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Geotechnical Engineering for Disaster Mitigation and Rehabilitation

STUDY ON STRENGTH CRITERION OF INTACT SOFT CLAY AFTER MONOTONIC PRINCIPAL STRESS ROTATION

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Underestimating the influence of principal stress rotation on the foundation soil during the construction is the cause of some engineering accidents. Series of experiments were done to study the strength characteristics of intact soft clay after undrained monotonic principal stress rotation. It was found that compared with the progress of undrained monotonic principal stress rotation, the principal stress direction when samples failed influenced the soils' strength much more obviously. But the pore water pressure generated in the tests including principal stress rotation was much higher than that in the test of fixed principal stress direction shear. It was due to the shearing contraction of intact soft clay caused by principal stress rotation. A modified Lade-Duncan failure criterion was used to normalize these testing results and unify the soil's failure criterion including principal stress rotation. It showed that initial anisotropy was one of the most important determinate factors of intact clay's strength when principal stress rotation occurred during the construction.

INTRODUCTION

In the practical issues soil would undergo complex stress path. Monotonic principal stress rotation will occur as a kind of typical path when the foundation is subject to filling dams, excavation or some other constructions. It, coupled with soils' anisotropy, may influence soils' strength properties. And such influence would be amplified with the scale of construction expanding. So underestimating these influence will have grave consequences.

Laboratory experiment is one of the methods to evaluate these effects properly. Several researchers like Arthur et al. (1979), Hight et al. (1983), Symes et al. (1984,1988), Wijewickreme and Vaid (1993), Zdravkovic and Jardine (2001), Sivathayalan and Vaid

(2002), Han and Penumadu (2005) have done tests to study the soil's properties under principal stress rotation. But most samples tested before were remoulded silt or sand. Compared with them, clay, especially intact clay, may show quite different reaction on principal stress rotation because of its structural property, anisotropy and other characteristics. So the authors did a series of intact clay experiments to study the influence of principal stress rotation on its strength. How to generalize the strength criterion for such stress path is also discussed.

SOIL PROPERTIES AND TESTING PROCEDURES

The soil tested was a kind of typical intact soft clay from Hangzhou, and its properties are summarized in Table 1.The intact clay block was shaped into a hollow cylinder sample (height 200mm×outer diameter 100mm×inner diameter 60mm) with special apparatus (Zhou et al.,2007).

Table 1. Properties of testing soil

Specific gravity	Void ratio	Water content (%)	Liquid limit	Plastic limit	CU C_{cu} (kPa)	CU φ_{cu} (°)	Direct shear(R) c(kPa)	Direct shear(R) φ(°)
2.74	1.234	44.3	45.0	18.3	24.8	16.0	5.5	9.0

The testing apparatus is Hollow cylinder apparatus (HCA) deviced by Zhejiang University and GDS Ltd. Four independent loading parameters, namely axial load (W), torque (M_T), inner (p_i) and outer (p_o) pressures, can be applied and four corresponding stress components, i.e. major (σ_1), intermediate (σ_2), minor (σ_3) stress and the direction of σ_1 relative to the vertical(α) can be generated, which form the principal stress rotation stress path (see Figure 1) .And in this paper, another three equivalent parameters $p=(\sigma_1+\sigma_2+\sigma_3)/3$, $q=(\sigma_1-\sigma_3)/2$, $b=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$ instead of $\sigma_1,\sigma_2,\sigma_3$ were used to control the principal stress rotation path. p reflects the level of spherical stress , q reflects the size of failure Mohr's circle and b reflects the interrelation of the three principal stress, which could show the constitutive laws of soil better.

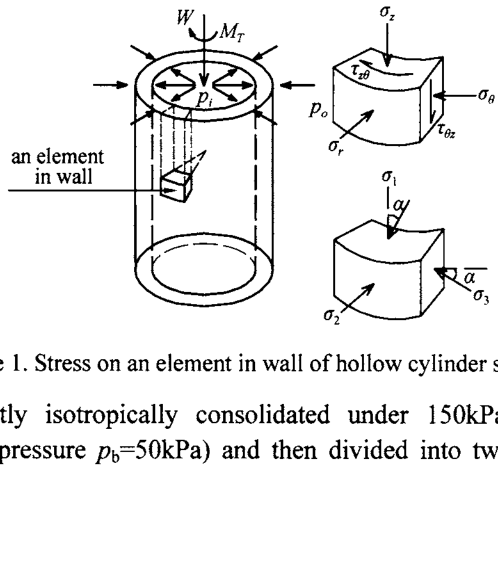


Figure 1. Stress on an element in wall of hollow cylinder sample

Samples were firstly isotropically consolidated under 150kPa (total cell pressure p=200kPa, and back pressure p_b=50kPa) and then divided into two groups for different undrained shear tests. One group consisted of the tests of fixed principal stress direction shear (named *T* group),and the other consisted of the tests of monotonic principal stress rotation shear (named *R* group).Plans for these tests are listed in Table 2 and 3.

