

Influences of the snow cover on landslide displacement in winter period: a case study in a heavy snowfall area of Japan

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Abstract The displacement of a relatively small reactivated landslide in a snowy area in Japan was monitored over a long period. The displacement rate of the landslide, which was approximately of 20 mm d^{-1} before the formation of snow cover, decelerated drastically during the continuous snow cover period every winter period. Possible causes included reduction in the amount of water that reached the ground surface (MR: meltwater and/or rainwater) and increase in snow load. Given that the actual displacement of the landslide was far below the predicted value based on the relationship between landslide displacement and MR immediately before the continuous snow cover period, the deceleration of landslide displacement was more likely attributable to the increase in snow load than to the reduction in MR. An investigation of the link between snow load and landslide displacement showed a negative logarithmic relationship. A dynamic analysis based on the limit equilibrium method showed that snow load increases the effective normal stress and the stability of a landslide in which the mean inclination angle of the slip surface is smaller than the internal friction angle. The stability of the actual slope was also analyzed by conducting soil tests on samples collected at the site and using the resultant parameters. The analysis also showed that the increase in snow load increases the safety factor and

reduces the landslide displacement. The displacement of a relatively small landslide that has a shallow slip surface was found to be greatly influenced by snow cover.

Keywords Snow load · Landslide displacement property · Stability analysis · Effective normal stress · Reactivated landslide

Introduction

Poorly consolidated alternating strata of Neogene sandstone and mudstone are distributed along the coast of the Sea of Japan, forming a landslide-prone area. Snowfall in this region is among the heaviest in the world and is considered a major cause of landslides (Kumagai 1985).

In general, snow cover supplies water to landslide and also acts as snow load, affecting the displacement of landslides. The supply of meltwater in particular is closely related to the occurrence of landslides, as supported by statistics: a high percentage of landslides occur during the snowmelt season (Aoyama et al. 1984).

However, few thorough investigations have been conducted on the effects of snow load on landslides. This is mainly due to the lack of available data on snow cover, such as snow depth and water equivalent of snow, and the difficult task of monitoring landslide displacement in winter. Developments in automatic monitoring technologies for the last two decades have made it easier to conduct monitoring. Landslides in snowy regions were found to occur in many forms (Sato et al. 2004), and the possibility of snow load affecting landslide displacement has also been proposed (Matsuura et al. 2003; Okamoto et al. 2008; Shibasaki et al. 2008).

The present study set out to clarify the influences of snow load on landslide displacement by investigating the

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monitored snow data and displacement of a landslide in a heavy snowfall area. Simplified dynamic analyses and stability analyses were also conducted by using a model of the actual slope and applying snow loads.

Study slope and monitoring method

The data used for analysis were monitored at a reactivated landslide having a width of about 50 m, length of about 300 m and relatively shallow slip surface of 5–7 m (Fig. 1). This landslide is composed of four blocks, that is to say, upper, middle, lower and toe. Although the upper block was stable, continuous displacement at both middle and lower block was observed. The landslide was located in a mountainous zone facing the Sea of Japan, where many landslides have occurred in the past and deep snow accumulates in winter. Annual precipitation in this area is approximately 3000 mm, about half of which is in the form of snow. Snow cover as deep as 3–4 m is observed in average years and exceeds 5 m in years of heavy snow (Matsuura et al. 2005). The ground is not frozen since the ground is covered with deep snow during every winter period. The snow covering period is the period from the day when snow was observed to the day when snow disappeared. Continuous snow cover period means the period during which snow accumulated continuously for more than 30 days. We use these two terms defined by Japan Meteorological Agency in this paper.

Displacement of the landslide was monitored by using borehole displacement gauges, and pore-water pressure was monitored by installing a piezometer directly in the borehole. Two lysimeters were installed at the meteorological station to monitor the amount of water that reached the ground surface (MR: meltwater and/or rainwater) during the snow cover period. Water observed by the lysimeters is rainwater when there is no snow cover, and meltwater when there is snow cover. When it rains on the snowpack, water that reaches the ground surface never consists of rainwater alone, but is always a mixture of rainwater and meltwater. Snow cover depth was monitored using ultrasonic snow depth gauges, and the water equivalent of snow, that is to say snow load was monitored using metal wafers, consisting of stainless steel containers filled with antifreeze fluid (Fig. 2).

