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The Shear Strength of Clayey Soils from Reactivated Landslides

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Synopsis

This article presents the results of two case studies of reactivated landslides which occurred in Japan. Field and laboratory investigations, including a series of drained ring-shear tests, were conducted in order to design a set of countermeasures and prevent further landslide movement. The obtained results indicated that residual shear strength of soil from the sliding surface contributed greatly to the behavior of landslide; and for this reason, a special effort was made to study the effect of clay content and clay mineralogy on the residual shear strength of soils. It was found that an increase in clay content as well as the presence of montmorillonite significantly reduced residual shear strength.

Keywords: reactivated landslides, residual shear strength, montmorillonite, plasticity index, clay content

1. Introduction

Reactivated landslides, which are usually found in Upper Tertiary mudstone-tuff formations, are common phenomena in Japan. According to the geotechnical classification of landslides proposed by Prof. Sassa (1985), the reactivated type of landslides is a residual slide that occurs on gentle slopes and moves slowly mainly due to an increase in ground water level. Resent studies have shown that the sliding surface is likely to be formed in clayey soils and exists in the residual state due to the previous movements (Shuzui, 2001; Gibo et al., 2002). Decidedly, knowledge of residual shear strength of these soils as well as factors affecting it is necessary for the hazard assessment and the design of remedial measures.

Fig. 1 Location of the studied landslides

This article briefly presents the results of two case studies of reactivated landslides which occurred in Hyogo Prefecture ("Kuchi-Otani" landslide) and in the vicinity of Biwa Lake ("Ogoto" landslide). Special

