SOILS AND FOUNDATIONS Vol. 33, No. 2, 1-13, June 1993 Japanese Society of Soil Mechanics and Foundation Engineering

FRICTIONAL BEHAVIOUR BETWEEN NORMALLY CONSOLIDATED CLAY AND STEEL BY TWO DIRECT SHEAR TYPE APPARATUSES

YASUNORI TSUBAKIHARAⁱ⁾ and HIDEAKI KISHIDAⁱⁱ⁾

ABSTRACT

Laboratory tests on friction between normally consolidated Kawasaki clay and mild steel were carried out by using two types of direct shear test apparatuses, namely, simple shear type and shear box type. The excess pore water pressure at the interface was measured. Frictional behaviour obtained was as follows: (1) There existed a critical steel roughness of approximately $10 \,\mu m R_{max}$ ($L=0.2 \, mm$). When the steel surface was smoother than the critical roughness, interface sliding occurred, followed by the reduction in frictional resistance. When the steel roughness exceeded the critical value, however, shear failure occurred within clay specimen, so that the maximum resistance of friction agreed with shear strength of clay. (2) The angle of interface friction in terms of effective stress did not depend on drainage condition and consolidation pressure of clay. (3) The loading speed was influential in the maximum resistance of friction, while less influential for smoother steel surface, and of little influence on the residual resistance of friction at the applied displacement of 10 mm. (4) For the tests of shear box type, shear strength of clay did not agree with the upper limit of the maximum resistance of friction, which was obtained when shear failure occurred within clay specimen. This was due to the difference of shear deformation of clay specimen in the shear box.

Key words: <u>clay</u>, consolidated undrained shear, <u>direct shear test</u>, drained shear, effective stress, friction, laboratory test, shear strength, steel (IGC: D6)

INTRODUCTION

Friction between soils and construction materials, such as skin friction around a pile, is an important phenomenon in geotechnical engineering. It is generally recognized at the present time that the vertical load applied to a pile head is mostly supported by the skin friction around a pile for the case of small pile displacement. In recent years, many buildings have been constructed in very soft cohesive soils, such as bay areas. Therefore, it is necessary to learn more about friction between cohesive soils and construction materials. In addition, the knowledge of this frictional behaviour is very useful for more ra-

ⁱⁱ⁾ Professor, Science University of Tokyo (formerly Professor, TIT).

Manuscript was received for review on March 4, 1992.

Written discussions on this paper should be submitted before January 1, 1994 to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4 F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

¹⁾ Research Engineer, Research & Development Institute, Takenaka Corporation, 5-14, 2-chome, Minamisuna, Koto-ku, Tokyo 136 (formerly Research Associate, Tokyo Institute of Technology).

tional design of a pile which can estimate the amount of settlement with a high degree of accuracy.

Although studies of frictional behaviour of piles have been mainly conducted by *in-situ* loading tests of full scale piles, their test results cannot be widely applied to the prediction of other pile behaviour. On the other hand, laboratory friction tests with obvious boundary conditions can provide fundamental information, such as correlations between frictional resistance and tangential displacement under various conditions, and factors of influence on frictional resistance.

Laboratory friction tests may be classified into two types, namely, direct shear type (such as shear box, simple shear and ring torsional shear) and indirect shear type (such as triaxial). The former test is capable of direct measurement of both normal and shear stresses at the interface. In the latter test, on the other hand, these stresses are measured indirectly on a certain assumption.

Certain researchers have studied friction between clay and steel by laboratory friction tests of direct shear type (Potyondy, 1961; Clark and Meyerhof, 1972; Littleton, 1976; Chang *et al.*, 1982). They all used shear box type apparatus, therefore the physical meaning of the measured tangential displacement was not clear. Although friction tests by simple shear type apparatus permit the simple shear deformation of clay specimen and provide more detailed components of the measured tangential displacement including the interface sliding, there is little previous research by this apparatus owing to its difficult operation.

The object of the present paper is to study the influence of several factors on frictional behaviour between clay and steel by using two apparatuses of simple shear type and shear box type. A relatively small soil sample was needed for conducting a test by these apparatuses. Test results by the two apparatuses were compared with each other. Shear tests of clay specimen were carried out in addition to friction tests.

