Physical and Chemical Index Properties of Residual Strength of Various Soils

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There are correlations between the residual strength and the soil index properties. The soil index are as follows; the clay fraction, F_{clay}, as related to physical property of soil particle, the *pH* and the salinity as related to chemical property of pore water, the liquid limit, w_L, and the plasticity index, I_P, as related to engineering properties of fine-grained soil. This study aimed for determining the residual strength from the soil index. To attain this purpose, the linear and involution functions are fitted to the relations. Additionally, the multiple regression analysis is carried out on our data and others, in order to examine correlation between the residual strength and the above index. For soils containing smectite dominantly, there are close correlations between the residual strength and the above index of the soils. Among the index properties used here, the ratio of the plastic limit to the liquid limit correlates most closely with the residual strength. The residual strength of such soils can be estimated based on both the index property and the mineral composition. It should be noted that the data used in the multiple regression analysis took account for mineral composition and type of laboratory test. As a result, the value of correlation coefficient improved in any combination of the explanatory variables. Therefore the residual strength can be estimated from F_{clay}, w_L and w_P of soil.

Key Words *: landslide, residual strength, physical and chemical property, mineral composition, type of laboratory test, multiple regression analysis*

INTRODUCTION

It is well known that residual strength of soil is an important parameter to evaluate the stability of reactivated landslide slope. In order to determine the residual strength, ring shear test and reversal box shear test are generally performed on a specimen prepared from reconstituted sample. The residual strength is usually determined using several specimens in laboratory test. It will take a long time to complete a series of tests. Because it is necessary for the test to maintain slow shearing speed reproducing a fully drained condition up to a considerably large shear displacement. Therefore various attempts to obtain the residual strength simply and quickly have been inquired into.

The correlations between the residual strength and the soil index have examined in detail, since Skempton (1964) reported a trend decreasing the internal friction angle in residual state, ϕ_r, accompanied by an increase in clay fraction. Afterward Lupini et al. (1981) established residual shear behavior classified into three modes; a sliding mode, a transitional mode and a turbulent mode, which were dependent of dominant particle shape and the coefficient of interparticle friction. Gibo et al. (1987) reported that there existed a clear correlation between content of smectite (Montmorillonite) and its residual strength. Smectite is regarded as a clay mineral which gives a low value of ϕ_r. They considered that a semctite particle was likely to be oriented in parallel to shearing direction.

The purpose of this study is to determine the residual strength from two or three soil indexes. In this study, the applicability of regression analysis for estimating the residual strength is demonstrated based on physical and chemical index properties of various soils. The used soil index have been taken up as follows: the clay fraction (<2μm), F_{clay} in terms of the physical property of soil particle; *pH*, sodium and calcium ion concentration in terms of the chemical property of pore water; the liquid limit, w_L and the plasticity index, I_P in terms of the consistency of soil. In the regression analysis, however, the explanatory

Table 1 Notation for data quoted from references

Type of soil	Number of data	Type of shear test	Symbols	Reference
Natural clays	9	RBST	□	Skempton(1964)
Natural soils	99	BST	○	De et al.(1973)
Shales	10	RBST	△	Townsend et al.(1973)
	22	RST	▲	
Mineral mixtures	48	RBST	▽	Kenny(1977)
Indonesian residual soils	4	RST	▼	Wesley(1977)
Ham river sand-mica powders mixtures	30	RST	+	Lupini et al.(1981)
Happisburgh clay-London clay mixtures	16		×	
Sand-bentonite mixtures	16		☆	
Natural clays	6	RBST	★	Skempton(1985)
Natural clays and shales, pure minerals	29	RBST	■	Mesri et al.(1986)
Natural soils	54	RBST	◇	Collotta et al.(1989)
	62	RST	◆	
Natural clays and pure minerals	8	RST	⦿	Moore(1991)
Natural clays	60	RST	◐	Yatabe et al.(1991)
Bentonite	4	BST	⧓	Murakami et al.(1993)
Kobe clay	10	-	⧗	Ikejiri et al.(1993)
Natural soils	17	RST	◎	Authors
	1	RBST		
Kaolinite	4	RST	◪	Authors
Montmorillonite	4	RST	⬔	

BST : Box shear test
RBST : Reversal box shear test
RST : Ring shear test

variables were not always selected based on the reliable data-base. Also the data have been not comprehensively considered from the viewpoint of mineral composition and test conditions.

This paper describes correlations of the residual strength with physical property of soil particle, chemistry of pore water and consistency of soil, respectively. Most of data were quoted from important references. In order to estimate the residual strength by combination of the consistency limit and the clay fraction, the applicability of single and multiple regression analysis are demonstrated in terms of the coefficient of correlation. In the regression analysis, the dependent variable is the residual strength, tan ϕ_r, whereas the explanatory variables are the consistency limit and the clay fraction. We survey the best combination of the explanatory variables can give a maximum value of the coefficient of correlation. The data also were selected among various laboratory tests such as ring shear and reversal direct box shear tests.

RELATIONSHIP BETWEEN PHYSICAL PROPERTY AND RESIDUAL STRENGTH

Skempton (1964) found out that the internal frictional angle in residual state trended toward decreasing with increasing the clay fraction. The residual strengths of various soils were investigated from the viewpoint of type and content of clay mineral (Voight, 1970; Kanji, 1971; Kenny, 1970, among the others). All data used in following figures are referred to Skempton (1964), (1985); De and Furdas (1973), Townsend and Gilbert (1973), Kenney (1977), Wesley (1977), Lupini et al. (1981), Mesri and Cepeda-Diaz (1986), Collotta et al. (1989), Moore (1991), Yatabe et al. (1991), Murakami et al. (1993), Ikejiri and Tanimoto (1993) and Suzuki et al. (2003). Table 1 shows type of soil, number of data, type of laboratory test, symbol of data and name of reference in each figure. The total number of data is 513. The parameter of residual strength, tan ϕ_r, where ϕ_r is the internal friction angle in residual state, is determined using either reversal box shear test or ring shear test, whereas the apparent cohesion in residual state, c_r is almost zero.