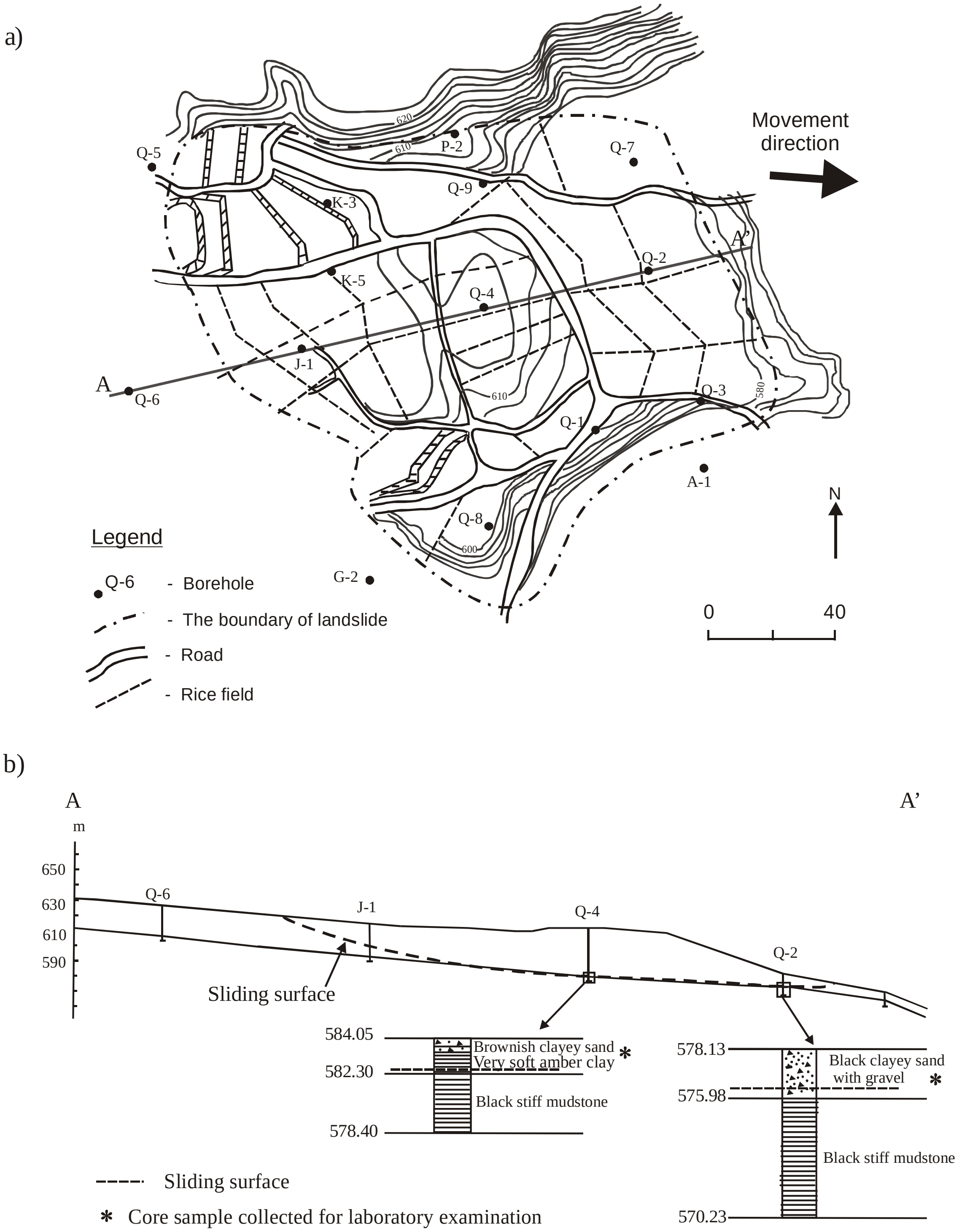

Fig. 2 Plan of the "Kuchi-Otani" landslide (a); and a cross-section (through A-A' on Fig. 2a) (b).

attention is given to factors affecting the residual shear strength of clayey soils such as clay content and clay mineralogy. This work shows that an increase in clay content decreases shear strength of clayey soils, and the presence of montmorillonite significantly reduces shear strength of clayey soils.

2. "Kuchi-Otani" landslide

The "Kuchi-Otani" landslide located in the Hyogo Prefecture, Japan (Fig. 1), was reactivated in 2003. The approximate 1.5 million m^3 of landmass has been creeping down progressively at an estimated rate of about 1 mm per month. The landslide area has been

Table 1. The properties of soils from the “Kuchi-Otani” landslide

	Brownish clayey sand	Amber silty clay	Black clayey sand
LL, %	88.2	96.3	38.6
PI, %	54.5	62.5	19.0
Clay content % <2 μm	11	66	8
Minerals	Quartz, Halloysite, Mica, Montmorillonite	Quartz, Halloysite, Mica	

extensively used by the local people for farming and further movement will likely result in a significant economic loss. In order to design a set of countermeasures and prevent a potential disaster, a comprehensive investigation of this area was conducted by the Hyogo Prefectural Government in cooperation with the Research Centre on Landslides, Kyoto University.

2.1 Field investigation

To study the geology of the landslide site, a number of boreholes were drilled (Fig. 2a). The borehole cores were thoroughly collected and visually examined. Then, borehole inclinometers were set to determine the location of the sliding surface and to monitor direction and rate of movements of the landslide. During the one year monitoring with measurement intervals of 10 days, the following landslide characteristics have been revealed: 1) the dip angle of the sliding surface was gentle and varied from 5 to 7 degrees; 2) the maximum depth of the sliding surface was estimated to be more than 30 m; and 3) the sliding velocity was constant and its maximum value of about 1 mm/month was measured in the central part of the landslide (boreholes Q-4, J-1 and K-5). A cross-section A-A’ (Fig. 2b) will be used to briefly introduce the landslide characteristics and the lithological composition of the area. According to the data obtained by borehole’s inclinometers (borehole Q-4), the sliding surface is located near the boundary of stiff black mudstone and soft silty clay, which is overlain by clayey sand containing rock fragments that are several millimeters to several tens of centimeters in size. In Q-2 the zone of deformation based on the inclinometer record was detected in the layer of clayey sand containing rock fragments of different sizes.

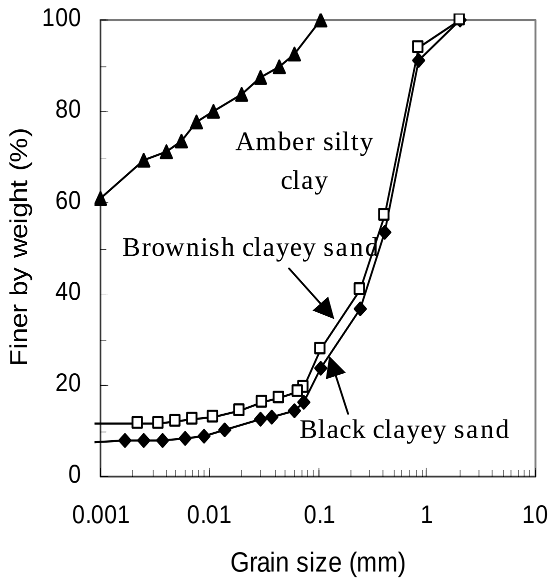

Fig. 3 Particle size distribution curves for the tested soils from the “Kuchi-Otani” landslide

