COMPARATIVE STUDY ON SAMPLE QUALITY USING SEVERAL TYPES OF SAMPLERS

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ABSTRACT

Sample quality was studied at two different sites in Japan where thick marine holocene clay is deposited. Six different types of samplers used in this study were: the Japanese standard thin wall samplers with and without piston, the Laval sampler, the Shelby tube, NGI 54 mm and ELE 100 mm piston (ELE100) samplers. Sample quality was evaluated by the unconfined compression test, which is a standard test for evaluating undrained shear strength in Japan. It was found from this comparative study that the sample quality obtained by the Japanese piston sampler is the same as that obtained by the Laval sampler. The Shelby tube and the ELE 100 sampler, however, both provided poor quality samples.

It is important in practice to establish a method for evaluating shear strength of soft soils without being affected by sample quality. Three types of laboratory tests were performed to evaluate the influence of sample disturbance on undrained shear strength: laboratory vane test and recompression techniques using triaxial and direct shear testing equipment. It was observed that these methods are quite useful to evaluate shear strength even for poor quality samples.

Key words: cohesive soil, direct shear test, sample disturbance, sampling, shear strength, triaxial compression test, unconfined compression test (IGC: C6)

INTRODUCTION

Perfect sampling, a method for collecting in situ soil sample without any mechanical disturbance, has been one of the challenging goals in geotechnical engineering. Japan is one of the few countries that have a strict standard for sampling soft clays. According to the Japanese standard, the thin wall tube sampler with a stationary piston should be used for collecting soft clay under any or all conditions (The sub-committee on soil sampling International Society for Soil Mechanics and Foundation Engineering (ISSMFE), 1981). By contrast, it has been observed that the Shelby tube, a type of open drive samplers, is extensively used for routine geotechnical investigation in most countries. The reason why Japan established such a strict standard seems to be that the unconfined compression test (UCT) is widely used to evaluate the undrained shear strength for cohesive soils. Norwegian Geotechnical Institute, NGI has also developed various types of samplers to obtain high quality samples for sensitive clays such as quick clay, and some of them

are used in several countries (Andresen and Kolstad, 1979).

From the end of the 1980's through the beginning of the 1990's, extensive geotechnical investigations were performed at the Bothkennar site in the United Kingdom, and a lot of valuable test results were reported in *Géotechnique* (1992). The most striking conclusion from these investigations was that the samples collected by the tube sampler were considerably disturbed. They indicated that samplers with large diameter, such as the Laval and the Sherbrooke samplers, are superior to other conventional tube samplers.

Although sample quality is a very important factor in determining soil properties, a practical geotechnical engineer should strike a balance between the cost for sampling and the accuracy of soil parameters measured from laboratory tests. It should also be kept in mind that the operation of a sophisticated sampler requires high-skilled technicians who might not be available everywhere. Therefore, instead of obtaining a high quality sample, it is important in practice to establish a testing method for

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Manuscript was received for review on April 13, 1995.

Written discussions on this paper should be submitted before January 1, 1997 to the Japanese Geotechnical Society, Sugayama Bldg. 4 F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

evaluating the design parameters free from disturbance caused during the sampling process. Several researchers have proposed different techniques to evaluate the undrained shear strength to overcome the effect of sample quality. These include: the recompression technique (Bjerrum, 1973), the SHANSEP (stress history and normalized soil engineering properties) technique (Ladd and Foott, 1974), the recompression method using the direct shear test (Hanzawa, 1992), the advanced q_u method (Tsuchida and Mizukami, 1991).

It has been recognized that the site location is a very important factor in the determination of properties of soft soils. It should be noted, however, that modern soil mechanics was established in the northern part of the globe where the effect of glaciers predominates in clay deposits. Hanzawa and Tanaka (1992) and Tanaka (1994) presented the strength properties of Japanese clays and revealed a distinct difference between Japanese clays and Scandinavian or east Canadian clays. The empirical relationships established in these areas, for example, $s_u/p = 0.11 + 0.0037I_p$, where s_u is the undrained shear strength, p is the consolidation pressure and I_p is the plasticity index, cannot be directly applied to Japanese marine clays (Tanaka, 1994).