Relationship between landslide displacement and individual factors based on monitored data

Monitored landslide displacement

Figure 3 plots the monitored landslide displacement data of two borehole displacement gauges from December 7, 1990,

to July 1, 1998. For each year, the largest displacement was observed in October to December before the continuous snow cover period, and displacement dropped sharply after the continuous snow cover formed.

There are two possible factors: reduction in MR and increase in snow load. In snowy areas, snow cover forms on the ground surface when the precipitation changes from a liquid to solid phase. The snow cover melts from the heat in the air and solar radiation, and meltwater reaches the ground surface at various timings and intensities. At the beginning of the (continuous) snow cover period, there is considerable melting due to high air temperature and heat flow in the ground. In midwinter, the amount of water that reaches the ground (MR) decreases because the surface snowmelt decreases and the percentage of solid precipitation increases. Generally speaking, the MR causes a decrease in the effective stress accompanying a rise in the pore-water pressure, resulting in landslide displacement. Therefore, reduction in the MR is considered to suppress landslide displacement.

On the other hand, the snow cover at the beginning of the (continuous) snow cover period is light and has a low specific gravity. Repeated snowfall and snow consolidation increase the specific gravity and weight of the snow cover. Snow accumulates to 3–5 m deep in the area monitored, which results in a snow load exceeding 15 kN m^{-2} acting on the landslide. Such a large snow load may possibly increase the effective stress and stabilize the landslide under certain conditions.

To identify the factors controlling landslide displacement at the beginning of the continuous snow cover period to midwinter, thorough investigation is needed to determine whether the deceleration in displacement is attributable to the reduction in MR or the increase in snow load.

Relationship between MR and landslide displacement

Landslide displacement during the continuous snow cover period was calculated from the relationship between MR and landslide displacement before the continuous snow cover period. Agreement between the calculated and monitored values would suggest that the deceleration of displacement was attributable to the reduction in MR, and disagreement would indicate a large influence of the snow load.

Attempts have been made to calculate the relationship between MR (rainfall) and landslide displacement by using lumped and distributed models (Dehn et al. 2000; Kamihara 2002). In the present study, landslide displacement during the continuous snow cover period was estimated from the relationship between effective MR (EMR) and