EXPERIMENT

Apparatuses

Figs. 1 and 2 show the simple shear type apparatus for this study. The circular contact surface between clay and steel was 60 mm in diameter. The contact area remained constant during a test. Normal and tangential loads were applied by the vertical and tangential hydraulic actuators. The container of clay specimen was a stack of 1 mm thick aluminum frames with a circular space of 60 mm in diameter. The nominal thickness of clay specimen in the container was 12 mm. The surface of each aluminum frame was lubricated to allow the container to follow the shear deformation of clay specimen with minimum frictional resistance. For the shear test of clay, the bottom aluminum frame and commercially available Toyoura sand were glued onto the surface of steel specimen to prevent interface sliding.

The applied normal load was measured by a strain gauge type transducer above the loading plate as shown in Fig. 2 and controlled by a servomechanism during a test. The tangential load was also measured by a strain gauge type transducer below the steel specimen as shown in Fig. 2 and applied by another servomechanism in displacement control method.



Fig. 1. General view of simple shear type apparatus



Fig. 2. Sectional detail of simple shear type apparatus



Fig. 3. Sectional detail of shear box type apparatus

Fig. 3 shows the shear box type apparatus for this study. The rectangular contact surface was 100 mm in length and 40 mm in breadth. While the contact area in the friction test remained constant during a test, the cross sectional area in the shear test of clay decreased with the increment of the tangential displacement. The correction of a cross sectional area used for obtaining the shear stress was therefore made for the shear test of clay. Normal and tangential loads were applied by the same actuators as those for the simple shear type apparatus. The container of clay specimen was a 23 mm thick steel box, electroplated with chromium, which had a 100 $mm \times 40$ mm square space. The inner side surface of the container was lubricated by silicone oil. For the shear test of clay, a 1.5 mm thick aluminum frame and Toyoura sand were glued onto the surface of steel specimen to prevent interface sliding. The nominal thickness of clay specimen in the container for the friction test and the shear test of clay were 9 mm and (9+1.5=)10.5 mm respectively. The container was lifted up by a very small distance during a test to avoid the friction between its bottom and the steel specimen.

The applied normal and tangential loads were measured by the same transducers, and controlled by the same servomechanisms as those for the simple shear type apparatus.

Fig. 4(a) shows a schematic diagram of tangential displacements for the simple shear type apparatus. The total displacement, δ , and the sliding displacement at the clay-steel interface, δ_1 , were measured between steel specimen and the top and bottom aluminum Each frame, respectively. displacement measurement was made by a Linear Variable Differential Transformer (LVDT) displacement transducer. The displacement due to the shear deformation of clay specimen was obtained as $\delta_2 = \delta - \delta_1$. Furthermore, the shear strain of clay specimen, γ , was obtained as the ratio of δ_2 to the initial height of clay specimen. The tangential displacement of steel specimen was controlled by a servomechanism using the transducer for the total displacement. The change in the height of clay specimen was measured by a strain gauge type transducer (accuracy: 0.002 mm/digit) in Fig. 1, located at the top of the apparatus.

Fig. 4(b) shows a schematic diagram of the tangential displacement, D, which was measured by a LVDT type displacement transducer and controlled by a servomechanism, for the shear box type apparatus. The change in the height of clay specimen was measured by the same method as that for the



Fig. 4. Measurement of tangential displacements

simple shear type apparatus.

Clay

The reconstituted Kawasaki marine clay $(G_s=2.65, w_L=86.0\%, I_P=48.1)$ was used as a clay specimen in this study. The grain size distribution curve is shown in Fig. 5. Clay was stirred by an air-vacuumed mixer and consolidated from the slurry, which had a water content of approximately 1.5 times the liquid limit. For the tests of simple shear type, clay slurry was preliminarily consolidated in the oedometer with a circular space of 60 mm in diameter at the pressure of 29.4 kPa (0.3 kgf/cm^2). After that, clay was put on the steel specimen, confined by a stack of aluminum frames, and normally consolidated step-bystep up to the pressure of 294 kPa (3.0 kgf/cm^2) under a load increment ratio of 1. The consolidation time of the last step was 12 hours, by which time the excess pore water pressure measured in the center of the interface was almost completely dissipated. For the tests of shear box type, clay slurry was directly poured into the container put on the steel specimen and consolidated by the same method as the above.

