VARIATION IN RESIDUAL STRENGTH OF CLAY WITH SHEARING SPEED

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ABSTRACT

In order to clarify the stability of high-speed landslides caused by an earthquake or the volcanic activities, the change in residual strength of slip surface material due to the change in shearing speed is investigated using a ring shear apparatus. The shear displacement rates adopted in the ring shear tests were varied in a range of 0.02 to 2.0 mm/min, and the soil samples tested were kaolin and mudstone. The effect of the shear displacement rate on the residual strength of the clays is discussed in terms of physical properties of soils, i.e. the clay fraction, the plasticity index and the activity. In addition, the microstructure of clay particles near the shear surface reaching the residual state was observed by using a scanning electron microscope.

Key Words: *landslide, clay, residual strength, shear displacement rate, physical property, ring shear test*

INTRODUCTION

In general, the activated landslides show a displacement rate from 5 cm/year to 50 cm/day. A strength parameter mobilized on a slip surface changes, accompanying a change of displacement rate in an objective landslide block. Therefore, this factor should be taken into account while carrying out a slope stability analysis with a great accuracy.

The residual strength of a soil is one of the most important strength parameters to evaluate the stability of a reactivated landslide slope (Skempton (1964)). The relationship between the residual strength and the shear displacement rate of various soils has been examined using reversal box shear test apparatus (Skempton et al. (1967), Ramiah et al. (1971) and Skempton (1985)) or ring shear test apparatus (Lemos et al. (1985), Skempton (1985), Yatabe et al. (1991) and Suzuki et al. (2000)). Skempton (1985) emphasized that the change in residual strength can be neglected when the shear displacement rate is between 0.002-0.01 mm/min generally adopted in the laboratory tests. Yatabe et al. (1991) reported that the residual strengths of clays in fractured-zone landslide areas hardly increase with increasing the shear displacement rate. In contrast, Lemos et al. (1985) pointed out that the residual strength of soils with a high clay content increases with the increasing shear displacement rate, whereas the residual strength of soils with a low clay content decreases with the increasing shear displacement rate. Suzuki et al. (2000) have clarified that the residual strength of a clay increases linearly with an increase in the logarithm of shear displacement rate under the fully drained conditions.

To clarify the effect of shear displacement rate on the residual strength of soil, consolidated constant pressure ring shear tests with different shear displacement rates (0.02-2.0 mm/min) were performed. Based on the test results, the variation of the residual strength with the shear displacement rate is discussed from the viewpoints of the clay fraction, the plasticity index, and the activity with respect to a new parameter, α', proposed by the authors.

RING SHEAR TEST WITH DIFFERENT SHEAR DISPLACEMENT RATES

Preparation of soil samples

Soil samples used in this study are kaolin and mudstone whose physical properties are given in Table 1. The test samples were prepared with the particles passing through 425 μm size sieve, and mixed with distilled water to a slurry 2 times the liquid limit. The prepared samples were then preconsolidated under a pressure of 167 kPa for one day. After this, the specimens to be used in ring shear test were cut from the preconsolidated samples.

Test apparatus

Figure 1 shows the essential features of the ring shear test apparatus employed in this study. A ring shear test apparatus is fundamentally similar to the Bishop-type apparatus (Bishop et al. (1971)). The ring shaped specimen measures 6 cm in inner diameter, 10 cm in outer diameter, and 2 cm in thickness. The

Table 1 Physical properties of the soil samples

Soil sample	Kaolin	Mudstone
ρ_s (g/cm^3)	2.618	2.760
CF (%)	35.3	24.0
w_L (%)	62.0	63.0
I_p	21.8	25.5
D_{max} (mm)	0.20	0.85
D_{50} (mm)	0.007	0.020

