SHEAR STRENGTH AND CONSOLIDATION YIELDING STRESS OF PLEISTOCENE CLAY FOUND AT IZUMI-HILL OF OSAKA DISTRICT

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ABSTRACT

Shear strength and consolidation yielding stress of heavily overconsolidated Pleistocene clay found at Izumi-hill of Osaka District are presented. Unconfined compression, field vane and various kinds of direct shear tests were conducted for evaluating the shear strength, while standard and strain controlled oedometer tests were carried out for determining the consolidation yielding stress. It was found that unconfined compressive strength is about half of field vane and direct shear strengths, and this difference was suggested to be caused by that extensive failure at a weak point takes place in most case in unconfined compression test. It was also found that field vane test is an effective tool for evaluating the shear strength of this kind of material. Consolidation yielding stress determined by standard and strain controlled oedometer tests are discussed as related to the undrained shear strength obtained from direct shear test. It was strongly suggested that the consolidation yielding stress should be determined by strain controlled oedometer test and the clay investigated is fundamentally classified into normally consolidated aged clay.

Key words : consolidation yielding stress, direct shear strength, overconsolidated clay, Pleistocene clay, shear strength, stress history, unconfined compression strength, vane shear strength (IGC : D/6)

INTRODUCTION

A formation, so named the Osaka Formation, which was deposited from the end of Neogene to Pleistocene, is widely found in Osaka District. This formation was formed under either marine or fresh water condition and there are 13 marine clay strata, which are symbolized with Ma 0, Ma 1, ... and Ma 12 from the older, bounded by sand layers each

other. In addition, the same stratum can be classified into the two types, 1) found at significantly deep depth in subsiding basin including Osaka Bay and 2) found at elevating hill as shown in Fig.1. The former is in a lightly overconsolidated state, while the latter, generally containing cracks more or less, is in a heavily overconsolidated state.

Main subjects for heavily overconsolidated clay found at hilly area are 1) slope stability

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Fig. 1. Idealized plot showing soil conditions in Osaka district

in excavation and cutting and 2) bearing capacity and consolidation settlement when subjected to loading. Many efforts have been devoted to evaluation of slope stability and some fruitful results have been obtained as reported by Mochizuki and Mikasa (1985) and Nishigaki (1986). It seems, however, that the studies on bearing capacity and settlement are unexpectedly few. Accurate determination of the shear strength, τ_f and the consolidation yielding stress, σ'_y is the essential requirement in evaluating these two subjects. However, practical method for determining τ_f and σ'_y of heavily overconsolidated clay has not been established yet.

Unconfined compression test, q_u test has generally been used for determining τ_f of clay in Japan. When such material in stiff to hard state is subjected to loading without confining stress like in q_u test, however, extension failure could be generated because of stress concentration to a weak point like crack as pointed out by Nishigaki (1979). It is easily suggested, therefore, that τ_f from q_u test should be uncertain and too conservative. Actually, Mikasa, et al. (1967) reported that the value of q_u of a Pleistocene clay found at Senri-hill is less than half of that from unconsolidated undrained triaxial test.

Since constructed structures have become large scaled, on the other hand, proper prediction of ground subsidence even for such a hard clay is also an important subject. Nakakita and Watanabe (1977) reported that settlement of Pleistocene clay reached more

than 1m in a preloading work at Kobe Island. Settlement amount of hard clay is greatly dependent on how the value of σ'_y is appropriately determined. It is also suggested, however, that accurate determination of σ'_y of Pleistocene clay is difficult by standard oedometer test because of its large load increment ratio as already demonstrated by Ishii et al. (1984).

A series of field and laboratory tests were carried out on Ma 3 and Ma 4 clays found at Izumi-hill located at south-east part of Osaka district. Undrained and drained shear strengths, τ_{uf} and τ_{df} are first presented and then values of σ'_y obtained from standard and strain controlled oedometer tests, hereafter called S-oed. and S.C-oed. tests, respectively are described. Main cause for overconsolidated state of both clays is discussed based on a relationship observed between τ_{uf} and σ'_y and on strength-deformation behaviour in D.S test. Further, a procedure for determining τ_f and σ'_y of this kind of material is presented.

