NORMALIZED UNDRAINED STRENGTH OF CLAY IN THE NORMALLY CONSOLIDATED STATE AND IN THE FIELD

HIDEO HANZAWA¹⁾ and HIROYUKI TANAKA¹⁾

ABSTRACT

Undrained strength, S_u normalized with the effective overburden stress, σ'_{vo} or the consolidation stress in the laboratory tests is an important index in evaluating engineering properties of a clay. Extensive studies have been made on this subject and the results mostly suggest that there is a correlation between the normalized undrained shear strength and plasticity index, I_p . In this paper, undrained strength in the normally consolidated state, S_{un} normalized with the vertical consolidation stress, σ'_{vc} obtained from K_0 -consolidated triaxial compression and extension, and direct shear tests is first presented for various clays with $I_p=5$ to 100 together with discussions on previous studies on this subject. Undrained strength in the field, S_{uf} normalized with σ'_{vo} and the consolidation yielding stress, σ'_y investigated by field vane, direct shear and oedometer tests is then presented for 7 clays in Arabian Gulf, Indonesia and Japan. Further, a strain rate effect on S_u is also investigated.

Conclusive points obtained from this study are : -1) Normalized undrained shear strengths, S_{un}/σ'_{vc} and S_{uf}/σ'_{vo} as well as strength anisotropy are not correlated to I_p , 2) S_{uf} of clays investigated is expressed by $S_{un}+k_1$ to a certain σ'_{vo} and $S_{un}\times k_2$ beyond this σ'_{vo} , where k_1 and k_2 are constants, 3) S_{uf}/σ'_y shows a constant value being close to S_{un}/σ'_{vc} irrespective of overconsolidation ratio and I_p , and 4) the effect of strain rate on S_u is independent on I_p .

Key words : clay, laboratory test, overconsolidation, shear strength, plasticity, vane shear test (IGC : D/6)

INTRODUCTION

Normalized undrained shear strength with the effective overburden stress or the consolidation stress in the laboratory tests, $S_u/$

σ'_{vo} or S_u/σ'_c is an important index for evaluating the shear strength and stress history of a clay in-situ. Normalized field vane shear strength, $S_{uf(v)}/\sigma'_{vo}$ of normally consolidated clays was already reported in fifties

¹⁾ Director, Technical Research Institute, Toa Corporation, 1-3, Anzencho, Tsurumiku, Yokohama city, Kanagawa.

¹⁾ Head, Soil Investigation Laboratory, Port and Harbour Research Institute, Ministry of Transportation, 3-1-1, Nagase, Yokosuka city, Kanagawa.

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relating to plasticity index, I_p (Skempton and Henkel, 1954 ; Bjerrum, 1954) and liquid limit, w_L (Hansbo 1957). On the other hand, Bjerrum and Simons (1960) investigated the normalized compression strength of normally consolidated clays, $S_{un(c)}/\sigma'_c$ obtained from isotropically consolidated triaxial tests, where $S_{un(c)}/\sigma'_c$ ratios were calculated from the formulae given by Skempton and Bishop (1954) and Bishop (1958).

Extensive experimental studies were made in sixties in order to investigate the strength anisotropy of clay. Based on these studies, Ladd and Edgers (1972), and Berre and Bjerrum (1973) presented the normalized simple shear strength in the normally consolidated state (hereafter called NC state), $S_{un(s)}/\sigma'_{vc}$ where $S_{un(s)}$ and σ'_{vc} are simple shear strength in the NC state and vertical consolidation stress (Ladd and Edgers), and the normalized compression, simple shear and extension strengths in the field, $S_{uf(c)}/\sigma'_{vo}$, $S_{uf(s)}/\sigma'_{vo}$ and $S_{uf(e)}/\sigma'_{vo}$ (Berre and Bjerrum). Recently, Nakase and Kamei (1983 ; 1988) conducted extensive triaxial compression and extension tests on normally consolidated clays with $I_p=10$ to 60 and provided useful information on S_{un}/σ'_{vc} and S_{un}/σ'_c ratios.

The normalized undrained shear strengths in the NC state and in the field presented in these studies described above are summarized in Fig.1 where the modified $S_{uf(v)}/\sigma'_{vo}$ versus I_p by Larsson (1980) was used instead of $S_{uf(v)}/\sigma'_{vo}$ versus w_L given by Hansbo. As can be seen from Fig.1, it is likely that both S_{un}/σ'_{vc} and S_{uf}/σ'_{vo} ratios are closely related to the I_p except those by Nakase and Kamie.

On the other hand, there have been strong criticisms to uniquely relating S_u to the I_p . Based on extensive unconfined compression, triaxial and direct shear tests results on alluvial and diluvial clays of Osaka District, Mikasa (1966 ; 1967) demonstrated that there is no unique relationship between S_u and I_p , and insisted that physical properties like I_p can not work as an index for directly evaluating the shear strength characteristics of clay. Schmertman and Morgenstern (1977), and Hanzawa (1983) also insisted that S_u is much more dependent on regional variations such as formation process than the I_p .

Since S_{uf}/σ'_{vo} and S_{un}/σ'_{vc} ratios are indices directly indicating the shear strength itself, it is strongly suggested that the undrained shear strength for design use, $S_{u(mob)}$ is

Fig. 1. Normalized undrained shear strength previously investigated with different methods plotted versus I_p

uniquely related to the I_p if these ratios can directly be related to the I_p . Actually, the procedure to determine $S_{u(mob)}$ from $S_{uf(v)}$ proposed by Bjerrum (1972) and the general report by Ladd et al. (1977) in the Tokyo Conference were made based on this view point. However, the fact that half of the unconfined compression strength, $q_u/2$ can be used as $S_{u(mob)}$ for Japanese marine clays with a wide range of I_p ranging from 30 to 90 (Nakase, 1967; Tsuchida et al., 1989) also suggests the independency of S_u on the I_p .

