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Geotechnical investigations of the Sawatari Landslide in Shikoku, Japan

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ABSTRACT

Many large landslides are found in various parts of Japan. Among them, the Sawatari Landslide in the Shikoku Region is quite different from others, as it contains expansive clays. This study focuses on the mineralogy, strength parameters, and index properties of the slip layer clay of the Sawatari Landslide. The study of clay mineralogy revealed significant chlorite and expansive chlorite content. The angle of residual shearing resistance of the slip layer soil containing expansive clay minerals is much smaller than that of the soil containing non-expansive minerals.

INTRODUCTION

Japan has many large landslides owing to its mountainous and fragile terrain. In Shikoku (one of the four major islands of the country) alone, there are 662 active and 1290 potential landslides (as of March 1992) under the jurisdiction of the national government (Landslide in Japan 1992). Most of the landslides (Fig. 1) are seen to have occurred in the region between the east–west trending Median Tectonic Line (MTL) and Mikabu Tectonic Line (MiTL). The MTL separates the Sambagawa and Izumi geological belts, whereas the MiTL lies in a geological belt of greenstones (called the Mikabu Belt). The rocks in these belts are highly fractured and weathered giving rise to thick soil layers containing weak clay minerals (such as chlorite, smectite, and vermiculite). Consequently, many large landslides are active for many decades (Yatabe et al. 1991).

This paper outlines the general features and geotechnical properties of the Sawatari Landslide. The paper also elucidates the influence of clay mineralogy on the strength characteristics of the slip layer.

THE SAWATARI LANDSLIDE

The Sawatari Landslide is located in the town of Mikawa, in the Ehime Prefecture of Japan. Plan and longitudinal section of the landslide are shown in Fig. 2 and 3 respectively (The Sawatari Landslide 1995).

This landslide is known to have started moving in 1948. Cracking and bulging of retaining walls, cracks in concrete pavements, and ground subsidence were some of the indications of its movement. A continuous creep, particularly during the rainy season, of a huge mountain block was a signal of great danger to the human life at the locality. Consequently, people started leaving their places, and the number of households in the area reduced to 31 by 1961 (from 49 in 1948). Since then, the prefectural government has given a high priority to the stability of the landslide block, and consequently to prevent the damming of the river and incurring adverse effects in the surrounding areas (The Sawatari Landslide 1995).

The geological investigations revealed that the soil mass at the site is resting mainly on the green tuff of the Mikabu Belt and partly on the calcareous schist. The green tuff is soft and weathered. As it is characterised by a high water storage capacity, there is generally a higher water table. The

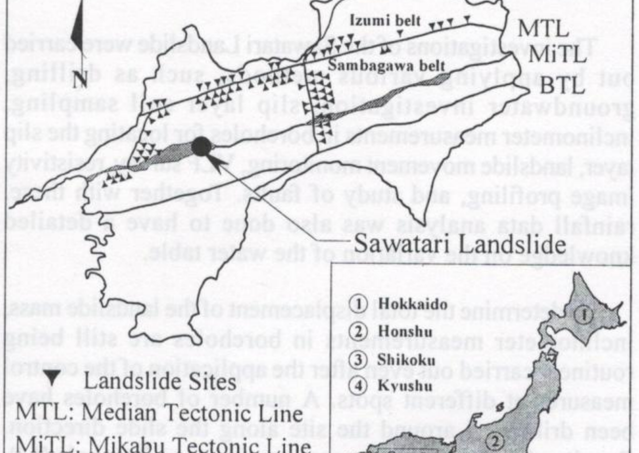

Fig. 1: Map of Shikoku showing the location of the Sawatari Landslide

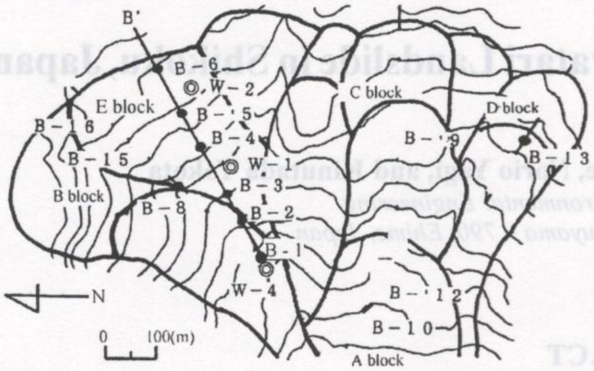

Fig. 2: Map of the Sawatari Landslide showing various blocks and borehole locations

