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# Shear strength of landslide clay soil containing weathered serpentinite

**K. Yokota, R. Yatabe, N. Yagi, and N. P. Bhandary**
*Department of Civil and Environmental Engineering, Ehime University,*
*3 Bunkyo-cho, Matsuyama 790-8577, Japan*

## ABSTRACT

Serpentinite is a rock consisting magnetite, brucite, and serpentine minerals. It is supposed to have formed on the deep sea floor by a sudden eruption of mantle matters or by cracking of the crust and coming in contact with water. It is generally associated with basic and sedimentary rocks. Among three constituent minerals, brucite easily dissolves in water, whereas magnetite does not. Hence, at a border between serpentinite and other rocks, formation of pores in the weathered serpentinite mass takes place due to leaching of brucite. These pores act as groundwater conduits all through the weathered rock mass, causing weathering of other rocks too. In the weathering process, chlorite changes partially to smectite and partially to expansive chlorite, which then form a clay layer with very weak strength. When this clay layer further loses strength, the soil mass resting on it starts moving, creating a landslide.

Many landslide sites in Japan lie at the boundary of serpentinite and metamorphic basic rocks like greenschist and black (sedimentary) schist. The slip layer clays of these sites contain various minerals such as serpentine, talc, chlorite, and montmorillonite. The angle of internal friction for serpentinite is about 30°, whereas those of minerals like talc, chlorite, and montmorillonite is between 20° and 10°. In them, the decrease from peak to residual strength is high. Slopes of serpentinite soil containing a high amount of these weak clay minerals are prone to sliding.

## INTRODUCTION

Serpentinites have so far been found at different mountain ranges like the Alps, Urals, and Himalayas, which are the results of collision of two plates. It was supposed until quite recently that serpentinites were metamorphosed from peridotite whose main components are olivine and pyroxene, but the latest reports show that some serpentinites were formed at the sea mounts on the deep sea floor (Fujioka et al. 1994, Ishizuka and Fujimoto 1995). Serpentinite, because of its characteristic pattern, is sometimes valued as a decorative material. On the other hand, the serpentinite on mountain surfaces is usually in fractured state and is known generally as a fragile rock.

Many landslides can be found in so-called serpentinite areas (Sokobiki et al. 1994). It is known that serpentinite is an intrusive rock and the serpentine clay resulted from fault action and weathering forms the slip surface of the landslides. But this fact does not give sufficient idea about the characteristic of "serpentinite landslide", their distribution, and occurrence even on gentle slopes. It is considered that these features of landslide depend on the serpentinite formation process and distribution. Along with this, the objective of this paper is to make clear the mechanism of formation of "serpentinite landslide" by the mineralogical method.

## FORMATION AND WEATHERING OF SERPENTINITE

Some serpentinites with peridotite can be found in Japan on the top layers of high mountains. However, many serpentinite blocks are spread along the tectonic lines (Miyashiro 1965) and are generally in association with greenschist and black schist. At the outcrop, the weathered serpentinite usually turns greyish blue or green, forming a striking contrast against other dark brown weathered basic rocks.

### Contact surface of serpentinite and other rocks

In Plate 1, the contact surface between the serpentinite and greenschist is depicted on the cut slope of Nishikiyama (the Hidaka Village, Kochi Prefecture) and in Fig. 1, the geological map of the Choja Landslide site (the Niyodo Village, Kochi Prefecture) is shown (Fujita and Takeuchi 1982). These figures show that serpentinite is frequently associated with metamorphic greenschist or sedimentary black schist. Therefore, it is justified to state that it is not an intrusive rock.

### Fe and Mg in serpentinite and other rocks

Fig. 2 depicts the Sambagawa greenschist and black schist, the Mikabu greenstones, and the metallic elements leached from serpentinite in the acidic solution. The acid used was $H_2CO_3$ with pH 6.3. Leaching of Mg from the serpentinite is higher than that of others, whereas leaching of Fe is lower than that of others. In similar way, many other metallic elements were leached from the other rocks.