Steel

Steel used was a low-carbon structural type of 220 mm in length and 120 mm in breadth. The surface roughness of steel was evaluated by R_{max} (Japanese Standards Association, 1976). R_{max} has been employed for evaluating the roughness of construction materials in the previous studies (Yoshimi and Kishida, 1981;





Uesugi and Kishida, 1986). The gauge length L=0.2 mm (Uesugi and Kishida, 1986), which is nearly the mean grain size of Toyoura sand, was used in measuring R_{max} for convenience. R_{max} was measured in the direction of tangential load both before and after each friction test. The value of R_{max} was the average of 75 points over the surface of each steel specimen.

Six kinds of steel specimens whose surface roughness are 1, 5, 10, 15, 20 and 30 μ m R_{max} , were produced by the following methods: For $1 \,\mu m R_{max}$, the surface is polished by lapping on fine emery cloth with water. For 5 μ m $R_{\rm max}$, the surface is sand-papered in the direction normal to that of tangential load in the test. For 10, 15, 20 and 30 μ m R_{max} , the surface is filed and/or scratched with a cutting knife in the direction normal to that of tangential load. The finished steel surface was thoroughly cleaned by acetone before the friction test. The above mentioned procedures are the same as those used in Uesugi et al. (1986) except for using a cutting knife. Typical surface profiles of steel specimens are shown in Fig. 6.

The excess pore water pressure at the claysteel interface was measured in the center of the steel surface through a porous stone with a circular surface of 4 mm and 6 mm in diameter for the tests of simple shear type and shear box type, respectively. Each area of the porous stone was approximately 0.4% and



Fig. 6. Typical surface profiles of steel specimens

0.7% of that of the friction surface respectively, so that the existence of the porous stone was of little influence on frictional resistance. The porous stone was fitted into a tube made by drilling into the steel specimen. On the side of the steel specimen, a pressure transducer of strain gauge type (accuracy: 0.28 kPa/digit) for measurement of excess pore water pressure was screwed to the tube so that the water filled into the tube was in contact with a diaphragm of the transducer. The water in the tube was distilled by boiling with the steel specimen for half an hour to prevent a reduction in water pressure by the existence of air bubbles.

Loading Conditions

The normal load was kept constant at a specific value, which corresponded to the consolidation pressure of clay, or controlled so that the height of clay specimen was constant during a test. The tangential load was applied so as to keep the rate of total displacement, δ , or tangential displacement, D, constant in control.

The loading speed was 0.01 mm/min for the tests of simple shear type, and 0.1, 0.5 or 10 mm/min for the tests of shear box type. A very slow loading speed of 0.01 mm/min was selected so that the generation of excess pore water pressure in the clay specimen was as small as possible.

FACTORS OF INFLUENCE

Tests of Simple Shear Type

Factors of influence on frictional resistance, mainly considered for the tests of simple shear type, were the surface roughness of steel and the drainage condition. Additional factors were the consolidation pressure and the height of clay specimen.

The consolidated drained shear and the consolidated constant volume shear were employed as the drainage conditions. In this paper, the test under each condition is designated for convenience as a constant pressure test and a constant volume test respectively. For the latter condition, the normal load was controlled so that the height of clay specimen was constant during a test. The effective stress was evaluated by subtracting the excess pore water pressure at the clay-steel interface from the normal stress on the surface of the loading plate. It should be noted that the latter condition was a substitute for the consolidated undrained shear because the volume of clay specimen could not be kept constant under constant normal load for technical reasons.

Tests of Shear Box Type

Factors of influence on frictional resistance, mainly considered for the tests of shear box type, were the surface roughness of steel, the loading speed and the consolidation pressure of clay specimen.

All tests were carried out under the consolidated constant volume shear condition.

CLAY DEFORMATION AND INTERFACE SLIDING

The surface roughness of steel used in the figures following is that measured before a test. It was considered as the same value with that measured after a test if taking the scatter of measured values into consideration.

