Comparison of theory and test on excavation causing the variation of soilmass strength

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ABSTRACT: In view of the excavation unloading characteristic, the variation of soilmass strength is studied through the theoretical deduction and the test analysis. Based on Hvorslev’s real strength theory, the strength ratio of the unloading soil and the normal compressed soil considering the pore-water pressure is deduced and the test simulating excavation is carried out. Through comparing data of the theory and test, the soilmass is caused to be at the overconsolidated state, and the soil microstructure is damaged, then the soilmass strength is reduced in the unloading process. The analysis result of theory and test are helpful to the further understanding of the effect of unloading in excavation on the variation of the soilmass strength, which are very significant for avoiding project accidents.

1 INTRODUCTION

With the rapid and remarkable development of city construction, an increasingly large number of the exploitation of the underground spaces have emerged, such as high-story building, the underground market and underground garage etc., which need to excavate for building foundation. The excavation, including the influence of the soilmass’s engineering property and the variation of the environment characteristic, have been systematically studied by numerous scholars. Rutledge (1944) summarized the soil sample disturbance to the influence of the unconfined compression strength and the initial tangential modulus in stress and strain curve, and the result showed that the initial tangential modulus of the remoulded soil sample is smaller than the one of the undisturbed value by about 20%, some were even 3%~4%. On resonant column test, Drnevich & Massarsch (1979) discovered that even if the soil sample suffered from the small disturbance, its initial tangential modulus also obviously reduced. Broms (1980) pointed out that the soil sample disturbance in the brittle soil to the stress and strain curve’s influence was much bigger than in the plastic soil. Zeng (1995) studied the subway double lines shield tunnel construction to the influence of the surface, the buildings and the underground pipelines, and analyzed the tunnel interval to the influence of stress and the displacement of surrounding soilmass. Zeng & Pan (1988) studied stress path to the influence of the undrained strength in excavation. Wei (1987) has studied the relation of the excavation unloading and passive soil pressure.

Several examples of the collapse of foundation pits in the past had very serious consequences, which urged the people to study the design and construction of foundation pit deeply. At present the maintenance structure of foundation pit is designed and calculated by using the elastic foundation beam law or the elastoplasticity finite element method. The routine-test parameters generally were adopted as the computation parameters, which had not really considered the excavating and unloading to the influence of soilmass strength. The variation of soilmass strength after excavating and unloading is studied through the analysis of theory and test in this paper. The result of the study indicates that the unloading in excavation has influence on the variation of soilmass strength, which can be of some help to avoid project accidents.
2 THEORETICAL DEDUCTION OF SOILMASS STRENGTH UNDER UNLOADING

After excavation, the surrounding soil can be seen as the overconsolidated soil layer, and Wei (1987) deduced the undrained strength of the excavation unloading soft clay according to the Hvorslev (1960) real strength theory, which was the same formula that Mayne (1980) obtained the undrained strength of overconsolidated clay soil according to the statistics of a large number of test data. After the excavation, in fact, the effective stress of bottom soil layer of foundation pit is in unceasingly developing and changing process, rather than the static overconsolidated state that above formula derives. In this process, because of unloading, the negative pore water pressure dissipates slowly, and effective stress decreases gradually, and eventually stops at the overconsolidated state. According to the Hvorslev real strength theory, the undrained strength of the soils after excavation and unloading is deduced.

The Hvorslev strength formula is as follows:

\[ \tau = \rho \log \phi_e + c_e \]  

where \( c_e = \xi \cdot p_c \); In normal consolidated soil, \( p_c \) is equal to the current effective stress (drained shear strength) or the consolidation pressure (undrained shear strength); In overconsolidated soil, \( p_c \) is the consolidation pressure that the test specimen failure’s porosity ratio corresponds in the normal pressure dense curve. \( \tan \phi_e \) is the increment ratio which the shearing strength increases along with the effective stress change when the water content is constant; \( P \) is the effective stress.