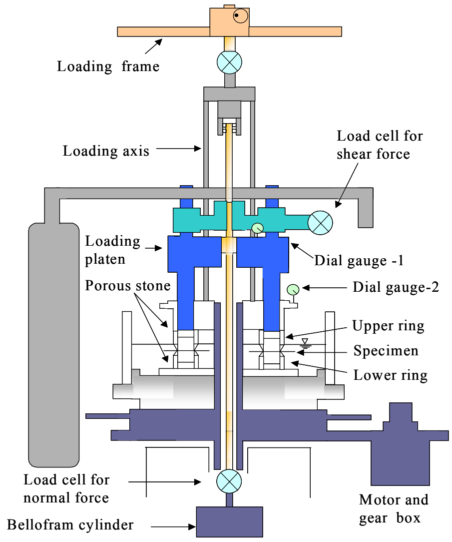


Figure 1 Ring shear test apparatus

Table 2 Cases and results of ring shear tests

Soil sample	Test No.	w_0 (%)	e_0	S_{r0} (%)	σ_C (kPa)	e_C	$\dot{\theta}$ (rad/min)	$\dot{D}$ (mm/min)	σ_N (kPa)	τ_p (kPa)	τ_p/σ_N	τ_r (kPa)	τ_r/σ_N
Kaolin	1-1	59.0	1.554	99.5	196	1.221	0.0005	0.02	196	98.5	0.534	33.6	0.172
	1-2	59.2	1.572	98.6	196	1.202	0.0025	0.1	196	97.8	0.529	35.8	0.183
	1-3	59.9	1.575	99.5	196	1.202	0.005	0.2	196	100.2	0.525	40.2	0.205
	1-4	59.4	1.580	98.5	196	1.228	0.025	1	196	99.0	0.493	43.0	0.220
	1-5	60.1	1.580	99.5	196	1.263	0.05	2	196	87.8	0.461	42.5	0.217
Mudstone	2-1	47.6	1.337	98.3	196	1.067	0.0013	0.05	196	91.6	0.494	31.2	0.159
	2-2	44.5	1.194	100	196	0.989	0.0025	0.1	196	99.5	0.545	38.1	0.194
	2-3	43.9	1.177	100	196	0.999	0.005	0.2	196	109.5	0.661	47.6	0.243
	2-4	45.5	1.245	100	196	1.007	0.025	1	196	52.9	0.279	34.3	0.175

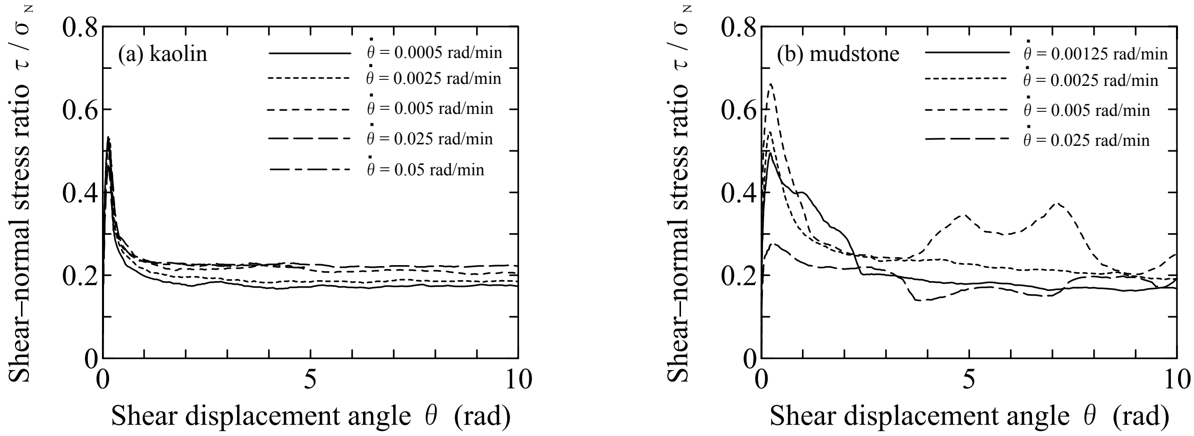
specimen is sheared through a level of 1 cm above the base plate. During the test, shear force, normal force, frictional force, and vertical displacement are monitored and recorded automatically. The consolidation stress, σ_c was fixed to 196 kPa. The consolidation time was 60 min for kaolin and 120 min for mudstone. The duration of primary consolidation by 3t-method was 15 min for kaolin and 20 min for mudstone.

