A possible mechanism to explain reactivated landslides which begin to move in the early cold season

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Abstract

On gentle clayey slopes in weathered argillaceous rock areas, many landslides reactivate repeatedly with slow movement. From field data monitored at landslide sites in Japan, it has become clear that some landslides with a relatively shallow slip surface begin to move and become active in late autumn or early winter each year. In these cases, the triggering mechanisms of landslides have not yet been determined, because landslide initiation and movement do not always clearly link to rise in pore-water pressures (ground water levels). In this study, we focused on the influence of seasonal variation in ground temperature on slope stability, and investigated the effect of temperature on the shear strength of slip-surface soils. We performed ring-shear and box-shear experiments on slip-surface soils from two landslides in low temperature ranges. Experimental results showed that shear strength decreased with decreasing temperature. These data indicate that if slip surface soils contain a high fraction of smectite, decrease in ground temperature can lead to lowered shear resistance at the slip surface and to the triggering of slow landslide movement.

Keywords: reactivated landslide, residual strength, temperature, smectite

1. Introduction

There are many reports describing slow-moving landslides that occur and reactivate on over-consolidated clayey slopes all over the world. In Niigata Prefecture, a well-known heavy snow area in Japan, landslides frequently occur on gentle slopes in areas of soft sedimentary rocks deposited in the Neogene period. Landslides in this area have been the subject of many research studies focused on their mechanisms, including the effects of snow cover and snowmelt on landslides. Slip-surface soils of these landslides are sometimes composed predominantly of the swelling (water absorbing) clay mineral (smectite) which is well known to exhibit an extremely low residual friction angle.

From field data monitored at landslide sites in this area, it has become clear that some landslides with relatively shallow slip surface, begin to move and become active in late autumn or early winter each year (e.g., Sato et al., 2004). In these cases, the triggering mechanisms of landslides remain unclear, because landslide initiation and movement do not always clearly link to rise in pore water pressures (ground water levels). In this study, we focus attention on the influence of seasonal variation in ground temperature on slope stability, and investigated the effect of temperature on the shear strength properties of slip-surface soils.

2. Outline of investigated sites

2.1 Localities and geological backgrounds

Two landslides, Sumikawa in Akita Prefecture, and Busuno in Niigata Prefecture, were investigated in this study (Fig.1). Sumikawa Landslide is located in a geothermal area near the active volcano, Mt. Akita-Yakeyama; therefore, the landslide area is composed of highly altered volcanic rocks and tuffaceous rocks influenced by intense hydrothermal activities. The size of the landslide is defined by its total slope length of 450 m, width of 20–40 m, and maximum depth of 8 m. Busuno Landslide is located in the Higashi-kubiki mountainous district, where Neogene mudstone and tuffaceous rocks are widely distributed. These near-surface rocks are exposed to strong weathering. This landslide has a total slope length of 400 m, width of 30–40 m, and average depth of 4–6 m.

Both landslides are located in heavy snow areas and have many common characteristics (i.e., slope angles, sizes, elongated planar shapes of the landslide body divided into some sub-blocks, smectite-rich slip-surface soils, landslide behavior, and groundwater conditions). The slope angles of both landslides are 10 ° for the middle and lower blocks of