Figure 1 shows a diagram of tan ϕ_r plotted against the clay fraction of various soils. According to Skempton (1985), when the clay fraction was about 50%, the residual strength was controlled almost entirely by sliding friction of clay minerals, and further increase in clay fraction has little effect. As above mentioned, a correlation between semctite content and its residual strength was evidently recognized (Gibo et al, 1987). On the other hand, the data from Kenney (1977) and Wesley (1977), which are scattered in this figure, contain mica and allophone exceedingly. Such the mineral gives a higher value of internal friction angle at residual as compared with other minerals. The data from Yatabe et al. (1991) are also scattered in the range of low F_{clay}. They pointed out that any correlations between the residual strength and the clay fraction of soil having little smectite was not entirely recognized in the fractured-zone landslide areas. Our data also are scattered in the range of low F_{clay}. The physical properties of our samples are very similarly with those used by Yatabe et al (1991).

Figure 2 shows relationship between the ratio of tan ϕ_r to tan ϕ_p and F_{clay}. Here ϕ_p is defined as the internal friction angle in peak state. tan ϕ_r/tan ϕ_p corresponds to a degree of strength reduction from peak value to residual value. tan ϕ_r/tan ϕ_p of soil having platy and small particles becomes a lower value as compared with soil having round and big particles. As F_{clay} is increased, tan ϕ_r/tan ϕ_p is decreased. A soil with a high F_{clay}, which contains much small-size clay particle, would indicate a remarkable strength reduction.

Figure 3 shows relationship between tan ϕ_r and the sand fraction, F_{sand}. In all data, a correlation was not at all seen in this relation. In each data, tan ϕ_r increases continuously with the increasing F_{sand}. Yatabe et al. (1996) showed that ϕ_r rapidly increased when F_{sand} was 30 %. They considered that when F_{sand} became higher than 80 %, the value of ϕ_r was almost equivalent to that in F_{sand}=100 %.

The effect of gravel content on the residual strength has been never clarified, except for Yatabe et al. (1996). They concluded that ϕ_r increased continuously with increasing the gravel content based on the results of direct box and simple ring shear tests.