In this paper, S_{un}/σ'_{vc} and S_{uf}/σ'_{vo} ratios shown in Fig. 1 are first discussed and then S_{un}/σ'_{vc} ratios of various clays in the NC state measured by K_0 -consolidated triaxial compression and extension, and direct shear tests (hereafter called CKoTCT, CKoTET and DST) are presented. The normalized undrained shear strength in the field is conceptually related to various aging effects to which the clay in-situ has been subjected since deposition more or less, and then the normalized field vane and direct shear strengths, $S_{uf(v)}/\sigma'_{vo}$ and $S_{uf(d)}/\sigma'_{vo}$ are presented for 7 marine clays found in Arabian Gulf, Indonesia and Japan together with discussions on aging effects to which each clay has been subjected. Further, the normalized undrained shear strength in the field with the consolidation yielding stress, σ'_y determined by standard and constant rate oedometer tests (hereafter called S-oed. T and CR-oed. T) are also presented and discussed. Finally, the effect of strain rate on S_u , which was reported to be greatly dependent on I_p (Bjerrum, 1973), is discussed based on a series of CKoTCT results on various clays.

DISCUSSIONS ON THE NORMALIZED UNDRAINED SHEAR STRENGTH CURRENTLY PRESENTED

The famous Skempton-Bjerrum line was reported for normally consolidated clay, but it should first be pointed out that the shear strength used in this line is $S_{uf(v)}$ measured by field vane test, FVT. As reported by Bjerrum (1967), clay in-situ is generally in

an overconsolidated state more or less and the degree of overconsolidation greatly depends on geological stress history as demonstrated by Hanzawa and Adachi (1983). It can be said, therefore, that the Skempton-Bjerrum line does not show the normalized shear strength of clay in the NC state but only gives some information on $S_{uf(v)}/\sigma'_{vo}$ for some clays found in northern part of Europe. Actually, there are lots of indications that the Skempton-Bjerrum line does not work for highly plastic clays found in South East Asia and India (Cox, 1970; Lumb, 1977; Mohan and Bhandari, 1977). Larsson (1980) pointed out that the Hansbo-Larsson line shows good agreement with $S_{uf(v)}/\sigma'_y$ ratios of Scandinavian clays. In any event, the fact that $S_{uf(v)}/\sigma'_{vo}$ ratios of clays found in the same area can be expressed by the two different lines, strongly suggests that S_{uf}/σ'_{vo} can not be uniquely related to the I_p but should depend on factors other than the I_p .

The ratios of $S_{un(c)}/\sigma'_c$ reported by Bjerrum and Simons were obtained by calculation using ϕ' at the maximum σ'_1/σ'_3 ratio and when ϕ' at the maximum $(\sigma'_1 - \sigma'_3)$ is used, $S_{un(c)}/\sigma'_{vc}$ ratio indicates smaller value than shown in Fig. 1. But when it is considered that S_{un}/σ'_{vc} ratio can directly be obtained from the triaxial test very easily, the Bjerrum-Simons line for S_{un}/σ'_{vc} ratio is useless at the present time.

The ratios of $S_{un(s)}/\sigma'_{vc}$ presented by Ladd and Edgers indicate a constant value of 0.26 when the I_p is equal to or more than 40, decrease with decreasing I_p from 40 to 15 and again show a constant value of 0.20 when the I_p is equal to or less than 15. The ratios of $S_{un(c)}/\sigma'_{vc}$ and $S_{un(e)}/\sigma'_{vc}$ obtained from CKoTCT and CKoTET investigated by Nakase and Kamie, on the other hand, strongly suggests that there is no unique relationship between these ratios and the I_p .

The most questionable one is the Berre-Bjerrum line. Clay in-situ is generally in an overconsolidated state, and they assumed that the main factor for overconsolidation is secondary compression which was also assumed

Fig. 2. Idealized plot showing S_{uf} and S_{uf}/σ'_{vo} of clay subjected to chemical bonding

Fig. 3. An example indicating regional variation of chemical bonding for 2 clays in Tokyo Bay and Kyushu Island

to be greater with increasing I_p (Bjerrum, 1973). An increase of S_{uf}/σ'_{vo} ratios with increasing I_p as shown in Fig.1 is just for this reason. But Hanzawa and Adachi (1983) revealed that the main factor for overconsolidation is rather chemical bonding than secondary compression for clays found in Arabian Gulf, Tokyo Bay and Singapore. The clay samples used for laboratory tests to determine S_{uf} by Berre and Bjerrum were mostly taken from depths shallower than 10 m. The effect of chemical bonding is

greater the shallower the depth as schematically shown in Fig.2, and its amounts greatly change regionally as also shown in Fig.3 which was reported by Hanzawa et al. (1991). In addition, the test conducted on a clay with I_p more than 35 is only Bangkok clay with $I_p=88$.

The second questionable point is the uncertainty in determining $S_{uf(e)}$. The axial strain at the maximum ($\sigma_1 - \sigma_3$) in CKoTET, $\epsilon_{f(e)}$ is much larger than $\epsilon_{f(c)}$ in CKoTCT, and sometimes reaches more than 15%, particularly in the NC state. Berre and Bjerrum used $(\sigma_1 - \sigma_3)/2$ at about twice of $\epsilon_{f(c)}$ as $S_{uf(e)}$, and as well be known $\epsilon_{f(c)}$ decreases with decreasing I_p , which results in smaller $S_{uf(e)}$ with decreasing I_p . Further, they recommended the reconsolidation time reaching several 10 days in determining S_{uf} in the laboratory tests, which should give higher S_{uf} than the actual one.