FIELD AND LABORATORY TESTS CONDUCTED

The investigations were executed twice, 1985 and 1987 on Ma 3 (1985) and Ma 4 (1987) and various tests were conducted as explained in the following.

1) F.V test : Standard type with diameter, $D=45$ mm and height, $H=90$ mm and special type with $D=60$ mm and $H=35$ mm were used in order to investigate field vane strength, designated with the symbol, $\tau_{ufo(v)}$

Fig. 2. Vane shear apparatus used in the investigation

in this paper. Since both clays are in hard state, a special vane 2.5 mm thick made of stainless steel was used as shown in Fig. 2. Rotating rate was $1^\circ/10$ sec. and two guide rollers were used to prevent irregular rotation of vane.

2) Undisturbed sampling : Stationary piston sampler and Denison type sampler were used for undisturbed sampling.

3) q_u test : The specimen with $D=35$ mm and $H=85$ mm was trimmed from undisturbed sample and then subjected to q_u test at a strain rate of $1.0\%/min$.

4) D. S test : 4 kinds of direct shear tests were conducted on the specimen with $D=60$ mm and $H=20$ mm as explained below.

a) DSU_1 test where the specimen was consolidated at a vertical consolidation stress, σ'_{vc} being equal to the effective overburden stress, σ'_{vo} for 10 minutes and then sheared under constant volume condition at a displacement rate of 0.1 mm/min in order to obtain in-situ undrained direct shear strength, designated with the symbol, $\tau_{ufo(s)}$ in this paper.

b) DSD_1 test where the specimen was reconsolidated at σ'_{vo} and then sheared under drained condition at a displacement rate of 0.025 mm/min in order to obtain in-situ drained shear strength, designated with the symbol, $\tau_{dfo(s)}$.

c) DSU_2 test where representative samples from Ma 3 and Ma 4 clays were remoulded under liquid condition, then normally consolidated and finally sheared under constant volume condition at the same displacement rate as for DSU_1 test in order to obtain undrained direct shear strength in the normally consolidated state, designated with the symbol, $\tau_{ufn(s)}$ in this paper.

d) DSU_3 test where samples used for DSU_2 test were first normally consolidated, then rebounded at a given overconsolidation ratio, OCR and finally sheared under constant volume condition in order to obtain strength decrease induced by swelling. Both consolidation and swelling were terminated when primary compression and swelling have been achieved.

5) Oedometer test: Two kinds of oedometer

Table 1. Field and laboratory tests conducted

Tests		Numbers		Symbol
		Ma 3	Ma 4	
F. V	standard	11	11	$\tau_{ufo(s)}$
	special	9		
q_u		18	13	$q_u/2$
Direct shear	DSU_1	10	16	$\tau_{ufo(s)}$
	DSD_1	10	7	$\tau_{dfo(s)}$
	DSU_2	4	8	$\tau_{ufn(s)}$
	DSU_3	5	10	
Oedometer	S-oed.	10	16	
	S.C-oed.		8	

tests, S-oed. and S.C-oed. tests were carried out on the specimen with $D=60$ mm and $H=20$ mm as explained below.

a) S-oed. test where the specimen was subjected to consolidation stress, σ'_c doubling the previous one for 24 hours as follows : -20, 40, 80, 320, 640, 1280 and 2560 Kpa.

b) S.C-oed. test where the specimen was subjected to consolidation under strain controlled condition at a strain rate satisfying full drainage condition in order to minimize the strain rate effect on σ'_y , and a strain rate of $0.02\%/min$, which was determined by preliminary test, was adopted. Since the device for this test was manufactured in 1986, S.C-oed. test was executed on Ma 4 clay alone.

Field and laboratory tests explained above are summarized in Table 1 together with numbers of the tests and symbols of the shear strengths used in this paper. In addition, water content, specific gravity, liquid and plastic limits, and gradation analysis tests were also carried out.