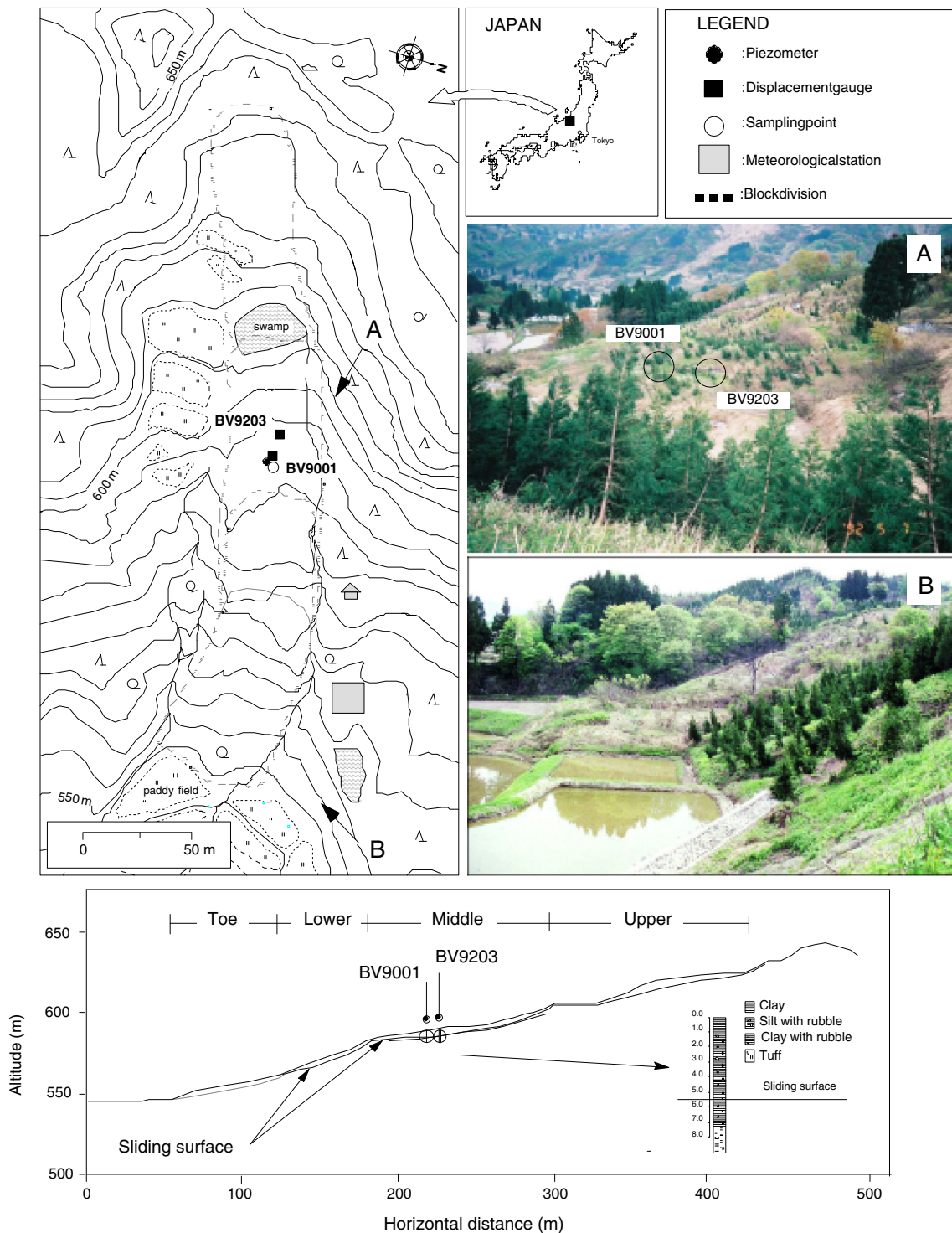


Fig. 1 Overview of the investigated landslide

landslide displacement. EMR is a method of estimating the present groundwater content from the timing and intensity of the antecedent MR (Chow 1964) and is closely related to groundwater level and landslide displacement (Matsuura et al. 2003). The concept is that a single day's EMR is determined by the cumulative antecedent EMR, but the

influence decreases as the time difference relative to the present day increases. For example, when the half-life is set to 5 days, the EMR for a particular day is calculated by integrating the values obtained by multiplying the MR of that day by 0.871, the MR of the previous day by 0.759, the MR of 5 days ago by 0.5, and so on. However, unlike

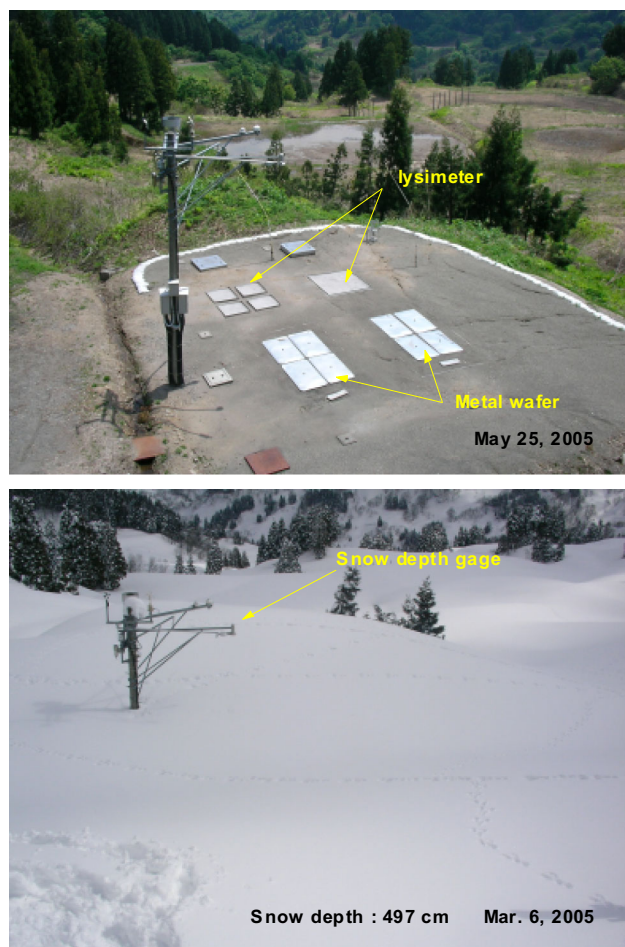


Fig. 2 Overview of the meteorological station

physical models, the method cannot explain the infiltration process of MR and the resultant rise in pore-water pressure.