Main minerals of basic rocks such as pyroxene, hornblende, and chlorite have $Mg^{2+}$, $Fe^{2+}$, $Ca^{2+}$, $Al^{3+}$, and $Fe^{3+}$ in their crystal structures as anhydrous or hydrous silicates. It is considered that Fe and other elements are

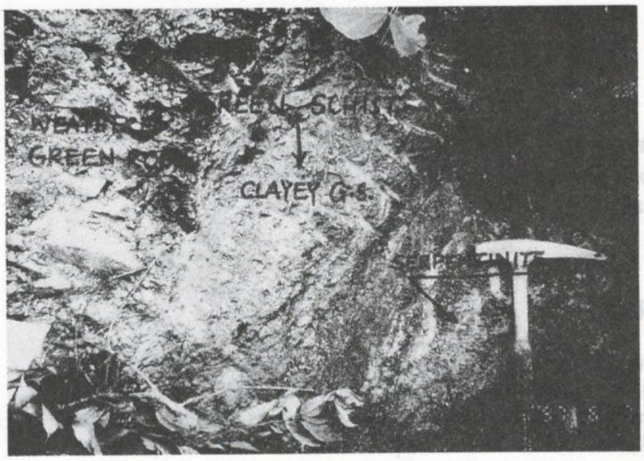


**Plate 1: Serpentinite contact surface on the Nishikiyama cut slope**

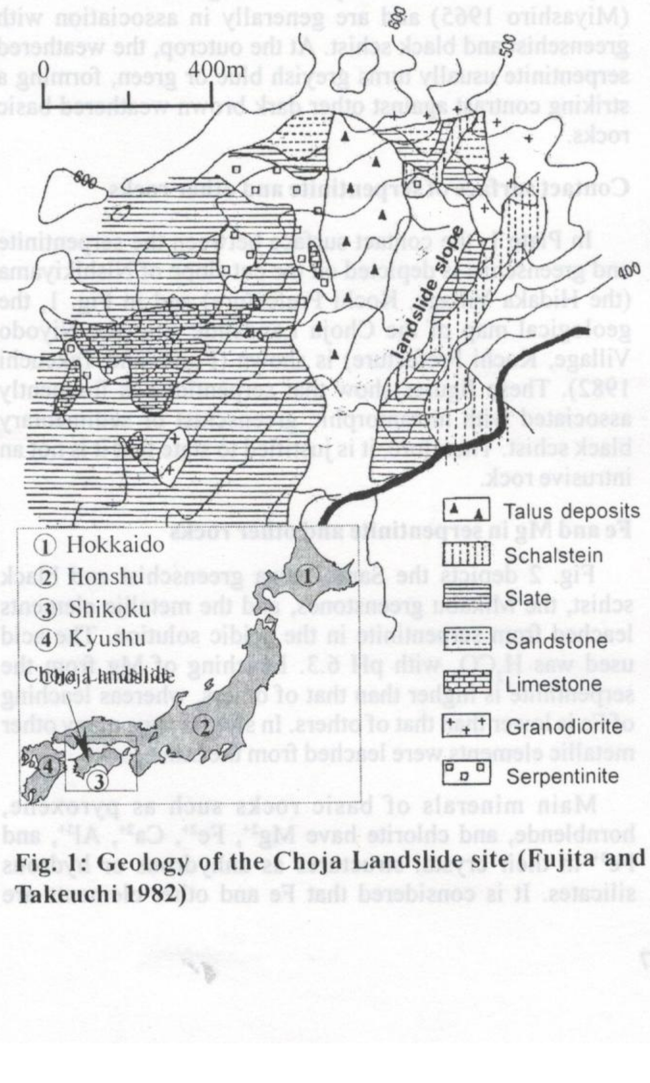


**Fig. 1: Geology of the Choja Landslide site (Fujita and Takeuchi 1982)**

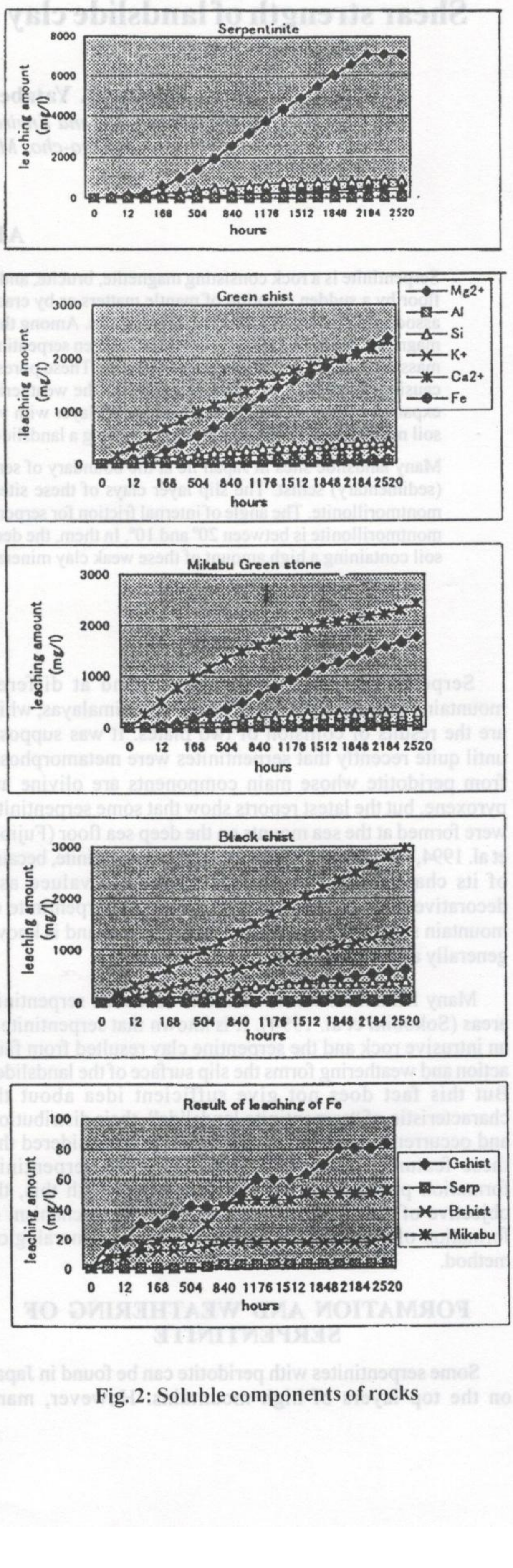


**Fig. 2: Soluble components of rocks**

dissolved in acidic or basic solution with destruction of the crystal structure and they turn dark brown indicating the formation of $Fe(OH)_3$.

**Serpentinite**

Serpentinite consists basically of some lumps of magnetite with serpentine and some veins of brucite with chrysotile. It is one of the magnesium-rich hydrous silicates, and is classified into antigorite, chrysotile, and lizardite based on mode of occurrence, temperature, and pressure.

Fig. 3 illustrates the proportion of brucite that is contained in respective serpentinite blocks all over Japan. It is clear from the figure that all the samples of peridotite and serpentinite have brucite in their blocks. Brucite generally exists in the inner part of ultrabasic rocks. It is the only magnesium hydroxide mineral that does not dissolve even in strong basic solution with pH higher than 11, but dissolves easily in acids or weak basic water.

