are determined through basic laboratory soil tests, see table 1.

In order to systematically study the load increment (the difference between the next load and the previous load) and the compressive deformation characteristic of undisturbed loess with different moisture contents to acquire the influencing rules of undisturbed loess on the stability of the whole high fill foundation, the paper carries out laboratory compression tests, please see table 2 and table 3 for detailed test schemes.

The test instrument is a WG single-lever high-pressure consolidation apparatus, and the samples are 30 cm² * 2 cm in size. The loading time of each stage of load is 24 h. In the test process, a wet towel is wrapped around a pressure cell to reduce moisture evaporation so as to guarantee the result accuracy of the whole test, and all the samples are pre-pressed at 25 kPa.

1.2 Analysis on Consolidation Test Data

Through the laboratory high-pressure consolidation compression test on the undisturbed loess, e-p and e-lg(p) curves under different load increments and different moisture contents are obtained and shown in FIG.1 and FIG.2. The compression indexes are shown in table 4.

According to the FIG.1, changes of the compression curves of the loess are broadly divided into three stages (Shen 1998): firstly, the void ratio changes slowly, then accelerates and finally tends to be stable. The reason is that undisturbed loess is an under-consolidated clay soil with high structural strength, in the initial stage, most of the vertical load is born by the bonding strength between soil particles, and the soil particles are difficult to move; however, the
bonding function between the soil particles is destroyed along with increase of load, and the soil particles start to move to voids, manifested in quick reduction of the void ratio; and when the load increases to a certain degree, the macro-void characteristic of the loess no longer exists, movement of the soil particles is blocked to decrease by the frictional force between the particles, manifested in slowing of reduction of the void ratio, and at the moment, the compression property of the loess is approximate to that of disturbed soil.

Table 4. Compression Index.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>1#</th>
<th>2#</th>
<th>3#</th>
<th>4#</th>
<th>5#</th>
<th>6#</th>
<th>7#</th>
<th>8#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression Coefficient $\alpha_{e-p}(\text{MPa}^{-1})$</td>
<td>1.14</td>
<td>1.105</td>
<td>1.05</td>
<td>0.74</td>
<td>1.12</td>
<td>1.21</td>
<td>1.33</td>
<td>1.71</td>
</tr>
<tr>
<td>Compression Index $C_e$</td>
<td>0.378</td>
<td>0.367</td>
<td>0.348</td>
<td>0.245</td>
<td>0.372</td>
<td>0.402</td>
<td>0.442</td>
<td>0.568</td>
</tr>
</tbody>
</table>

According to the FIG.1 and the table 4, we find that soil used in the test is high-compressibility soil. Along with reduction of the load increment, the soil shows higher compressibility, and the compression coefficient under the load increment of 25 kPa is about 1.54 times of that under the load increment of 150 kPa. In the same stress level, the smaller the load increment in the loading process is, the denser the soil can be compressed. In the perspective of the stability of high fill foundation, once permitted by the project time limit, the cost, etc., the height of placement in layers should be reduced as much as possible to improve the overall stability of the hill fill foundation, providing a guarantee for normal use of high fill foundation.

According to the FIG.2, the compression curves under different moisture contents are also in three stages. Owing to obvious difference between the compression curves under the different moisture contents, the existence of water in soil is a key factor that influences the consolidation compression
characteristic of loess. Long with increase of the moisture content, the compressibility of structural loess becomes higher and higher, the compression index under the moisture content of 24.1% is about 1.53 times of that under the moisture content of 7.9%. Through analysis, the reason is that loess particles are connected mainly through the bonding action, while the increase of water weakens the bonding action between soil particles, and generally speaking, the higher the moisture content is, the stronger the compressibility is. Therefore, in the filling process of high fill foundation, changes of the moisture content of the original foundation should be monitored in real time, and further the compressibility of the original foundation is judged to provide references for follow-up filling construction.

2 Analysis on Creep Characteristic

In order to study the high-pressure creep characteristic of undisturbed loess, high-pressure creep tests at 1,000 kPa, 1,600 kPa and 3,200 kPa are carried out for 667 h by creep under respective loading. Results of the creep tests are handled to obtain time-stress-strain curves as FIG. 3.