To study the properties of the soils from the shear zone, two core samples were collected from Q-2 and Q-4 at the depths marked in Fig. 2b. An initial examination showed that the black clayey soil from Q-2 is harder than that from Q-4. In addition, the core sample from Q-4 consisted of two parts: the upper - brownish clayey sand, and the lower - very soft and plastic amber clay. The slickenside was observed in the amber clay.

2.2 Laboratory investigation

Particle size distribution and X-ray diffraction analyses as well as a series of drained monotonic speed-controlled ring-shear tests were performed to determine the properties of the clayey soils.

According to the results from X-ray diffraction analysis carried out by the Geo-Research Institute, Osaka, quartz, halloysite and mica are the dominant minerals in all the soils; however, the mineral composition of the brownish clayey sand also includes montmorillonite (Table 1). Figure 3 presents the particle size distribution for the soils used for ring-shear tests. As can be seen, the amber silty clay has a significant amount (≈67%) of clay fraction (<2μm), while the brownish and black clayey sands contain only about 11 and 8 %, respectively. The index properties of the soils were also studied (Table 1). The relatively higher plasticity indices of the amber clay (PI=62.5) and the brownish clayey sand (PI=54.5), compared to that of the black clayey sand (PI=19.0) can be explained by the difference in clay content (in the case of the amber silty clay) and the presence of montmorillonite (in the case of the brownish clayey sand).

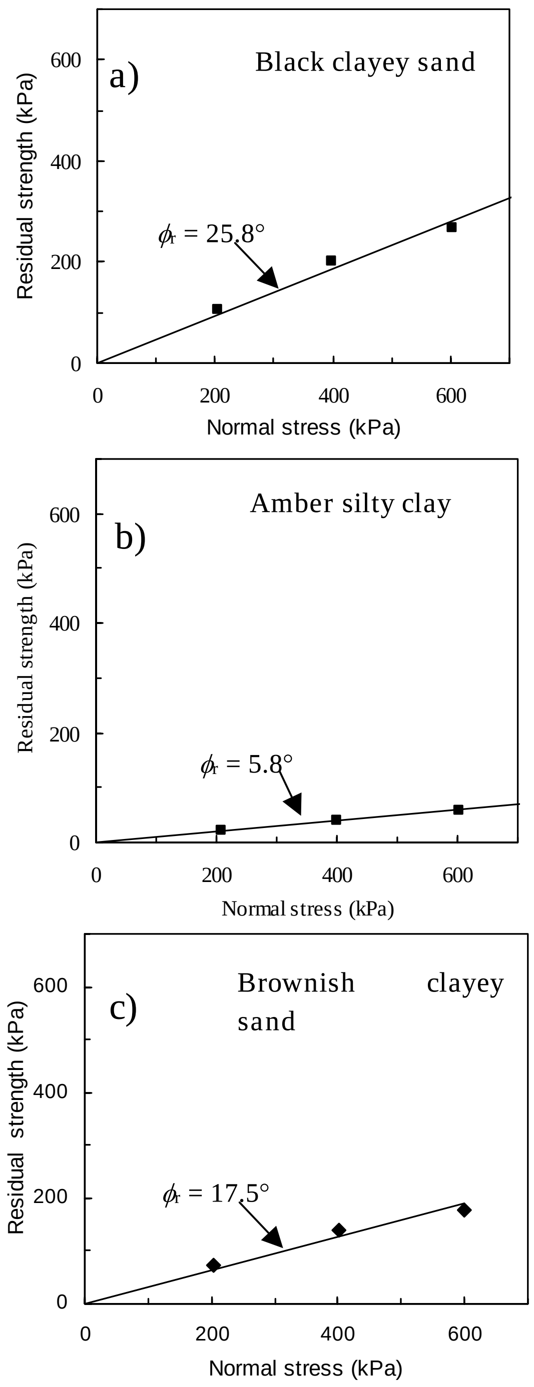

Fig. 4 Results from drained speed-controlled ring-shear tests on the soils from the “Kuchi-Otani” landslide