Similarly, magnetite is one of the iron oxides and is not weathered at the ground surface. Fig. 4 shows the particle size distribution of serpentinite with proportion of Fe and Mg against Si. The proportion of Fe, which is the main element in magnetite, decreases with the decrease in particle size, whereas that of Mg is constant. It makes clear that magnetite with serpentine does not crush into particles smaller than silt. As brucite is soluble in water, serpentinite is easily weathered and breaks into pieces. But magnetite being insoluble, makes coarse-grained particles, which contribute to higher residual strength and look greyish blue or green in colour.

**Peridotite**

Olivine, which is a main mineral of ultrabasic rocks, has $Mg^{2+}$ and $Fe^{2+}$ in its crystal structure as anhydrous silicate minerals, namely forsterite and fayalite. The thin surface of weathered peridotite turns reddish brown, but inner part of it turns clear olive green. It can be considered that Fe is dissolved with the destruction of crystal structure, which clarifies that weathered peridotite does not metamorphose to serpentinite. Some thin, soft, and straight white veins of fibrous chrysotile can be found at the peridotite outcrop. It is reported that the peridotite has some veins of brucite and chrysotile, which keep the fluidity of upper mantle matter (Morimoto 1989). White veins are the traces of the fact that brucite was dissolved in water at the ground surface.