PHYSICAL PROPERTIES

Natural water content, w_n , liquid and plastic limits, w_l and w_p , and gradation components of Ma 3 and Ma 4 clays are shown in Fig. 3. The values of w_n of Ma 3 clay are 60% in average through the depth except 2 samples indicating about 80%, while there is some difference in plasticity index, I_p , which are 60% and 50% for the upper and the

Fig. 3. Physical properties of Pleistocene clays investigated

Fig. 4. Values of $q_u/2$ and $\tau_{ufo(v)}$ measured in q_u and F.V tests

lower parts, respectively. On the other hand, there is a thin sandy layer at a depth of 10 m for Ma 4 clay, and the values of w_n of the upper and the lower clay bounded by this sand are greatly different indicating 45% and 70% in average for the upper and the lower clays, respectively. But there is no significant difference in I_p values between both clays showing 53% and 48% for the upper and the lower clays, respectively.

IN-SITU SHEAR STRENGTH

The values of $q_u/2$ and $\tau_{ufo(v)}$ measured in q_u and F.V tests are presented in Fig.4. First of all, it is noted that $q_u/2$ values are about half of $\tau_{ufo(v)}$ values. One of the reasons for this difference is probably that the shear strength in q_u test is greatly affected by weak point like crack, while the shear plane in F.V test is limited to a specified plane along the vane. But there is a possibility in F.V test on such a hard clay that the shear plane is not maintained along the vane. For an example, there could be a chance for occurrence of crack during rotation, which produces larger shear plane than the specified one. In this case, stress-rotating angle curve should indicate a discontinuity near failure point. Some representative stress-rotating angle curves are presented in Fig.5, where any discontinuity can not be observed.

In order to investigate the difference in $q_u/2$ and $\tau_{ufo(v)}$ values in more detail, DSU₁ tests were carried out because the shear mechanism in D.S test is similar to that in F.V test. In D.S₁ test, the specimen prepared from an undisturbed sample is consolidated at σ'_{vo} for 10 minutes and then sheared under constant volume condition at a dis-

Fig. 5. Representative stress-rotating angle curves obtained from F.V test

Fig. 7. Frequency of compressive and extensive failures in q_u test plotted vs. $q_u/2$

Fig. 6. Values of $\tau_{ufo(s)}$ and $\tau_{ufo(v)}$ obtained from DSU_1 and F.V tests

placement rate of 0.1 mm/min. The values of $\tau_{ufo(s)}$ measured in DSU_1 test are shown in Fig. 6 together with $\tau_{ufo(v)}$ values shown in Fig. 4. Both strengths ranged in the same zone and showed good correspondence each other. It can be concluded, therefore, that the shear plane in F.V test was maintained at the specified plane determined by D and H of the vane.

Failure type observed in q_u test was investigated in the next step. Frequencies of compressive and extensive failures in q_u test

Fig. 8. Ratios of $\tau_{ufo(v)v}/\tau_{ufo(v)h}$ of Ma 3 clay

are plotted versus $q_u/2$ in Fig. 7. It should be noted that 24 specimens among 37 ones, that is, 65% showed extensive failure. The values of $q_u/2$ were 115 kPa and 75 kPa in compressive and extensive failures in average. The lower $q_u/2$ values compared with $\tau_{ufo(v)}$ and $\tau_{ufo(s)}$ should be attributed, therefore, to that failure took place at a weak point like crack and extensive strength, sig-

nificantly smaller than compressive strength, was measured in most case. It can be said that the shear strength of such a hard clay measured in q_u test is uncertain and should be reconsidered when used for practice.

F.V tests with different shapes as shown in Fig. 2 were conducted on Ma 3 clay. It is then possible to obtain separately the vane shear strengths on horizontal and vertical planes, designated with the symbols, $\tau_{ufo(v)h}$ and $\tau_{ufo(v)v}$. The ratios of $\tau_{ufo(v)v}/\tau_{ufo(v)h}$ are presented in Fig. 8. Though there are con-

siderable scatters, $\tau_{ufo(v)v}/\tau_{ufo(v)h}$ ratios are mostly distributed in the range from 0.4 to 0.7 without showing any trend with depth. The fact, $\tau_{ufo(v)h}$ being greater than $\tau_{ufo(v)v}$ suggests that overconsolidated state of Ma 3 clay was not caused by release of the overburden but probably by chemical bonding like cementation as revealed later.