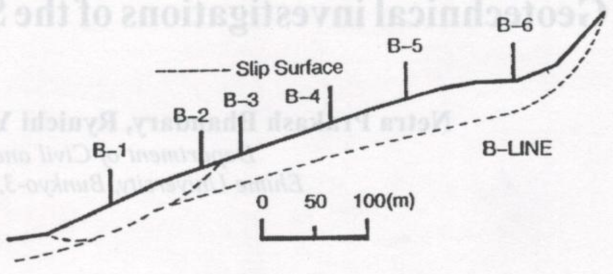

Fig. 3: Longitudinal section of the Sawatari Landslide

investigations also confirmed that this rock at a certain depth is in a completely weathered state owing to the chemical action of groundwater. Therefore, it is evident that the residual soil (derived from weathering of tuff) has formed the slip layer of the Sawatari Landslide.

The creeping block of the landslide is very large, and measures more than one sq km in slope area and 30 to 40 m in slip layer depth. The slip angle is comparatively gentle (varying from 10° to 20°). The moving soil mass consists of five major and a number of minor blocks as shown in Fig. 2. Near the toe, it has a typical bottleneck shape. The movement speed, compared to that of other landslides in the belt, before the application of drainage wells to lower the water table was very high (i.e. several centimetres per year), but it has reduced to only a few centimetres per year after the construction of six drainage wells at various locations.

LANDSLIDE INVESTIGATION METHODS

The investigations of the Sawatari Landslide were carried out by applying various methods, such as drilling, groundwater investigation, slip layer soil sampling, inclinometer measurements in boreholes for locating the slip layer, landslide movement monitoring, VLF survey, resistivity image profiling, and study of faults. Together with these, rainfall data analysis was also done to have a detailed knowledge on the variation of the water table.

To determine the total displacement of the landslide mass, inclinometer measurements in boreholes are still being routinely carried out even after the application of the control measures at different spots. A number of boreholes have been drilled all around the site along the slide direction. Results of the inclinometer measurements on borehole B-9, where the slip surface depth is 23 m, are shown in Fig. 2 and 4. It is seen that the total displacement of the landslide block at the surface in just 11 months is about 22 mm, and the cumulative displacement from its original position is more than 50 mm.

EXPERIMENTS AND RESULTS

The laboratory works carried out in this study comprised the determination of strength parameters, index properties, and mineralogical analysis of the clay from landslide slip surface. For this purpose, the borehole samples were used. Shear strength tests, some basic tests for index properties, and x-ray diffraction analysis for clay mineral content were carried out on a number of clay samples.

Strength tests

All the shear strength tests were carried out upon remoulded soil samples with particle size below 200 µm. Triaxial tests in undrained condition were carried out to determine the angle of effective shearing resistance, whereas ring shear tests in drained condition were performed to

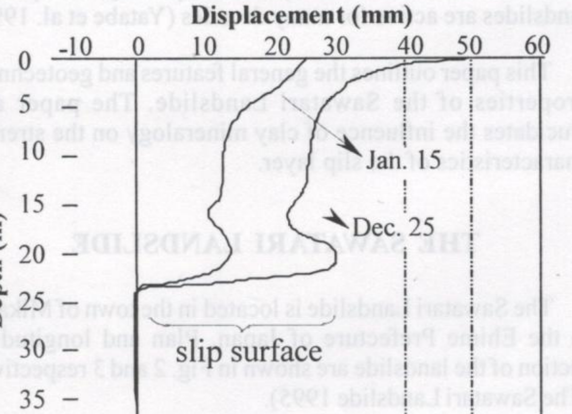

Fig. 4: Results of inclinometer measurements in the bore hole B-5

determine the angles of peak and residual shearing resistance. However, being in a state of continuous sliding, the angle of residual shearing resistance governs the stability of the landslide. It is also supposed that the value of apparent as well as effective cohesion for landslide clays is equal to or nearly zero, since a soil mass bears no cohesion at its residual state (Enoki et al. 1993).