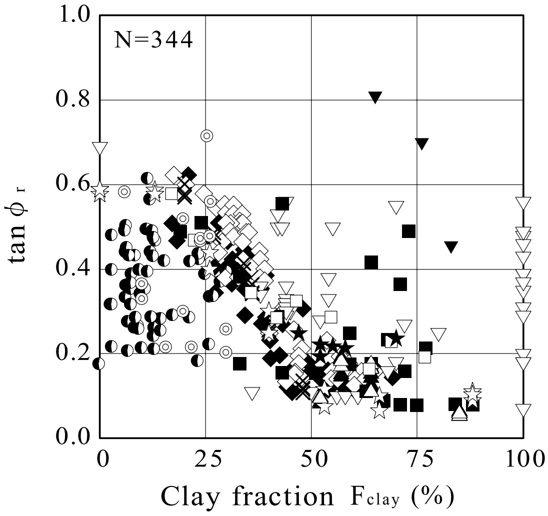

Fig.1 Relationship between clay fraction and residual strength

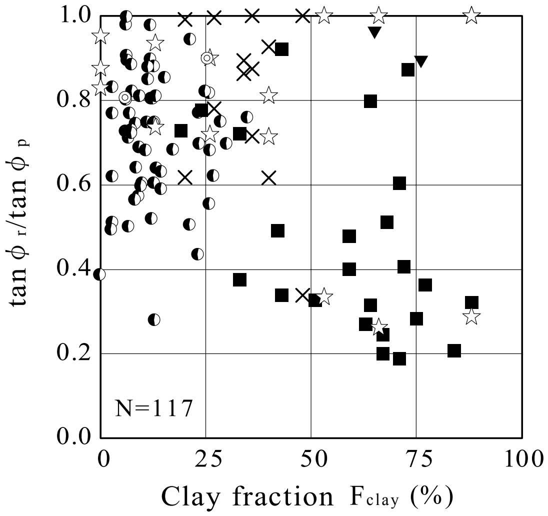

Fig.2 Relationship between clay fraction and tan ϕ_r/tan ϕ_p

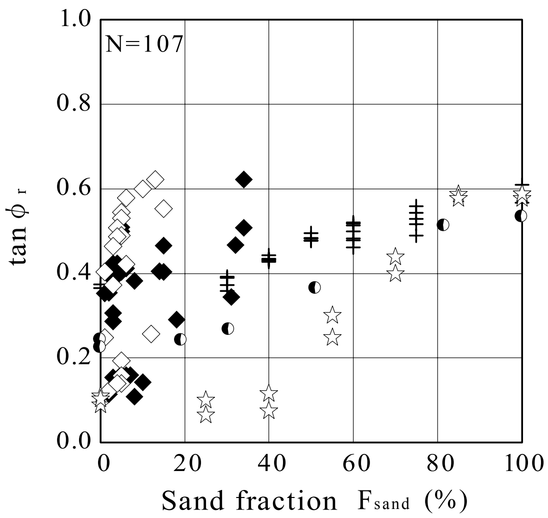

Fig.3 Relationship between sand fraction and residual strength

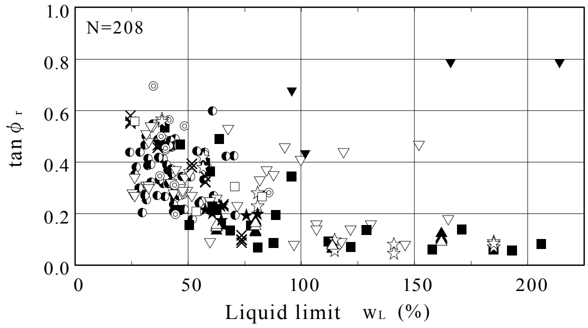

Fig.4 Relationship between liquid limit and residual strength

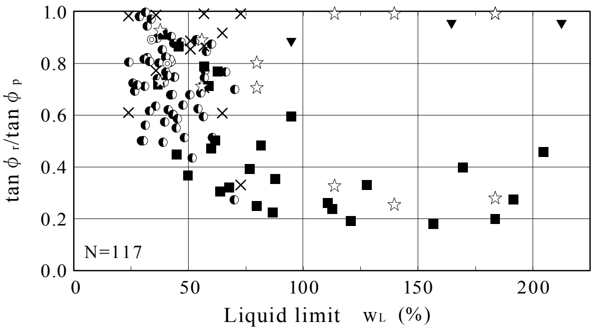

Fig.5 Relationship between liquid limit and tan ϕ_r/tan ϕ_p

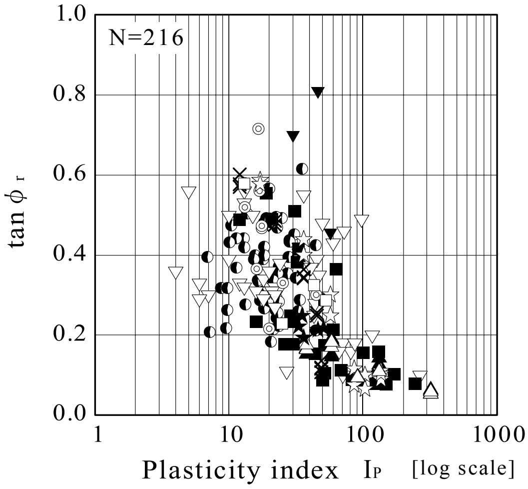

Fig.6 Relationship between plasticity index and residual strength

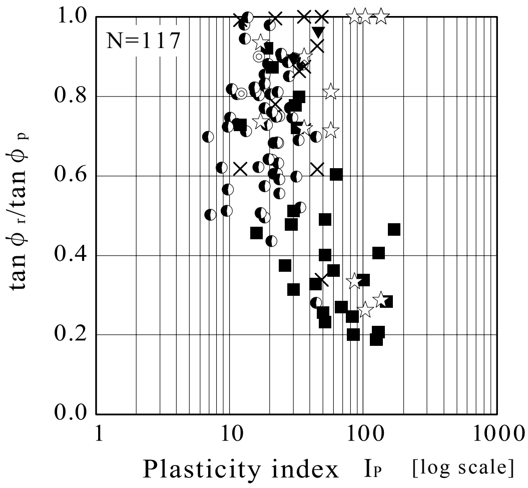

Fig.7 Relationship between plasticity index and tan ϕ_r/tan ϕ_p

RELATIONSHIP BETWEEN CONSISTENCY OF SOIL AND RESIDUAL STRENGTH

Voight (1973) implied that there existed a correlation between the residual strength and the plasticity index of soil. The relations of the liquid limit and other indices to the residual strength have been investigated since then. According to Wesley(2003), for soils with w_L above 50 %, the position occupied on the plasticity chart with respect to the A-line is a good indicator of likely residual strength: a plot of ϕ_r' against ΔI_P ($=I_P$-0.73(w_L-20), distance above or below the A-line) shows a consistent trend. On the contrary, for soils with w_L below about 50 %, the correlation breaks down: this is believed to be due to instability on the slip surface, where shearing may be either turbulent or sliding, or may involve both modes.

Figure 4 shows relationship between tan ϕ_r and the liquid limit, w_L. As above mentioned, the data from Yatabe et al. (1991) are scattered in low range of w_L. The data of Kenney (1977) and Wesley (1977) were deviated upward in high range of w_L. Although all data were scattered in this relation, except for specific minerals, tan ϕ_r trends toward decreasing with an increase in the liquid limit. Figure 5 shows relationship between tan ϕ_r/tan ϕ_p and w_L. The data of Wesley (1977) are deviated upward in range of high w_L. As the liquid limit is increased, tan ϕ_r/tan ϕ_p seems to be decreased.

Figure 6 shows relationship between tan ϕ_r and the plasticity index, I_P. The scatter of data is seen in the low range of I_P. The data distributed in high I_P range are deviated upward. Except for a part of data, tan ϕ_r gradually decreases with an increase in the value of the plasticity index as well as the liquid limit (see in Fig.4). Figure 7 shows relationship between tan ϕ_r/tan ϕ_p and I_P. Although the data are scattered as a whole, tan ϕ_r/tan ϕ_p seems to decrease with the increase in I_P.