Since Pleistocene clay found at hilly area is in an overconsolidated state, it is suggested that the drained shear strength, τ_{dfo} is smaller than the undrained shear strength,

Fig. 9. Values of $\tau_{dfo(s)}$ obtained from DSD_1 test and $\tau_{dfo(s)}/\tau_{ufo(s)}$ ratios

Fig. 10. Representative $e-\log \sigma'_c$ and $e-\sigma'_c$ curves obtained from S-oed. test

τ_{uf0} . The values of $\tau_{df0(s)}$ obtained from DSD₁ test and $\tau_{df0(s)}/\tau_{uf0(s)}$ ratios are shown in Fig.9 together with $\tau_{uf0(s)}$ values from DSU₁ test. The ratios of $\tau_{df0(s)}/\tau_{uf0(s)}$ indicate approximately a constant value, 0.6 to 0.7 for Ma3 clay and 0.7 to 0.8 for Ma4 clay. The ratio of τ_{df}/τ_{uf} for overconsolidated clay formed by release of overburden alone decreases with increasing OCR. As presented later, OCR values of the clays investigated are 5 to 7 and 6 to 17 for Ma3 and Ma4 clays, respectively and decrease with increasing depth. The constant $\tau_{df0(s)}/\tau_{uf0(s)}$ ratios shown in Fig.9 disagree with the well known fact observed for overconsolidated clay caused by stress release alone.

CONSOLIDATION YIELDING STRESS

Representative e -log σ'_c and e - σ'_c curves obtained from S-oed. test on Ma3 clay are

Fig. 11. Step-wise distribution of σ'_y obtained from S-oed. test for Pleistocene clay at New Kansai International Airport (after Ishii et al.)

presented in Fig.10. The stress at maximum curvature point in e -log σ'_c curves is approximately 640 kPa, which gives a same σ'_y value for all the sample provided that compression index, C_c is the same. Actually, Ishii et al. (1984) reported that σ'_y values from S-oed. test on Pleistocene clays found at the proposed site for New

Fig. 12. Representative e - σ'_c curves obtained from S.C-oed. test for Ma4 clay together with those from S-oed. test

Fig. 13. Idealized plot showing stress-strain curve in oedometer test

Kansai International Airport indicated a step-wise distribution with depth as shown in Fig. 11. On the other hand, a yielding point at $\sigma'_c = 640$ kPa can also be seen in $e-\sigma'_c$ curves. It can not be said, however, that this stress agrees with the real yielding stress because of the great difference in σ'_c values before and after $\sigma'_c = 640$ kPa. There is no doubt that the difficulty in determining accurate σ'_y from S-oed. test is caused by its large load increment ratio.

In order to overcome the disadvantage of S-oed. test in evaluating σ'_y , S.C-oed. test was carried out on Ma 4 clay. In this test, load was applied at the top end and excess pore water pressure, Δu was measured at the bottom end. In order to minimize the strain rate effect on σ'_y as reported in detail by Leroueil et al. (1983), S.C-oed. test was carried out at a strain rate which satisfies

full drainage condition. The strain rate determined by preliminary test was 0.02%/min.

Representative $e-\sigma'_c$ curves obtained from S.C-oed. test on Ma 4 are presented in Fig. 12 together with those from S-oed. test. Clear yielding point can be observed in $e-\sigma'_c$ curves from S.C-oed. test, while not clear in those from S-oed. test. Oedometer test is one kind of loading test without lateral strain and σ'_y is the yielding stress on stress-strain curve in this loading test as ideally shown in Fig. 13. From this point of view, σ'_y should be determined by arithmetic scale. Some representative stress-strain curves from S.C-oed. test are summarized in Fig. 14 together with Δu measured at the bottom end. It can also be seen that yielding stress is easily possible to determine on stress-strain curve from S.C-oed. test.

The values of σ'_y obtained from S-oed. and

Fig. 14. Representative stress-strain curves and excess pore water pressure obtained from S.C-oed. test for Ma 4 clay

Fig. 15. Values of σ'_y determined by S-oed. and S.C-oed. tests plotted vs. depth

Fig. 16. Values of OCR determined by S-oed. and S.C-oed. tests

S.C-oed. tests are presented in Fig. 15 where σ'_y were determined by Casagrande method using e - $\log \sigma'_c$ curves and by yielding stress on e - σ'_c curves from S-oed. and S.C-oed. tests, respectively. The values of OCR for both clays are also presented in Fig. 16. The values of σ'_y from S.C-oed. test showed 1.25 to 1.5 times greater value than those from S-oed. test when they are represented by solid line. Such difference reaching 200 to

300 kPa should be important in predicting settlement. Which σ'_y value is more appropriate is discussed in the next section as related to the undrained shear strength.