2.3 Ring-shear tests

Ring-shear apparatus. The ring-shear apparatus used in this work is DPRI-4, one of a series of intelligent ring-shear apparatuses developed and improved at the Disaster Prevention Research Institute, Kyoto University (Vankov & Sassa 1998). It is an important tool for hazard assessment of rapid and long-travel landslides (Sassa et al., 2004) as well as earthquake-induced landslides (Fukuoka et al., 2004). The principal structure of a ring-shear apparatus as well as the method of sample preparation have been reported in the literature (Sassa et al. 2004) and for this reason only brief introduction of DPRI-4 will be given below.

One of the advantages is a big shear box having 210 mm and 290 mm in the inner and outer diameters, respectively. Two personal computers are set for test control and data recording. The test can be carried out using either shear torque control, shear speed control or shear displacement control. Pore pressure, applied stress and displacement are measured by the transducers and recorded automatically.

Sample preparation and test procedure. The specimens were prepared from a slurry, and then set into the shear box. The degree of saturation was examined by measuring B_D value, which was defined as the ratio between the increments of generated pore pressure (Δu) and normal stress ($\Delta\sigma$) ($B_D=\Delta u/\Delta\sigma$) (Sassa 1988). The ratio for each test was ensured to be more than 0.95, a value that approximates full saturation. The specimens were normally consolidated under confining stresses of 200, 400 and 600 kPa. To prevent generation of pore water pressure during testing the lowest speed of 0.1 mm/min was used. Figure 4 shows the results obtained for the black clayey sand, the amber silty clay and the brownish clayey sand, respectively. As can be seen, the value of the residual friction angle of the black clayey sand is relatively high and approximates 25.8°. In contrast, the results from ring-shear tests on the amber silty clay give a very low value of residual friction angle of 5.8°

(Fig. 4b). The residual friction angle of the brownish clayey sand was found to be of about 17.5° (Fig. 4c).