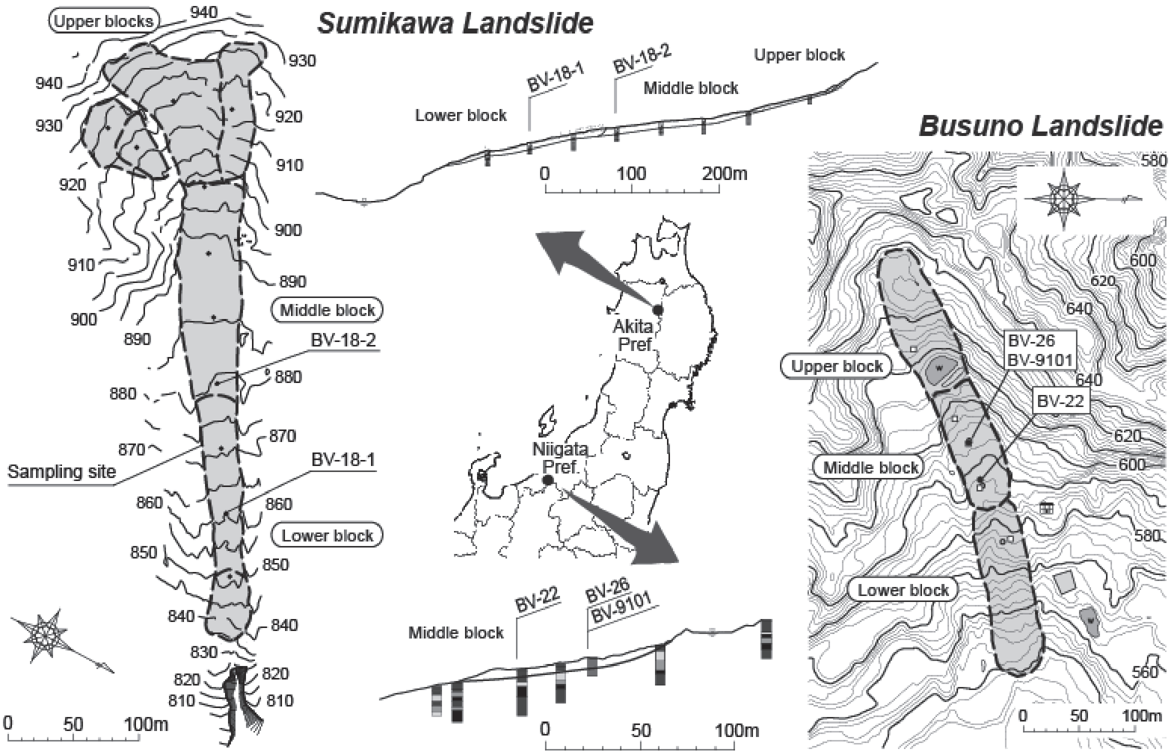


Fig.1 Map of investigation sites at the Sumikawa and Busuno Landslides

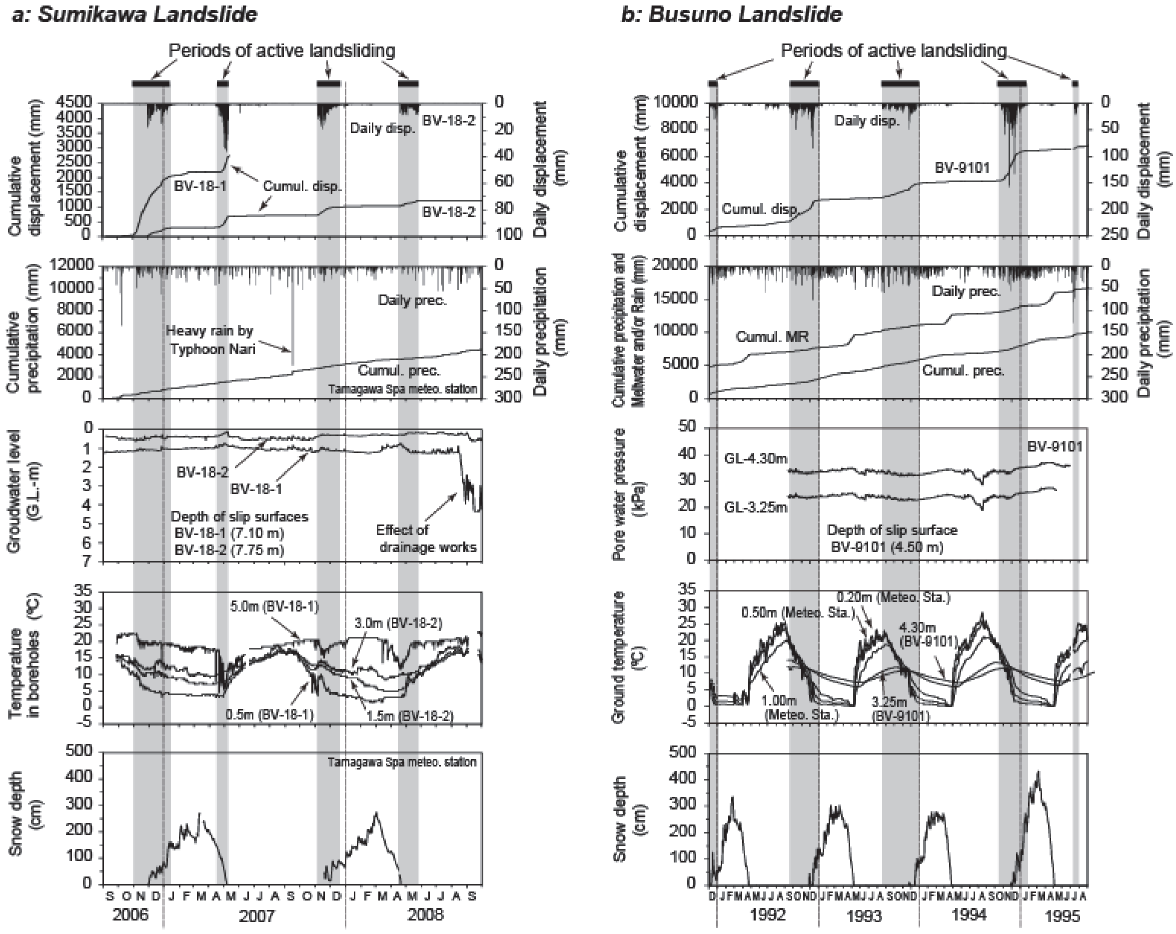


Fig.2 Behavior of the Sumikawa and Busuno Landslides

Sumikawa Landslide, and for the middle block of Busuno Landslide. The basement rocks are highly altered and weathered. The ground materials constituting the landslide bodies, are composed of strongly disturbed, weathered rocks and soils. Throughout the year, groundwater levels are constantly high and fluctuate slightly within the near-surface ground. In these landslides, smectite is the predominant clay mineral. Therefore, the slope stability and behavior of the two landslides, were strongly affected by the residual strength properties of smectite-rich slip surface soils.

2.2 Landslide behavior and hypothesized landslide mechanism

Fig.2a shows the behavior of Sumikawa Landslide over two years (Sep. 2006 to Sep. 2008). This landslide became active during late autumn and early winter, and also reactivated during the snowmelt period. In this landslide, groundwater levels are constantly high throughout the year. Annual fluctuation in groundwater levels is small. It is not clear whether landslide movement is regulated by a rise in pore-water pressures. Landslide displacement was not confirmed during extremely-heavy rainfall in a summer typhoon.

The behavior of the Busuno Landslide and the meteorological properties around the landslide site have been investigated in detail since the late 1980's (Matsuura et al., 2003, 2009). Field data revealed that this landslide became particularly active during late autumn and early winter each year, as did the Sumikawa Landslide. Landslide movement became negligible during the heavy snow season and did not reactivate during the snowmelt period (Fig.2b). Matsuura et al. (2009) reported that landslide velocities are slow and well correlated with pore-water pressures during early winter. On the other hand, long-term monitoring over four years (from Dec. 1991 to Aug. 1995) suggests that remarkable increases in pore-water pressures and cumulative precipitation were not observed during the periods of active landsliding.