The authors performed a comparative study on sample quality using different types of samplers at two test sites in Japan with thick soft marine clay deposits. This paper describes the results of this investigation and methods for evaluating the undrained shear strength of cohesive soft soils without being affected by sample quality.

TEST SITES

Test sites were selected at Ariake and Kinkai whose locations are indicated in Fig. 1 and their fundamental properties are shown in Figs. 2 and 3. The soil layer tested at both sites consists of a holocene clay deposit. Liquid limit w_l and plastic limit w_p are relatively high for a

usual Japanese marine clay, and the natural water content w_n exceeds w_l , which suggests that the sensitivity of the clay is high, and the strength is influenced extensively by sample disturbance. The pre-consolidation pressure p_c was obtained from the constant rate of strain (CRS) oedometer test with a strain rate of 0.02%/min. The p_c values were always larger than those of the in situ effective burden pressure σ'_{vo} . This does not mean that these layers are geologically overconsolidated, but this apparent overconsolidation is due to the ageing effect, resulting from the secondary consolidation and cementation. The field vane shear test (FVT) using a penetration type vane (Tanaka, 1994) and the cone penetration test (CPT) were made. The results of these tests are shown in Figs. 2 and 3 where q_t is the tip resistance of the CPT corrected by the cone effective area and σ_{vo} is the total overburden pressure.

Fig. 1. Location of test sites

Fig. 2. Properties of clay deposit at Ariake site

Fig. 3. Properties of clay deposit at Kinkai site

SAMPLERS USED AND SAMPLING METHODS

Six different types of samplers, as listed in Table 1, were used in this investigation.

JPN(P) Sampler

The Japanese sampler JPN(P) is a thin wall tube sampler with a stationary piston, which has been standardized by the Japanese Society of Soil Mechanics and Foundation Engineering (JSSMFE) (now, Japanese Geotechnical Society (JGS)) and used to collect soft cohesive soils with Standard Penetration Test N value less than 4 in routine work in Japan. The dimension of the tube is 1,000 mm in length (sample length is 800 mm), 75 mm in the inner diameter and 1.5 mm in thickness. The tube is made of seamless stainless steel. The piston is fixed by inner rods from the ground surface.

JPN(O) Sampler

This sampler is not used in Japan, but it was used in this investigation in order to determine the effect of the piston on sample quality. The sampler has the same sampling tube as JPN(P), but it does not have a piston. This sampler is hereafter designated as JPN(O).

Laval Sampler

This sampler was originally developed by the geotechnical group at Laval University in the 1970's (La Rochelle et al., 1981). The sampler was introduced to Japan at the end of the 1980's by Oka et al. (1992) and slightly modified to be suitable for sampling operations in Japan. The diameter of the sampling tube is 208 mm, which is the largest of all the samplers used in this comparative study. In order to avoid the effect of friction between the tube and the soil sample during penetration, the length of the tube was 600 mm so that the ratio of the length to the diameter of the tube (L/D) is the smallest of the samplers used in this study. After the tube was pushed into the soil layer, soil around the tube was over cored to reduce the force for extraction. A ball valve maintains vacuum in the tube in order to prevent the sample from moving instead of the piston while the sampler is withdrawn.

Shelby Tube

This sampler is an open drive sampler without a piston. It has been used extensively for site investigations around the world. The SHANSEP method, for example, was established by tests using soil specimens collected by the Shelby tube (Ladd and Foott, 1974). The sampler, imported from the United States of America, consists of a mild steel tube, 72 mm in diameter, 610 mm long and 1.65 mm thick, as specified by American Society for Testing and Materials (ASTM). Since the mild steel tube is easily stained after being used, the roughness inside the tube is changed after the tube is used. In order to evaluate the effect of change in roughness caused by stain on the sample disturbance, new and used tubes were both used at the Kinkai site (designated for the new tube as SHELBY(N), and for the old tube as SHELBY(O)), while only the new tubes were used at the Ariake site.