**Formation process of serpentinite and other rocks**

The difference between serpentinite and peridotite, or serpentinite and basic rocks shows that serpentinite has a unique occurrence and formation process. It is supposed that serpentinite formation took place on the deep sea floor by the reaction of water on suddenly erupted upper mantle matter or cracked ocean crust, whereas other basic or ultrabasic rocks solidified slowly from lava of upper mantle matter. The conceptual process is illustrated in Fig. 5 (Arai 1992; Cannet 1995). It is also known that serpentinite has a close association with basic rocks at the sea floor, and after many years, the serpentinite is covered by the sedimentary rocks.

## LANDSLIDE AT THE BORDER BETWEEN SERPENTINITE AND OTHER ROCKS

A huge ultrabasic rock body consisting of peridotite with serpentinite generally forms a high mountain. It is found that veins of brucite and chrysotile create some cracks in the ultrabasic rocks simultaneously causing rock fractures. On the other hand, some serpentinite rock body is very fragile due to dissolution of brucite in water and it usually

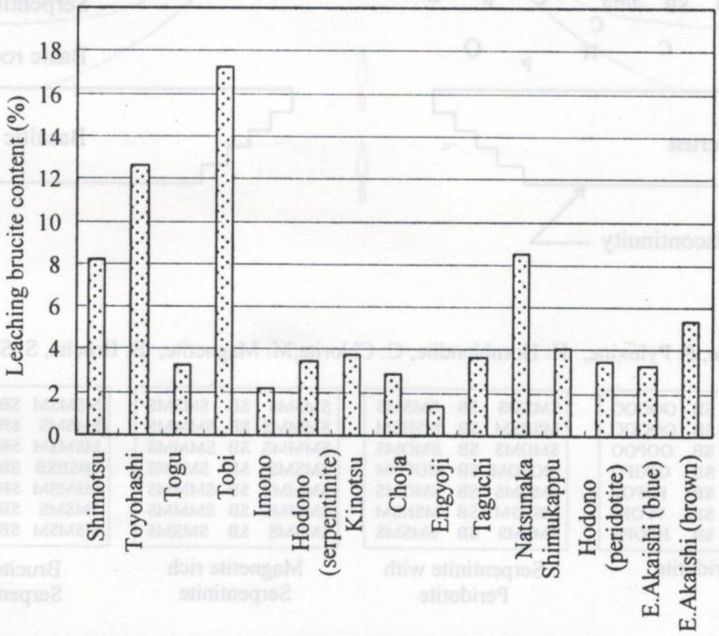


**Fig. 3: Leaching brucite content in different sites**

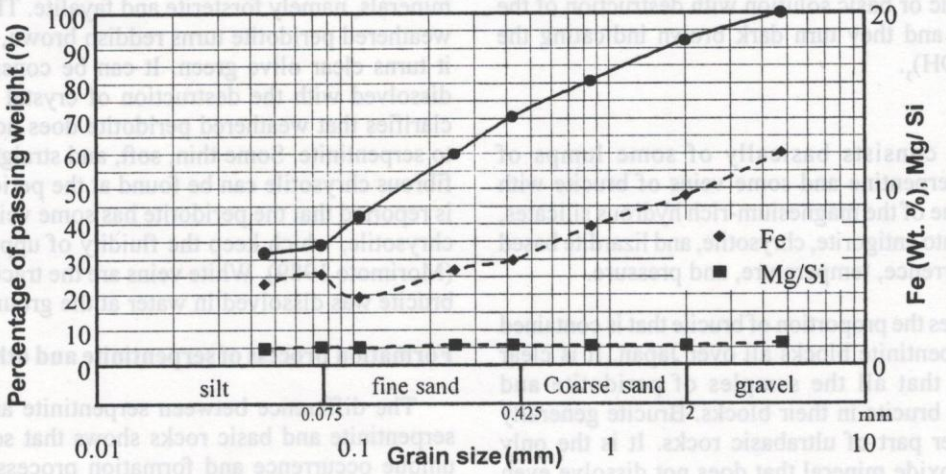


**Fig. 4: Particle size distribution of serpentinite sample and Fe, Mg content**

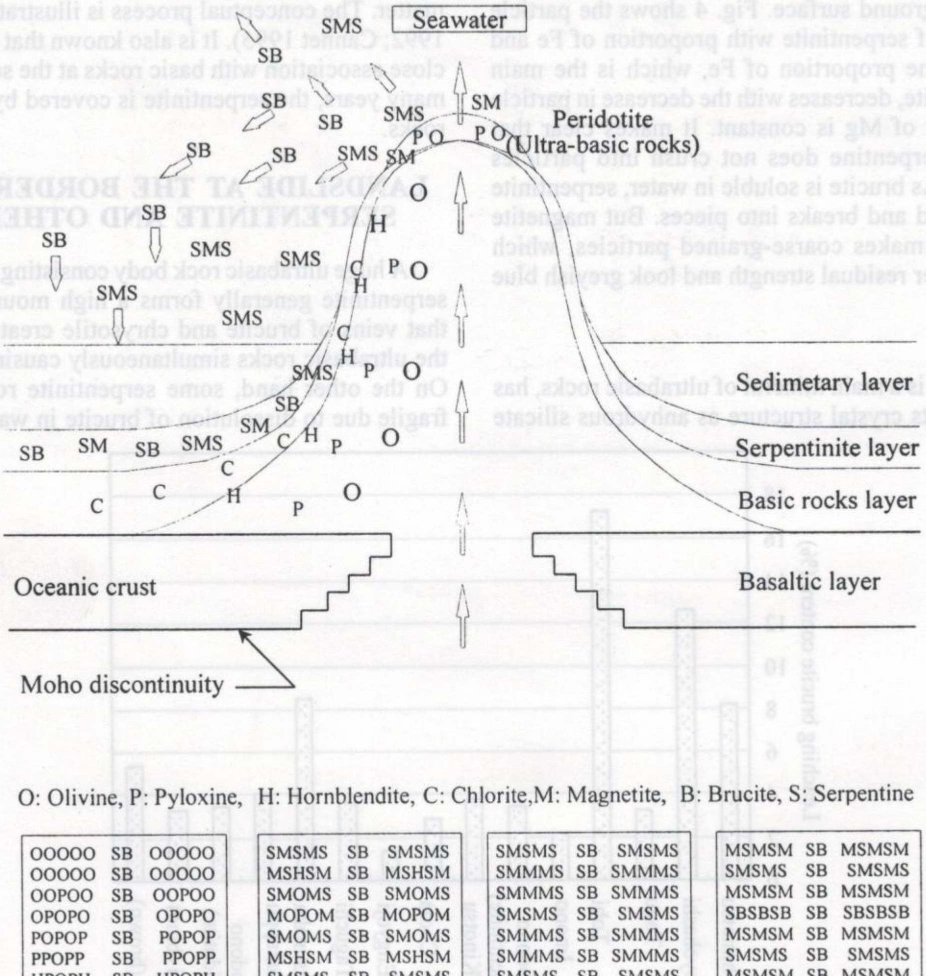


**Fig. 5: Conceptual process of serpentinite**

breaks into pieces. Therefore, a mountain of ultrabasic rocks has steep cliffs as well as gentle slopes, and as weathered serpentinite on the outcrop, usually does not break into clayey particles, no landslides occur there.

Many landslides have occurred at the boundary between serpentinite and metamorphic greenschist or sedimentary black schist. At the landslide sites of this study, some boring cores showed many alternating layers of serpentinite and other rocks.

## Minerals in slip surface and their shear strength

Table 1 shows the component minerals of weathered serpentinite analysed by the x-ray diffraction, and strength parameters obtained by the ring shear test. The minerals of slip surface soil at a "serpentinite landslide" site generally are serpentine, talc, chlorite, and montmorillonite. In Fig. 6, the angles of shearing resistance of main minerals are shown. Serpentine has a high angle of shearing resistance, about 30°, whereas talc, chlorite, and montmorillonite have low values, about 20° to 10°, and the decrease from peak to residual strength is high. Chlorite is one of the main minerals of weathered greenschist, and montmorillonite is one of the main minerals of weathered black schist. It is known that montmorillonite has remarkable hydrophilicity, which expands with water. Sometimes, it is also found that chlorite at the outcrop swells with water.