CONSOLIDATION YIELDING STRESS AS RELATED TO UNDRAINED SHEAR STRENGTH

Overconsolidated clay is fundamentally clas-

Fig. 17. Idealized plot showing $\tau_{uf0}-\sigma'_v$ paths for normally consolidated aged clay and overconsolidated young clay

sified into two types, 1) normally consolidated aged clay, NCA clay and 2) overconsolidated young clay, OCY clay as first proposed by Bjerrum (1973). The main factor for overconsolidated state is aging effect such as chemical bonding and secondary compression for the former, while release of the overburden for the latter. The path of τ_{uf} and σ'_v (=effective vertical stress) for both clay since deposition to the present time is as ideally shown in Fig. 17, and τ_{uf0} is given by Eq. (1) (Hanzawa, 1983).

$$\begin{aligned}\tau_{uf0} &= \tau_{ufn}/\sigma'_v \times \sigma'_{y1} \text{ for NCA clay} \\ &= \tau_{ufn}/\sigma'_v \times \sigma'_{y2} \times \alpha \text{ for OCY clay}\end{aligned}\quad (1)$$

where τ_{ufn}/σ'_v = undrained strength ratio in the normally consolidated state

α = coefficient of strength decrease induced by swelling caused by release of the overburden

The stress history of Pleistocene clay including geological one is much more complicated than of alluvial clay. It could be able to judge, however, that the clay is classified to which type of overconsolidated clay when τ_{uf0} determined by Eq. (1) is compared with measured τ_{uf0} value.

DSU₂ and DSU₃ tests, where the values of τ_{ufn}/σ'_v and α in Eq. (1) are obtained, were carried out on representative samples from Ma 3 and Ma 4 clays. Upper clay from Ma 3 and both upper and lower clays from Ma 4 were chosen as representative samples.

Fig. 18. Values of $\tau_{ufn(s)}$ plotted vs. σ'_{vc} obtained from DSU₂ test

Fig. 19. Correction coefficient for strength decrease induced by swelling, α plotted vs. OCR obtained from DSU₃ test

Fig. 20. Comparison of $\tau_{uf0(s)}$ values corresponding to NCA and OCY clays and from DSU₁ test

The values of τ_{ufn}/σ'_v and α versus OCR obtained from DSU₂ and DSU₃ tests are presented in Fig.18 and 19. Then the values of τ_{ufo} corresponding to NCA and OCY clays can be easily determined by Eq.(1) using σ'_y values shown in Fig.15. The values of $\tau_{ufo(s)}$ corresponding to NCA and OCY clays thus determined are presented by solid (NCA) and dotted (OCY) lines in Fig.20 together with measured $\tau_{ufo(s)}$ values in DSU₁ test. The following two comments can be made.

1) The values of $\tau_{ufo(s)}$ obtained as NCA clay showed relatively good agreement with the measured $\tau_{ufo(s)}$ values, while $\tau_{ufo(s)}$ values obtained as OCY clay are about half of the measured values, which strongly suggests that both Ma3 and Ma4 clays are fundamentally classifiable to NCA clay.

2) When $\tau_{ufo(s)}$ values as NCA clay determined with the use of σ'_y values from S-oed. and S.C-oed. tests are compared, it can be observed that $\tau_{ufo(s)}$ values calculated using σ'_y values from S.C.-oed. test show better agreement with the measured $\tau_{ufo(s)}$ values.

Kurihara et al. (1988) also demonstrated that σ'_y values obtained from Eq. (1) ($\sigma'_y = \tau_{ufo} \div \tau_{ufn}/\sigma'_v$ for NCA clay) and S.C-oed. test showed quite good agreement with each other for an alluvial marine clay classifiable to NCA clay.

From the discussion presented in this and the previous sections, it can be concluded that S.C-oed. test is better than S-oed. test in determining σ'_y value by the following two reasons.

1) Since continuous stress-strain curve is obtained in S.C-oed. test, it is possible to determine the yielding point easily on arithmetic scale plot, which eliminates various problems in determining σ'_y from e -log σ'_c curve.