Tests of Simple Shear Type

Figs. 7, 8 and 9 show the shear stress, τ , as a function of the total displacement, δ , the sliding displacement at the interface, δ_1 , and the shear strain of clay specimen, γ , respectively. In these figures, the curve for the shear test of clay also represents that for 20 μ m R_{max} or more, because there was no sliding at the interface with 20 and 30 μ m R_{max} . The constant pressure test results for consolidation pressure of clay specimen of 98 kPa (1.0 kgf/cm²) are also presented in addition to those for 294 kPa (3.0 kgf/cm²).

As shown in Fig. 7, the curves of shear stress vs. total displacement for 1 and 10 μ m R_{max} fit very well with those for the shear tests of clay up to their peak strengths, followed by the reduction in frictional resistance which was obvious for 1 μ m R_{max} . The total displacement at the peak strength increased with the increment of steel roughness. It was also larger for constant pressure tests than that for con-



Fig. 7. Total behaviour (simple shear type)



Fig. 8. Interface behaviour (simple shear type)

stant volume tests, while the same value for different consolidation pressures. As shown in Fig. 8, interface sliding occurred slightly before the peak strength. It may be considered that the measured sliding displacement up to the peak strength was caused by the partial sliding at the interface. As shown in Fig. 9, the curves of shear stress vs. shear strain of clay specimen for 1 and $10 \,\mu m R_{max}$ fit very well with those for the shear tests of clay up to their peak strengths, followed by a little fur-



Fig. 9. Shear deformation of clay specimen (simple shear type)

ther increase in the shear strain. The shear strain at the peak strength increased with the increment of steel roughness.

The further increase in the shear strain after the peak strength for 1 and $10 \,\mu m R_{max}$ may have been due to the increase in the deformation of a shear zone formed in the clay along the interface. In this study, shear zone formation in clay-steel friction was not evident because no observation of clay deformation along the interface was made. In sand-steel friction, however, shear zone formation in the sand along a rough interface was observed by Uesugi *et al.* (1988).

From the test results mentioned above, the followings are concluded. For $10 \,\mu m R_{max}$ or less, the clay specimen deforms the same as that for the shear test of clay up to its peak strength. After that, interface sliding occurs followed by the reduction in frictional resistance and little further shear deformation of clay specimen. This friction process of the clay-steel interface is very similar to that of the sand-steel interface (see Fig. 8 of Uesugi and Kishida, 1986).

Fig. 10 shows the change in the volumetric strain of clay specimen for each constant pressure test. For $10 \,\mu m R_{max}$ or less, the decrease in the volumetric strain stopped

NII-Electronic Library Service

slightly after the total displacement at the peak strength in Fig. 7(a), because of little further increase in shear deformation of clay specimen.

Fig. 11 shows the change in the effective normal stress at the interface for each constant volume test. The effective normal stresses for $10 \,\mu m R_{max}$ and for the shear test of clay decreased much more than that for $1 \,\mu m R_{max}$ owing to larger shear deformation of clay specimen.

In addition to the aforementioned tests, a friction test with a clay specimen whose height was approximately double was carried out to assess the validity of friction tests in this study. In Fig. 12, two test results for $1 \mu m R_{max}$ under constant volume condition with different heights of clay specimen are presented. While the peak strengths of the two tests were in good agreement with each other, the total displacement at the peak strength for the thicker clay specimen was larger than that for the thinner one (see Fig. 12(a)). Nevertheless, the curves of the shear stress as func-



Fig. 10. Negative dilatancy behaviour (simple shear type)



Fig. 11. Decrease in confining pressure (simple shear type)

tions of the shear strain of clay specimen and the effective normal stress were in good agreement between two tests (see Figs. 12(b) and (c): Fig. 12(c) is the so-called vector curve). Therefore, the test results with different heights of clay specimen can be expressed as entirely the same as each other, using the curve of shear stress vs. shear strain and the vector curve (the stress path).

