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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. Baseed on the 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 only 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:

$$\tau = ptg\varphi_e + c_e \tag{1}$$

where $c_e = \xi \cdot p_e$; In normal consolidated soil, p_e is equal to the current effective stress (drained shear strength) or the consolidation pressure (undrained shear strength); In overconsolidated soil, p_e is the consolidation pressure that the test specimen failure's porosity ratio corresponds in the normal pressure dense curve. $tg\varphi_e$ 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:

$$p_b' = p + \Delta p_b' = p_e - \Delta p_e' \tag{2}$$

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:

$$\Delta p_e' = \Delta p_a' \cdot \frac{p_e}{p_a} \tag{3}$$

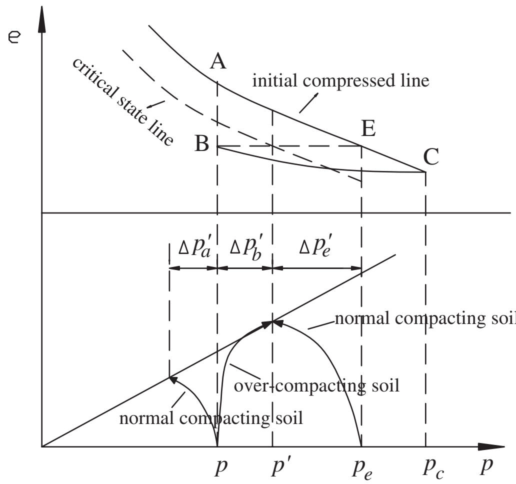

Figure 1. The constant consolidation pressure and the undrained stress path for the normal consolidated soil and the overconsolidated soil (Wei 1987).

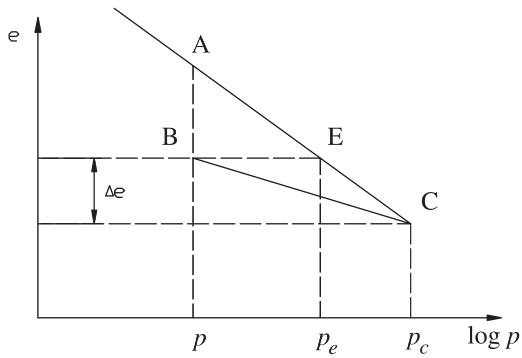

Figure 2. The relation curves for the normal consolidated soil and the overconsolidated soil.

The undrained shear strength of overconsolidated soil sample B is as follows:

$$S_{ub} = (p_t - u_{bt} + \Delta p_b')tg\varphi_e + \xi p_e \tag{4}$$

$$\text{Let } p = p_t - u_{bt} \tag{5}$$

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

$$S_{ub} = (p_{et} - \frac{p_{et}}{p_a} \cdot \Delta p_a')tg\varphi_e + \xi \cdot p_{et} \tag{6}$$

The undrained shear strength of normal consolidated soilmass A in initial consolidation pressure P_c is as follows:

$$S_{ua} = (p_a - \Delta p_a') \cdot tg\varphi_e + \xi \cdot p_a \tag{7}$$

$$\begin{aligned} S_{ub} - S_{ua} &= \left[p_{et}(1 - \frac{\Delta p_a'}{p_a}) - p_a + \Delta p_a' \right] \cdot tg\varphi_e + \xi \cdot (p_{et} - p_a) \\ &= (1 - \frac{\Delta p_a'}{P_a})(p_{et} - p_a) \cdot tg\varphi_e + \xi \cdot (p_{et} - p_a) \\ &= (\frac{p_{et}}{p_a} - 1)\left[(p_a - \Delta p_a') \cdot tg\varphi_e + \xi \cdot p_a \right] \\ &= (\frac{p_{et}}{p_a} - 1) S_{ua} \end{aligned} \tag{8}$$

Then $\dfrac{S_{ub}}{S_{ua}} - 1 = \dfrac{p_{et}}{p_a} - 1$

Therefore $$\frac{S_{ub}}{S_{ua}} = \frac{p_{et}}{p_a} \tag{9}$$

In Figure 2:
On the initial compression line AEC,

$$\frac{1}{C_c} = \frac{\log p_{et} - \log p_c}{\Delta e}$$

On the unloading and swelling line BC,

$$\frac{1}{C_s} = \frac{\log p - \log p_c}{\Delta e}$$

Then $$\frac{C_s - C_c}{C_c} = \frac{\log p_{et} - \log p}{\log p - \log p_c} \tag{10}$$