It has been shown that EMR is significantly related to the displacement of reactivated landslides in fracture or tertiary zones and is useful for predicting short-term displacement (Matsuura et al. 2003). Here, the relationship between EMR and landslide displacement was investigated

by using the MR data for one month immediately before the continuous snow cover period from November 11 to December 10, 1992, when a large amount of displacement was observed (Fig. 3). The highest correlation was observed between EMR_{5d} , which has a half-life time of 5 days, and daily displacement (Fig. 4).

The method was used to calculate the landslide displacement for the period from the first day of snow (December 11) to March 25 when the maximum snow load was recorded. The resultant calculated displacement was far different from the actually monitored value (Fig. 5). The estimation, which used EMR_{5d} , calculated a cumulative displacement of about 920 mm during the 104 days until March 25, when the maximum snow load was recorded, but the actual cumulative displacement was only about 220 mm, less than a quarter of the estimated value.

During the coldest days of January 7 to 10, MR reached at least 20 mm d^{-1} due to rainfall, and on February 22, MR was 44 mm d^{-1} due to strong winds and rainfall. However, the monitored landslide displacement was only about 5 and 2 mm d^{-1} , respectively. On the other hand, on December 3 and 8, when snow had not yet fallen, MR values of 41 and 49 mm d^{-1} were recorded, respectively, and the corresponding maximum displacement was 57 and 81 mm d^{-1} . Landslide displacement during the continuous snow cover period showed completely different characteristics.

Relationship between pore-water pressure and landslide displacement

The daily changes in pore-water pressure and landslide displacement during the period are shown in Fig. 6. Before the continuous snow cover period, landslide displacement responded sharply to a pore-water pressure change as small as 1 kPa or smaller. On December 9, immediately before the formation of continuous snow cover on the ground, a large displacement of 80.9 mm d^{-1} was recorded. For a while after the continuous snow cover had formed, landslide

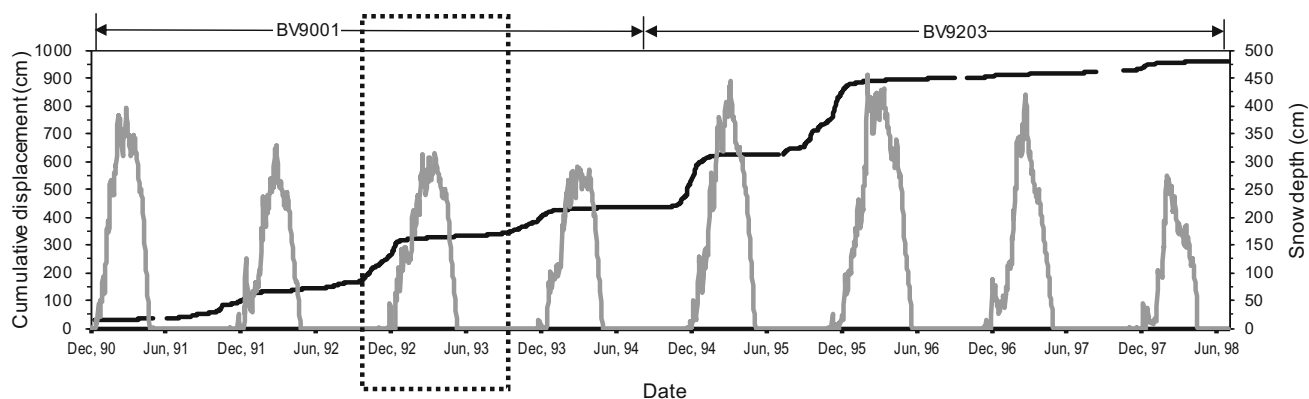


Fig. 3 Relationship between snow depth and landslide displacement during the monitoring period

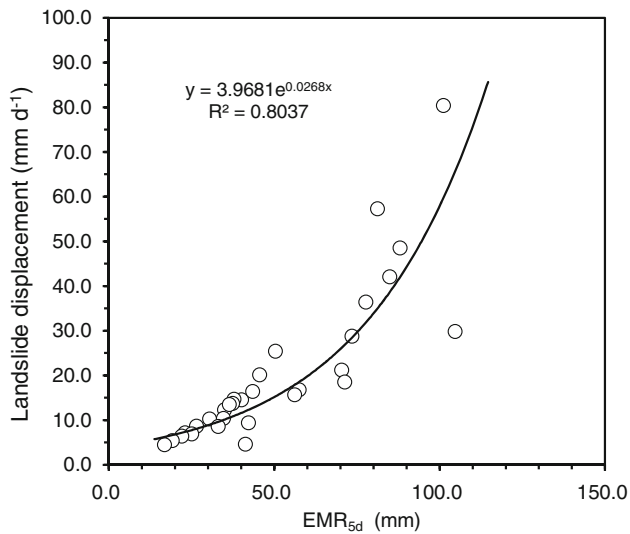


Fig. 4 Relationship between MR of a half-life of 5 days and landslide displacement

displacement responded slightly to the rise in pore-water pressure, but no notable displacement was recorded thereafter although pore-water pressure rose in response to MR.