Figure 8 shows relationship between tan ϕ_r and the ratio of the plastic limit to the liquid limit, w_P/w_L(=1-I_P/w_L). The correlations of w_P/w_L to the residual strength have been already discussed by De and Furdas (1973) and So and Okada (1978). tan ϕ_r trends toward a linear increase with an increase in

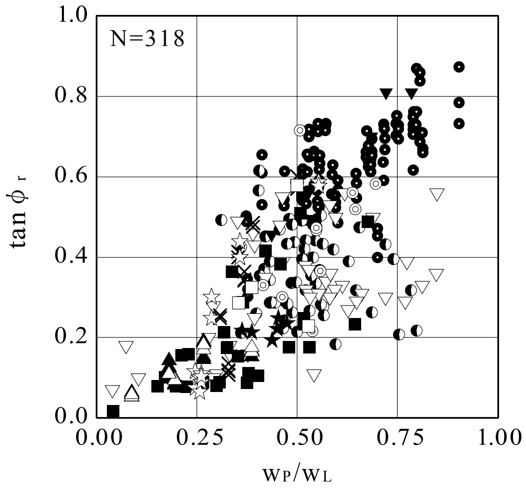

Fig.8 Relationship between ratio of plastic limit to liquid limit and residual strength

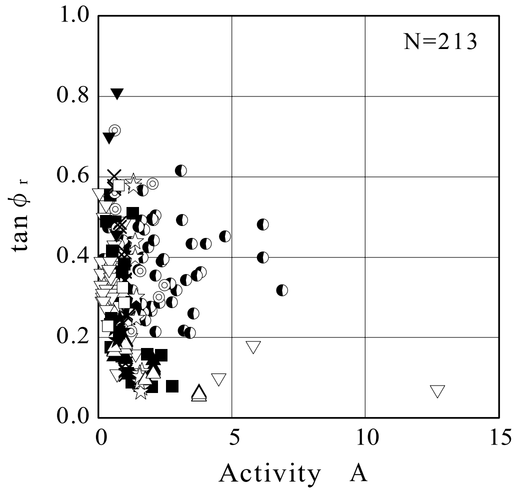

Fig.10 Relationship between activity and residual strength

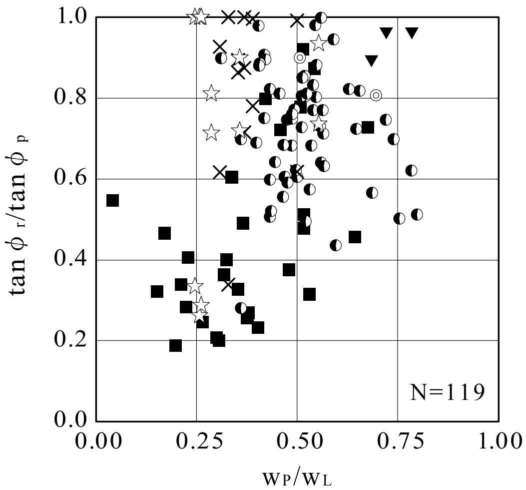

Fig.9 Relationship between ratio of plastic limit to liquid limit and tan ϕ_r/tan ϕ_p

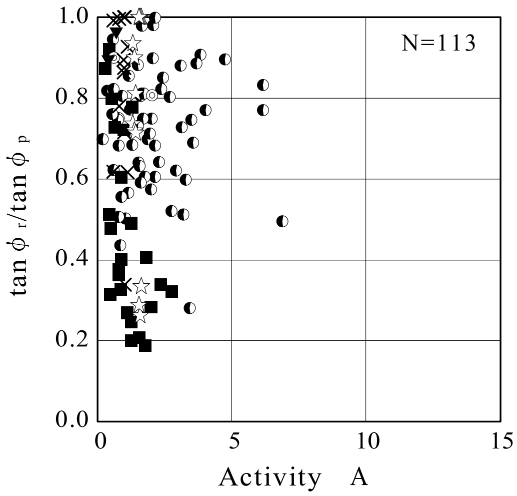

Fig.11 Relationship between activity and tan ϕ_r/tan ϕ_p

w_P/w_L. Figure 9 shows relationship between tan ϕ_r/tan ϕ_p and w_P/w_L. The scatter is seen in this relation. In other words, there seems to be no clear trend in the relation.

Figure 10 shows relationship between tan ϕ_r and the activity, A. All data are wholly scattered. Except for the data from Yatabe et al. (1991), tan ϕ_r rapidly decreases with increasing the activity. Figure 11 show relationship between tan ϕ_r/tan ϕ_p and A. tan ϕ_r/tan ϕ_p does not decrease with the increase in activity, except for Yatabe et al (1991).

RELATIONSHIP BETWEEN CHEMICAL PROPERTY AND RESIDUAL STRENGTH

Since Kenney (1977) suggested that the residual strength was dependent on chemistry of pore water, the residual strength of chemical treated soil had been examined. In this chapter, the effects of ion concentration of hydrogen, sodium and calcium are investigated based on new ring shear tests on pure clay minerals adjusted with NaCl solutions. The used samples were kaolinite and Na montmorillonite. Each sample was remolded at required water content by adding either fresh water or NaCl solutions at 0.1, 0.3 and 1.0 mol/*l*. The initial water content of each sample was prepared to be higher than its liquid limit. The slurry sample was one-dimensionally consolidated under pre-consolidation stress, p_c=83 kPa. End of primary consolidation time was judged on the basis of 3t-method. The dimension of the specimen before shearing was 6 cm in inner diameter, 10 cm in outer diameter and 2 cm in thickness. At first, consolidated constant pressure ring shear tests were performed using different shear displacement rates under conditions of a constant normal stress, σ_N =196 kPa, to examine rate effect. Subsequently, a series of tests