According to the real strength theory and the critical state’s concept, when soilmass has withstood a simple loading–unloading cycle in stress history, it can be assumed that the failure point of overconsolidated soil is coincidence with the failure point of the normal consolidated soil at the same water content when stress path reaches at critical state line, as shown in Figure 1 and Figure 2. Then the effective stress of the overconsolidated soil is as follows:

\[ p_e' = p + \Delta p_e' = p_e - \Delta p_e' \]  

Based on the confirmation of a large number of tests, it can be considered approximately that the shapes of undrained stress path of the normal compacting soil sample is geometrical similarity under the different consolidation pressure, and the variation value of effective stress and consolidation pressure are in proportion (Wei 1987). Therefore their relation can be proposed from the following equation:

\[ \Delta p_e' = \frac{p_e'}{p_e} \cdot \frac{p_c}{p_e} \]  

Taking the equation (2),(3),(5) into the equation (4), then:

\[ S_{ob} = (p_e - u_m + \Delta p_e) \rho \tan \phi_e + \xi \cdot p_e \]  

Let \( p = p_e - u_m \)

\[ S_{ob} = (p_e \cdot \frac{p_c}{p_e} \cdot \frac{p_e'}{p_e} \rho \tan \phi_e + \xi \cdot p_e \]
The undrained shear strength of normal consolidated soil mass A in initial consolidation pressure $P_c$ is as follows:

$$S_{us} = (p_o - \Delta p_o) \cdot \tan \phi_o + \xi \cdot \rho_o$$

(7)

$$S_{ub} - S_{us} = \left[ p_o \left( 1 - \frac{\Delta p_o}{p_o} \right) - p_o + \Delta p_o \right] \cdot \tan \phi_o + \xi \cdot (p_o - p_o)$$

$$= (1 - \frac{\Delta p_o}{p_o}) \left( p_o - p_o \right) \cdot \tan \phi_o + \xi \cdot (p_o - p_o)$$

$$= \left( \frac{p_o}{p_o} - 1 \right) \left( p_o - \Delta p_o \right) \cdot \tan \phi_o + \xi \cdot (p_o - p_o)$$

(8)

$$= \left( \frac{p_o}{p_o} - 1 \right) S_{us}$$

Then $\frac{S_{ub}}{S_{us}} = 1 - \frac{p_o}{p_o} - 1$

Therefore $\frac{S_{ab}}{S_{us}} = \frac{p_o}{p_o}$

(9)

In Figure 2:

On the initial compression line AEC,

$$\frac{1}{C_c} = \frac{\log p_o - \log p_e}{\Delta e}$$

On the unloading and swelling line BC,

$$\frac{1}{C_s} = \frac{\log p_o - \log p_e}{\Delta e}$$

Then $C_s - C_c = \frac{\log p_o - \log p_e}{\Delta e}$

(10)

Therefore $\frac{p_o}{p} = \left( \frac{p_o}{p} \right)^{\frac{C_s - C_c}{C_s}}$

(11)

$$P_o = P_o \times \frac{P_i - u_i}{P_i}$$

$$S_{ab} = \left( \frac{P_i - u_i}{P_i} \right) \left( \frac{C_s - C_c}{C_s} \right) \times \frac{P_i - u_i}{P_i}$$

$$= \left( \frac{P_i - u_i}{P_i} \right)^2 \frac{P_i - u_i}{P_i}$$

(12)

$$i = \frac{C_s - C_c}{C_c}$$

The equation (12) is the undrained strength ratio of the excavation unloading soil and the normal consolidation soil.

In the above deduction process:

$S_{ab}$ – The undrained strength of the excavation unloading soils;

$S_{us}$ – The undrained strength of the normal consolidated soils;

$u_i$ – The negative pore-water pressure of the unloading soil mass, with time dissipation;

$P_i$ – The soil mass consolidation pressure of current state;

$P_o$ – The soil mass consolidation pressure under natural state;

$C_c, C_s$ – The compression index and swelling index of soil mass.

The law is reflected in the equation (12) that soil mass strength reduces gradually with the negative pore-water pressure dissipation after unloading. When $u_i = 0$, soil is at the complete over-compacting state.

The key that estimates the soil mass strength after unloading is to determine the parameter $i$. Because of the errors of the sampling disturbance and instrumentation equipment, the computed result of the parameter $i$ which is determined by consolidation test's result $C_c, C_s$, is bigger than the real value, needing to calculate the parameter $i$ by the strength test.