A series of ring shear tests was performed on kaolin and mudstone with the shear displacement rates from 0.02 to 2.0 mm/min. To prevent swelling of the specimen due to submergence, distilled water was poured into the water bath immediately after applying the consolidation stress. To minimize the friction between the upper and lower rings and the outflow of the sample from the shear surface, the gap between the upper and lower rings was fixed at 0.20 mm. The actual normal stress applied on the shear surface of the specimen should be calculated by subtracting a measured frictional force generated between the rigid ring and the soil specimen due to dilatancy. Table 2 shows the cases and the results of the ring shear tests. In the table, θ is shear displacement angle corresponding to the angle of rotation about the loading axis (see Figure 1), and D is shear displacement corresponding to the intermediate circular arc between the inner and outer rings. Thus, $\dot{\theta}$ and $\dot{D}$ are the rates of the shear displacement angle and the shear displacement, respectively. Similarly, θ_{end} and D_{end} are respectively the values of θ and D at the end of the shear test; w_0, e_0 and S_{r0} are respectively the water content, the void ratio, and the degree of saturation of the soil specimen in initial condition; and e_c is the void ratio immediately after the consolidation.

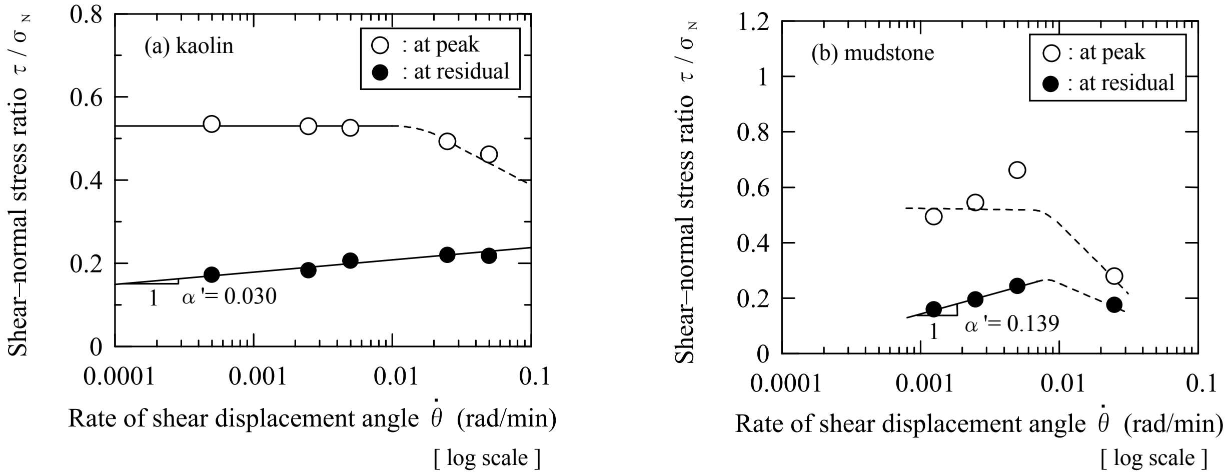
RESULTS AND DISCUSSIONS

Ring shear behaviors of kaolin and mudstone

It is pointed out that the residual strength of a soil is notably changed by the shear displacement rate, and this tendency seems to be dependent on the physical



Figures 2 Relationship between shear-normal stress ratio and shear displacement angle for kaolin and mudstone