## Function of water conduits in serpentinite

Table 2 shows some characteristics of the boring core from the Sawatari Landslide. The Sawatari Landslide (the Mikawa Village, Ehime Prefecture) lies within the Mikabu greenstone belt. At this site, no serpentinite is found at the ground surface, but about 20 m deeper, metres of serpentinite

**Table 1: Mineral content and angles of shearing resistance**

1a: so-called weathered clayey serpentinite at the cutting slope

| Tectonic belt | Sampling spot | | Minerals | $\phi'$ | $\phi_r$ |
|---|---|---|---|---|---|
| Kamuikotan | Fukuyama | Cut slope | Se. | 34.6 | 33.6 |
| | Seihuzan | Cut slope | Se. Ch. | 32.7 | 28.1 |
| Kurosegawa | Yusuhara | Cut slope | Se. | 30.1 | 26.7 |
| | Osakayama | Cut slope | Se. Ch. | 31.8 | 28.4 |
| Sambagawa | Shimotsu - 1 | s.c.s. | Ch.Fe.Se. | 31.7 | 14.4 |
| | Shimotsu - 2 | s.c.s. | Mo. | 23.2 | 9.4 |
| Sangun | Yamaguchi - 1 | s.c.s. | Ta. Se. | 24.8 | 20.2 |
| | Yamaguchi - 2 | s.c.s. | Ta. | 28.7 | 8.9 |

($\phi'$ $\phi_r$: angles of effective and residual shearing resistance; s.c.s.: swelling cutting slope)

1b: boring core at landslide site

| Landslide site | Country rock | Depth (m) | Minerals | $\phi'$ | $\phi_r$ |
|---|---|---|---|---|---|
| Choja | Serpentinite | 17.5-20.0 | Tr.Se.Ch. | | |
| | Slate | 20.5-22.0 | Mo.Ch.Tr. | | |
| | | 22.0-22.3 | Fe. Tr. | | |
| | Slip surface Serpentinite | 24.5-25.0 | Tr. Ch. | | |
| | | 25.0-28.0 | Se. | | |
| | | 28.0-29.0 | Se. Mo. | 21.7 | 17.2 |
| | | 29.8-32.8 | Se. Ch. | | |
| | | 36.0-38.0 | Se. | 27.4 | 27.3 |
| | Slate | 44.0-45.0 | Mo. Se. | 23.0 | 16.8 |
| Taguchi | Slip surface Serpentinite | 27.0-28.0 | Se. Ta. | 18.5 | 12.9 |
| | | 28.0-29.0 | Ta. Se. | 19.3 | 14.0 |
| | | 29.0-30.0 | Ta. Se. | 29.3 | 28.7 |
| | | 30.0-31.0 | Se. Ta. | 32.4 | 32.6 |

1c: pure minerals (available in the market)

| | $\phi'$ | $\phi_r$ |
|---|---|---|
| Se. | 32.2 | 27.7 |
| Ch. | 28.1 | 17.5 |
| Ta. | 19.4 | 17.5 |
| Mo. | 12.0 | |