Table 2. Tests plan for undrained fixed principal stress direction shear(*T* group)

Number of samples	Characteristics of stress parameters when loading			
	p (kPa)	b	α (°)	q (kPa)
T101	200	0	0	Increase from 0 until sample fails
T102			10	Increase from 0 until sample fails
T103			15	Increase from 0 until sample fails
T104			25	Increase from 0 until sample fails
T105			45	Increase from 0 until sample fails
T106			60	Increase from 0 until sample fails
T107			75	Increase from 0 until sample fails

Table 3. Tests plan for undrained principal stress rotation shear(*R* group)

Number of samples	Characteristics of stress parameters when loading		
	p (kPa)	b	Relation between q (kPa) and α (°)
R171	200	0	When=30° , increase q from 0 to 35kPa. Then keep q=35kPa and rotate from 30° to 60° .Finally keep =60° , increase q until sample fails
R172			When =0° , increase q from 0 to 35kPa. Then keep q=35kPa and rotate from 0° to 60° .Finally keep =60° , increase q until sample fails

TESTING RESULTS AND ANALYSIS

When samples failed in the *T* and *R* group tests, q reached peak values(named q_{max}).Figure 2 shows the values of q_{max} (namely the size of failure Mohr's circle) in *T* group. p'_o is the samples' initial effective cell pressure(equal to 150kPa).It revealed that when samples were sheared at fixed principal stress direction, the strength obtained were quite different due to the clay's intrinsic anisotropy.

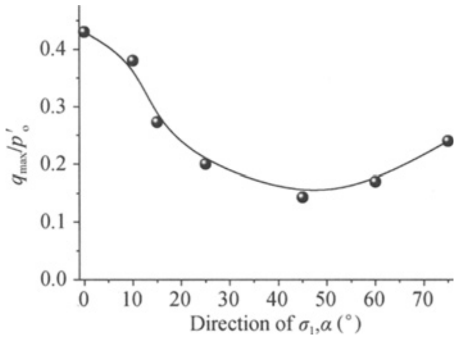


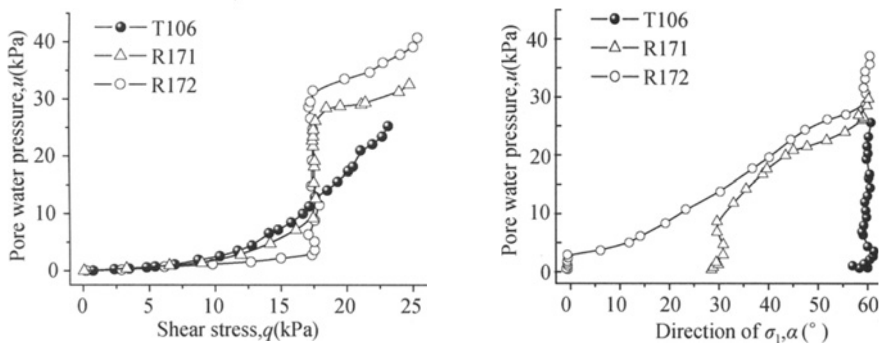
Figure 2. Anisotropical normalized shear strength of *T* group tests

The values of q_{max} obtained in *R* group are also shown in Table 4 and Figure 3(a).It could be seen that q_{max} of R171 and R172 are very similar to the T106's. Although R171, R172 had undergone one stage including principal stress rotation, they failed at the same direction of principal stress direction with T106.So it could be concluded that the undrained monotonic principal stress rotation didn't influence the size of failure Mohr's circle. This conclusion is similar to that drawn from the remould sand and clay test results of Symes et al.(1984), Hong et al.(1989) and Sivathayalan et al.(2002).

While it could also be seen in Figure 3 that at the failure point, the pore pressure generated in R171 and R172 are much more than in T106. So it showed that although the size of failure Mohr's circle didn't change, the "superflous" pore water pressure generated and caused the change of effective spherical stress correspondingly, which was due to the existence of principal stress rotation. Such phenomenon seems confusable if Mohr-Coulomb failure criterion is used to evaluate the strength of the samples. But it may be explained by other criterion more properly. In this paper, a modified Lade-Duncan failure criterion was put forward, with which the "superflous" pore water pressure generated in principal stress rotation could be normalized into a unified effective stress system properly.

Table 4. Values of some stress parameters when samples failed

Number of samples	The values of some stress parameters when samples failed			
	α (°)	q_{max} (kPa)	q_{max}/p_0	k_f
R171	60.0	25	0.167	27.9
R172	60.0	25.7	0.171	28.0
T106	60.0	24.9	0.166	27.8



(a) (b)

Figure 3. Pore pressure characteristic of T107, R171, R172.