NGI54 Sampler

This sampler is a stationary piston sampler developed by NGI for practical investigations. It is a composite type

Table 1. Sampler dimensions

Name of sampler	Inside diameter (mm)	Sampler length (mm)	Thickness (mm)	Area ratio (%)	Piston
JPN(P)	75	1000	1.5	7.5	Yes
JPN(O)	75	1000	1.5	7.5	No
Laval	208	660	4.0	7.3	No
Shelby	72	610	1.65	8.6	No
NGI54	54	768	13.0	54.4	Yes
ELE100	101	500	1.7	6.4	Yes

sampler consisting of two concentric tubes. The soil specimen is stored in the inner plastic tube with 54 mm inside diameter. The outer diameter of the outer tube is 80 mm so that the area ratio is the largest of all the samplers used in this investigation.

*ELE100 Sampler**

This sampler is also a stationary piston sampler developed by the Engineering Laboratory Equipment Limited (ELE) and Geonor. The sampler head is basically similar to the NGI54, but the sampling tube is a single stainless steel tube whose diameter, length and thickness are 101 mm, 500 mm and 1.7 mm, respectively. This sampler has normally been used for obtaining samples of soft clays in the United Kingdom (Hight et al., 1992).

The NGI54 and the ELE100 samplers are displacement type samplers that are directly pushed into the subsoil at a depth to be sampled without a bore hole. In this investigation, however, a bore hole was made by rotary coring with drilling mud for both the NGI54 and the ELE100 samplers. Hight et al. (1992) reported that for the ELE100 sampler an air pressure line was fixed to the sampling tube to reduce suction effects, when the sampler was withdrawn. All samplers except for the Laval sampler, however, were directly withdrawn after the sampling tube was pushed into the subsoil. The sampling tube for the Laval sampler was twisted to reduce suction effect on the sample before the sampler was withdrawn. At the Ariake site, three bore holes were made for sampling; the first hole for the JPN(P) sampler and the Shelby tube, the second hole for the NGI54 and the ELE100 samplers, and the third hole for only the Laval sampler. The sampling interval for these four samplers was 1.0 m, and that of the Laval sampler was 1.8 m. At Kinkai, a separate bore hole was made for each sampler. The sampling interval was 1.5 m for all samplers. The bottom of the bore hole was cleaned carefully using a core tube before sampling. The soil samples obtained with these samplers were then transported from the test sites to the laboratory, maintaining the sampling tube with wax sealed at both ends.

TEST RESULTS

UC Test

Several methods have been proposed for evaluating sample quality, such as the magnitude of strain at failure in shear tests, the shape of the e - $\log p$ curve (including p_c value) in oedometer tests, the magnitude of the volumetric strain at σ'_{vo} after recompression and so on. In this comparative study, however, the sample disturbance was evaluated by the unconfined compression test (UCT). This is because the undrained shear strength s_u in Japan is traditionally evaluated by the UCT, i.e., one half of the unconfined compressive strength from the UCT, q_u /

Fig. 4. Stress and strain curves from unconfined compression tests.

2. In addition, it is believed that the q_u value is the most sensitive to soil disturbance caused by sampling (Lacasse et al., 1985). The UCT was carried out according to the JSSMFE (JGS) standard with an axial strain rate of 1%/min. The specimen was trimmed with a wire saw to 35 mm in diameter and 80 mm height.

Figure 4 shows a typical example of the stress strain curves obtained from the UCT at Ariake. The curves for specimens collected by the JPN(P) and the Laval samplers are almost identical, and their peak strength and secant modulus are the largest of all samples collected at Ariake. Samples collected with the Shelby tube and the ELE100 sampler had lower peak strength and larger strain at failure ϵ_f . Figs. 5 and 6 show $q_u/2$ values obtained on samples obtained with different samplers. It can also be seen in these figures that the shear strength for the JPN(P) and the Laval samplers was greater than that for other samplers, and the values are less scattered. To compare with s_u measured by the FVT, the strength line obtained by the CPT is drawn with $N_{kt}=10$ for Ariake clay and $N_{kt}=14$ for Kinkai clay. Tanaka (1994) presented that the $q_u/2$ value is almost the same as the strength measured by the FVT for Japanese marine clays with high plasticity, provided that the samples are collected according to the Japanese standard sampling method. Data points obtained from the JPN(P) and the Laval samplers are distributed along the line obtained from the CPT. This fact also confirms that the $q_u/2$ value for a good quality sample, such as that obtained by the JPN(P) or the Laval samplers, is also the same as s_u by the FVT. Figure 7 shows ϵ_f for Ariake clay and indicates that the ϵ_f values range between 2 and 3% for soil sam-