Therefore $$\frac{p_{et}}{p} = \left(\frac{p}{p_c} \right)^{\frac{C_s - C_c}{C_c}} \tag{11}$$

$$\frac{p_{et}}{p_t} = \frac{p_{et}}{p} \times \frac{p_t - u_t}{p_t}$$

$$\begin{aligned} \frac{S_{ub}}{S_{ua}} &= \left(\frac{p_t - u_t}{p_c} \right)^{\frac{C_s - C_c}{C_c}} \times \frac{p_t - u_t}{p_t} \\ &= \left(\frac{p_t - u_t}{p_c} \right)^{i} \times \frac{p_t - u_t}{p_t} \end{aligned} \tag{12}$$

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

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

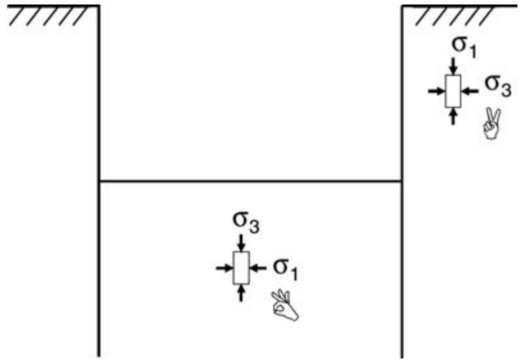

Figure 3. The diagram of the stress variation for excavation.

In the above deduction process:

S_{ub} – The undrained strength of the excavation unloading soils;
S_{ua} – The undrained strength of the normal consolidated soils;
u_t – The negative pore-water pressure of the unloading soilmass, with time dissipation;
P_t – The soilmass consolidation pressure of current state;
p_c – The soilmass consolidation pressure under natural state;
C_c, C_s – The compression index and swelling index of soilmass.

The law is reflected in the equation (12) that soilmass strength reduces gradually with the negative pore-water pressure dissipation after unloading. when $u_t = 0$, soil is at the complete over-compacting state. The key that estimates the soilmass 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 SOILMASS STRENGTH AFTER UNLOADING

3.1 *Test plans*

In the excavation process, as shown in Figure 3, the soilmass unit A of around foundation pit wall is lateral

Table 1. The triaxial test plans of constant pressure consolidation.

Variation mode of the stress	Consolidation pressure $\sigma_v = \sigma_H$ (kPa)			
	100	200	300	400
Unloading – σ_v unloading failure	I01	I02	I03	I04
Unloading – σ_v loading failure	J01	J02	J03	J04
σ_v unloading failure			K03	
σ_v loading failure			L03	

Table 2. The triaxial test plans of K_0 consolidation.

Variation mode of the stress	Consolidation pressure $\sigma_v = \sigma_H/K_0$ (kPa)		
	180	240	400
σ_H unloading failure	M01	M02	M03

unloading, and vertical pressure is nearly invariable; The soilmass unit B of the lateral and vertical in the bottom of foundation pit simultaneously unloads, and the vertical stress drops more quickly than lateral stress, but still retains quite a part of incomplete unloading stress, therefore the influence of the unloading only possibly exists in a certain scope below foundation pit bottom surface. The stage excavation method is generally selected for the foundation pit. The first supporting structure immediately be taken when the first layer soil is excavated to reach at the design elevation; Then the second layer soil is excavated. During the excavation, the soilmass units are in the process that the soil is unloading and expanding and the negative pore-water pressure is dissipating slowly.

According to the unloading characteristic of above soilmass unit A, B, test plans are designed as shown in Table 1 and Table 2.

I, J group tests simulate the stress path of the unit B, and the soil samples are consolidated for 24 hours under constant pressure; then according to the stress path $\Delta\sigma_v = \sigma_v/3$, $\Delta\sigma_v/\Delta\sigma_H = 2$, the test specimen are unloaded simultaneously on the vertical and the lateral, and the value was recorded when the negative pore-water pressure are stable after unloading; This process needs for 2–3 hour from starting unloading to stability of reading value, then turns on the drain valve, and makes the negative pore-water pressure dissipation, the soil sample completes consolidation under the new low stress condition, the consolidation time is 8 hours. Then the I group is loaded to the test specimen compression failure on the vertical, and the J group is unloaded to the test specimen extrusion failure on the vertical. As a reference test, K group and L group specimen are consolidated in the confining pressure of setting, without unloading disturbance, and respectively are loaded and unloaded to the test specimen failure on the vertical.