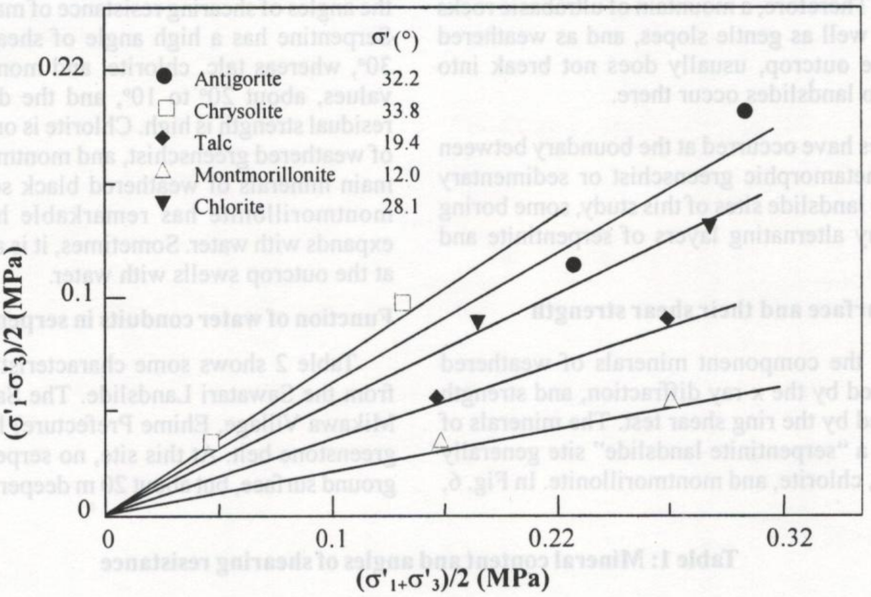


**Fig. 6: Angles of shearing resistance for pure minerals**

**Table 2: Characteristics of boring core at the Sawatari Landslide, Japan**

| Boring depth (m) | Layers | Calcite veins | Main minerals | Brucite % | Swelling | Permeability |
|---|---|---|---|---|---|---|
| 0-5.00 | Debris | | | | | partial water leak |
| 5-8.95 | Migrated rocks | wide | | | | |
| 8.95-10.50 | Debris (?Slip surface) | | Ch. Tr. | | small | low permeability |
| 10.5-13.25 | Clayey fracture zone | mesh | Ch. Tr. | | nil | |
| 13.25-14.10 | (?Slip surface) Fracture zone | | Ch. Tr. | | small | |
| 14.80 | Greenstones (weak or mid-weathered rocks) | wide | Ch. Tr. | 8.87 | | |
| 17.55 | | | Ch. Tr. | | | partial water leak |
| 18.21 | | | Ch. Tr. | 7.00 | nil | |
| 18.45 | | | Se. Tr. | 4.76 | nil | |
| 18.55 | | | Ch. Tr. | | large | |
| 18.65 | | | Se.Ch.Tr. | 19.60 | middle | |
| 19.59 | Serpentinite (weak weathered rocks) | mesh | Se. Ta. | | | |
| 19.80 | | | Se. Ta. | | | |
| 20.38 | | | Se. Tr. | 10.21 | | |
| 20.69 | | | Se.Cr.Tr. | | | |
| 20.89 | | | Se.Tr.Ta. | | | |
| 21.22 | | | Se.Ch.Tr. | 6.07 | small | |
| 21.70 | | | Se.Ch.Tr. | | | |
| 22.00 | Greenstones (weak weathered rocks) | wide | Ch. Tr. | 5.04 | nil | |
| 22.28 | | | Ch. Tr. | | | |
| 22.48 | | | Ch. Tr. | | | |
| 23.35 | | | | 9.70 | | |
| 24.00- | Bed rock (Mikabu Greenstones) | | | | | |

Se: Serpentinite (Magnetite with Serpentine and Brucite with Serpentine) Ch: Chlorite
Ta: Talc Tr: Tremolite Mo: Montmollironite Fe: Feldspar

layers between the country rock and fractured zone of the Mikabu greenstones can be seen. A partial water leakage zone is also found near the serpentinite layer. At the boundary between the serpentinite and other rocks, many pores are formed in the rock due to the dissolution of brucite veins in water, which act as groundwater conduits causing weathering of neighbouring rock.

The schematic weathering process of chlorite to smectite is shown in Fig. 7. It is considered that the swelling or expansive chlorite is a mixture of chlorite and smectite. In Fig. 8, the variation in angles of shearing resistance with the increase in the amount of swelling chlorite is shown.

**Primary collapse with landslide**

A clay layer containing swelling chlorite and montmorillonite is formed between the weathered soft serpentinite and other rocks. The weathered serpentinite has the characteristics of high permeability and high residual strength, whereas the swelling chlorite and montmorillonite have low permeability but low residual strength. When the clay layer containing these clay minerals further loses strength, the soil slope starts sliding.

**The secondary landslide**

It has been reported that there are many alternating thin layers of serpentinite and slate at the Choja Landslide (Fig. 1). The thickness of the layers varies from a few cm to tens of cm. The main minerals of slate are also talc, chlorite, and montmorillonite.