* The authors misunderstood that this sampler would be the NGI sampler with large diameter, because it was also purchased through Geonor. However, after talking to a member from NGI, it turned out that this sampler is not the sampler developed by the NGI. It is unfortunate that this sampler was named NGI100 in some papers (Tanaka H. and Tanaka M., 1995; Tanaka M. et al., 1995; Tang et al., 1994).

Fig. 5. Undrained shear strength at Ariake site

Fig. 7. Strain at failure at Ariake site

Fig. 6. Undrained shear strength at Kinkai site

ples collected by the JPN(P) and the Laval samplers, whereas ε_f for samples obtained with a Shelby tube and the ELE100 sampler are mostly greater than 3% and the scatter is more pronounced than that from the JPN(P) and the Laval samplers.

Unlike a reconstituted sample duplicated in the laboratory, the characteristics of intact soil are not uniform but vary with depths in the field. In addition, the sampling depth does not always correspond for different samplers. Thus, strictly speaking, values measured in the laboratory, including $q_u/2$, cannot be compared directly with each other to study differences in sample quality. The standard undrained shear strength $(s_u)_{st}$ is defined using the point resistance q_t from the CPT, assuming that the cone factor N_{kt} is 10 for Ariake clay and 14 for Kinkai

clay. This means that the $(s_u)_{st}$ values are equivalent to those from the FVT (see Figs. 2 and 3). Histograms of strength ratio for different samplers are plotted based on $(s_u)_{st}$ in Fig. 8, where n , m and SD are the number of specimens, the mean of the strength ratio $(q_u/2)/(s_u)_{st}$ and the standard deviation, respectively. The JPN(P) and the Laval samplers clearly give the highest strength ratio of all samplers. The ELE100 sampler and the Shelby tube present quite small strength ratios: i.e., only 60% of strength for samples collected by the JPN(P) and the Laval samplers.

Hight et al. (1992) studied disturbance effects for Bothkennar clay using the Laval and the ELE100 samplers and concluded that the strength from the ELE100 sampler is 65% to 75% of that by the Laval based on the unconsolidated undrained (UU) triaxial test. Since then, it has generally been agreed internationally that the sample quality obtained by the conventional tube sampler is so bad that the test results for samples collected by such a sampler are not reliable. Indeed, even from this investigation, the difference in s_u from the Laval and the ELE100 samplers are identical to that at Bothkennar, as shown in Fig. 8. It might be reasonable to consider that the larger the diameter of the sampler tube is, the better quality sample can be obtained because the volume of the disturbed soil caused by the friction between the wall of the tube and soil becomes relatively small, as indicated by Baligh (1985). In this investigation, however, it was found that the sample quality obtained by the JPN(P) sampler was the same as that from the Laval sampler whose L/D ratio is much smaller than that of the JPN(P). Lacasse et al. (1985) conducted a comparative study on the sample qual-

Fig. 8. Histogram of strength ratio for various types of samplers

ity using the Sherbrooke and the NGI 95 mm piston samplers (not same as the NGI54 either ELE100 in this study) at three Norwegian sites. They concluded that in the case of lean quick clays, the sample quality obtained by the Sherbrooke sampler is clearly superior to that by the NGI 95 mm sampler, but in the case of plastic clays, the sample qualities for these two samplers are similar. From the studies performed in Japan and Norway, it may be concluded that the sampler with a large diameter does not necessarily provide better sample quality than the tube sampler.

At the Kinkai site, three types of open samplers with different tubes were used. Considering the roughness of the inner surface of the tube, the sample quality obtained by the JPN(O) sampler should be the best, and that from the Shelby (O) should be the worst of all open samplers. Remarkable differences are not seen in Fig. 6. This observation suggests that the existence of the piston definitely

has a stronger influence on sample quality than the roughness of the tube.