Tests of Shear Box Type

For the tests of shear box type, the relationship between shear stress and tangential displacement is influenced by the confinement of clay deformation at the ends of the inner space of the shear box in the direction of tangential load. This confinement causes the progressive failure of clay specimen. Consequently, the tangential displacement, D, has poor physical meaning and cannot be compared on equal terms with the total displace-



Fig. 12. Test results with different heights of clay specimen (simple shear type)

ment, δ , for the tests of simple shear type.

Figs. 13, 14, 15 and 16 show the friction test results for loading speed of 0.5 mm/min as a function of the tangential displacement. The parameters employed were the surface roughness of steel using the values of 1 and 30 μ m R_{max} , and the consolidation pressure of clay using the values of 176.4 and 294 kPa (1.8 and 3.0 kgf/cm²). The test results in Figs. 13, 14 and 15 are normalized by consolidation pressure.



Fig. 13. Frictional resistance (shear box type)



Fig. 14. Excess pore water pressure at interface (shear box type)

As shown in Fig. 13, the shear stress normalized by consolidation pressure, τ/p_c , did not depend on consolidation pressure for each steel roughness. This characteristic is similar to that well-known for the shear strength of normally consolidated clay. The curves for 1 μ m R_{max} fit with those for 30 μ m R_{max} up to their peak strengths followed by the reduction in frictional resistance. This characteristic resembles that of the curves of shear stress vs. total displacement for the tests of simple shear



Fig. 15. Decrease in confining pressure (shear box type)



Fig. 16. Coefficient of friction (shear box type)

type (see Fig. 7).

As shown in Fig. 14, the excess pore water pressure normalized by consolidation pressure, $\Delta u/p_c$, was larger for $30 \,\mu m R_{max}$ than that for $1 \,\mu m R_{max}$.

In Fig. 15, the effective normal stress, σ'_n , is evaluated by subtracting the excess pore water pressure, Δu , from the normal stress, σ_n . The effective normal stress normalized by consolidation pressure, σ'_n/p_c , had an almost constant value after 3 mm of the tangential displacement for each steel roughness. The value for 30 μ m R_{max} was smaller than that for 1 μ m R_{max} because of the larger amount of clay deformation.

In Fig. 16, the shear stress ratio, τ/σ'_n , (the coefficient of friction) is defined as the shear stress divided by the effective normal stress. For more than a certain tangential displacement, it had almost constant values of 0.4 for $1 \mu m R_{max}$ and of 0.8 for $30 \mu m R_{max}$, irrespective of consolidation pressure. The difference by steel roughness was caused by the different mechanism of interface sliding.

FRICTIONAL RESISTANCE

Tests of Simple Shear Type

Fig. 17(a) shows the influence of surface roughness of steel on the maximum shear stress normalized by consolidation pressure of clay specimen, $\tau_{\rm max}/p_c$. Fig. 17(b) shows the shear strengths of clay normalized by p_c in several shear tests. Shear test numbers in this figure are used in common with those in Figs. 18(b) and 24(b). The maximum resistance of friction for each steel roughness, including the shear strength of clay, was smaller for a constant volume test than that for a constant pressure test. This reason was that the reduction in the effective normal stress took place only for the constant volume tests. Regardless of drainage condition, there existed a critical steel roughness of approximately 10 μ m R_{max} . The critical roughness was consistent with whether the interface slides or not (see Fig. 8). This fact and Fig. 17 can lead to the following conclusions. (1) When the steel surface is smoother than the critical roughness, sliding occurs at the clay-steel interface. The max-



Fig. 17. Maximum resistance of friction (simple shear type)



Fig. 18. Residual resistance of friction at $\delta = 10 \text{ mm}$ (simple shear type)

imum resistance of friction increases with the increment of steel roughness. (2) When the steel roughness exceeds the critical value, however, shear failure occurs within clay specimen interface instead of sliding. Therefore, the maximum resistance of friction is upper-bounded by the shear strength of clay. This upper-bounded characteristic is consistent with the so-called minimum energy concept which predicts the occurrence of failure at the weakest surface. All the characteristics mentioned above are very similar to those of the sand-steel interface (Uesugi and Kishida, 1986).