The relationship between daily changes in pore-water pressure and landslide displacement was investigated. Before the continuous snow cover period, landslide displacement increased with the rise in pore-water pressure, showing a gentle exponential or power function. On the other hand, during the continuous snow cover period, no clear relationship was observed between the two (Fig. 7). Therefore, the relationship between pore-water pressure

Fig. 5 Landslide displacement during the snow cover period estimated based on the displacement data from before the continuous snow cover period and actual displacement

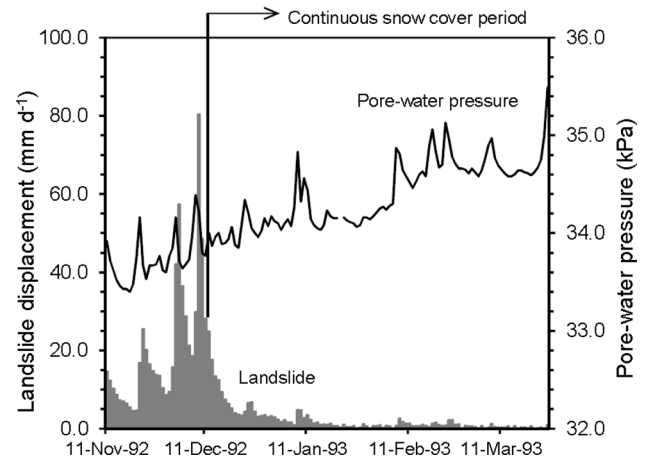
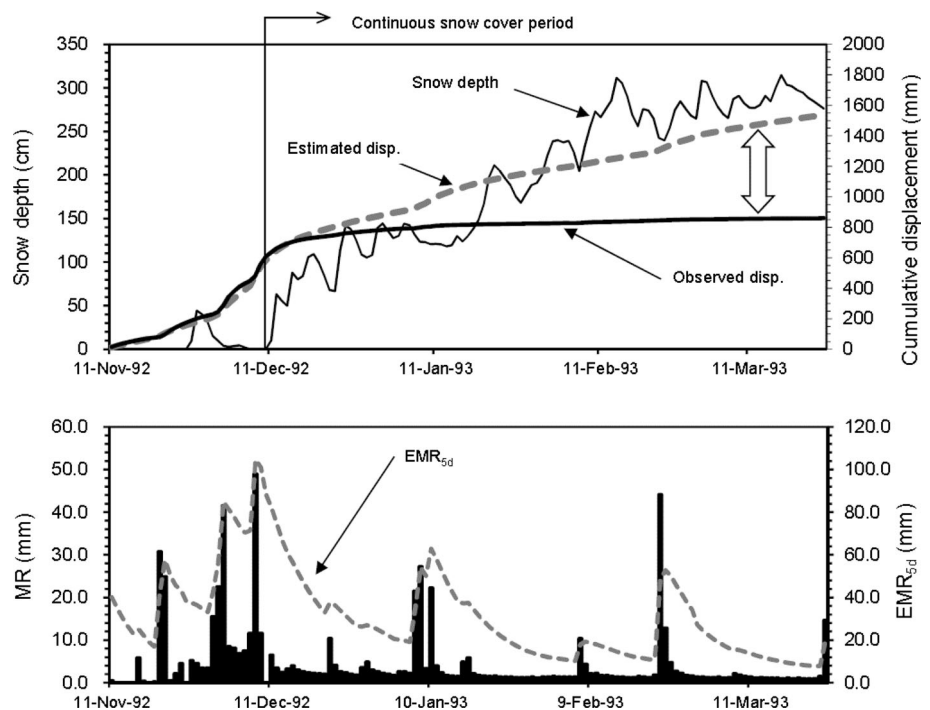


Fig. 6 Relationship between pore-water pressure and landslide displacement before and during the continuous snow cover period

and landslide displacement was completely different depending on whether it was before and during the continuous snow cover period. During the continuous snow cover period, one or more factors suppressed landslide displacement even with a rise in pore-water pressure.