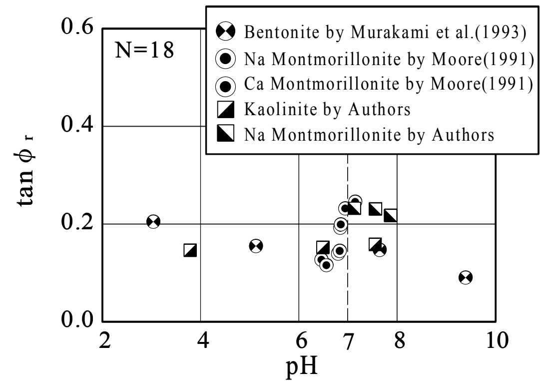

Fig.12 Relationship between pH and residual strength

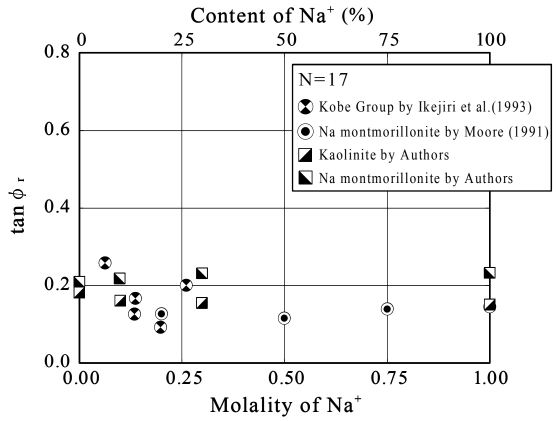

Fig.13 tan ϕ_r plotted against concentration of sodium cation

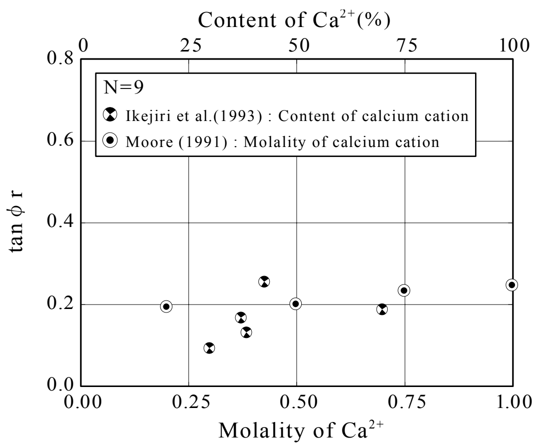

Fig.14 tan ϕ_r plotted against concentration of calcium cation

using different consolidation stresses was performed to examine constant pressure shear strength with respect to the consolidation stress. The specimen was normally consolidated and then submerged after applying consolidation stress. When the specimen adjusted to required molality of NaCl was testing, the same solution was poured into an acrylic water bath attached with the apparatus. The opening between

Table 2 List of clay minerals

Clay minerals	Number of data	Symbol
Smectite	323	○
Illite	3	●
Chlorite	1	▲
Kaolinite	9	△
Allophane	2	■
Halloysite	2	□
Mica	37	◆
Quartz	1	◇
Vermiculite	1	▽

lower and upper rings was set at 0.20 mm during shearing.

Figure 12 shows changes in tan ϕ_r of soils subjected to a change in *pH*. The data from Murakami et al. (1993) were obtained by adding montmorillonite (bentonite) to hydrochloric acid. It can be seen from this figure that tan ϕ_r slightly decreased with increasing *pH*. It was also reported that the liquid and plastic limits increased with the increasing *pH*. On the other hand, it was shown that tan ϕ_r of montmorillonite rapidly increased with a small increase in *pH* (Moore, 1991). Our data with different *pH*s were obtained by adding the sample to NaCl solution prepared at required molarity. It is seen from this figure that tan ϕ_r of kaolinite slightly increases with increasing *pH*, whereas tan ϕ_r of montmorillonite is almost constant.

Relationships between tan ϕ_r and ion concentration of sodium and calcium are respectively shown in Figure 13 and 14. The data from Moore (1991) were obtained by adding montmorillonite to NaCl and $CaCl_2$. It was considered that tan ϕ_r was changed by concentration of these cations. However, the data from Ikejiri et al. (1993) showed that the effect of cation was very little. It can be seen from our data that tan ϕ_r was not changed by ion concentration of sodium. Although the residual strength is considered to be more or less affected by chemistry of pore water, the effect is negligible for engineering purpose. This finding is supported by our results and others.