The ratios of $S_{un(c)}/S_{un(s)}$ and $S_{un(e)}/S_{un(s)}$ versus I_p presented by Ladd (1973) are shown in Fig.4 together with $S_{uf(c)}/S_{uf(s)}$ and $S_{uf(e)}/S_{uf(s)}$ ratios made from three kinds of S_{uf}/σ'_{vo} ratios by Berre and Bjerrum. The ratios by Ladd indicate a symmetry above and below 1.0, and locate more apart from 1.0 as I_p decreases, which demonstrates that $S_{un(s)}$ is equal to the average strength of $S_{un(c)}$ and $S_{un(e)}$ and the strength anisotropy is greater the lower the I_p . But such correlations can

Fig. 4. $S_{u(c)}/S_{u(s)}$ and $S_{u(e)}/S_{u(s)}$ ratios by Ladd and Berre-Bjerrum plotted versus I_p

not be observed in the ratios by Berre and Bjerrum.

NORMALIZED UNDRAINED SHEAR STRENGTH IN THE NORMALLY CONSOLIDATED STATE

A series of CKoTCT, CKoTET and DST were carried out on various clays in the NC state. Physical properties of clays, sample preparation methods and the laboratory tests conducted are summarized in Table 1. Undisturbed and slurry methods in sample preparation are that undisturbed samples were K_0 -consolidated under σ'_{vc} being more than twice of σ'_y in the former, while slurry

state clays preliminarily consolidated were mounted on a device and then K_0 -consolidated in the latter. Because of difficulty in obtaining low plastic pure clays in Japan, low plastic clays were artificially prepared with mixing sand or silt sized particles as shown in Table 1 except Fao clay in the Arabian Gulf.

Testing Procedures and Conditions

K_0 -consolidation in the triaxial test was conducted with the procedure explained in the following. A preliminarily consolidated sample from slurry state was trimmed and mounted on the device. Consolidation at a constant horizontal consolidation stress, σ'_{hc}

Table 1. Properties of clays, sample preparation methods and tests conducted for investigating S_{un}/σ'_{vc} ratio in the NC state

Clay			I_p	Gradation			Sample preparation		Tests conducted		
				Clay	Silt	Sand	Undisturbed	Slurry	CKoTCT	CKoTET	DST
Artificially prepared	Okinawa	OS-1	40	56	42	2		○	○	○	
		-2	24	36	49	15		○	○	○	
		-3	13	21	48	31		○	○	○	○
		-4	5	9	91	0		○	○	○	
	Kashiwazaki	KS-1	51	48	52	0		○	○	○	
		-2	39	43	37	20		○	○	○	
		-3	32	26	34	20		○	○	○	
		-4	22	18	22	60		○	○	○	
		-5	16	14	22	64		○	○	○	
		-6	13	12	19	69		○	○	○	
	Natsushima		50				○		○	○	○
	Haneda	Upper	65					○	○	○	
		Lower	15					○	○	○	
	Kuwana	Upper	35					○	○	○	○
		Lower	55					○	○	○	○
Japan	Ariake	Upper	70					○	○	○	○
		Lower	50					○	○	○	○
	Isogo	Upper	50					○			○
		Lower	25					○			○
	Surabaya		85					○	○	○	○
Indonesia	Banjar-masin	Upper	60					○	○	○	○
		Lower	70					○	○	○	○
Arabian G	Fao		20				○		○	○	
	Khor Al-Zubair		35				○		○	○	

was commenced and σ'_{vc} was controlled so as to satisfy the condition given by $\Delta V = A_0 \times \delta_v$ during consolidation, where ΔV , A_0 and δ_v are volumetric change, initial sectional area of the specimen and vertical deformation of the specimen, respectively. After σ'_{vc} showed a constant value for 60 minutes, a new σ'_{hc} was applied and a new σ'_{vc} to satisfy the condition of $\Delta V = A_0 \times \delta_v$ was determined. Repeating this operation several times, K_0 value given by $\sigma'_{hc}/\sigma'_{vc}$ was obtained as presented in Fig. 5 which indicates a test result for Ariake clay found in Kyushu Island, Japan. After the determination of K_0 value with this method, the specimen for shear test was consolidated with σ'_{vc} and σ'_{hc} from the beginning stage until primary consolidation has been achieved. Completion of primary consolidation was determined by $\log t$ method for the triaxial test and $\sqrt{t}$ method for the direct shear test. The specimen was then subjected to shear at a strain rate of 0.1%/min in CKoTCT and CKoTET, and a deformation rate of 0.25 mm/min in DST. A back pressure of 200 kPa was applied both during consolidation and shear stages in CKoTCT and CKoTET, while the modified direct shear device developed by Mikasa (1960), where constant volume shear is possible, was used for DST. Dimensions of the specimen were 35 mm in diameter, D and 85 mm in height, H for the triaxial test, and 60 mm in D and 20 mm in H for the direct shear test. Drain papers with a long strip and a spiral shape were used in

Fig. 5. A result to determine K_0 value in triaxial consolidation test

CKoTCT and CKoTET, respectively together with doughnut shaped membranes lubricated with silicone grease at both ends of the specimen.