The behavior in these two cases raises the question of why these landslides show vigorous movement specifically in the early cold season. Similar behavioral patterns were reported for many landslides in Niigata Prefecture by Sato et al. (2004). Many slow-moving landslides that activate in the early cold season are quite shallow, sometimes less than 10 m in depth. The near-surface ground is susceptible to seasonal variations in temperature. Monitor data for the two landslides shown in Fig.2 also suggest that landslides became active during the period when the temperatures of near surface ground drastically decreased. We then hypothesized that changes in ground temperature could affect the slope stability.

3. Methods

3.1 Test samples

We collected slip-surface soil from two landslides. At the Sumikawa Landslide, a 'slickenside' slip surface was observed on the sidewall of the lower block (Photo.1). We collected a disturbed soil sample for a ring shear experiment. At the Busuno Landslide, we collected undisturbed slip-surface soils by boring at two spots (BV-22, BV-26) in the middle block (Photo.2). The drill-core samples used for the box-shear experiments were carefully obtained using a rotary double-tube sampler with sleeve, following the method of JGS Standard 1224. Analysis of the slip-surface soils provided data on their basic soil properties (i.e., natural water content, consistency index, grain size distribution, mineralogical composition, cation exchange capacity (CEC), and exchangeable cations).

Photo.1 Slip-surface observed at the side-wall of Sumikawa Landslide

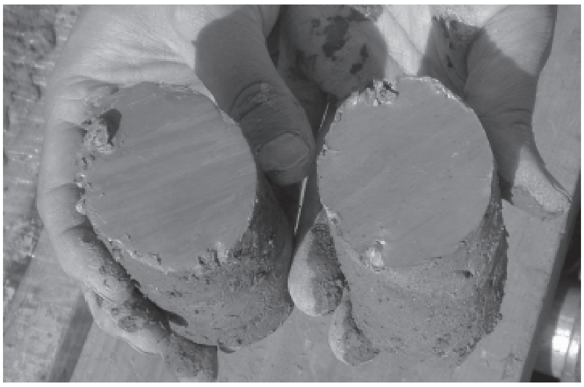


Photo.2 Slickensided slip-surface of a drill-core collected from the middle block of Busuno Landslide

3.2 Ring shear test

In this study, we conducted temperature-change experiments (cooling-event tests) on a reconstituted soil sample from Sumikawa Landslide under the residual strength condition. We used the conventional ring-shear apparatus. The machinery of this apparatus is fundamentally similar to that developed by Bishop et al. (1971). The size of the test specimens used in the apparatus was 15 cm and 10 cm, in outer and inner diameter, respectively. A normal load is applied through a pneumatic system, and normal stress acting on the test samples is evaluated by deducting side friction between the upper confining ring, and the test specimen. During the shear tests, the gap between the upper and the lower confining rings was kept slightly open to avoid ring-to-ring friction.

3.3 Reversal box shear test

We investigated the effect of temperature on shear strength of an undisturbed slip-surface soil. Box shear experiments were conducted on a soil sample collected from the Busuno Landslide. The shear apparatus used in this study was designed for reversal (cyclic) shear test for applying a large displacement to the test specimen, and for measuring the residual strength of soils. Both the shear displacement-controlled test and shear stress-controlled test (creep test) are available with this apparatus. Normal stress acting on the test sample is measured directly by a load cell located above the shear box. Normal load on the tested sample is maintained by a computer-controlled feedback system using a servomotor. The servomotor-controlled shear system also enables shear stress-controlled experiments. In this study, a slickensided slip-surface within the test specimen was coincided with the shear plane of the shear box, and shear displacement was applied precisely along the localized slip surface, following the method of Mayumi et al. (2003).

3.4 Viscosity test

To understand better the detailed temperature-dependent soil properties, we investigated viscosities of clay suspensions with varying water contents. Using Marsh Funnel viscometer, we conducted viscosity tests on clay suspensions of smectite-rich soils (bentonites) and kaolin clay. This apparatus is a simple device for measuring viscosity by observing the time that a 500ml volume of liquid flow from a cone through a short tube.