ESTIMATION OF RESIDUAL STRENGTH OF SOIL BASED ON MULTIPLE REGRESSION ANALYSIS

Simple regression analysis results

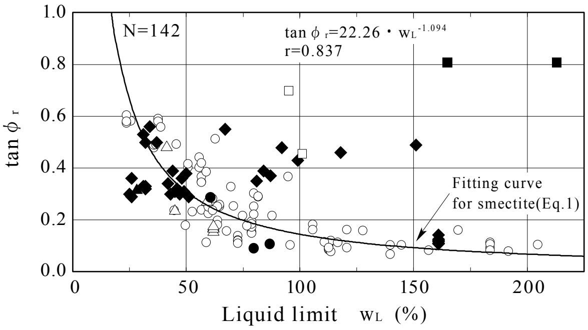

Fig.15 Relationship between liquid limit and residual strength

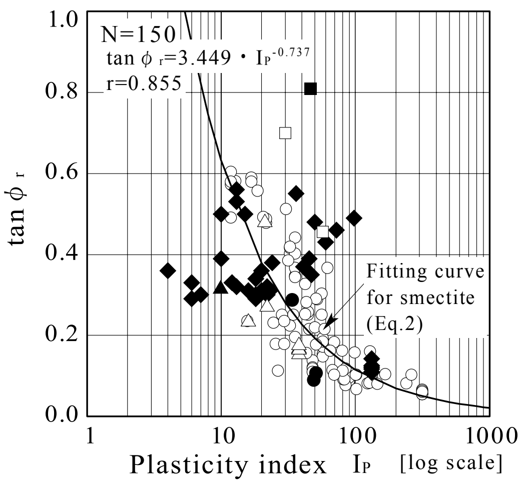

Fig.16 Relationship between plasticity index and residual strength

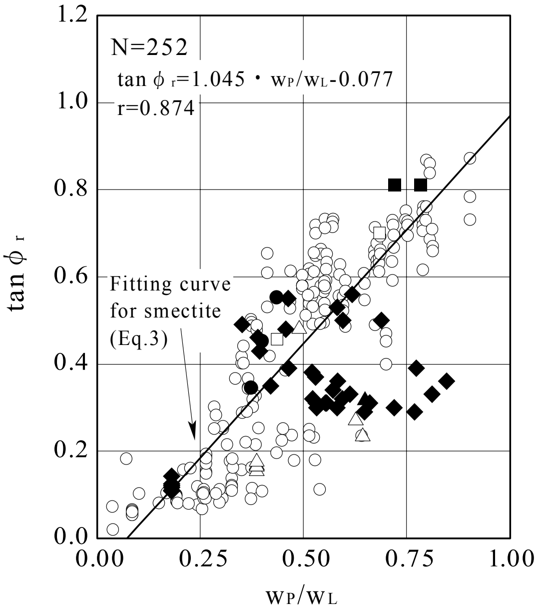

Fig.17 Relationship between ratio of plastic limit to liquid limit and residual strength

Figure 15 shows relationship between tan ϕ_r and the liquid limit. The data used in this figure are same as those of Fig.4. The data used here were sort out among dominant clay mineral. The soils used as soil specimen in each reference, contain a variety of minerals such as smectite (montmorillonite), illite, chlorite, kaolinite, allophane, halloysite, mica, quartz and so on. The number and symbols of soils containing each clay mineral exceedingly are listed in Table 2. The total number of soils used here are 379. A part of data symbols is overlapped those in Table 1. The number of used data, N, is shown in this figure. The data of soils containing allophane, halloysite and mica dominantly are scattered in the range of the liquid limit above almost 70 %. In view of the data of soils containing smectite dominantly, tan ϕ_r of such soils gradually decreases with an increase in the value of the liquid limit. These data are approximated by an involution function as follows:

$$\tan \phi_r = 22.26 w_L^{-1.094} \quad (1)$$

where the regression coefficient are obtained from the least-squares method fitted to the data in relation between log(tan ϕ_r) and log(w_L). As like this, Non-linear model can be handled as linear regression by function conversion. The validity of data fitting can be assessed by the coefficient of correlation, r. The coefficient of correlation is r =0.837 in this case, so that the equation (1) is in good agreement with the experimental data, especially in the range of the liquid limit above almost 100 %. The data of soils containing illite, chlorite and kaolinite dominantly also are distributed near the curve in Fig.15.

Figure 16 shows relationship between tan ϕ_r and I_P. The data of soils containing allophane, halloysite and mica dominantly also are scattered. A regression equation for soils containing smectite dominantly is expressed as follows:

$$\tan \phi_r = 3.449 I_P^{-0.737} \quad (2)$$

The coefficient of correlation is r =0.855 in this case, so that the equation (2) is good agreement with the experimental data.

Figure 17 is a diagram of tan ϕ_r plotted against w_P/w_L. Although the soils contain several dominant mineral except mica, the data are distributed near the line in this figure. In view of the data of soils containing smectite dominantly, tan ϕ_r of such soils increases linearly with an increase in the value of w_P/w_L. These data are approximated by a linear function as follows:

$$\tan \phi_r = 1.045(w_P/w_L)-0.077 \quad (3)$$

,where the regression coefficient are obtained by the least-squares method fitted to the data in relation between tan ϕ_r and w_P/w_L. The coefficient of correlation is r =0.874 in this case, so that the equation (3) are in best agreement with the experimental data in this paper.

Figure 18 shows relationship between tan ϕ_r and the activity, A. The activity as well as w_P/w_L shows a high correlation with tan ϕ_r in case of allophane and halloysite. An approximation formula for soils containing smectite dominantly is expressed as follows:

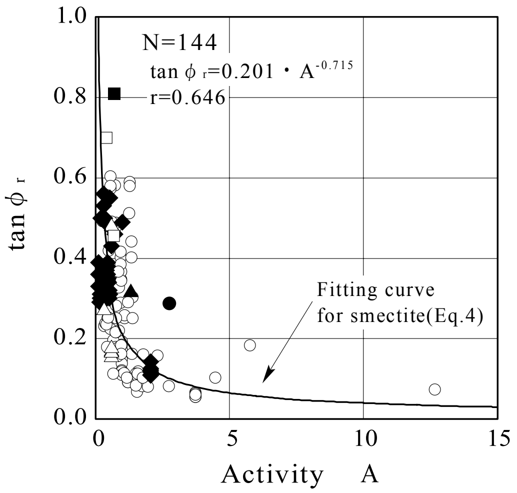

Fig.18 Relationship between activity and residual strength

$$\tan \phi_r = 0.201A^{-0.715} \tag{4}$$

The coefficient of correlation is r =0.646 in this case.

Multiple regression analysis results

The results of multiple regression analysis are shown in Table 3 and Tables 4(a), (b). The analysis result of total data is shown in Table 3. Two or three explanatory variables are selected among F_{clay}, w_L, w_P, I_P and w_P/w_L. Here, N and C correspond to number of data in regression analysis and constant in regression equation, respectively. It must be emphasized that it paid attention to multicollinearity when the explanatory variables were chosen. The linear regression equation is derived as follows.

$$\tan \phi_r = C + aX_1 + bX_2 \tag{5}$$

where a, b are the regression coefficient. In combination of F_{clay} and w_P/w_L, the coefficient of correlation become a maximum value, r =0.650.