K_0 Value

The values of K_0 determined by the method explained above are plotted versus I_p in Fig. 6 which clearly indicates that K_0 values decrease with decreasing I_p and there is no significant difference in K_0 values of clays

Fig. 6. K_0 values obtained from triaxial test plotted versus I_p

Fig. 7. S_{un}/σ'_{vc} ratios and $\varepsilon_{f(c)}$ in CKoTCT plotted versus I_p for Okinawa and Kashiwazaki clays prepared artificially

prepared with different methods. In order to make clear that K_0 - I_p relationship, however, it is desirable to investigate the K_0 value of low plastic pure clay because the low plastic pure clay used in the tests was only Fao clay in Arabian Gulf.

S_{un}/σ'_{vc} ratios

The ratios of $S_{un(c)}/\sigma'_{vc}$ and $S_{un(e)}/\sigma'_{vc}$ and their average values for Okinawa and Kashiwazaki clays artificially prepared are plotted versus I_p in Fig. 7 together with $\varepsilon_{f(c)}$ values in CKoTCT and $S_{un(e)}/\sigma'_{vc}$ ratios at the axial strain being twice of $\varepsilon_{f(c)}$. When the maximum $(\sigma_1 - \sigma_3)$ is not obtained until the axial strain reaches 15% m, $(\sigma_1 - \sigma_3)/2$ at 15% was adopted as $S_{un(e)}$. When $S_{un(c)}/\sigma'_{vc}$ ratio is noticed, this ratio decreases with increasing I_p for Okinawa clay, while it indicates approximately a constant value irrespective of I_p for Kashiwazaki clay. There is a tendency that $S_{un(e)}/\sigma'_{vc}$ ratio decreases with decreasing I_p , particularly when I_p is less than 20, but the average of $S_{un(c)}/\sigma'_{vc}$ and $S_{un(e)}/\sigma'_{vc}$ shows approximately a constant value of 0.28 to 0.29 irrespective of I_p . It can clearly be observed that $\varepsilon_{f(c)}$ values decrease with decreasing I_p and the values of Okinawa clay are smaller than those of Kashiwazaki clay. The ratios of $S_{un(e)}/\sigma'_{vc}$ at the axial strain being twice of $\varepsilon_{f(c)}$ are ranged from 0.05 to 0.2, decreasing with decreasing I_p except for the OS-4 sample with $I_p=5$ which mostly consists of silt sized particles as shown in Table 1. This is a quite natural result from the change of $\varepsilon_{f(c)}$ values with I_p shown in the figure.

Various test results on all the samples are summarized in Fig. 8 (a), (b) and (c). The ratios of S_{un}/σ'_{vc} do not suggest any correlation between this ratio and I_p , which agrees with the test results by Nakase and Kamei presented in Fig. 1. In Fig. 8 (b) are indicated the strength ratios between $S_{un(d)}$ and the average strength of $S_{un(c)}$ and $S_{un(e)}$. The ratio of $2S_{un(d)}/(S_{un(c)} + S_{un(e)})$ is 0.99 in average which demonstrates that $S_{un(d)}$ is equal to the average of $S_{un(c)}$ and $S_{un(e)}$. The ratios of $S_{un(c)}/S_{un(d)}$ and $S_{un(e)}/S_{un(d)}$

Fig. 8. S_{un}/σ'_{vc} ratios (a), $2S_{un(d)}/(S_{un(c)} + S_{un(e)})$ (b), and $S_{un(c)}/S_{un(d)}$ and $S_{un(e)}/S_{un(d)}$ (c) obtained from CKoTCT, CKoTET and DST plotted versus I_p

$S_{un(d)}$ are presented in Fig. 8(c) together with those by Ladd for S_{un} , and by Berre and Bjerrum for S_{uf} . It is difficult to find out any correlation between these ratios and I_p , which is different from Ladd's indication.

CLAY PROPERTIES AND TESTS CONDUCTED

The ratios of S_{un}/σ'_{vc} in the NC state were presented in the previous section. In the followings of this paper, the ratios of S_{uf}/σ'_{vo} in the field are investigated and discussed for 7 marine clays found in Arabian Gulf, Indonesia and Japan. Tests conducted on each

Table 2. Properties and tests conducted for 7 marine clays for investigating S_{uf} and σ'_v in this study

Clay		I_p	S_{un}/σ'_{vc}			FVT		DST	Oedometer	
			$S_{un(e)}$	$S_{un(s)}$	$I_p S_{un(d)}$	SFVT	Drilling.		S-oed. T	CR-oed. T
Arabian G	Fao	10~30	0.39	0.29			66		6*-1	
	Khor Al-Zubair	32~36	0.355	0.25			40		10*-2	
Indonesia	Surabaya	48~103	0.34	0.22	0.27	51		56	34	
	Banjar-masin	Upper	54~110	0.29	0.24	0.27		20		16
		Lower	52~105	0.31	0.22	0.27		29		20
Japan	Ariake	Upper	45~91	0.31	0.24	0.28	11	11	11	11
		Lower	33~63	0.32	0.20	0.27	8	8	8	8
	Isogo	Upper	30~60		0.30			16	12	14
		Lower	24~27		0.30			6	4	6
	Kuwana	Upper	31~38	0.35	0.20	0.27	7	7	7	7
		Lower	45~60	0.35	0.20	0.27	5	13	13	13

*-1: $t_c=2$ hrs. & $\Delta\sigma_c/\sigma'_c=1/4$, *-2: $t_c=2$ hrs. & $\Delta\sigma_c/\sigma'_c=1$

Numbers of FVT, DST and Oedometer test are numbers of tests

Fig. 9. Water content, liquid limit and plastic limit of the clays investigated in this study

clay are summarized in Table 2 together with I_p and S_{un}/σ'_{vc} ratios. SFVT and drilling methods for FVT are the penetration type of sheathed FVT and drilling type FVT, respectively. Undisturbed samples were primarily consolidated at σ'_{vo} and then subjected to shear at a deformation rate of 0.25 mm/min in DST. Two kinds of oedometer tests, S-oed. T and CR-oed. T were carried out. Consolidation time, t_c and stress incremental ratio, $\Delta\sigma_c/\sigma'_c$ in S-oed. T were 24 hours and 1.0, respectively except for Fao and Khor Al-Zubair clays in Arabian Gulf. The

t_c and $\Delta\sigma_c/\sigma'_c$ for these two clays were 2 hours for both clays, and 1/4 and 1.0 for Fao clay and Khor Al-Zubair clay. Strain rates in CR-oed. T were determined to be 0.02%/min from preliminary tests so as to satisfy the full drainage condition until σ'_v is obtained. The values of water content, w_n , liquid limit, w_L and plastic limit, w_P of each clay are presented in Fig. 9.