After the synthetical comparison, Mayne (1980) propose that $1 - C_s/C_c$ takes the statistical average value 0.64 to be quite reasonable according to the statistics of a large number of experimental data and in situ measurement; Furthermore, Zhang & Wei (1987) have confirmed this viewpoint. Therefore the parameter $i$ is taken $-0.64$ in this paper.

3 EXPERIMENT ANALYSIS OF SOIL MASS STRENGTH AFTER UNLOADING

3.1 Test plans

In the excavation process, as shown in Figure 3, the soil mass unit A of around foundation pit wall is lateral
Table 1. The triaxial test plans of constant pressure consolidation.

<table>
<thead>
<tr>
<th>Variation mode of the stress</th>
<th>σᵥ unloading failure</th>
<th>σᵥ loading failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloading – σᵥ unloading failure</td>
<td>I01, I02, I03, I04</td>
<td>K03</td>
</tr>
<tr>
<td>Unloading – σᵥ loading failure</td>
<td>J01, J02, J03, J04</td>
<td>L03</td>
</tr>
</tbody>
</table>

Table 2. The triaxial test plans of K₀ consolidation.

<table>
<thead>
<tr>
<th>Variation mode of the stress</th>
<th>σᵥ = σᵥ/H/K₀ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>σᵥ unloading failure</td>
<td>180, 240, 400</td>
</tr>
<tr>
<td>σᵥ loading failure</td>
<td>M01, M02, M03</td>
</tr>
</tbody>
</table>

Table 3. The basic index of mechanical property of Silt clay.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>52.6%</td>
</tr>
<tr>
<td>γ</td>
<td>16.9 KN/m³</td>
</tr>
<tr>
<td>e</td>
<td>1.487</td>
</tr>
<tr>
<td>Sr</td>
<td>97.3%</td>
</tr>
<tr>
<td>I₀</td>
<td>23.2</td>
</tr>
<tr>
<td>I₁</td>
<td>1.231</td>
</tr>
<tr>
<td>α₁-2</td>
<td>1.20 MPa⁻¹</td>
</tr>
<tr>
<td>c</td>
<td>11 kPa</td>
</tr>
<tr>
<td>ψ</td>
<td>9.3°</td>
</tr>
</tbody>
</table>

Table 4. The negative pore-water pressure data of soil sample after unloading (kPa).

<table>
<thead>
<tr>
<th>Serial number</th>
<th>I (J) 01</th>
<th>I (J) 02</th>
<th>I (J) 03</th>
<th>I (J) 04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative pore-water pressure (kPa)</td>
<td>–</td>
<td>–</td>
<td>–30.9</td>
<td>–34.1</td>
</tr>
</tbody>
</table>

Note: Because of instrument failure, the data of 01 and 02 can not be detected, the latter two data are average value of I, J group.

The soil samples of tests are the typical soft soil of the Shanghai area, its basic index of mechanical property as shown in Table 3.

After unloading, the negative pore-water pressure is shown in Table 4.

3.2 Test results

The soil samples of tests are the typical soft soil of the Shanghai area, its basic index of mechanical property as shown in Table 3.

4 THE COMPARISON ANALYSIS BETWEEN THEORY RESULT AND TEST RESULT OF THE SOILMASS STRENGTH AFTER EXCAVATING AND UNLOADING

The theory deduction and the test simulation about soil strength of the excavation has been discussed.
Now we will discuss the comparison result of theory and test.

The stress–strain relation curve of different confining pressure of I, J two groups tests are normalized, and \(\sigma_m = (\sigma_1 + 2\sigma_2)/3 = 233\) kPa, then the curves can be drawn as shown in Figure 4 and Figure 5, in which K line, L line are the soil stress-strain curves of natural compaction after normalization, and I02, I03, J01, J02, J04 are the normalizing stress-strain curve of over-compacting soil after the unloading.

After excavation unloading, the stress value of the soil sample stress-strain relations curve approaches or surpasses the stress value of the natural normal compacting soil as shown in Figure 4 and Figure 5; For eliminating the test error, after unloading, soil sample peak value \((\sigma_1 - \sigma_3)_{\text{max}}\) can be taken the average value of each normalized curve peak value, as shown in Table 5: For comparing with test result, theoretical calculation is taken by the formula (12), the parameter \(P_c = 300\) kPa, \(P_t = 233\) kPa, the test results and the theoretical formula results, are shown in Table 5.