4. Results and discussions

The soil properties of the slip-surface soils from the two landslides are shown in Table.1. In general, clayey soils in natural conditions generally contain some amount of water. The natural water content of the slip-surface soils at the two landslides are in the range of 35-60 %. Both soils showed high-plasticity properties (75 < WL < 136, 46 < IP < 85) and contain high fractions of smectite (Fig.3). Exchangeable cations indicate that Ca-type and Mg-type smectite are predominant at the Sumikawa Landslide, whereas Ca-type and Na-type smectite are predominant at the Busuno Landslide.

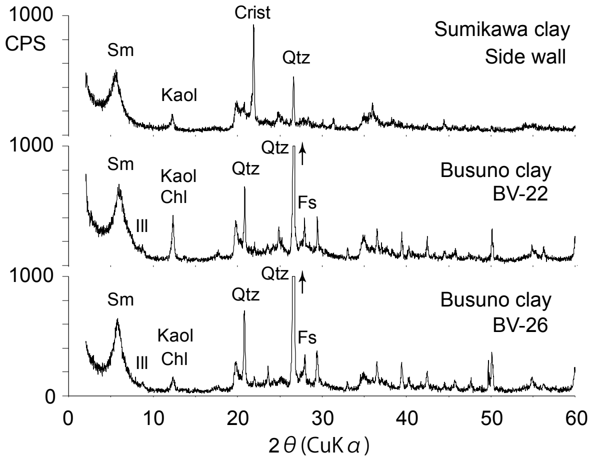


Fig.3. XRD patterns of slip-surface soils

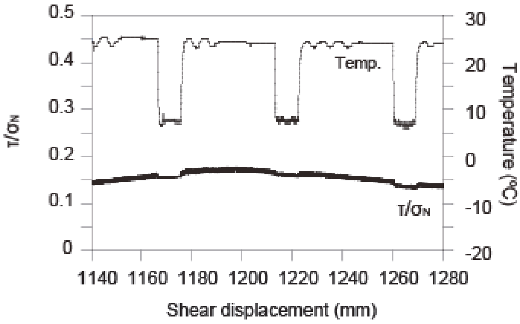
Fig.4 shows the result of ring-shear experiment performed on slip-surface soil from Sumikawa Landslide. Cooling-event tests were conducted at the shear rates of 0.005 mm/min and 0.02 mm/min. In an experiment at 0.005 mm/min, shear strength slightly decreased with decreasing temperature (Fig.4a). On the other hand, temperature-dependent shear behavior was not recognized at 0.02 mm/min (Fig.4b), suggesting that shear weakening with decreasing temperature is typical under a slow shearing-rate condition.

In addition, shear behavior also changed in accordance with temperature. The plotted line of the frictional coefficient, τ/σ_N, at the shearing rate of 0.005 mm/min, notably showed that small stress fluctuations (stick-slip behaviors) occur at room temperature. In contrast, no stress fluctuation was

Table.1 Soil properties of slip-surface soils

Sample		Depth (G.L.-m)	Water content (%)	Grain Size distribution			Consistency index			CEC	Exchangeable cations			
				Clay	Silt (%)	Sand	WL (%)	WP (%)	IP	(cmol/kg)	Na^+	K^+ (cmol/kg)	Ca^{2+}	Mg^{2+}
Sumikawa	Side wall	0	60.3	61	34	5	135.7	63.4	72.3	19.6	0.6	0.3	2.4	2.7
Busuno	BV-22	4.61	35.8	60	32	7	76.0	29.2	46.8	34.7	9.3	0.7	19.9	2.1
	BV-26	4.72	56.6	100	-	-	125.8	41.1	84.7	28.0	7.3	0.5	16.9	1.8

a Shearing rate: 0.005 mm/min



b Shearing rate: 0.02 mm/min

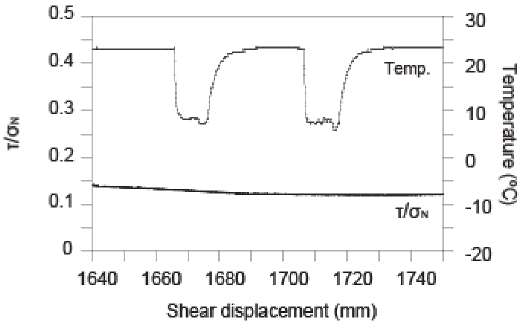


Fig.4 Temperature-change ring shear experiments on Sumikawa Landslide soil (σ_N=200kPa)

observed and stable-sliding behavior prevailed during cooling-event tests.