Fig. 18(a) shows the influence of steel roughness on the residual shear stress normalized by consolidation pressure, τ_r/p_c . The residual shear stress was defined as the shear stress at the total displacement, δ , of 10 mm. The reason of this definition of residual shear stress derives from the fact that the maximum applied values of δ were 10 mm and 15 mm over the constant pressure and constant volume tests. It should be noted that the residual shear stress defined here was probable to be larger than the shear stress obtained when further total displacement was applied. Fig. 18(b) shows the residual shear strengths of clay normalized by p_c at $\delta = 10$ mm. In Fig. 18(a) it can be seen that the critical roughness is more evident than that of the maximum resistance of friction, because the reduction in the shear stress for $1 \,\mu m \, R_{\text{max}}$ was obvious compared with that for more than $1 \,\mu m R_{max}$. It should be noticed that the residual shear stress for the steel surface of more than critical roughness was likely to be unavailable the same as that for shear tests of clay, because shear failure occurred within clay specimen resulting in the significant reduction in the cross sectional area at the discontinuous failure surface. For the case smoother than critical roughness, on the other hand, the shear stress was available owing to the occurrence of interface sliding resulting in the constant contact area at the interface until the end of loading.

Tests of Shear Box Type

It must be noted that the shear box type apparatus used for the shear test of clay was specially improved to be compared with the friction tests as on equal terms as possible. Fig. 19 shows the schematic diagrams of shear deformation of clay specimen in the shear boxes. Figs. 19(a)-(c) are cases of (a) the friction test in which no interface sliding occurs, (b) the shear test of clay using the conventional type apparatus designated as "type-1" whose upper and lower shear boxes have the same thick clay, and (c) the shear test of clay using the improved apparatus (used in this study) designated as "type-2" whose lower shear box is very thin to take the shear deformation of clay specimen close to that of the friction test in Fig. 19(a). The shear strength obtained by type-2 was found to be a little more than 1.2 times that obtained by type-1 from the results of shear tests of clay by two types for loading speed of 0.5 mm/min. This may be attributed to the fact that the degree of



(a) Friction test (no sliding at interface)





the progressive failure of clay specimen in type-2 was lower than that in type-1. As shown in Figs. 19(b) and (c), the distribution of the shear strain of clay from edge to center of the shear zone in type-2 was more uniform than that in type-1 because a thinner lower shear box was used. Furthermore, it can be considered that the strain rate of clay in type-2 was nearly twice that in type-1 for nearly half the thick shear zone. It is well-known that the undrained shear strength of clay increases with the increment of the strain rate (Skempton and Bishop, 1954). Fig. 20 shows the in-



Fig. 20. Influence of loading speed on shear strength of clay (shear box type)

fluence of loading speed on the shear strength of clay obtained by type-2. From this figure, it can be estimated that the rate of increase in the shear strength with twice strain rate was approximately $(10\% \times \log 2=)3\%$, consequently the increase in the strain rate of clay was of little influence.

Fig. 21(a) shows the influence of steel roughness on the maximum shear stress normalized by consolidation pressure, τ_{max}/p_c , for two loading speeds of 0.1 and 10 mm/min. Fig. 21(b) shows the shear strengths of clay normalized by p_c in four shear tests obtained by type-2 for each loading speed. Shear test numbers in this figure are used in common with those in Fig. 22(b). Irrespective of loading speed, there existed a critical roughness of 10 μ m R_{max} , which was nearly the same value as that for the tests of simple shear type. The smoother steel surface, the less significant the influence of loading speed on the maximum resistance of friction. For more



Fig. 21. Maximum resistance of friction (shear box type)



Fig. 22. Residual resistance of friction at D=10 mm (shear box type)

than 10 μ m $R_{\rm max}$, the rate of increase in the maximum shear stress with loading speed of (10/0.1=)100 times was approximately 19%. This was consistent with the rate of increase of approximately 22% for shear tests of clay, because shear failure occurred within clay specimen for both friction tests and shear tests of clay. The shear strength of clay was, however, a little lower than the upper limit of the maximum resistance of friction, in spite of using a very thin lower shear box for shear tests of clay. This indicates that the precise agreement between the maximum resistance of friction when no interface sliding occurs and the shear strength of clay cannot be expected for the tests of shear box type.