From the FIG.3, we find that T-ε curves at different stresses have large instant elastic-plastic strain, along with time increase, the strain of soil is substantially in linear variation, manifested in obvious constant-speed creep process, and strain increases along with improvement of the stress level. Meanwhile, we find that creep strain at all stress levels is large in proportion, so this kind of deformation should be drawn into consideration in deformation calculation and control of high fill foundation to avoid adverse impact on a project due to overlarge creep deformation in the later period.

Through analysis on the obtained creep curve, the paper finds that it more conforms to exponential function, and therefore defines an equation for describing the loess creep characteristic as follows:

\[ \varepsilon(t) = \varepsilon_0 + 1 - e^{-\alpha t^b} \]  

(1)
Wherein $\varepsilon_0$ is initial strain, and $a$ and $b$ are parameters.

Fitting of the test creep curve is performed according to the above formula to determine the values of $a$ and $b$ in different stress levels and analysis is made to find that the values of $a$ and $b$ and the stress levels meet the formula below:

$$
a = \alpha (\sigma - \beta)^{\eta} \\
b = \mu (1 + \sigma)^{\zeta}
$$

Substituting them into the formula (1) gives:

$$
\varepsilon(t) = \varepsilon_0 + 1 - \exp(-\alpha (\sigma - \beta)^{\eta} * t^\mu (1+\sigma)^{\zeta})
$$

The above formula is the strain-time-stress relationship of undisturbed loess, wherein $\varepsilon_0$ is initial strain, $\sigma$ is vertical stress born by soil, $\alpha, \beta, \eta, \mu, \zeta$ are all test parameters, and all can be obtained through fitting of test curves.

![Graph](image.png)

**Figure 4. Comparison between Test Data and Fitting Curve.**

The above formula is written into origin software for fitting the curves at all pressures. Through comparison between the test data and the fitting curve (see FIG. 4), we find that the fitting curve and the test data are basically the same, illustrating that the provided loess stress-strain-time formula can reasonably describe the high-pressure creep characteristic of undisturbed loess.

3 Tri-axial Test on Structural Loess

3.1 Sample Preparation

Tri-axial test takes undisturbed loess as soil sample with the basic indexes shown in the table 1 and the dimension of 39.1 mm * 80 mm, and the sample preparation process is in strict accordance with the soil test standards. A saturated soil sample is prepared by placing a soil sample in a vacuum saturator to be saturated for at least 24 h; and an unsaturated soil sample is directly prepared by cutting an undisturbed soil sample. The test apparatus is TSZ-3 strain-controlled high-pressure tri-axial apparatus of which the highest applicable confining pressure is 2,000 kPa.

3.2 Test Scheme

In the test, consolidated undrained test on saturated undisturbed loess is performed at first at the initial consolidation confining pressures of 200, 400, 800 and 1,000 kPa, and the strain rate of 0.08 mm/min in the shearing process; and after that, unconsolidated undrained shearing test on unsaturated loess is performed at the confining pressures of 200, 300, 400, 800, 1,000 and 1,200 kPa and the strain rate of 0.1 mm/min in the shearing process.
3.3 Analysis on Stress-Strain Relationship Curve

Based on consolidated undrained tri-axial test on laboratory saturated undisturbed loess, stress-strain curves and pore pressure-strain curves are drawn as FIG. 5. According to the FIG. 5, the stress-strain curves at different confining pressures are softening, but the softening degrees at the confining pressures are somewhat different: at post-peak of deviatoric stress at the confining pressure of 200 kPa, the deviatoric stress decreases at a low rate along with increase of axial strain, manifested in weak softening; at the confining pressures of 400 kPa and 800 kPa, the stress decreases at a high speed after soil reaches the stress peak, but finally keeps stable, manifested in stable softening; and at the confining pressure of 1,000 kPa, the stress post-peak curve falls extremely quickly, manifested in strong softening.