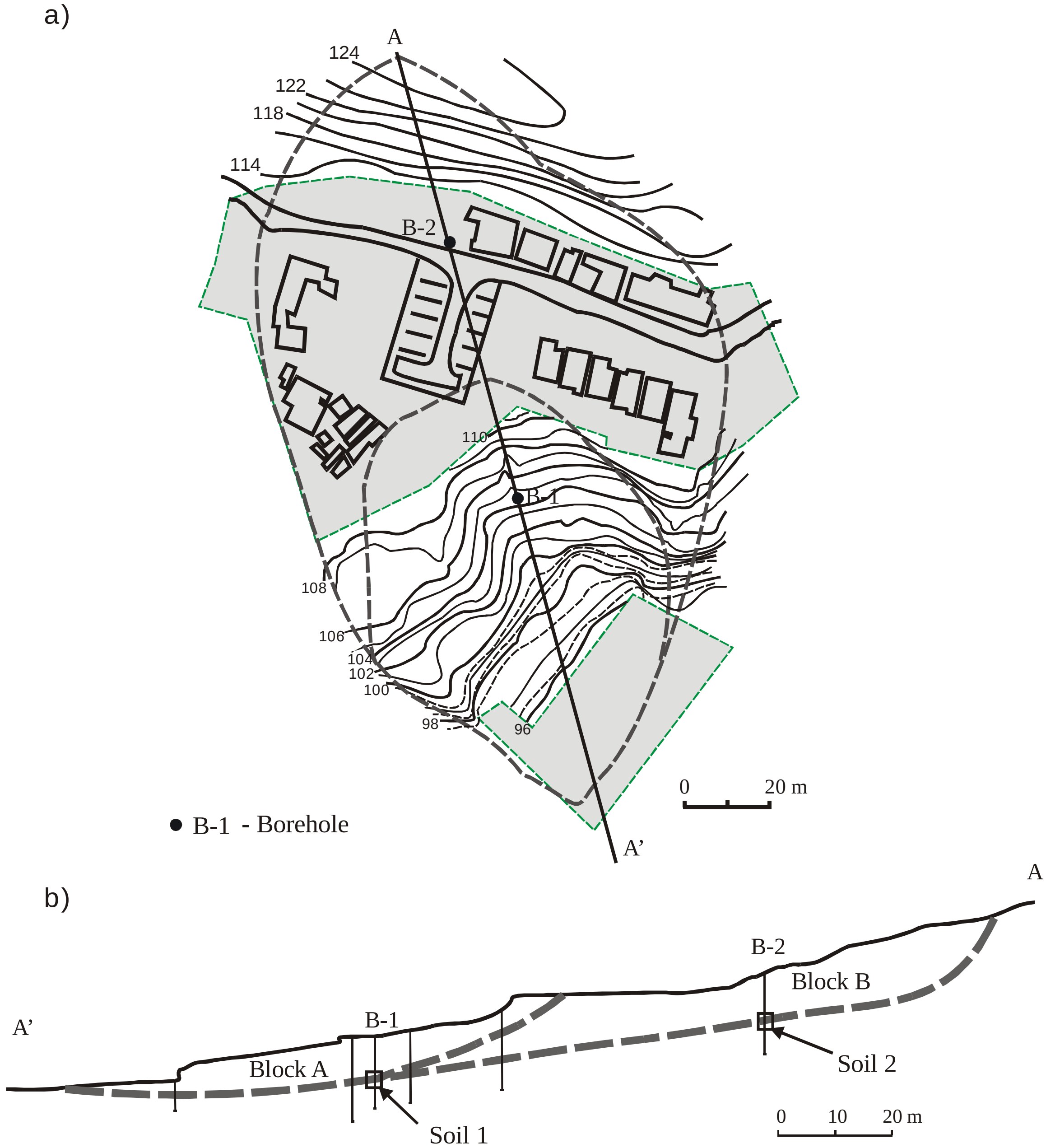

Fig. 5 Plan of the “Ogoto” landslide (a); and a cross-section (through A-A’ on Fig. 5a) (b).

3. “Ogoto” landslide

The “Ogoto” landslide was reactivated in 2004 in Otsu-city in the vicinity of Biwa Lake (Fig.1). Due to its location in a residential area and its constant movement, the “Ogoto” landslide can be seen as a threat to the local people and their property. For this reason, immediate contrameasures based on the field and laboratory investigations need to be put into place to prevent a potential disaster.

3.1 Filed investigation

The methods of filed investigation used to study the geology of the “Ogoto” landslide are similar with those used for the “Kuchi-Otani” landslide (see section 2.1) including borehole core examination and monitoring of movement by a series of borehole inclinometers. The results are schematically presented in Fig. 5 in the form of a schematic map (Fig. 5a) and a cross-section AA’ (Fig. 5b). The monitoring revealed two landslide blocks (A and B) with a dip angle of the sliding surface to be about 11°. The estimated velocity of the A-block is about 0.5 mm/month, which is much higher than that of the B-block (about 0.06 mm/month).

To obtain the geotechnical characteristics of soils from the sliding surfaces of the both blocks, core samples were collected from the boreholes B-1 (Soil 1) and B-2 (Soil 2) (Fig. 5b). An initial examination showed that the Soil 1 is softer and more plastic than the Soil 2. The sliding surface was observed in the both soils.

Table 2. The properties of soils from the "Ogotoi" landslide

Description	Soil 1	Soil 2
LL, %	96.3	76.1
PI, %	57.2	49.5
Clay content % < 2μm	≈ 67	≈ 59
Minerals	Montmorillonite, Mica, Kaolinite, Quartz, Plagioclase	

3.2 Laboratory investigation

The results of laboratory examination that included particle size distribution, X-ray diffraction and plasticity analyses are presented in Fig. 6 and Table 2. The mineral composition appeared to be the same comprising montmorillonite, Mica, Kaolinite, Quartz and Plagioclase. The particle size distribution analysis revealed different proportion of clay fraction (less than 0.002 mm), which was about 67% in the Soil 1, and about 59% in the Soil 2 (Fig. 6). This difference is likely to account for the higher plasticity index of the Soil 1 (PI≈57.2) than that of the Soil 2 (PI≈49.5).