Box shear experiments were performed on undisturbed slip-surface soil collected from Site BV-22 of the Busuno Landslide. To confirm steady-state (residual) shear-strength condition before the cooling-event tests, two cycles of reversal shear tests, with the maximum displacement of 7 mm for both forward and backward shearing directions, were conducted. A total displacement of 56 mm was applied to the test specimen at the normal stress of 25 kPa and shearing rate of 0.05 mm/min. Cooling-event tests were subsequently performed under four different normal stresses at the shearing rate of 0.005 mm/min. Fig.5 shows the results of a box shear experiment at the normal stress of 100 kPa. Shear strength drastically decreased with decreasing temperature. Shear strength envelopes for two temperature conditions (Fig.6) show that the frictional angle decreased with decreasing temperature from 8.9º at 25 ºC to 7.7º at 9 ºC. The impact of cooling on cohesion was small.

We further conducted a shear stress-controlled experiment (creep test) on the same test specimen (Fig. 7). After the shear displacement-controlled test, shear stress was held constant at a slightly lower level than the steady-state shear strength. The cooling-event test was then started. Several minutes after cooling, shear displacement suddenly initiated and slow-speed displacement, up to 0.015 mm/min, continued while conditions were cool. Shear displacement gradually decelerated with increasing temperature and finally stopped at room temperature. We did cooling-event tests three times to confirm the reproducibility of this phenomenon. If this behavior can be applied to the field, it indicates that slow-

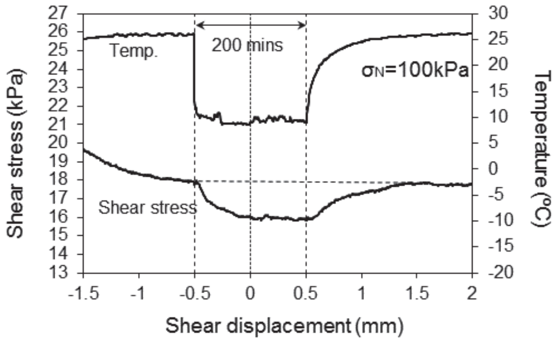


Fig.5 Temperature-change box shear experiments performed on the undisturbed slip-surface soil from Busuno Landslide (Shear rate: 0.005 mm/min).

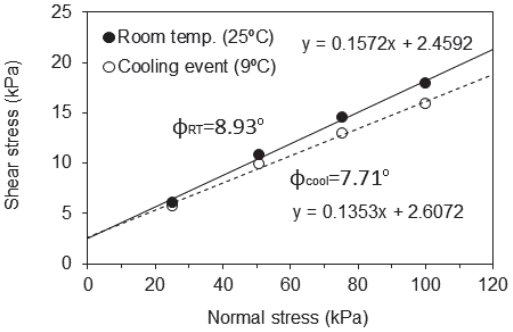


Fig.6 Shear strength envelopes of undisturbed slip-surface soil from Busuno Landslide under two temperature conditions