Engineering properties of clay in-situ are closely related to geological history as demonstrated by many engineers. From this point of view, sedimentation time of each clay

Fig. 10. Sedimentation time of each clay investigated and sea water level change for past 20,000 years

Fig. 11. Point resistance of Khor al-Zubair and Banjarmasin clays subjected to cementation and desiccation stress in the past

are first summarized in Fig. 10 together with the sea level change for past 20,000 years. Clay appeared on land when the sea level was lowered was subjected to either desiccation stress, cementation and oxidation or their combined actions as discussed in detail by Hanzawa and Adachi (1983). Point resistance, q_c of khor Al-Zubair clay in Arabian Gulf and Banjarmasin clay in Indonesia, which were subjected to small scaled sea level lowering for past 5,000 years for the former and large scaled sea level lowering at 10,000 years ago for the latter, are shown in Fig. 11 which clearly indicates the drastic change of q_c at the depths subjected to cementation (Khor Al-Zubair clay) and desiccation stress (Banjarmasin clay).

NORMALIZED UNDRAINED SHEAR STRENGTH IN THE FIELD

In-situ clay is generally in an overconsolidated state more or less and main factors for overconsolidation are chemical bonding and secondary compression which are different from each other in mechanism. In-situ undrained shear strength, S_{uf} of clay subjected to these actions is expressed by Eq. (1).

$$\begin{aligned} S_{uf} &= S_{un} + k_1 \text{ for chemical bonding} \\ &= S_{un} \times k_2 \text{ for secondary compression} \end{aligned} \quad (1)$$

where k_1 and k_2 are constants.

Hanzawa and Adachi revealed that σ'_y of marine clays is fundamentally given by $\sigma'_y =$

Fig. 12. Idealized plot showing S_{uf} and S_{uf}/σ'_{vo} of clay subjected to combined actions of chemical bonding and secondary compression

$\sigma'_{v0} + k'_1$ to a certain σ'_{v0} and $\sigma'_y = \sigma'_{v0} \times k_2$ beyond this σ'_{v0} . Then S_{uf} and S_{uf}/σ'_{v0} of a clay in-situ are fundamentally given by Eq. (2) as schematically presented in Fig. 12.

$$\begin{aligned} S_{uf} &= S_{un} + k_1 \text{ to a certain } \sigma'_{v0} \\ &= S_{un} \times k_2 \text{ beyond a certain } \sigma'_{v0} \end{aligned} \quad (2.1)$$

$$\begin{aligned} S_{uf}/\sigma'_{v0} &= (S_{un} + k_1)/\sigma'_{v0} \text{ to a certain } \sigma'_{v0} \\ &= S_{un}/\sigma'_{vc} \times k_2 \text{ beyond a certain } \sigma'_{v0} \end{aligned} \quad (2.2)$$

The value of σ'_{v0} bounding $S_{un} + k_1$ and $S_{un} + k_2$ depends on amounts of chemical bonding and secondary compression.

In Fig. 13 are compared $S_{uf(v)}$ and $S_{uf(d)}$ values measured in SFVT and DST for Surabaya, Ariake and Kuwana clays. A unique correlation is obtained between $S_{uf(v)}$ and $S_{uf(d)}$ for each clay as given by $S_{uf(v)} = 0.8 S_{uf(d)}$ for Surabaya and Ariake clays and $S_{uf(v)} = S_{uf(d)}$ for Kuwana clay. Since $S_{uf(v)}$ of clay with sand seams and shells indicates a greater value than the actual one as typically observed for Kuwana clay and S_{uf} is a function of S_{un} as given by Eqs. (1) and (2), $S_{uf(d)}$ values were used in the following discussions except for clays in Arabian Gulf for which DST were not carried out.

S_{uf}/σ'_{v0} ratios

The ratios of $S_{uf(v)}/\sigma'_{v0}$ for Arabian Gulf clays and $S_{uf(d)}/\sigma'_{v0}$ for other clays are plotted versus σ'_{v0} in Fig. 14 together with S_{un}/σ'_{vc} ratios corresponding to vane and direct shear strengths. The following comments can be made for each clay.