When a repeated collapse of slope containing the serpentinite with other rocks occurs, many layers of debris containing clasts of various rocks are deposited on a gentle slope. The gentle slope is formed owing to the presence of minerals that have low angle of internal friction. Inside the deposit, many layers of weathered soft serpentinite and other clays are formed, which contain talc, chlorite, and montmorillonite (Table 1). Ultimately, one of the weakest contact surfaces becomes the slip surface at that place. When the layers of debris lose their strength and the soil mass loses stability due to erosion by rivers or formation of artificial cut slopes, there occurs a creeping landslide. It is supposed to be the mechanism of the landslides at the so-called Serpentinite Zone.

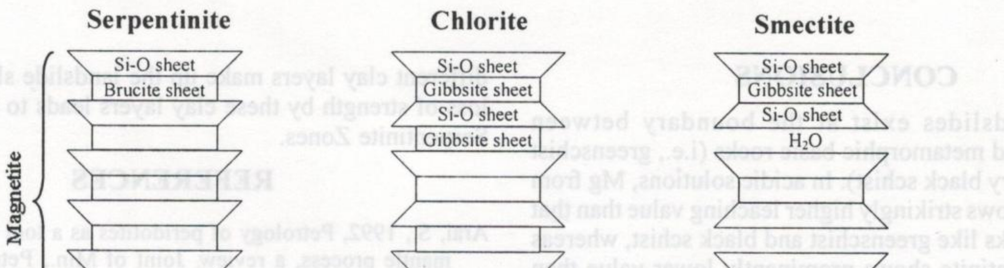


**Fig 7: Comparison of serpentine with chlorite and smectite**

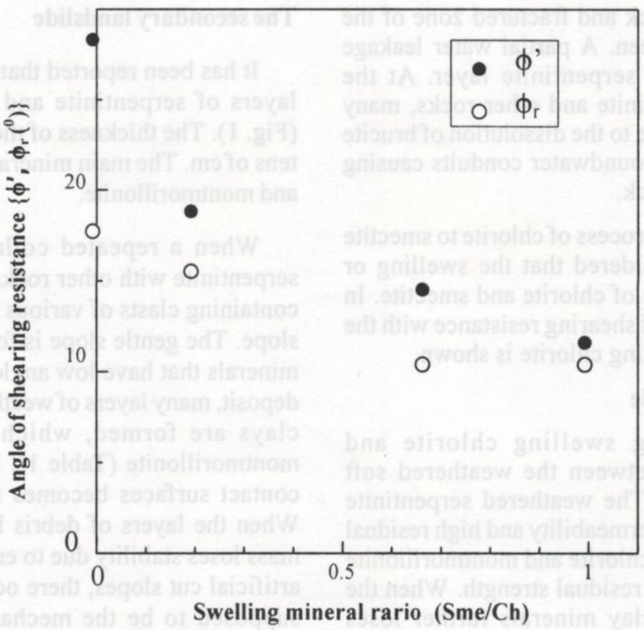


**Fig. 8: Angle of shearing resistance and swelling mineral ratio**

## CONCLUSIONS

Many landslides exist at the boundary between serpentinite and metamorphic basic rocks (i.e., greenschist and sedimentary black schist). In acidic solutions, Mg from serpentinite shows strikingly higher leaching value than that from other rocks like greenschist and black schist, whereas Fe from serpentinite shows prominently lower value than the other rocks. Serpentinite consists basically of some lumps of magnetite with serpentine and some veins of brucite with chrysotile. It is supposed to have formed from upper mantle matters and sea water on the deep sea floor by sudden eruption or cracking of ocean crust. It is frequently associated with basic and sedimentary rocks.

Slip surface soils at the "serpentinite landslide" sites frequently consist of serpentine, talc, chlorite, and montmorillonite. Serpentine has a higher angle of shearing resistance (about 30°), whereas talc, chlorite, and montmorillonite have lower angles (about 20° to 10°), and the decrease from peak strength to residual strength is large.

Brucite is easily soluble in water, whereas magnetite is not. For this reason, formation of many pores in the weathered serpentinite mass at its boundary with other rocks takes place, which act like groundwater conduits. This process causes weathering of other rocks, too. In this process, chlorite changes into smectite, and some layers of chlorite change into swelling or expansive chlorite layers. As a result, different clay layers make up the landslide slip surface. A loss of strength by these clay layers leads to sliding in the Serpentinite Zones.

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