Relationship between snow load and landslide displacement

The deceleration of landslide displacement during the continuous snow cover period was possibly attributable to the snow load. Figure 8 shows the changes in daily displacement and snow load. At the beginning of the

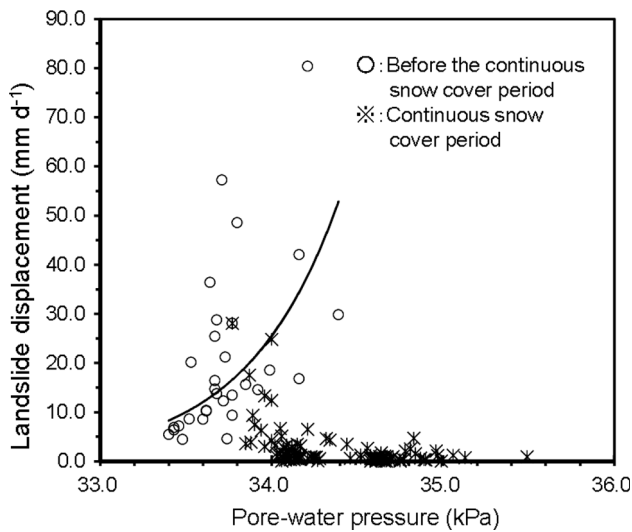


Fig. 7 Relationship between pore-water pressure and landslide displacement

continuous snow cover period, the snow depth changed sharply because the specific gravity of the snow was still small and the snow underwent rapid consolidation and settlement (Fig. 5). On the other hand, the snow load increased steadily during the continuous snow cover period although it fluctuated due to snowmelt at the surface and bottom of the snow cover. The largest snow load in this continuous snow cover period was 13.75 kN m^{-2} , which was recorded on March 25. As the snow load increased at the beginning of the continuous snow cover period, the displacement increased slightly, but as a whole, landslide displacement showed a decreasing trend.

To clarify the relationship between snow load and landslide displacement, the monitored displacement was plotted against the logarithm of the monitored snow load for the entire continuous snow cover period (Fig. 9). The plot shows that the displacement decelerated sharply until the snow load reached $5\text{--}8 \text{ kN m}^{-2}$. Therefore, the snow load suppressed the landslide displacement by means of increased normal stress increasing the effective normal stress, causing the resistance to the landslide driving force to reach equilibrium. However, even when the snow load exceeded 10 kN m^{-2} , the landslide displacement did not drop to 0, but instead remained at $0.1\text{--}1.0 \text{ mm d}^{-1}$.

Investigation of landslide stabilization dynamics by snow load

Limit equilibrium analysis

The long-term monitoring of landslide displacement showed that the displacement behavior during the snow