(1) There are some scatters in $S_{uf(v)}/\sigma'_{v0}$ ratios of Fao clay with $I_p = 10$ to 30 but it could be possible to represent the $S_{uf(v)}/\sigma'_{v0}$ by $S_{un(v)}/\sigma'_{vc}$ ratio of 0.31 which was predicted from correlation among $S_{uf(c)}$, $S_{uf(v)}$ and $S_{un(c)}/\sigma'_{vc}$ as indicated below. Hanzawa (1977) reported that σ'_y of Fao clay determined by special S-oed. T with $t_c = 2$ hours and $\Delta\sigma_c/\sigma'_c = 1/4$ showed good agreement with σ'_{v0} , while σ'_y from ordinary S-oed. T were much smaller than σ'_{v0} indicating $\sigma'_y = 0.7 \sigma'_{v0}$. Since there is no reason that Fao clay is in an underconsolidated state, Hanzawa (1977) concluded that Fao clay is in the normally consolidated state. It is reasonable to express $S_{uf(v)}/\sigma'_{v0}$ of this clay by $S_{un(v)}/\sigma'_{vc}$ ratio.

$$\begin{aligned} * S_{un(c)}/\sigma'_{vc} &= 0.39 \text{ \& } S_{uf(v)} = \frac{S_{uf(c)}}{1.25} \\ &\rightarrow S_{un(v)}/\sigma'_{vc} = 0.39/1.25 = 0.31 \end{aligned}$$

(2) The ratios of $S_{uf(v)}/\sigma'_{v0}$ of Khor Al-Zubair clay subjected to complicated aging effects such as desiccation stress and cementation indicate approximately a constant value of 0.30 in the zone beyond $\sigma'_{v0} = 80$ kPa except the cemented zone from $\sigma'_{v0} = 115$ to 125 kPa, and this suggests that secondary compression is predominant in the zone beyond $\sigma'_{v0} = 80$ kPa. The ratio of $S_{un(v)}/\sigma'_{vc}$ was predicted to be 0.22 as shown below and then overconsolidation ratio, OCR is given by $0.30/0.22 = 1.4$ which shows good agreement with OCR determined using σ'_y from a special S-oed. T with $t_c = 2$ hours and $\Delta\sigma_c/\sigma'_c = 1.0$ as revealed later.

Fig. 13. $S_{uf(v)}$ measured by FVT plotted versus $S_{uf(d)}$ measured by DST for Surabaya, Ariake and Kuwana clays

Fig. 14. Normalized undrained shear strength, $S_{uf(v)}/\sigma'_{vo}$ and $S_{uf(d)}/\sigma'_{vo}$ of 7 clays plotted versus σ'_{vo}

$$* S_{un(c)}/\sigma'_{vc} = 0.355 \text{ \& } S_{uf(v)} = \frac{S_{uf(c)}}{1.6}$$

$$\rightarrow S_{un(v)}/\sigma'_{vc} = 0.355/1.6 = 0.22$$

(3) The ratios of $S_{uf(d)}/\sigma'_{vo}$ of Surabaya clay with $I_p=48$ to 103 covered with an alternation layer of sand and clay of 6 m thick decrease with increasing σ'_{vo} until σ'_{vo} reaches 90 kPa, while the ratios beyond $\sigma'_{vo}=90$ kPa indicate a constant value of 0.41, which is just the same as S_{uf}/σ'_{vo} ratio given by Eq. (2.2). It is therefore suggested that chemical bonding is predominant for the

upper part ($\sigma'_{vo} \leq 90$ kPa), while secondary compression for the lower part ($\sigma'_{vo} \geq 90$ kPa) where OCR is predicted to be $0.41/0.27=1.5$

(4) The ratios of the upper Banjarmasin clay with $I_p=54$ to 110 indicate a typical ratio subjected to chemical bonding, while the ratios of the lower clay with $I_p=52$ to 105 show approximately a constant value of 0.5 except the desiccated zone. A constant S_{uf}/σ'_{vo} ratio suggests that secondary compression is predominant for the lower clay, but as pointed out by Subagio and Setiawani (1991), the fact that there are lost of slickenside cracks in the lower clay also suggests that the lower clay was entirely subjected to desiccation stress more or less.

(5) The ratios of $S_{uf(d)}/\sigma'_{vo}$ of the upper Isogo clay with $I_p=30$ to 60 clearly indicate that the upper clay was subjected to relatively large chemical bonding, while the ratios of the lower clay with $I_p=24$ to 27% indicate a constant value of 0.64 which gives OCR of 2.1 ($=0.63/0.30$). This OCR shows good agreement with OCR determined by σ'_y from CR-oed. T as indicated later.

(6) The ratios of $S_{uf(d)}/\sigma'_{vo}$ of the upper Ariake clay with $I_p=45$ to 91 also indicate a typical ratio of the chemically bonded clay, while the ratios of the lower clay with $I_p=33$ to 63 approximately show a constant value though there are some scatters. These characteristics in $S_{uf(d)}/\sigma'_{vo}$ ratio are consistent with those for an Ariake clay found at coastal reclaimed area as reported in detail by Hanzawa et al. (1990).

(7) It is suggested that secondary compression is predominant for Kuwana clay covered with a sand layer of 10 m thick as ideally indicated in Fig. 12. As can be seen from Fig. 14, the $S_{uf(d)}/\sigma'_{vo}$ ratios indicate a constant value of 0.38 in the zone of $\sigma'_{vo} \leq 200$ kPa irrespective of the upper clay with $I_p=31$ to 38 and the lower clay with $I_p=45$ to 60, and the ratio beyond $\sigma'_{vo}=200$ kPa is 0.44. Study on geological history does not suggest any possibility for this discontinuity in formation process of the lower clay. On the other hand, pumping up of the groundwater had been done in the past and then

Fig. 15. Undrained shear strength in the field, S_{uf} of each clay plotted versus σ'_{vo} as related to aging effects

Table 3. Summary for S_{uf} as related to aging effects for 7 clays investigated in this study