Fig. 22(a) shows the influence of steel roughness on the residual shear stress normalized by consolidation pressure, τ_r/p_c . The residual shear stress was defined as the shear stress at the tangential displacement, D, of 10 mm. The reason of this definition of residual shear stress derives from the fact that the maximum applied value of D was 10 mm over the tests for two loading speeds of 0.1 and 10 mm/min. Fig. 22(b) shows the residual shear strengths of clay normalized by p_c at D=10mm. It was found that loading speed was of little influence on the residual resistance of friction at D=10 mm for each steel roughness, as well as the residual shear strength of clay at D=10 mm.

FRICTION ANGLE

In this section the angle of interface friction in terms of effective stress is presented only for the tests of simple shear type. As for tests of shear box type, their results are omitted owing to the relatively unreliable measurement of excess pore water pressure at the clay-steel interface with high loading speed.

Fig. 23 shows the vector curves, namely, the relationships between the shear stress, τ , and the effective normal stress, σ'_n . In Fig. 23(a), under constant pressure condition, a slight change in the effective normal stress corresponds to the excess pore water pressure which was almost zero at the peak strength. In Fig. 23(b), under constant volume condition,



Fig. 23. Vector curves (simple shear type)

all the curves turn to the left owing to the negative dilatancy of normally consolidated clay. It can be seen in Figs. 23(a) and (b) that all the curves of friction tests fit very well with those of the shear tests of clay up to their peak strengths. This confirms the fact that interface sliding almost never occurs up to the peak strength.

Fig. 24(a) shows the influence of steel roughness on the angle of interface friction in terms of effective stress, δ' . Fig. 24(b) shows the angles of internal friction of clay, ϕ' . Each tangent of δ' or ϕ' is a value of maximum shear stress divided by the effective normal stress at the peak strength. The angles of interface friction were upper-bounded by the angle of internal friction of clay. For the steel sur-



Fig. 24. Angles of interface friction (simple shear type)

face smoother than critical roughness, the smoother the steel surface, the smaller their values. The relationship between the angle of interface friction and steel roughness was unique irrespective of consolidation pressure. The difference of angles of interface friction between two drainage conditions was very little, while it may be seen that the value under constant volume condition was slightly lower than that under constant pressure condition.

CONCLUSIONS

Friction between Kawasaki clay and steel was studied in laboratory tests using two apparatuses of simple shear type and shear box type. Conclusions are followings:

critical (1) There existed surface а roughness of steel whose value was 10 μ m R_{max} (L=0.2 mm) or a little more. This value did not depend on test apparatus, drainage condition and loading speed. When the steel surface was smoother than the critical roughness, interface sliding occurred at the peak strength, followed by the reduction in frictional resistance and little further shear deformation of clay specimen. The maximum resistance of friction increased with the increment of steel roughness. When the steel roughness exceeded the critical value, however, shear failure occurred within clay specimen instead of interface sliding. The maximum resistance of friction was upper-bounded by the shear strength of clay.

(2) The angle of interface friction at the peak strength in terms of effective stress did not depend on drainage condition and consolidation pressure of clay.

(3) The loading speed was influential in the maximum resistance of friction, while less influential for smoother steel surface, and of little influence on the residual resistance of friction at the applied displacement of 10 mm.

(4) For the tests of shear box type, shear strength of clay did not agree with the upper limit of the maximum resistance of friction, which was obtained when shear failure occurred within clay specimen. This was due to the difference of shear deformation of clay specimen in the shear box.

ACKNOWLEDGMENTS

The authors greatly acknowledge the comments and advice of Associate Prof. M. Uesugi, Chiba University. They also wish to thank Prof. emeritus A. Nakase, Prof. T. Kimura and Associate Prof. J. Takemura, Tokyo Institute of Technology, and Dr. K. Ina, Geotop Corporation, for their helpful suggestions. The enthusiastic efforts by Messrs. M. Akinaga and Y. Uchikawa in carrying out the experiments are appreciated. This study was financially supported in part by Grant-in-Aid for Scientific Research (B), No. 62460167, and by Grant-in-Aid for Developmental Scientific Research, No. 01850132, from the Ministry of Education, Science and Culture of the Japanese Government.