The results of the strength test in terms of angles of shearing resistance and plasticity index are shown in Fig. 5. The figure shows the angles of effective and residual shearing resistance of all the collected landslide clay samples. It is seen in the figure that the angles of effective shearing resistance (ϕ') of the slip layer clays vary from 20° to 30°, whereas those of residual shearing resistance, (ϕ_r) vary from 10° to 25°. A notable difference in the angles of shearing resistance of different samples can be observed, which may be because the plasticity index, Ip of each test sample is different. It means the samples do not have same index properties. However, it is noticed that the difference between ϕ' and ϕ_r of the soil samples with higher plasticity index is greater than that between the angles of shearing resistance of the samples with lower plasticity index. This means the soil samples that have higher plasticity index possess smaller angle of residual shearing resistance, which is due to the presence of a higher amount of expansive clay minerals. Although the angle of effective shearing resistance for all the tested samples is constant with respect to the plasticity index, the angle of residual shearing resistance decreases with the increase of the plasticity index. Therefore, under the condition of continuous sliding, the strength of the slip layer soil in the Sawatari Landslide is governed by the angle of residual shearing resistance, which is very small due to the presence of expansive clay minerals in a considerable amount. In addition, the above values of angles of shearing resistance are considered smaller from the stability point of view of either a slope or a landslide block. Table 1 shows all

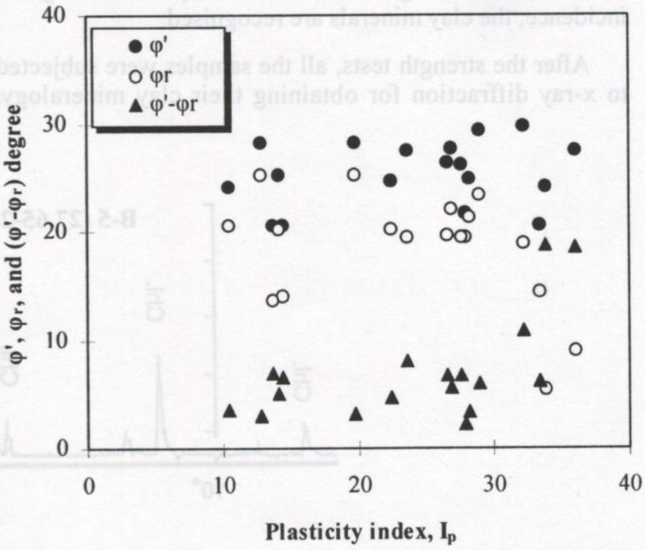

Fig. 5: Plots of angle of shearing resistance versus plasticity index for the Sawatari Landslide.

Table 1: Results of strength and other basic tests

Bore hole	Depth (m)	LL (%)	PL (%)	I_p (%)	Gs	φ' (degree)	φ_d (degree)	φ_r (degree)	$\varphi'-\varphi_r$ (degree)
B1	8.9-9.5	44.00	24.20	19.80	2.79	28.3	-	25.2	3.1
B2-1	18.0	47.20	19.30	27.90	2.83	21.7	-	19.4	2.3
B2-2	-	55.80	22.40	33.40	2.80	20.5	-	14.4	6.1
B3-1	11.7-11.8	56.90	24.70	32.20	2.74	29.7	-	18.8	10.9
B3-2	23.0-23.5	66.60	37.70	28.90	2.50	29.3	-	23.3	6.0
B3-3	-	51.10	27.50	23.60	2.82	27.4	-	19.4	8.0
B3-4	-	58.20	30.00	28.20	2.93	24.8	-	21.4	3.4
B12-1	6.5-7.0	35.40	24.90	10.50	2.81	24.1	-	20.5	3.6
B12	20-20.5	60.48	24.46	36.02	2.93	27.5	-	9.06	18.4
B12-3	31.6-32.0	50.40	27.90	22.50	2.90	24.7	-	20.1	4.6
B13-1	15.4-16.0	41.30	14.80	26.50	2.77	26.3	-	19.6	6.7
B13	23.5-24.0	52.72	18.89	33.83	2.87	24.1	-	5.44	18.7
B13-3	27.5-28.0	37.40	23.00	14.40	2.98	20.5	21.7	14.0	6.5
B13-4	29.3-30.0	37.60	23.90	13.70	2.94	20.5	20.2	13.6	6.9
B13	35.5-37.0	44.46	16.87	27.59	2.94	26.2	-	19.5	6.7
B15-1	5.4-6.0	44.90	18.10	26.80	2.94	27.7	25.6	22.0	5.7
B15-2	9.6-10.0	36.30	22.10	14.20	2.94	25.2	29.6	20.1	5.1
B15-3	14.5-15.0	31.20	18.40	12.80	2.85	28.2	33.2	25.2	3.0