The unloading stress variation process of unit A is simulated by M group test. $K_0 = 0.6$, the consolidation pressure is exerted by staged loading; For avoiding the accidental failure of the test specimen, the staged loading is divided 10 levels to exert; The axial stress $\Delta\sigma$ is exerted in each level loading, at the same time, the confining pressure $\Delta\sigma_H = K_0\Delta\sigma_v$ is exerting, consolidation time 24 hours. After consolidation completes, $\Delta\sigma_v$ is maintained invariable, and the test specimen is compressed to failure by the lateral unloading.

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

Parameters	Values
w	52.6%
γ	16.9 KN/m^3
e	1.487
Sr	97.3%
I_p	23.2
I_L	1.231
$\alpha_{1\text{-}2}$	1.20 MPa^{-1}
c	11 kPa
φ	9.3°

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

Serial number	I (J) 01	I (J) 02	I (J) 03	I (J) 04
Negative pore-water pressure (kPa)	–	–	−30.9	−34.1

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.

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.

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

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.

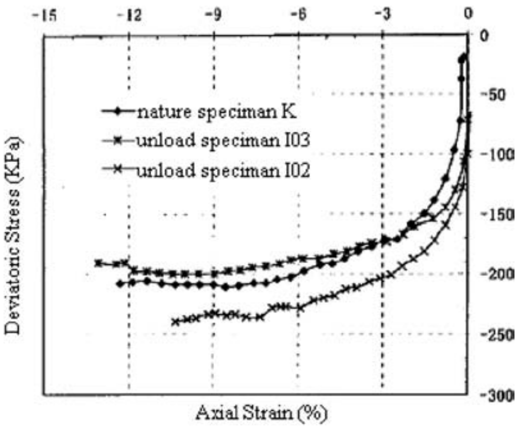

Figure 4. The normalization stress of the unloading soil of I group.

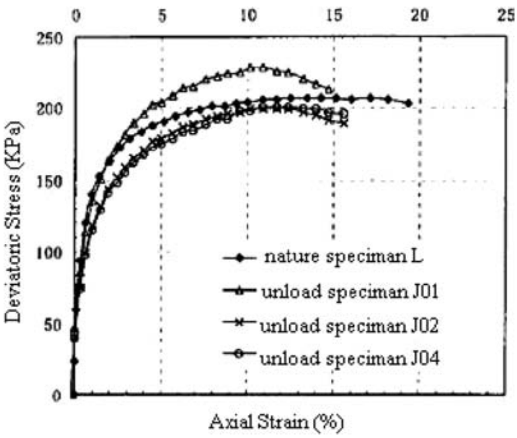

Figure 5. The normalization stress of the unloading soil of J group.

Now we will discuss the comparison reuslt 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 $(\sigma_1 - \sigma_3)_{\max}$ can be taken the average value of each normalized curve peak value, as shown

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

	Project				
	Peak value $(\sigma_1 - \sigma_3)_{\max}$ (kPa)				
Test number	Natural soil sample	Soil sample of unloading disturbance	Test result S_{ub}/S_{ua}	Theory result S_{ub}/S_{ua}	Difference value (%)
I	208.2	219.0	1.052	1.175	12.3
J	205.1	212.5	1.040	1.175	13.5

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 $c\$\$\varphi$ of the simulating excavation unloading and the parameters $c\$\$\varphi$ of routine-test are listed in Table 6.

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 φ value is smaller, furthermore, the values of $c\$\$\varphi$ are obviously different from the result of conventional consolidated quick shear test. Because of lack

Table 6. The strength parameter value $c\$\$\varphi$ of the soilmass failure.

Parameter	Test number			
	A unit of M group (unloading failure)	B unit of I group (unloading failure)	B unit of J group (loading failure)	The result of conventional consolidated quick shear
Cohesion c (kPa)	26.5	24.3	7.36	11
Angle of internal friction φ (°)	15	13	16	9.3

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

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