NOTATION

- D = tangential displacement (for shear box type apparatus)
- L = gauge length of R_{max}
- R_{max} = maximum height over a gauge length L (Japanese Standards Association, 1976)
 - γ = shear strain of clay specimen (for simple shear type apparatus)
 - δ =total displacement (ditto)= $\delta_1 + \delta_2$
 - δ_1 = sliding displacement at the clay-steel interface (ditto)
 - δ_2 = displacement due to the shear deformation of clay specimen (ditto)
 - δ' = angle of interface friction in terms of effective stress (ditto)
- $\Delta u =$ excess pore water pressure at the clay-steel interface
- $\sigma_n = \text{normal stress}$
- $\sigma'_n = \text{effective normal stress} = \sigma_n \Delta u$
- $\tau =$ shear stress
- τ/σ'_n = shear stress ratio (i.e. the ratio of shear stress to effective normal stress)
- $\tau_{\rm max}/p_c$ = maximum shear stress normalized by consolidation pressure of clay specimen
 - τ_r/p_c =residual shear stress (i.e. the shear stress for total displacement, δ , or tangential displacement, D, of 10 mm) normalized by consolidation pressure of clay specimen
 - ϕ' = angle of internal friction of clay in terms of effective stress (for simple shear type apparatus)

REFERENCES

- 1) Chang, H., Shirako, H., Akaishi, M. and Inada, M. (1982): "The experimental study of negative friction acting on model piles and measuring method," Jour. of JSSMFE, Vol. 22, No. 4, pp. 143-151 (in Japanese).
- 2) Clark, J. I. and Meyerhof, G. G. (1972): "The behavior of piles driven in clay: Part 1, An investigation of soil stress and pore water pressure as related to soil properties," Canadian Geotechnical Journal, Vol. 9, pp. 351-373.
- Japanese Standards Association (1976): Surface Roughness, Japanese Industrial Standard B0601-1976.
- 4) Littleton, I. (1976): "An experimental study of the adhesion between clay and steel," Journal of Terramechanics, Vol. 13, No. 3, pp. 141-152.
- 5) Potyondy, J. G. (1961): "Skin friction between various soils and construction materials," Géotechnique, Vol. 11, No. 4, pp. 339-353.
- 6) Skempton, A. W. and Bishop, A. W. (1954): Soils, Chapter 10 of Building Materials, North Holland Publ. Co., Amsterdam, pp. 417-482.
- 7) Tsubakihara, Y., Kishida, H. and Uesugi, M. (1988):
 "Frictional behavior between clay and steel," Proc., 23th Japan National Conf. on SMFE, Miyazaki, pp. 609-610 (in Japanese).
- 8) Tsubakihara, Y., Akinaga, M., Kishida, H. and Uesugi, M. (1989): "Effects of steel roughness and rate of loading on frictional resistance between clay and steel," Proc., 24th Japan National Conf. on SMFE, Tokyo, pp. 647-648 (in Japanese).
- 9) Tsubakihara, Y., Uchikawa, Y. and Kishida, H. (1990): "Effect of test apparatus on frictional behavior between clay and steel," Proc., 25th Japan National Conf. on SMFE, Okayama, pp. 705-706 (in Japanese).
- 10) Uchikawa, Y., Tsubakihara, Y. and Kishida, H. (1990): "Friction between clay and steel by simple shear type test apparatus," Proc., 25th Japan National Conf. on SMFE, Okayama, pp. 707-708 (in Japanese).
- 11) Uesugi, M. and Kishida, H. (1986): "Influential factors of friction between steel and dry sands," Soils and Foundations, Vol. 26, No. 2, pp. 33-46.
- 12) Uesugi, M., Kishida, H. and Tsubakihara, Y. (1988):"Behavior of sand particles in sand-steel friction," Soils and Foundations, Vol. 28, No. 1, pp. 107-118.
- Yoshimi, Y. and Kishida, T. (1981): "A ring torsion apparatus for evaluating friction between soil and metal surfaces," Geotechnical Testing Journal, GTJODJ, Vol. 4, No. 4, pp. 145-152.

NII-Electronic Library Service