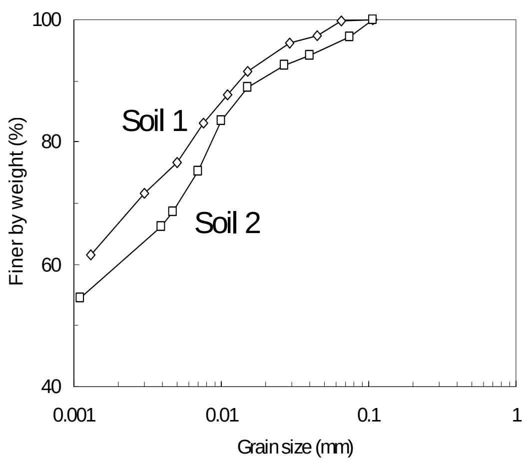

Fig. 6 Particle size distribution curves for the tested soils from the "Ogoto" landslide

3.3 Ring-shear tests

The ring-shear apparatus as well as the test procedure were the same as those described in section 2.3. The only difference is that the specimens from the "Ogoto" landslide were consolidated under confining stresses of 50, 100 and 200 kPa.

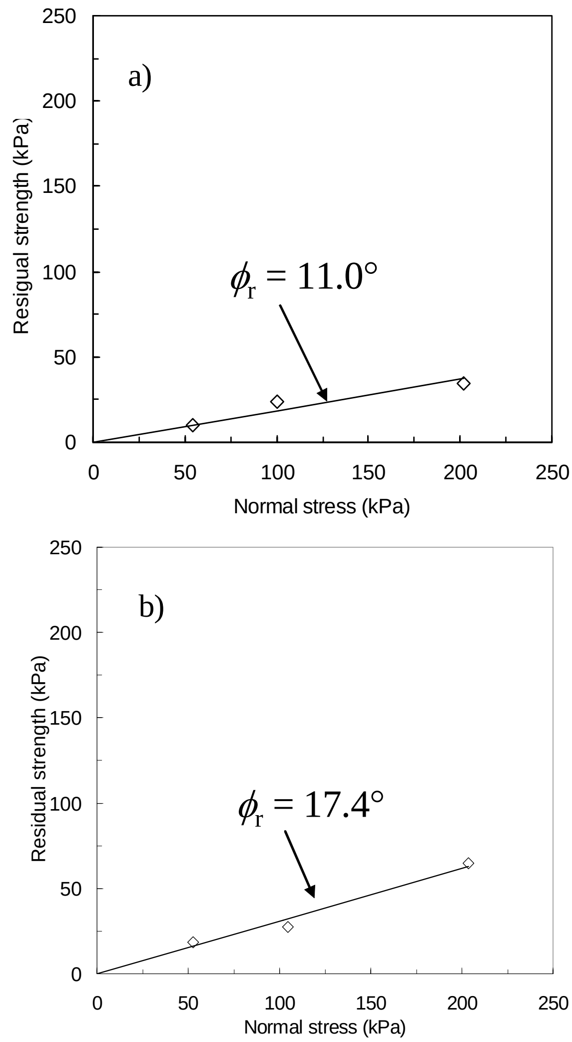

Fig. 7 Results from drained speed-controlled ring-shear tests on the soils from the "Ogotoi" landslide

Fig. 7 shows the results obtained for the Soil 1 and Soil 2. As can be seen, the value of the residual friction angle of the Soil 1 was measured to be about 11°, which is smaller than that of the Soil 2 (about 17.4°).

4. Shear strength of soil

Analysis of the laboratory results indicated a significant influence of clay content and clay mineralogy on the residual shear strength of the tested soils collected from the "Kuchi-Otani" landslide. For example, the mineralogical compositions of the amber silty clay and black clayey sand were found identical (Table 1); however, the former had a significantly higher amount of clay, a property that presumably accounted for its lower value of residual shear strength (Fig. 4b) compared to the latter (Fig. 4a). Comparisons made between the samples of black clayey sand and brownish clayey sand revealed very similar fine particle distribution (Fig.3) but different mineral composition; that is, the presence of montmorillonite in the brownish clayey sand (Table 1). This difference in clay mineralogy seemed to be responsible for the lower residual shear strength of the brownish clayey sand (Fig. 4c) compared to that of the black clayey sand (Fig. 4a).