![Graph](image)

**Figure 5.** Consolidated Undrained Tri-axial Test Curves of Saturated Loess.

From the perspective of breakage mechanics for geological materials (Shen et al., 2004), the paper analyzes the causes that lead to softening and different softening degrees of saturated undisturbed loess. In the early stage of shearing of saturated undisturbed loess, stress of soil is mainly taken on by bonding strength, and therefore, the deviatoric stress is increased; and along with constant shearing, bonding and arrangement of soil are destroyed, and structural brittle failures of soil are caused, reducing the capability of structurally playing the role of resisting external load, besides, due to possible destroy of the soil particles per se in the shearing process and the “lubrication” function of water in soil, the frictional force between soil particles is reduced, and accordingly, the bearing capacity of the frictional part in compensating for the structural breakage part is weakened. Meanwhile, the increase of confining pressure may increase the breakage ratio of soil particles to further weaken the compensating capability of frictional force, manifested in different softening degrees, that is, the higher the confining pressure is, the higher the softening degree is.

Based on unconsolidated undrained shearing test on unsaturated loess, curves of stress-strain relationship at different confining pressures are drawn as FIG. 6.
According to the FIG. 6, we find that the stress-strain curves of unsaturated loess are all of strain hardening type but the hardening degrees at the confining pressures are somewhat different: the stress-strain curves are of weak hardening type at low confining pressures (200, 300 and 400 kPa), and are of strong hardening type at high confining pressures (800, 1000 and 1,200 kPa). The main cause of the difference of the hardening degrees is that $Q_4$ loess has high structural strength under the condition of low moisture content, and when the whole confining pressure is smaller than or equal to the structural strength, applying of the confining pressure causes almost no breakage of the whole loess structure, and then weak hardening is shown in the shearing process; however, when the confining pressure is bigger than the structural strength, internal breakage of soil has been caused during applying of the confining pressure, the breakage degree becomes higher and higher along with increase of the confining pressure, and the mechanical property of the whole undisturbed loess develops to compaction disturbed loess, that is, strong hardening is shown in the shearing process.

3.4 Strength Characteristic

Based on laboratory tri-axial test, the test data are processed, and curves of relationship between the maximum shearing stress $\tau_{\text{max}}$ and the average stress $(\sigma_1+\sigma_3)/2$ are drawn as FIG.7. According to the FIG.7, the shearing strengths of undisturbed loess have similar variations under different conditions: along with increase of confining pressure, the shearing strength of soil has a growing trend all the time, and changes non-linearly on the whole, and at the moment, the linear Mohr-Coulomb Intensity Criterion is not applicable any more.

According to the viewpoint of breakage mechanics for geological materials, the shearing strength of structural soil is mainly provided by bonding strength and frictional strength, and when the confining pressure is smaller than the structural strength, the bonding strength is substantially in charge of providing the shearing strength in the early stage of shearing and is replaced with frictional strength between soil particles in the later stage; and when the confining pressure is higher than the structural strength, the bonding strength of soil has been destroyed, the undestroyed bonding strength and the frictional strength are primarily in charge of providing the shearing strength in the early stage, and in the later stage, friction between the soil particles completely takes on it. However, the shearing strength of disturbed soil is mainly provided by frictional strength, and it is precisely the mechanism difference of the shearing strength that causes non-linearity of the shearing strength of structural loess.
CONCLUSIONS

(1) Based on high-pressure consolidation tests under different load increments and moisture contents, we find that the compression curves of undisturbed loess are in three stages; the compressibility of soil becomes higher and higher along with reduction of the load increment or increase of the moisture content.

(2) Based on high-pressure creep test at different stress levels, creep deformation of undisturbed loess at high pressure increases at constant speed, and the initial creep strain becomes bigger and bigger along with improvement of the stress level; and the stress-strain-time formula in the exponential function form is put forward and its rationality is verified by tests.

(3) Based on laboratory high-pressure tri-axial test, we find that the stress-strain relationships of saturated and unsaturated loess at high pressure are respectively softening and hardening, and the softening or hardening degree increases along with increase of the confining pressure; the strength of undisturbed loess at high confining pressure shows obvious non-linearity; and the breakage mechanism of undisturbed loess at high confining pressure is analyzed under the frame of breakage mechanics for geological materials.

REFERENCES

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