Clay			S_{un}/σ'_{vc}	σ'_{vo} (kPa)	S_{uf} (kPa)	Aging effects
Arabian G.	Fao		$S_{un(v)}/\sigma'_{vc}=0.31$		$0.31 \sigma'_{vo}$	Young clay with OCR=1
	Khor Al-Zubair		$S_{un(v)}/\sigma'_{vc}=0.22$	≤ 50	$(0.4\sim 2.7) \sigma'_{vo}$	Desiccation stress
				50~60 115~125	$(0.6\sim 1.3) \sigma'_{vo}$ $0.55 \sigma'_{vo}$	Cementation
				≥ 80	$0.30 \sigma'_{vo}$	Secondary compression
Indonesia	Surabaya		$S_{un(d)}/\sigma'_{vc}=0.27$	38~90 ≥ 90	$12+0.27 \sigma'_{vo}$ $0.41 \sigma'_{vo}$	Chemical bonding Secondary compression
	Banjar-masin	Upper	$S_{un(d)}/\sigma'_{vc}=0.27$	0~80	$10+0.27 \sigma'_{vo}$	Chemical bonding
		Lower	$S_{un(d)}/\sigma'_{vc}=0.27$	≥ 80	$(0.3\sim 0.7) \sigma'_{vo}$	Desc. stress+Secd. comp
Japan	Ariake	Upper	$S_{un(d)}/\sigma'_{vc}=0.28$	≤ 45	$9+0.28 \sigma'_{vo}$	Chemical bonding
		Lower	$S_{un(d)}/\sigma'_{vc}=0.27$	≥ 45	$0.48 \sigma'_{vo}$	Secondary compression
	Kuwana	Upper	$S_{un(d)}/\sigma'_{vc}=0.27$	100~140	$0.38 \sigma'_{vo}$	Secondary compression
		Lower	$S_{un(d)}/\sigma'_{vc}=0.27$	140~200 ≥ 200	$0.38 \sigma'_{vo}$ $0.44 \sigma'_{vo}$	Secondary compression Pump-up of groundwater
	Isogo	Upper	$S_{un(d)}/\sigma'_{vc}=0.30$	≤ 130	$35+0.30 \sigma'_{vo}$	Chemical bonding
		Lower	$S_{un(d)}/\sigma'_{vc}=0.30$	≥ 130	$0.64 \sigma'_{vo}$	Secondary compression

this factor which gives higher σ'_y at the lower part of the clay is the most probable reason for discontinuity in $S_{uf(d)}/\sigma'_{vo}$ ratio of the lower clay.

The values of S_{uf} of each clay and the aging effects that the clays have been subjected to are presented for S_{uf} versus σ'_{vo} in Fig. 15 and summarized in Table 3. It can be seen that S_{uf} of each clay is expressed by Eq. (2.1) except for the desiccated and the cemented zones.

S_{uf}/σ'_y ratios

As presented in Fig. 15 and table 3, S_{uf} of each clay is fundamentally given by Eq. (2.1). Such clay is classified into normally consolidated aged clay and its σ'_y and OCR can be obtained from Eq. (3) (Hanzawa (1979)).

$$\sigma'_y = S_{uf} \div S_{un} / \sigma'_{vc}$$

$$\text{OCR} = S_{uf} / \sigma'_{vo} \div S_{un} / \sigma'_{vc} \quad (3)$$

On the other hand, the value of σ'_y from an oedometer test is greatly influenced by $\Delta\sigma_c/\sigma'_c$, t_c and strain rate (Leonards, 1962; Crawford, 1964; Leroueil, 1983). According to these studies, smaller $\Delta\sigma_c/\sigma'_c$, shorter

t_c and faster strain rate give larger σ'_y . The values of σ'_y determined by CR-oed. T show greater σ'_y than by S-oed. T as reported in detail by Leroueil et al. (1983) and Hanzawa (1989). But an important advantage of CR-oed. T is that σ'_y can easily be determined from stress-strain curve as also indicated by Leroueil et al. and Hanzawa.

In Fig. 16 are presented OCR of each clay except Fao clay with OCR=1.0 obtained from S-oed. T and CR-oed. T and from Eq. (3). It can be pointed out first of all that OCR from CR-oed. T and Eq. (3) showed good agreement with each other, while the values from S-oed. T are smaller with larger scatters when OCR of Ariake, Isogo and Kuwana clays are compared. The same trend can be observed in OCR of Surabaya and Banjarmasin clays for which either S-oed. T (Surabaya clay) or CR-oed. T (Banjarmasin clay) was conducted. The values of OCR of Khor Al-Zubair clay determined by Special S-oed. T with $t_c=2$ hours show quite good agreement with OCR from Eq. (3).

On the other hand, S_{uf} of clay is a unique function of σ'_y irrespective of nor-

Fig. 16. Overconsolidation ratio determined by S-oed. T, CR-oed. T and Eq. (3) plotted versus σ'_{vo} which starts with 50 kPa for Kuwana clay

mally consolidated aged clay or overconsolidated young clay as given by Eq. (4).

$$S_{uf} = S_{un}/\sigma'_{vc} \times \sigma'_y \text{ for normally consolidated aged clay}$$

$$= S_{un}/\sigma'_{vc} \times \sigma'_y \times \alpha \text{ for overconsolidated young clay} \quad (4)$$

where α = coefficient for strength decrease induced by swelling.

From this point of view, it is an important check point in determining a proper σ'_y value whether or not σ'_y determined by any method can well explain the correlation given by Eq. (4). Though there is a problem in determination of σ'_y by CR-oed. T, that is, how the appropriate strain rate should be, it is recommended to determine σ'_y by CR-oed. T than by S-oed. T because of its easier determination of σ'_y from a stress-strain curve and better correspondence to the correlation between S_{uf} and σ'_y as can be seen from OCR compared in Fig. 16.