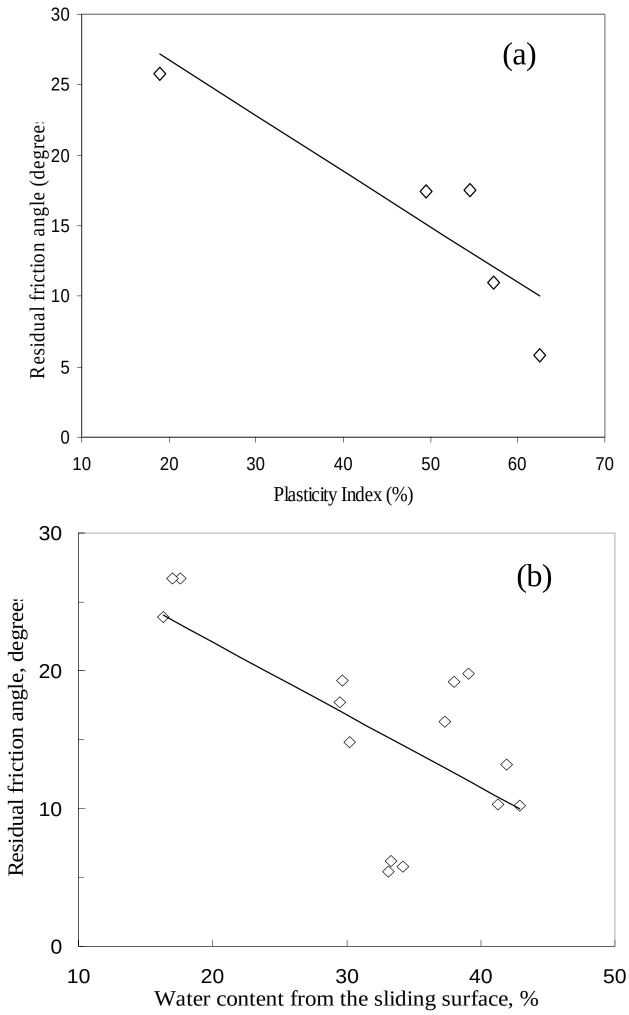

Fig. 8 Relations between residual shear strength and (a) plasticity index, and (b) water content

Laboratory examination of the soils from the "Ogoto" landslide pointed out a great effect of clay content on the residual shear strength. It was demonstrated that the higher clay content of the Soil 1 (Fig. 6 and Table 2) was the main reason for its lower residual shear strength (Fig. 7a) compared to that of the Soil 2 (Fig. 7b).

It is known that the plasticity index of soil, being a function of clay content and clay mineralogy, can be used as a parameter for the comparison of different clayey soils. As can be seen in Fig. 8a, which was plotted in terms of residual shear strength against plasticity index, an increase in plasticity decreases the residual shear strength of soil. The obtained results are in agreement with those obtained by Lupini et al. (1981) and Tika et al. (1999). Fig. 8b presents the relation between the water content of soil measured after each test and its residual shear strength. It is clear that soil with higher water content has lower residual shear strength.

The obtained relations presented in Fig. 8 have practical application and can be used for an approximate estimation of residual shear strength of soil, for example in the process of field investigation. However, in order to obtain a precise value of residual shear strength it is still necessary to conduct a series of drained monotonic ring-shear tests.

5. Conclusions

Residual shear strength of five different clayey soils collected from two reactivated landslides in Japan as well as the soil's properties such as clay content, clay mineralogy and plasticity were studied and the following conclusions were drawn:

- Increase in clay content decreases residual shear strength of soil;
- The presence of montmorillonite decreases residual shear strength of soil;
- Increase in plasticity decreases residual shear strength of soil;
- Soil with higher water content tends to have lower residual shear strength.
- The obtained relations between residual shear strength and plasticity and between residual shear strength and water content (Fig.8) can be used for an approximate estimation of

residual shear strength of soil provided that water content of soil or its plasticity is known.

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再活動地すべり地粘性土のせん断強度

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要旨

ここでは日本で起きた 2 種類の再活動地すべりの研究結果を示す。対応策の設計および地すべり活動の阻止のため、現地および実験室にて調査を行った。得られた結果より、すべり面の残留強度が地すべり活動に大きく寄与することが示され、土の残留強度時における粘土含有率や粘土鉱物について研究した。これにより、粘土含有率の増加はモンモリロナイト含有時と同様に、残留強度を十分に減少させることが示された。

キーワード:再活動地すべり， 残留強度, モンモリロナイト, 塑性指数, 粘土含有率