2) The value of σ'_y from this test indicated good agreement with that from Eq. (1), $\sigma'_y = \tau_{ufo} \div \tau_{ufn}/\sigma'_v$ for NCA clay.

It was strongly suggested from the discussion presented in this section that both Ma3 and Ma4 clays can fundamentally be classi-

Fig. 21. Deformation at failure, d_f obtained from DSU₁ and DSU₃ tests plotted vs. OCR

fiable to NCA clay. The major difference between NCA and OCY clays are the following two as revealed by Hanzawa (1983).

1) Coefficient of earth pressure at rest, K_0 of NCA clay is independent on OCR and is approximately constant irrespective of OCR.

2) Strain or displacement at failure in shear test for NCA clay is also independent on OCR and its stress-strain behaviour indicates significantly brittle behaviour when compared with that of OCY clay.

It has been recognized that strength anisotropy depends on K_0 value (Shibata, 1967; Hanzawa, 1983). If this clay is an OCY clay of which K_0 value increases with OCR, it is strongly suggested that $\tau_{ufo(v)}/\tau_{ufo(h)}$ ratio may reach more than 1.0. On the other hand, when the first characteristic of NCA clay is considered, this ratio should be less than 1.0 when this clay is a NCA clay. The ratios of $\tau_{ufo(v)}/\tau_{ufo(h)}$ being smaller than 1.0 and approximately constant with depth as shown in Fig.8 is corresponding to the first characteristic of NCA clay pointed out above.

The values of displacement at failure, des-

ignated with the symbol, d_f in DSU₁ and DSU₃ tests where the specimen is in over-consolidated young state are compared in Fig. 21 where OCR values in DSU₁ test are those from S.C-oed. test. The values of d_f in DSU₃ test increase with increasing OCR which is an important characteristic of OCY clay, whereas d_f values in DSU₁ test indicate approximately a constant value irrespective of OCR. Comparison of d_f values shown in Fig. 21 strongly support the suggestion made in this study that both Ma 3 and Ma 4 clays are classifiable to NCA clay.

CONCLUSIONS

Results of a series of field and laboratory tests conducted on heavily overconsolidated Pleistocene clay found at Izumi-hill of Osaka District were presented. The following conclusions can be made from the study.

1) The values of $q_u/2$ are about half of $\tau_{uf0(v)}$ and $\tau_{uf0(s)}$, and such a great difference was strongly suggested to be caused by that extensive failure at a weak point took place in most case in q_u test on such a hard clay.

2) It can be said, therefore, that q_u of such a hard clay is uncertain and should be too conservative when used for evaluating the bearing capacity.

3) The values of $\tau_{uf0(v)}$ and $\tau_{uf0(s)}$ from F.V and DSU₁ tests showed good correspondence each other, which demonstrates that F.V test is available to use for evaluating the in-situ shear strength of such a hard clay.

4) The value of σ'_y of this kind of material should be determined by S.C-oed. test because of easy finding of yielding stress from $e-\sigma'_c$ curve and good correspondence to the measured shear strength.

5) From the relationship observed between τ_{uf0} and σ'_y , and the behaviour in DSU₁ test, it can be concluded that both Ma 3 and Ma 4 clays are essentially classifiable to NCA clay.

NOTATION

d_f =displacement at failure in direct shear test

α =coefficient of strength decrease induced by swelling

σ'_c =consolidation stress

σ'_v =vertical effective stress

σ'_{vc} =vertical consolidation stress

σ'_{vo} =effective overburden stress

τ_{df} =drained shear strength

τ_{dfo} =in-situ drained shear strength

$\tau_{dfo(s)}$ =in-situ drained direct shear strength

τ_{uf} =undrained shear strength

τ_{uf0} =in-situ undrained shear strength

τ_{ufn} =undrained shear strength in the normally consolidated state

$\tau_{uf0(s)}$ =in-situ undrained direct shear strength

$\tau_{uf0(v)}$ =in-situ vane shear strength

$\tau_{uf0(v)h}$ =in-situ vane shear strength on horizontal plane

$\tau_{uf0(v)v}$ =in-situ vane shear strength on vertical plane

Δu =excess pore water pressure

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