Residual Effective Stress

Residual effective stress σ'_r was measured for some specimens before conducting the UCT. The specimen was placed on a ceramic disc (Air Entry Value = 300 kPa) to maintain saturation until the measured suction became constant (Hatakeyama and Matsumoto, 1992). Several researchers have tried to interpret the sample quality by σ'_r values. Figure 9 shows the σ'_r values measured by Kudoh et al. (1994), and Hatakeyama and Matsumoto (1992) for Japanese clays obtained with a JPN(P) sampler. The σ'_r/σ'_{vo} ratio was influenced by the properties of the clay, especially the coefficient of earth pressure at rest K_0 and OCR as well as sample disturbance. It can be seen in this figure that the measured σ'_r is in the range of $1/4$ to $1/7$ σ'_{vo} . The σ'_r value was also measured by the authors for the Bothkennar clay that was collected by the Laval sampler and was transported from the site in the United Kingdom to the authors' laboratory. These data points are distributed along the same line as Japanese clays. Ladd and Lambe (1963) measured σ'_r by the Undrained Unconsolidated (UU) triaxial test and reported that the σ'_r/σ'_p ratio ranges from 0.11 to 0.43 with an average value of 0.28 for the Kawasaki clay (a Japanese marine clay), where σ'_p is the residual effective stress in the perfect sample, and they reported the σ'_p value to be 0.56 ± 0.05 of σ'_{vo} . As a result, the σ'_r/σ'_{vo} ratio measured was around 0.14, which is somewhat smaller than that shown in Fig. 9.

The σ'_r values measured in this investigation are presented in Fig. 10. The Japanese and the Laval samplers, which give the highest strength in the UCT, also indicate the highest σ'_r values. The Shelby and the ELE100

Fig. 9. Suction of soil specimens collected by the Japanese standard sampler

Fig. 10. Suction of soil specimens collected by various types of samplers

Fig. 11. The relationship between $s_u/(s_u)_{st}$ and σ'_{vo}/σ'_r

samplers, which present relatively small strength, provide smaller σ'_r . The strength reduction for the Shelby and the ELE100 samples may be considered to be due to dissipation of the negative pore water pressure during the sampling process. The σ'_{vo}/σ'_r ratio is plotted against the strength ratio of $s_u/(s_u)_{st}$ in Fig. 11. It can be seen that the $s_u/(s_u)_{st}$ ratio decreases as σ'_{vo}/σ'_r increases.

Let us consider the reduction of σ'_r during the sampling process on e - $\log p'$ relation as shown in Fig. 12, where e and p' are the void ratio and the mean effective stress, respectively. When the clay is normally consolidated, the in situ p' is equal to $(1 + 2K_o)\sigma'_{vo}/3$ at point A in the figure. The p' value is reduced to σ'_{r1} or σ'_{r2} , due to the sampling and trimming of the specimen for the laboratory test under undrained conditions, i.e., void ratio e

Fig. 12. Reduction of effective stress due to sampling

remains constant in the process (A→B→C). The stress condition for a specimen before the UCT may be the same as a specimen previously subjected to the pressure of σ'_{max} (point G) and swelled to the pressure of σ'_{r2} (point C): i.e., $OCR = \sigma'_{max}/\sigma'_{r2}$. Okumura (1971) studied the strength reduction along the constant void ratio line by exposing cyclic axial strains to a soil specimen under undrained conditions in order to simulate disturbance caused by sampling. He concluded that the strength reduction is followed by a unique line defined by the relation between s_u/s_{up} and σ'_p/σ'_r , where σ'_p and s_{up} are the residual effective stress and the shear strength for the perfect sample, respectively. It is very interesting to compare his proposed line with results from this study using different samplers. The test for the strength reduction curve is, however, a time consuming task which requires a large number of soil samples with the same quality. Instead of the strength reduction curve along the e constant (A→B→C) line, therefore the strength reduction due to swelling (G→E→C) is compared with that caused by the decreasing σ'_r .