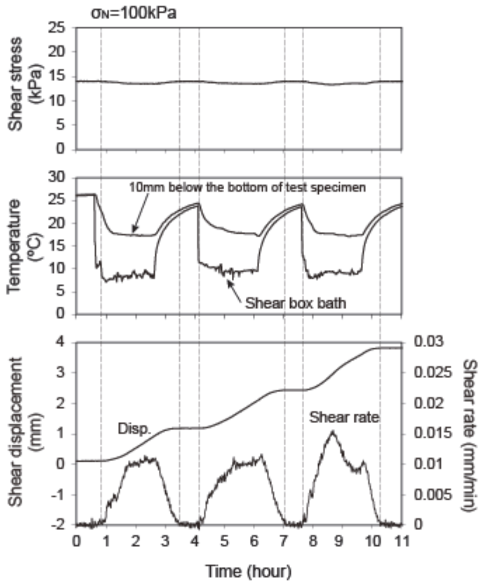


Fig.7 Shear stress-controlled box-shear experiment performed on an undisturbed slip-surface soil from Busuno Landslide

moving landslides can be triggered repeatedly during any season when the ground temperature decreases.

Ring-shear and box-shear experiments revealed that the residual strength of smectite-rich slip-surface soils strongly depends on temperature. To understand better the soil properties of smectite-rich soils, we investigated the effect of temperature on viscosity of clay suspensions. Fig.8 shows the results of funnel viscosity tests on two bentonites and kaolin clay with varying water content. Test results showed that the viscosity of the Na-type bentonite suspension strongly depends on temperature. A Ca-type bentonite suspension with 5-times as much water as bentonite (Wn=500%), showed slightly stronger temperature-dependent viscosity than did a kaolin suspension with the same water content. This indicates that the rheological properties of smectite suspensions are very responsive to temperature. Although further research is needed, these rheological properties appear promising for understanding the mechanism of temperature-dependent residual strength characteristics of smectite-rich soils.

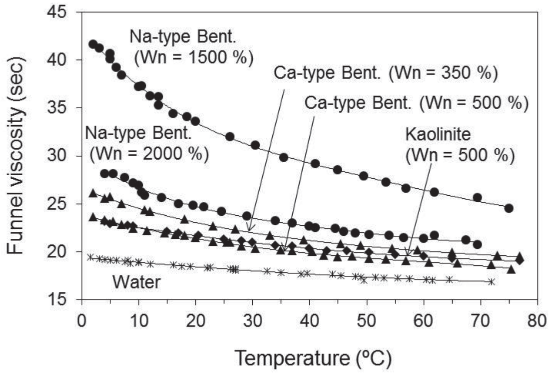


Fig.8 Funnel viscosities of clay suspensions

5. Conclusions

Results of temperature-change ring-shear and box-shear experiments showed that the shear strength of smectite-rich slip-surface soils decreased with decreasing temperature. Our results indicate that if slip surface soils contain a high fraction of smectite, decrease in ground temperature can lead to lowered shear resistance of slip surface, and to triggering of slow landslide movement. Except for earthquake-induced landslides, most landslides are induced by rise in pore-water pressure during rainfall and snowmelt seasons. Our findings newly raise the possibility that ground temperature influences slope stability. This means that monitoring ground temperatures as well as pore-water pressure is important for predicting landslides, especially for shallow landslides having smectite-rich slip-surface soils.

Smectite shows an extremely low residual frictional angle; therefore, landslides having such slip-surface soils can easily become unstable, and are likely to reactivate even on very gentle slopes. In Japan, reactivated-type landslides frequently occur in the areas of soft sedimentary rocks of Neogene and Paleogene Periods. As for the Sumikawa Landslide reported in this paper, many other landslides occur in geothermal areas around active volcanoes. In such areas, smectite is widely distributed due to hydrothermal alteration of host rocks, and the ground temperature condition strongly relates with geothermal activities. In consideration of the long-term stability of such landslides, it is also important to pay attention to ground temperature. This paper mainly focused on soil behaviors in a relatively low temperature range (5–25 °C). Shear behavior under higher temperature conditions, and the effect of drained conditions during heating and cooling, have not yet been determined. In order to elucidate fully the mechanism of such landslides, further research, involving both laboratory experiments and field monitoring, is required.

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