The ratios of S_{uf}/σ'_y determined by CR-

Fig. 17. Normalized undrained shear strength, $S_{uf(v)}/\sigma'_y$ and $S_{uf(d)}/\sigma'_y$ of each clay plotted versus overconsolidation ratio

oed. T and special S-oed. T are plotted versus OCR in Fig. 17 for Khor Al-Zubair, Banjarmasin and three Japanese clays. As quite naturally expected from Eq. (3), S_{uf}/σ'_y ratios of each clay show approximately a constant value being close to S_{un}/σ'_{vc} ratio irrespective of OCR though some scatters can be observed for Banjarmasin and Isogo clays. The ratios of S_{uf}/σ'_y are also plotted versus I_p in Fig. 18. As quite naturally expected from Eq. (3), no correlation exists between S_{uf}/σ'_y and I_p , there is no meaningful correlation between S_{uf}/σ'_y and I_p .

EFFECT OF STRAIN RATE ON UNDRAINED STRENGTH

Bjerrum (1972) presented a method to determine $S_{u(mob)}$ based on FVT in which $S_{uf(v)}$ values are corrected using factors obtained

Fig. 18. Normalized undrained shear strength, $S_{uf(v)}/\sigma'_y$ and $S_{uf(d)}/\sigma'_y$ of each clay plotted versus I_p

from a comparison of measured strength values with those required to give a factor of safety of 1.0 for observed failures. As pointed out by Ladd and Foott (1974), it is

Fig. 19. Correction factor, μ to determine $S_{u(mob)}$ from $S_{u f(v)}$ plotted versus I_p (after Bjerrum, 1973)

Fig. 20. $S_{u n(c)}/\sigma'_{vc}$ obtained from CKoTCT plotted versus strain rate

Fig. 21. Undrained strength ratio at strain rate of 1.0%/min and 10^{-3} %/min, S_{u1}/S_{u2} plotted versus I_p together with μ_R proposed by Bjerrum

assumed that the discrepancy in measured values is primarily due to strain rate effect, and then it was concluded that the strain rate effect on S_u is greater the higher the I_p as shown in Fig. 19. But it should be pointed out that $S_{u f(v)}$ value is affected by clay properties such as whether or not sand seams, shells and organic materials are contained. Such clays give higher $S_{u f(v)}$ value resulting in lower correction factor, μ . Factor of safety is also dependent on drainage conditions during construction. These points are not clear in the method proposed by Bjerrum.

K_0 -consolidated triaxial compression tests with different strain rates have been conducted on various clays in the NC state. The ratios of $S_{u n(c)}/\sigma'_{vc}$ are plotted versus strain rate for 7 clays with I_p ranging from 35 to 85 in Fig. 20. On the other hand, strain and rotating rates in unconfined compression tests, q_u tests and FVT are generally 1.0%/min and 6°/min which could be equivalent to each other, while the strain rate in actual stability problems has been said to be 10^{-2} to 10^{-3} %/min (Ladd and Foott, 1974; Larsson, 1980). From this point of view, strength ratios at a strain rate of 1.0%/min to at 10^{-3} %/min shown in Fig. 20 are plotted versus I_p in Fig. 21 together with μ_R shown in Fig. 19. Though it is desirable to investigate the strain rate effect on S_u for low plastic pure clay, it is difficult to find out any possibility from the S_{u1}/S_{u2} ratio in the figure to say that the strain rate effect is greater the higher the I_p .

CONCLUSIONS

Normalized undrained shear strength both in the normally consolidated state and in the field was investigated for various clays with a wide range of I_p . The following conclusions can be made from the study though more studies on low plastic pure clay are desirable.

(1) Normalized undrained shear strength both in the NC state and in the field, $S_{u n(c)}/\sigma'_{vc}$ and $S_{u f(v)}/\sigma'_{v0}$ as well as strength anisotropy

are not influenced by the I_p .

(2) Undrained shear strength in the field, S_{uf} of clays investigated in this study is given by Eq. (2.1) except for the desiccated and the cemented clays.

$$\begin{aligned} S_{uf} &= S_{un} + k_1 \text{ to a certain } \sigma'_{vo} \\ &= S_{un} \times k_2 \text{ beyond this } \sigma'_{vo} \end{aligned}$$

(3) Normalized undrained shear strength with the consolidation yielding stress, S_{uf}/σ'_y of clays investigated in this study shows approximately a constant value being close to S_{un}/σ'_{vc} irrespective of OCR and I_p , which demonstrates that all the clays are classified into normally consolidated aged clay except Fao clay in Arabian Gulf.

(4) It is strongly suggested that the strain rate effect on S_u is also independent of the I_p .

NOTATION

OCR=overconsolidation ratio

q_c =point resistance in cone penetrometer test

S_u =undrained shear strength

S_{uf} =undrained shear strength in the field

$S_{uf(c)}$ =compression shear strength in the field

$S_{uf(d)}$ =direct shear strength in the field

$S_{uf(e)}$ =extension shear strength in the field

$S_{uf(s)}$ =simple shear strength in the field

$S_{uf(v)}$ =vane shear strength in the field

S_{un} =undrained shear strength in the normally consolidated state

$S_{un(c)}$ =compression shear strength in the NC state

$S_{un(d)}$ =direct shear strength in the NC state

$S_{un(e)}$ =extension shear strength in the NC state

$S_{un(s)}$ =simple shear strength in the NC state

$S_{un(v)}$ =vane shear strength in the NC state

t_c =consolidation time in oedometer test

α =coefficient for strength decrease induced by swelling

μ_R =correction factor for strain rate effect

σ'_c =consolidation stress

σ'_{hc} =horizontal consolidation stress

σ'_{vc} =vertical consolidation stress

σ'_{vo} =effective overburden stress

σ'_y =consolidation yielding stress

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