Figures 3 Relationship between shear-normal stress ratio and shear displacement angle rate for kaolin and mudstone

properties of the soil (Suzuki et al. (2000)). Figures 2(a) and (b) show the relationships between the shear-normal stress ratio, τ / σ_N, and the shear displacement, θ for kaolin and mudstone, respectively. For example, θ=10 rad is equivalent to D=400 mm. The shear-normal stress ratio of all specimens clearly shows a strain softening characteristic. Also, τ / σ_N - θ curves are influenced by the rate of shear displacement angle. The residual strength of a soil is generally defined as a constant minimum shear stress during a drained shear test. However, it is difficult to exactly judge whether the relationship between the shear stress (or the shear-normal stress ratio) and the shear displacement obtained by the ring shear test becomes a constant value after a large shear displacement (Suzuki et al. (1997)). So, a hyperbolic curve is applied to approximate the post-peak relation between the shear-normal stress ratio and the shear displacement angle, and the shear-normal stress ratio at the residual state is defined as an asymptotic value of the hyperbola. The applicability of this method was sufficiently supported by the test results of kaolin and natural clays under various test conditions (Suzuki et al. (1997)). All the test results by this method are summarized in Table 2.

Relationships of shear displacement rate to peak strength and residual strength

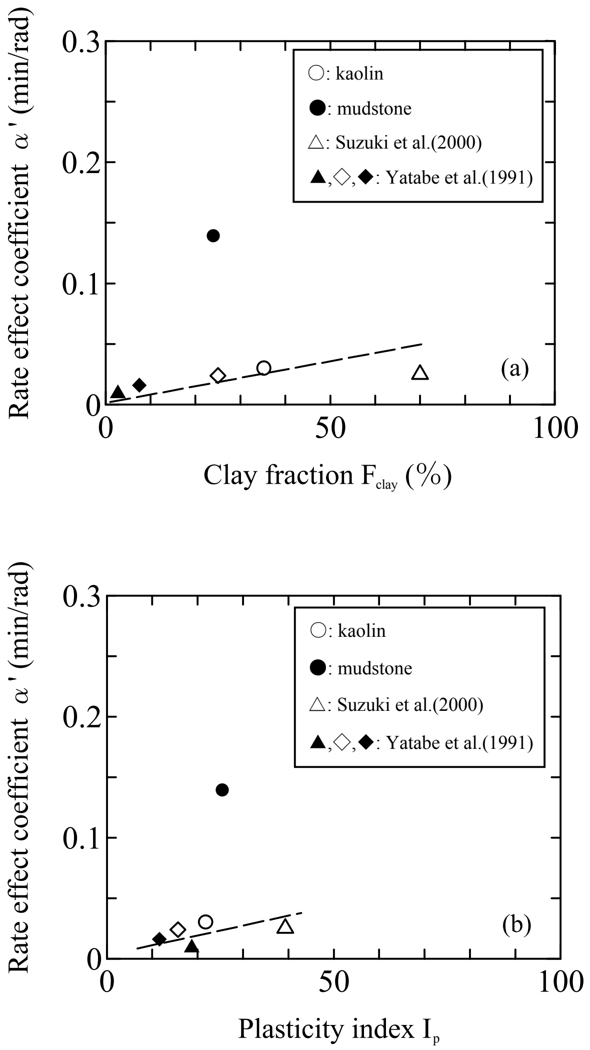
Figures 3(a) and (b) show the relationships between the shear-normal stress ratios at peak and residual states, i.e. τ_p / σ_N, τ_r / σ_N and the shear displacement angle rate, $\dot{\theta}$ for kaolin and mudstone, respectively. In the case of kaolin, τ_p / σ_N decreases with increasing the shear displacement angle rate above $\dot{\theta}$ =0.025 rad/min ($\dot{D}$=1.0 mm/min), whereas τ_p / σ_N becomes constant in a range of 0.0005 to 0.025 rad/min. In the case of mudstone, τ_p / σ_N decreases with increasing the shear displacement angle rate above $\dot{\theta}$=0.005 rad/min ($\dot{D}$=0.2 mm/min). These results agree with the previous results (Suzuki et al. (2000)). These phenomena may be induced by the generation of excess pore water pressure near the shear surface. In contrast, τ_r / σ_N for kaolin and mudstone increases linearly with an increase in the logarithm of the shear displacement angle rate below $\dot{\theta}$ =0.025 and 0.005 rad/min, respectively. τ_p / σ_N becomes almost constant in the same range of shear displacement angle rate. It should be allowed to achieve a fully drained condition, so that the excess pore water pressure generated inside the specimen does not cause a substantial change in effective normal stress on the shear surface. To quantitatively evaluate these experimental data, a rate effect coefficient, denoted as α', is proposed in the following equation: $\alpha' = d(\tau_r/\sigma_N)/d(\log\dot{\theta})$, which gives α'= 0.030 and 0.139 for kaolin and mudstone, respectively.