the test results in detail. It is seen that the physical properties of each sample are different and it may have resulted in the variation of angles of shearing resistance.

X-ray diffraction analysis

X-ray diffraction analysis consists of sample preparation with clay sized particles on glass slides and placing them in a metallic tube where x-rays strike the soil particles and get diffracted. According to the diffraction at particular angle of incidence, the clay minerals are recognised.

After the strength tests, all the samples were subjected to x-ray diffraction for obtaining their clay mineralogy. Two typical examples are presented in Fig. 6. It depicts that the soil samples contain a high percentage of chlorite and expansive chlorite along with other clay minerals. Table 2 (Ishii et al. 1999) shows a combination of results of strength tests and x-ray diffraction analysis and Table 3 shows the result of the x-ray diffraction analysis only. The data in Table 2 are plotted in Fig. 7, and it shows a distinct decrease in angles of shearing resistance with the increase in expansive clay-mineral content. Similarly, as seen in Table 3, all the soil samples contain chlorite, feldspar, and calcite. However, the amount differs from sample to sample, which is because of unequal degree of weathering.

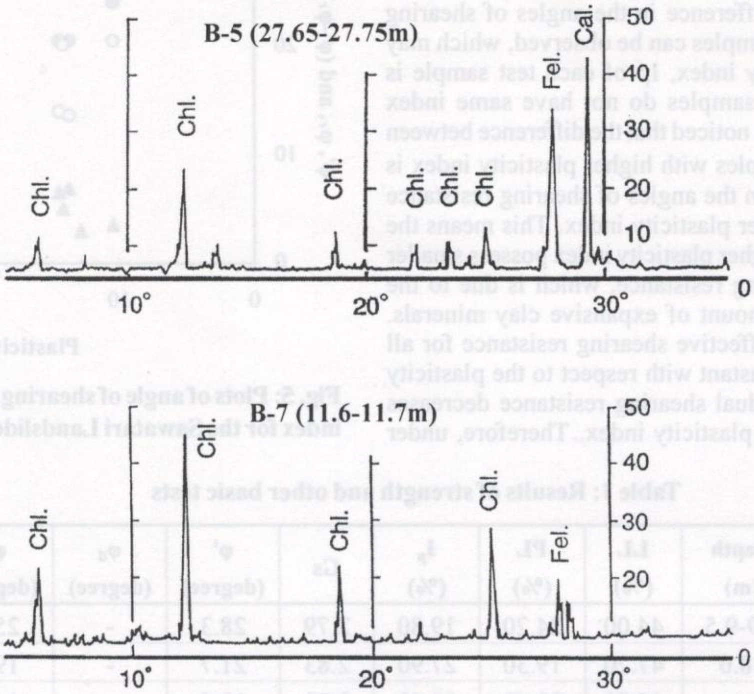

Fig. 6: Results of x-ray diffraction analysis

Table 2: Expansive clay minerals and their strength properties

Bore hole	S/C	Clay and other minerals	φ' (degree)	φ_r (degree)
B12-1	0.30	chl, tre	24.1	20.5
B12-3	0.25	chl, tre	24.7	20.1
B13-3	0.70	chl, tre	20.5	14.0
B13-4	0.50	chl, tre	20.5	13.6
B15-1	0.20	chl, tre	27.7	22.0
B15-2	0.10	chl, tre	25.2	20.1
B15-3	0.30	chl, tre, fel	28.2	25.2