In the Table 5, \(S_{ub}\) is the undrained strength of excavation unloading soil in I, J series tests by normalization; \(S_{ua}\) is the undrained strength of the normal compressed soils in K, L series tests by normalization.

In above tests, the influence of negative pore-water pressure (Table 4) is considered in soil sample. According to the computation of the formula (12), the soilmass strength ratio \(S_{ub}/S_{ua}\) is 1.229 and 1.235, which is higher about 5%~6% than the ratio of the pore-water pressure dissipating completely.

The comparison from Table 5 can be found that theoretical calculation result is bigger about 10% than test result. Not only The soilmass is caused to be at the overconsolidated state, but also the soil microstructure is damaged, and the soilmass strength is reduced in the unloading process. In this triaxial test, soil samples is unloaded according to the stress path of the test, soil stress is redistributed, and consolidated, the overconsolidated soil is formated, soil structure of the original system is also damaged.

5 THE VARIATION OF SOILMASS STRENGTH PARAMETERS AFTER EXCAVATING AND UNLOADING

Based on the stress-strain relation curves of tests, according to the Mohr-Coulomb criterion, the soilmass strength parameters \(c, \phi\) of the simulating excavation unloading and the parameters \(c, \phi\) of routine-test are listed in Table 6.

Table 5. The soil strength contrast between theory result and test result after unloading.

<table>
<thead>
<tr>
<th>Project</th>
<th>Peak value ((\sigma_1 - \sigma_3)_{\text{max}}) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test soil sample of unloading disturbance</td>
<td>Natural Soils Test Theory Difference value</td>
</tr>
<tr>
<td>Sample</td>
<td>(S_{ub}/S_{ua})</td>
</tr>
<tr>
<td>I</td>
<td>208.2</td>
</tr>
<tr>
<td>J</td>
<td>205.1</td>
</tr>
</tbody>
</table>

In Table 5, the cohesion, the angle of internal friction that unloading failure of I and M group obtained are quite close, their \(c\) value is bigger than J group, but the \(\phi\) value is smaller, furthermore, the values of \(c, \phi\) are obviously different from the result of conventional consolidated quick shear test. Because of lack...
Table 6. The strength parameter value $c$$\phi$ of the soilmass failure.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test number</th>
<th>A unit of M group (unloading failure)</th>
<th>B unit of I group (unloading failure)</th>
<th>B unit of J group (loading failure)</th>
<th>The result of conventional consolidated quick shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesion $c$ (kPa)</td>
<td>26.5</td>
<td>24.3</td>
<td>7.36</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Angle of internal friction $\phi$ (°)</td>
<td>15</td>
<td>13</td>
<td>16</td>
<td>9.3</td>
<td></td>
</tr>
</tbody>
</table>

of the sufficient test data, the relationship between the unloading stress and the strength parameters $c$$\phi$ can not be obtained, which needs further test to determine whether these parameters have the inevitable relation.

6 CONCLUSION

This paper chooses the typical excavation as the test study object, designs and carries out different stress paths indoor triaxial tests in I, J, K, L, M group tests. Some useful conclusions are drawn by analyzing the influence of excavation on the result of theory and test, which are very significant for avoiding project accidents:

1. By the assumption that the soil as overconsolidated soil with dissipation of the negative pore-water pressure after unloading, the undrained strength ratio between the soils of excavation unloading and the normal consolidated soils is deduced, namely the formula (12). With the dissipation of soil negative pore-water pressure, the soilmass strength is reduced. According to the analysis result, the scope of reduction is not large. Under the above test stress condition, the strength ratio range of variation is about 5%–6%.

2. The undrained strength ratio $S_{ub}/S_{ua}$ from the tests is smaller about 10% than undrained strength ratio from the above theoretical formula computation. The difference value in the test can be identified as the result that of unloading disturbance.

3. In the unloading process, the soilmass is caused to be at the overconsolidated state, the soil microstructure is damaged, and the soilmass strength is reduced.

4. The total stress strength parameters $c$$\phi$ obtained from the different stress path tests are much different from the parameters from the routine-test. Due to the insufficiency of data, the relationship between the unloading stress and the strength parameters $c$$\phi$ can not be obtained, which needs further test to determine whether these parameters have the inevitable relation.

REFERENCES