Rate effect coefficient and physical properties of soils

Figures 4(a) and (b) show the relationships of the rate effect coefficient, α' to the clay fraction, CF and the plasticity index, I_p, respectively. A part of the data shown in these figures is obtained from the previous studies (Yatabe et al. (1991) and Suzuki et al. (2000)). There seems to be linear relationships among α', CF and I_p. As the clay fraction or the plasticity index increases, the rate effect coefficient increases linearly. Figure 5 shows the relationships between the rate effect coefficient, α' and the activity, A. There seems to exist no significant relationship between α' and A. These findings showed that the residual strength of a soil with a high activity clay minerals remarkably increases with the increasing shear displacement rate, and the change in residual strength greatly depends on the clay fraction and the plasticity index. However, the tendency during a faster shearing rate cannot be explained currently in terms of the effective normal stress.

Microstructure of soil particle by SEM

Photographs 1 (a) to (c) show the soil structures of the shear surfaces of kaolin reaching the residual state in the cases when $\dot{\theta}$=0.0005, 0.005 and 0.025 rad/min, respectively. The shear surface of the sample was observed using a scanning



Figures 4 Relationships of α to CF and I_p

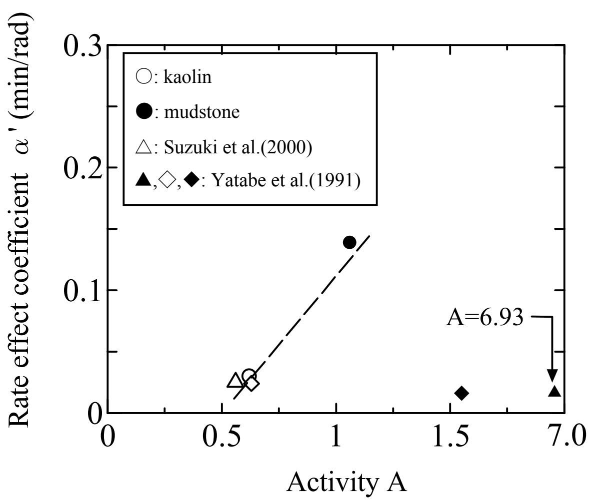


Figure 5 Relationship between α and A

(a) $\dot{\theta}$=0.0005 rad/min (b) $\dot{\theta}$=0.005 rad/min (c) $\dot{\theta}$=0.025 rad/min

Photographs 1 Microstructure of kaolin by SEM

electron microscope with 3,500× magnification. As observed, reorientation of the clay particle occurred along the shear surface. As the shear displacement angle rate increases, the roughness of the shear surface seems to be notable. Therefore, variation in residual strength with the shear displacement rate is considered to be relevant to the roughness of the shear surface.

CONCLUSIONS

The main conclusions are summarized as follows.

1) The residual strengths of kaolin and mudstone were significantly influenced by the shear displacement rate.
2) The proposed parameter, α' is an important index for evaluating the effect of the shear displacement rate on the residual strength.
3) There exist linear relationships between α' and the clay fraction and the plasticity index. Variation in the residual strength with the shear displacement rate seems to be relevant to the type and content of the clay minerals.

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