S/C: ratio of expansive to non-expansive clay mineral chl: chlorite, tre: tremolite, fel: feldspar

Table 3: Results of x-ray diffraction analysis

Bore hole	Depth (m)	Clay and other minerals	Bore hole	Depth (m)	Clay and other minerals
B-1	8.9–9.5	chl, fel,cal	B-9	49.7–49.8	chl, fel, cal
B-1	11.0	chl, fel	B-10	21.1–21.2	chl, fel, cal
B-2	18.0	chl, fel	B-10	24.3–24.4	chl, fel
B-3	11.7–11.8	chl, fel, cal	B-11	18.9–18.95	chl, fel, cal
B-3	23.0–23.5	chl, fel, cal	B-11	21.8–21.9	chl, fel, cal
B-4	19.7–19.8	chl, fel,	B-12	6.5–7.0	chl, fel
B-5	27.65–27.75	chl, fel, cal	B-12	10.8–11.0	chl, fel
B-5	34.0–34.1	chl, fel, cal	B-12	20.0–20.5	chl, fel
B-6	20.6–20.7	fel, cal	B-12	25.0–25.7	chl, fel
B-7	11.6–11.7	chl, fel	B-12	31.6–32.0	chl, fel
B-7	31.7–31.8	chl, fel, cal	B-12	36.8–37.0	chl, fel
B-8	27.7–27.8	chl, fel, cal	B-13	15.4–16.0	chl, fel
B-8	35.9–36.0	chl, cal	B-13	21.5–21.7	chl, fel
B-9	11.5–11.65	chl, fel	B-13	23.5–24.0	chl, fel
B-9	21.0–21.1	chl, fel	B-13	35.0–36.0	chl, fel
B-9	34.85–34.95	chl	B-13	48.7–49.0	chl, fel

chl: chlorite, fel: feldspar, cal: calcite

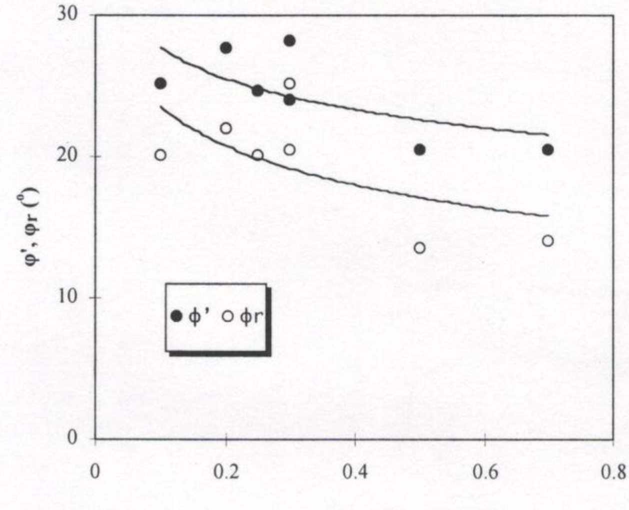

Fig. 7: Variation of ϕ' and ϕ_r with expansive clay mineral content

CONCLUSIONS

The bedrock of the Sawatari Landslide is in a fractured state. The fractures provide a better space for the storage of water. Also, the bedrock being tuff, has high water storage capacity. These two factors have led to a high water table at the landslide site.

The slip layer soil of the Sawatari Landslide contains mostly chlorite and smectite. These two minerals weaken significantly the strength of the whole soil mass containing them.

The strength of slip layer soil compared to other ordinary soils is low and the residual strength is even lower. The average angle of effective shearing resistance is 25° and that of residual shearing resistance is 17°. Also, the angle of residual shearing resistance of slip layer soil containing expansive clay minerals (indicated by a higher plasticity index) is much smaller than that of the soil containing non-expansive minerals.

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