After a soil specimen was isotropically consolidated at a confining pressure three times larger than σ'_{vo} , an undrained compression triaxial test was run at various OCR states. When the test results are plotted in Fig. 11, it becomes a question as to which point should be the origin. This is because the basic strength of $(s_u)_{st}$ corresponds to the strength that has already lost some amount of the effective stress: i.e., σ'_{vo}/σ'_r is not unity. As already mentioned, the strength of $(s_u)_{st}$ is equivalent to $q_u/2$ for a good quality sample, and its σ'_{vo}/σ'_r ratio is around 6 (see Fig. 9). It is assumed therefore that the strength ratio of $s_u/s_{u,max}$ is one at σ'_{vo}/σ'_r equal to 6, where s_u and $s_{u,max}$ are the undrained shear strengths at various values of OCR and at the maximum confining pressure ($OCR=1$), respectively. The test result is

represented by a solid line in Fig. 11. It should be kept in mind that this line in the figure overestimates the strength reduction because of the increase in the void ratio due to swelling (line A-C versus line G-C). As shown in Fig. 11, however, the strength reduction caused by sampling disturbance is much larger than that from the triaxial tests, and the discrepancy increases with increase in σ'_{vo}/σ'_r ratio. This implies that there is another reason for the strength reduction for a poor quality sample. This topic will be discussed in more detail in the following section of this paper.

METHODS TO OVERCOME SAMPLE DISTURBANCE

Laboratory Vane

Tanaka (1994) showed the usefulness of the laboratory vane test (LVT) for evaluating the strength of a poor quality sample. In the LVT, the vane is inserted 70 mm into the specimen being kept in the tube. The dimension of the vane used in this study was 20 mm in diameter D , 40 mm high H and 1 mm thick. The vane is rotated at a rate of 6 degree/min. The shear strength is calculated assuming that shear strength is fully mobilized on both ends of the vane as well as along the sides, i.e., $M = s_u(D^2H/2 + D^3/6)$, where M is the measured maximum torque.

The shear strength obtained from the LVT is shown in Figs. 13 and 14 for both Ariake and Kinkai clay, respectively. A scatter of the strength measured by the LVT is much smaller than that obtained from the UCT as shown in Figs. 5 and 6, and the strength values are distributed along a line obtained by the CPT. This means that the strength evaluated by the LVT is less sensitive to sample quality than that by the UCT. The main reasons for insensitivity of the strength obtained by the LVT to the sample quality may be due to: 1) progressive failure and 2) large

Fig. 13. Shear strength obtained from laboratory vane shear test for Ariake clay

Fig. 14. Shear strength obtained from laboratory vane shear test for Kinkai clay

effective confining pressure, as pointed out by Tanaka (1994). In the vane test, soil along the edge of the vane does not mobilize its peak strength at the same time, but failure takes place progressively (La Rochelle et al., 1973). If it is assumed that soil disturbance has an influence only on the peak strength but not on the residual strength, then different results from the UCT and the LVT can be explained. Another possible explanation is that the magnitude of the effective stress may be greater than that in the unconfined condition of the UCT, because the soil sample is kept in the tube during shearing. It may be considered that the considerable amount of suction in the specimen for the UCT is lost in the process of extruding the specimen from the tube and trimming the specimen. The LVT test can avoid the suction reduction caused in these processes.

Direct Shear Test

Direct shear test (DST) was run on the Ariake clay, using a direct shear apparatus developed by Mikasa (1960). The specimen size is 60 mm in diameter (50 mm for the NGI 54 sampler) and 20 mm high. The test procedure was followed in Hanzawa (1992)'s proposal: namely, the specimen was consolidated at σ'_{vo} for 10 min (this duration is long enough to complete the primary consolidation), and then sheared at a horizontal displacement rate of 0.25 mm/min under constant volume conditions. The test result is shown in Fig. 15. Compared with the results from the UCT in Fig. 5, the shear strength is noted to be less scattered. The difference in the s_u value, however, is still observed between poor and good quality samples.