On the contrary, the analysis result of a part of data is shown in Table 4(a). The data containing smectite were picked out. Especially, r in combination of F_{clay} and w_P/w_L becomes a maximum value, r =0.794. In any combination of explanatory variables, the value of r from sorted data becomes higher than that from total data.

Table 3 Result obtained from multiple regression analysis for all samples

	N	C	F_{clay}	w_L	w_P	I_P	w_P/w_L	r
tan ϕ_r	213	0.343	-0.00222	-0.000452	0.00346	-	-	0.509
	213	0.403	-0.00159	-0.000386	-	-	-	0.472
	217	0.400	-0.00174	-	-	-0.000409	-	0.488
	212	0.116	-0.00103	-	-	-	0.528	0.650
	218	0.287	-	-0.000554	0.00220	-	-	0.419

Tables 4 Results obtained from multiple regression analysis for samples containing smectite

	N	C	F_{clay}	w_L	w_P	I_P	w_P/w_L	r
tan ϕ_r	92	0.535	-0.00508	0.0000338	-0.00130	-	-	0.705
	92	0.520	-0.00554	0.0000218	-	-	-	0.703
	92	0.521	-0.00545	-	-	0.0000250	-	0.703
	92	0.231	-0.00325	-	-	-	0.531	0.794
(a)	97	0.463	-	-0.000112	-0.00817	-	-	0.572

	N	logC	logF_{clay}	logw_L	logw_P	logI_P	log(w_P/w_L)	r
log(tan ϕ_r)	92	1.010	-0.454	-0.642	0.193	-	-	0.828
	92	1.122	-0.401	-0.605	-	-	-	0.826
	92	0.792	-0.373	-	-	-0.507	-	0.838
	92	0.770	-0.697	-	-	-	0.616	0.815
(b)	97	0.882	-	-0.775	-0.0836	-	-	0.822

Table 5 Results obtained from multiple regression analysis for samples containing smectite in RBST

	N	logC	$\log F_{clay}$	$\log w_L$	$\log w_P$	$\log I_P$	$\log(w_P/w_L)$	r
$\log(\tan\phi_r)$	56	0.728	-0.259	-0.552	0.0420	-	-	0.739
	56	0.762	-0.252	-0.543	-	-	-	0.739
	56	0.400	-0.197	-	-	-0.454	-	0.757
	56	0.313	-0.441	-	-	-	0.579	0.715
	61	0.631	-	-0.649	-0.0803	-	-	0.767

Table 6 Results obtained from multiple regression analysis for samples containing smectite in RST

	N	logC	$\log F_{clay}$	$\log w_L$	$\log w_P$	$\log I_P$	$\log(w_P/w_L)$	r
$\log(\tan\phi_r)$	43	1.385	-0.721	-0.640	0.207	-	-	0.924
	43	1.501	-0.700	-0.573	-	-	-	0.923
	43	1.143	-0.582	-	-	-0.531	-	0.924
	43	1.207	-0.995	-	-	-	0.570	0.917
	43	1.147	-	-1.056	0.0997	-	-	0.901

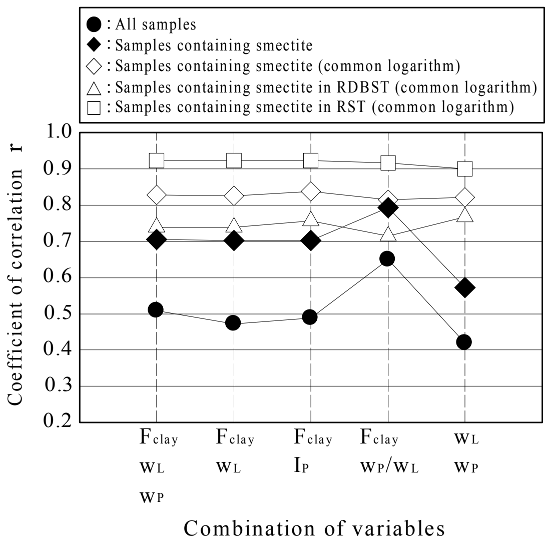

Fig.19 Relationship between combination of explanatory variable and coefficient of correlation in multiple regression analysis

Next, as above mentioned, the dependent and explanatory variables were converted to base-10 logarithmic function. In this case, the regression equation is deduced as follows:

$$\tan\phi_r = C X_1^a X_2^b \quad (6)$$

where a, b are the regression coefficient. The used data are the same as those shown in Table 4(a). This analysis result is shown in Table 4(b). The value of r in any combination of explanatory variables becomes higher. Especially r in combination of F_{clay} and I_P become a maximum value, r=0.838.

Furthermore, the data shown in Table 4(b) are again sorted among type of laboratory test, i.e. reversal direct box shear test (RBST) or ring shear test (RST). Tables 5 and 6 show the analysis results of data obtained by RBST and RST, respectively. As a result, the value of r in RST is higher than that in RDBST. r in combination of F_{clay}, w_L and w_P or F_{clay} and I_P become a maximum value, r=0.924. It is to be regretted that we do not find the reason.

Finally the relationships between the r value and the explanatory variables are summarized in Figure 19. It should be noted that it was able to estimate the residual strength of smectite using equation (7) with a practical accuracy.

$$\tan\phi_r = 10^{1.143} F_{clay}^{-0.582} I_P^{-0.531} \quad (7)$$

CONCLUSIONS

This paper described the correlations between the soil index and the residual strength of various soils, based on data quoted from our and previous studies. The main conclusions are summarized as follows.