The original Lade-Duncan failure criterion is expressed as

$$f(I_1, I_3, k_f) = \frac{I_1^3}{I_3} - k_f = \frac{27(p-u)^3}{(\sigma_1 - u)(\sigma_2 - u)(\sigma_3 - u)} - k_f = 0 \tag{1}$$

where

$$I_1 = (\sigma_1 - u) + (\sigma_2 - u) + (\sigma_3 - u)\ ;$$
$$I_3 = (\sigma_1 - u)\cdot(\sigma_2 - u)\cdot(\sigma_3 - u)\ ;$$

k_f is failure parameter of Lade-Duncan criterion.

Equation. (1) can also be rewritten in the form of p, q, b, α as:

$$\begin{aligned} f(p',q,b,k_f) &= \frac{2}{27}q^3(b^2-b+1)^{3/2}\sin 3(\arctan\frac{1}{\sqrt{3}}(2b-1)) \\ &-\frac{1}{3}q^2(p-u)(b^2-b+1)+(1-27/k_f)(p-u)^3=0 \end{aligned} \tag{2}$$

where u is the increment of pore water pressure generated in the T and R group tests.

The original model is fit for cohesionless soil, as to the clay samples in this paper, it should be modified with the cohesion. So in Equation. (1)or(2) σ_1, σ_2, σ_3 are replaced separately with σ_1+c_a , σ_2+c_a, σ_3+c_a to take clay's cohesion into the consideration. c_a is a cohesion modified parameter which is obtained by fitting the results of triaxial compression test ,direct shear test (see Table 1)and the shape line of q_{max} along all the directions of σ_1 in T group(see Figure 2).So c_a is expressed as follows:

$$\begin{aligned} c_a=&194.427\times[0.406+4.283\times10^{-4}\times\alpha-1.110\times10\ -3\times\alpha^{2}+4.197\times10^{-5}\times\alpha^{3} \\ &-5.825\times10^{-7}\times\alpha^{4}+2.85313\times10^{-9}\times\alpha^{5}]+7.555\ \ (\text{kPa}) \end{aligned} \tag{3}$$

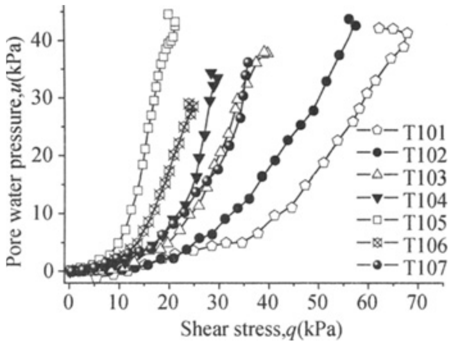


Figure 4. Pore pressure characteristics of T group tests

According to Equation (2)and the values of critical pore water pressure of each test(see Figure 3 and 4) ,the failure parameter k_f is obtained. It could be seen from Figure 5 that in T group k_f changes with the direction of σ_1 slightly. Since Equation (2) has taken b's influence into the consideration, the change of k_f mainly reflect the soil's intrinsic anisotropy. In Table 4, the values of R group's k_f are also listed, which are very similar to T106's. The above results of R and T group reveal that the modified Lade-Duncan criterion can be used to reflect the soil's intrinsic anisotropy and generalize the development of pore water pressure during the undrained principal stress rotation.

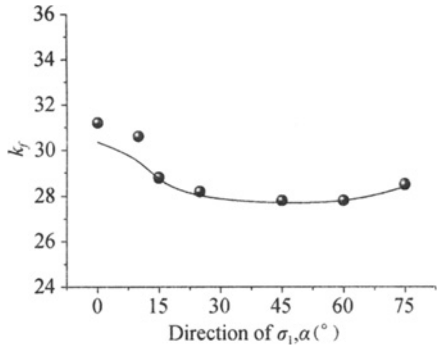


Figure 5. k_f for each sample of T group tests

Symes et al. (1984) did a series of tests and concluded whether the soil had undergone a history of principal stress rotation or not, the critical pore water pressure were similar. It seemed to contradict the phenomena present in this paper. Such "contradiction" can be explained by the generalized plastic mechanics. In the theory of generalized plastic mechanics principal stress rotation even with constant principal stress amplitude such as the rotation stage in R171 and R172,will also generate the increment of principal stress and cause the sample's volume to have a tendency to change correspondingly. The soil adopted in Symes's research (1984) was remoulded sand, while in this paper normal consolidated clay was used. The clay showed much more obvious shearing contraction than the sand, so samples in this paper could generate more pore water pressure in the principal stress rotation.

CONCLUSIONS

A series of intact soft clay experiments on the change of principal stress direction had been done. It is revealed that Hangzhou typical intact clay had obvious intrinsic anisotropy in strength, which was not related to the undrained principal stress rotation history. Under the complex stress path including principal stress rotation, the size of failure Mohr's circle at failure point can be used to evaluate the soil's strength .While in the effective stress system it is more proper to use a modified Lade-Duncan criterion to evaluate the strength parameter, which could reflect the soil's intrinsic anisotropy and the development of pore water pressure during the undrained principal stress rotation. These conclusions may be helpful on the evaluation of soil's strength parameters used in the design of embankment, excavation or some other constructions.

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