Triaxial Test

Tsuchida and Mizukami (1991) proposed a conventional test method for evaluating s_u from the triaxial test. This method is one of the recompression methods for the

Fig. 15. Shear strength obtained from direct shear test for Ariake clay

isotropically consolidated undrained compression test (CIU), but the test procedure is as simple as possible, considering the practical application. A specimen is isotropically consolidated under a confining pressure σ' of the mean in situ effective stress of $\sigma' = (\sigma'_{vo} + 2\sigma'_{ho})/3$, where σ'_{ho} is the in situ horizontal effective stress. In practice, especially in the case of normally consolidated clays, K_o is assumed to be 0.5, then σ' becomes $2/3\sigma'_{vo}$. The specimen size is 35 mm in diameter and 80 mm high, and the time for consolidation was 2 hours under lateral drainage conditions. The specimen was sheared under an axial strain rate of 0.1%/min.

The test results are shown in Fig. 16. Similar to the results from the LVT and the DST, the discrepancy becomes much smaller than that obtained by the UCT. All test results conducted in this investigation are summarized in Table 2. Strength values are normalized to $(s_u)_{st}$ measured by the CPT. It can be seen that these three test methods are significantly useful to reduce the influence of sample disturbance, but there still exist remarkable differences in the strength that cannot overcome by such methods.

The DST and the CIU used in this investigation are

Table 2. Summary of test results from unconfined compression, laboratory vane shear, direct shear and triaxial tests

Kinkai

		JPN(P)	JPN(O)	SHELBY(N)	SHELBY(O)
$q_u/2$	n ¹⁾	17	20	16	10
	m ²⁾	0.84(1.00) ⁴⁾	0.62(0.74)	0.44(0.527)	0.77(0.92)
	SD ³⁾	0.36	0.29	0.18	0.22
s_u (Lab vane)	n	11	10	5	—
	m	1.08(1.00)	1.05(0.98)	0.73(0.68)	—
	SD	0.31	0.42	0.14	—
s_u (CIU)	n	27	24	12	—
	m	1.09(1.00)	0.99(0.91)	0.96(0.88)	—
	SD	0.23	0.28	0.20	—

Ariake

		JPN(P)	LAVAL	SHELBY(N)	NGI54	ELE100
$q_u/2$	n	16	11	12	9	15
	m	0.97(1.00)	0.95(0.98)	0.61(0.63)	0.81(0.84)	0.59(0.61)
	SD	0.18	0.20	0.11	0.15	0.16
s_u (Lab vane)	n	8	—	7	8	8
	m	1.05(1.00)	—	1.02(0.97)	0.95(0.91)	1.05(0.99)
	SD	0.17	—	0.22	0.09	0.219
s_u (DS)	n	13	12	6	7	7
	m	1.10(1.00)	1.14(1.04)	0.98(0.89)	1.08(0.98)	1.02(0.93)
	SD	0.09	0.10	0.06	0.12	0.13

1) n: number of samples 2) m: mean of strength 3) SD: standard deviation of strength 4) normalized figure by strength obtained from JPN(P)

Fig. 16. Shear strength obtained from consolidated undrained triaxial test for Kinkai clay

one of the recompression methods where the reduction of in situ effective stress is compensated by means of confining pressure. A controversy has arisen on the recompression methods: whether they overestimate the strength of the soil due to volume change in the recompression process or not. As shown in Fig. 12, a poor quality sample in the e - $\log p$ space is located in the left side of the normally consolidated line (σ'_{11} or σ'_{12}). When such a specimen is subjected to a confining pressure equivalent to the in situ effective pressure, a large volumetric strain ϵ_c occurs. The amount of ϵ_c has therefore been considered to be a good indicator of sample quality, as proposed by Andresen and Kolstad (1979). Figure 17 shows the ϵ_c values for Ariake clay in the DST measured 10 min after

Fig. 17. Volumetric change after consolidation from direct shear test for Ariake clay

σ'_{v0} was applied to the specimen in the direct shear apparatus. Figure 18 shows the ϵ_c values for Kinkai clay in the CIU 2 hours after the confining pressure of $2/3 \sigma'_{v0}$ was applied to the specimen. A poor quality sample in fact yields a large amount of ϵ_c after consolidation. If the concept discussed in Fig. 12 is valid, then the poorer quality sample would have been previously subjected to a much higher consolidation pressure, and much higher strength should be obtained after consolidation of σ'_{v0} . The increase in strength must be in proportion to the amount of ϵ_c . This is a theoretical basis for overestimating shear strength of a poor quality sample in the recompression methods.