(1) It was confirmed that the residual strength gradually decreases with increasing the clay fraction.
(2) For soils containing minerals except smectite, there is a poor correlation between the residual strength and the clay fraction. On the other hand, for soils containing smectite, there is a good correlation between the residual strength and the clay fraction.
(3) The residual strength continuously increases with an increase in the sand fraction.
(4) The residual strength is slightly changed by pH, but is hardly changed by ion concentration of sodium and calcium. The relationship between the residual strength and chemical properties of

pore water are considered to depend on type of clay minerals.

(5) For soils containing allophane, halloysite and mica dominantly, there are no definite correlations between the residual strength and the index properties used here.

(6) For soils containing smectite dominantly, there are close correlations of the residual strength to the liquid limit, the plasticity index and the ratio of the plastic limit to the liquid limit, respectively.

(7) Among the index properties used here, the ratio of the plastic limit to the liquid limit correlates most closely with the residual strength.

(8) From the foregoing, the residual strength is estimated based on both the above index properties and the mineral composition.

(9) The multiple regression analysis was performed on the data of soil containing smectite dominantly. As a result, the coefficient of correlation, r is increased in any combination of the explanatory variables.

(10) When the dependent and the explanatory variables are converted by 10-base logarithm, the value of r is improved in any combination of the explanatory variables. Especially, r becomes a maximum value in the case of the clay fraction and the plasticity index.

(11) The multiple regression analysis was performed on the data obtained by ring shear test. As a result, the value of r is improved in any combination of the explanatory variables. The residual strength can be estimated from the clay fraction, the liquid limit and the plastic limit of soil.

REFERENCES

Collotta, T., Cantoni, R., Pavesi, U., Ruberl, E. and Moretti, P.C. (1989): A correlation between residual friction angle, gradation and the index properties of cohesive soils, *Geotechnique*, 39(2), 343-346.

De, P.K. and Furdas, B. (1973): Discussion - Correlation between Atterberg plasticity limits and residual shear strength of natural soils, *Geotechnique*, 23(4), 600-601.

Gibo, S., Egashira, K. and Ohtsubo, M. (1987): Residual strength of smectite-dominated soils from the Kamenose landslide in Japan, *Canadian Geotechnical Journal*, 24, 456-462.

Ikejiri, K. and Tanimoto, K. (1993): On the shear strength parameter of landslide clay in the Kobe Group, *Proc. of the 28th Japan National Conference on Geotechnical Engineering*, JGS, 2183-2186(in Japanese).

Kenney, T.C. (1967): The influence of mineral composition on the residual strength of natural soils, *Proc. of Geotechnical Conference*, Oslo, 1, 123-129.

Kenney, T.C. (1977): Residual strengths of mineral mixtures, *Proc. of the 9th I.C.S.M.F.E.*, 1, 155-160.

Lupini, J.F., Skinner, A.E. and Vaughan, P.R. (1981): The drained residual strength of cohesive soils, *Géotechnique*, 31(2), 181-213.

Mesri, G. and Cepeda-Diaz (1986): Residual shear strength of clays and shales, *Géotechnique*, 36(2), 269-274.

Moore, R. (1991): The chemical and mineralogical controls upon the residual strength of pure and natural clays, *Geotechnique*, 41(1), 35-47.

Murakami, Y., Tsuchikura, Y. and Suzuki, F. (1993): Basic study on relationship between pH and residual strength of landslide clay, *Proc. of the 48th Annual Conference of the Japan Society of Civil Engineering*, 956-957(in Japanese).

Skempton, A.W. (1964): Long-term stability of clay slopes, *Géotechnique*, 14(2), 77-102.

Skempton, A.W. (1985): Residual strength of clays in landslides, folded strata and the laboratory, *Géotechnique*, 35(1), 3-18.

So, E. and Okada, F. (1978): Some factors influencing the residual strength of remolded clays, *Journal of the Japanese Society of Soil Mechanics and Foundation Engineering*, 18(4), 107-118.

Suzuki, M. (1998): Basic study on residual strength of soils by ring shear test, Doctorial Thesis, Shinshu University (in Japanese).

Suzuki, M., Yamamoto, T., Sasanishi, T. and Sugawara, M. (2003): Residual strength characteristics of pure clay minerals prepared with different salinity, *Memoir of the Faculty of Engineering of Yamaguchi Univ.*, 54(1), 11-15.

Townsend, F.C. and Gilbert, P.A. (1973): Tests to measure residual strengths of some clay shales, *Géotechnique*, 23(2), 267-271.

Voight, B. (1973): Correlation between Atterberg plasticity limits and residual shear strength of natural soils, *Geotechnique*, 23(2), 265-267.

Wesley, L.D. (1977): Shear strength properties of halloysite and allophone clays in Java, Indonesia, *Géotechnique*, 27(2), 125-136.

Wesley, L.D. (2003): Residual strength of clays and correlations using Atterberg limits, *Geotechnique*, 53(7), 669-672.

Yatabe, R., Yagi, N. and Enoki, M. (1991): Ring shear characteristics of clays in fractured-zone-landslide, *Journal of Geotechnical Engineering*, JSCE, 436(Ⅲ-16), 93-101 (in Japanese).

Yatabe, R., Yagi, N. Mukaitani, M. and Enoki, M. (1996): Influence of shear test method and restraint condition on residual strength of soil, *Journal of Geotechnical Engineering*, JSCE, 554(Ⅲ-37), 139-146 (in Japanese).

(Receive Augusut 31, 2005)