Although the large ϵ_c value is measured for specimens obtained with a Shelby tube and the ELE100 sampler, the s_u values measured by the DST or the CIU tests are

Fig. 18. Volumetric change after consolidation from triaxial test for Kinkai clay

Fig. 19. Relationship between shear strength and volumetric strain for Ariake clay

Fig. 20. Relationship between shear strength and volumetric strain for Kinkai clay

still smaller than those for good quality samples, as shown in Figs. 15 and 16. Figures 19 and 20 show a relationship between s_u and ϵ_c yielded during consolidation. It cannot be seen in these figures that s_u increases with ϵ_c increasing, but s_u rather decreases in the CIU. This experimental fact indicates that the effect of mechanical disturbance during the sampling procedure on the strength is more dominant than that due to decreasing void ratio in the process of recompression. Several researchers have pointed out that natural intact clay possesses a much larger void ratio than a reconstituted soil (for example, Burland, 1990), and an increase in strength is not always associated with a decrease in void ratio.

In naturally deposited layers, the characteristics of soil, such as w_l and w_p vary with depth, as shown in Figs. 2 and 3. Volume change is therefore expressed by the liq-

Fig. 21. Relationship between liquidity index and effective burden pressure

uidity index $IL (= (w - w_p)/I_p)$, rather than void ratio. The IL values for Ariake and Kinkai clays are plotted against σ'_{vo} in Fig. 21. It can be seen in this figure that IL slightly decreases with increasing σ'_{vo} . The IL value is, however, considerably larger, and its gradient against σ'_{vo} is much smaller than those expected by the critical state theory (Schofield and Wroth, 1968). This means that most of ϵ_c is caused by change in structure during the sampling process, but it is not yielded by recompression on the swelling line ($G \rightarrow E \rightarrow C$ in Fig. 12). Different from reconstituted soil, the void ratio of natural intact clay is much greater than that in the intrinsic state. It may be concluded therefore that recompression techniques such as Tsuchida's or Hanzawa's methods are quite useful to evaluate the undrained shear strength for poor quality samples.

CONCLUSIONS

Sample quality was studied using various types of samplers which are widely in use all over the world for practical and research purposes. Sample quality was evaluated by the unconfined compressive test which is used extensively in Japan to measure the undrained shear strength for cohesive soils. Previous investigation conducted at Bothkennar indicated that the Laval and the Sherbrooke samplers have better performance than conventional tube samplers for obtaining good quality samples. It was found in this study, however, that sample quality obtained by the Japanese piston sampler is equivalent to that obtained by the Laval sampler. Samples collected by the Shelby tube and the ELE100 sampler, however, showed lower strength and larger strain at failure.

For geotechnical engineering practice, it is important to establish methods whereby the proper strength can be measured without the influence of sample quality. One of these methods is the recompression technique in which the specimen is subjected to confining stress to compensate for the reduction of the in situ effective stress caused in the sampling process. There has been a controversy that such a recompression technique overestimates the shear strength of a poor quality sample due to void ratio reduction after consolidation at certain confining pressure. In this study, two recompression techniques were examined, i.e., Hanzawa's and Tsuchida's proposals. It is true that volumetric change for a poor quality sample obtained by the Shelby tube and the ELE100 sampler is considerably greater than that indicated by the Laval and the Japanese samplers. The shear strength measured by these methods is not, however, affected by the volumetric strain caused during the recompression. It can be concluded therefore that the recompression technique is quite useful to evaluate shear strength for a poor quality sample.

ACKNOWLEDGMENTS

The Laval sampler, which played an important role in this paper, was developed by the geotechnical group of

Laval University and introduced to Japan by the group of Gifu University. The authors are grateful to Profs. P. La Rochelle and S. Leroueil of Laval University and Prof. F. Oka and Dr. A. Yashima of Gifu University. In addition, our gratitude is expressed to Dr. H. Hanzawa, the Director of the Technical Research Institute of Toa Corporation, who kindly provided valuable direct shear test results.

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