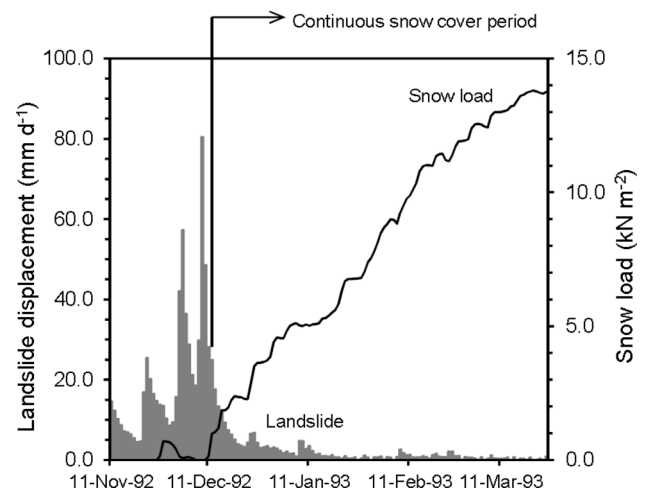


Fig. 8 Relationship between snow load and landslide displacement

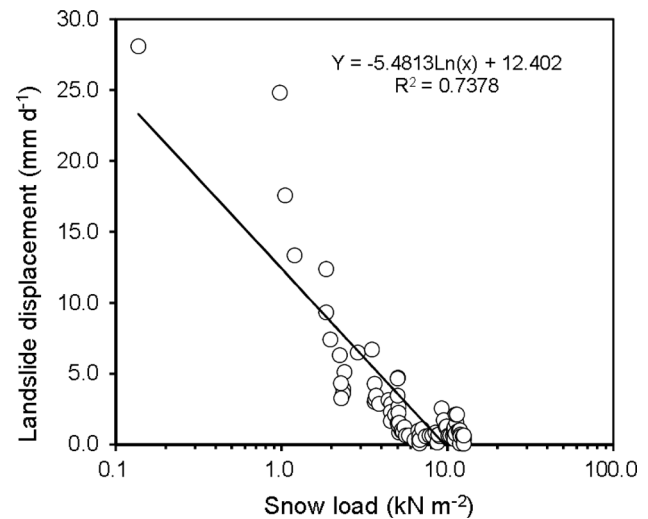


Fig. 9 Relationship between snow load and landslide displacement

cover period was completely different from when the ground was not covered by snow. A likely cause is the snow load. The influence of the snow load on the stability of the landslide was investigated using an equation for analyzing slope stability. To simplify the analysis, the Fellenius equation was used.

$$F = \frac{\sum\{c\ell + (W \cos \alpha - u\ell) \tan \phi\}}{\sum W \sin \alpha} \quad (1)$$

where c is cohesion, ϕ is internal friction angle, u is pore-water pressure, α is inclination angle of the slip surface, ℓ is the width of each slice, and W is weight of the landslide body. When $\{c\ell + (W \cos \alpha - u\ell) \tan \phi\} = R$ and $(W \sin \alpha) = D$, $F = R/D$.

By putting the safety factor for the snow weight of S as F_s ,

$$F_s = \frac{R + S \cos \alpha \tan \phi}{D + S \sin \alpha} \quad (2)$$

Therefore, the difference between the safety factor F_s under the snow cover and the safety factor F when there is no snow cover is given by

$$\begin{aligned}
 F_s - F &= \frac{R + S \cos \alpha \tan \phi - \frac{R}{D}}{DS \cos \alpha \tan \phi - RS \sin \alpha} \\
 &= \frac{D(D + S \sin \alpha)}{S(D \cos \alpha \tan \phi - R \sin \alpha)} \tag{3}
 \end{aligned}$$

where the denominator $D(D + S \sin \alpha) > 0$. Since $S > 0$, positive and negative are determined by the condition $(D \cos \alpha \tan \phi - R \sin \alpha)$. Dividing $(D \cos \alpha \tan \phi - R \sin \alpha)$ by $\cos \alpha$ gives $(D \tan \phi - R \tan \alpha)$.

Dividing this by D gives

$$\left(\tan \phi - \frac{R}{D} \tan \alpha \right).$$

Under the assumption $F_s - F > 0$, $\tan \phi > F \tan \alpha$. Since landslide displacement was observed, F was likely to be around 1.0. For the snow load to suppress landslide displacement, the internal friction angle $\tan \phi$ must be larger than the mean inclination $\tan \alpha$ of the slip surface.

In any landslide, displacement starts with the loss of dynamic balance due to a rise in pore-water pressure. During normal times when the landslide mass is stable and static, the internal friction angle is larger than the mean inclination angle of the slip surface.

The condition $F_s - F < 0$ signifies that the snow load may trigger displacement. In this case, $\tan \phi < F \tan \alpha$ or $F > \tan \phi / \tan \alpha$. Above the limit of $F = 1.0$, the snow cover destabilizes the landslide when $\tan \alpha > \tan \phi$. When F is sufficiently larger than 1.0, destabilization may occur at $\tan \alpha > \tan \phi$ when a large load acts on the steep surface or the load at the head increases due to uneven distribution of the snow load.

In this landslide, the increase in snow load caused a gradual decrease in displacement. Therefore, the internal friction angle $\tan \phi$ was likely to be larger than the mean inclination angle of the slip surface, and thus, the increase in snow load increased the shearing resistance of the landslide and increased the safety factor.

Results of soil test

For the stability analysis of the actual slope, specimens were sampled from the highly weathered layer that formed the slip surface, and both physical and mechanical soil tests were conducted. Specimen sampling was not done by the ordinary boring method because of the risk of discharging the clayey soil surrounding the gravel. Instead, the air-bubble boring method was used, which can sample a high

ratio of almost completely undisturbed core specimens. Sampling was conducted near Bore BV-9001 in the middle part of the middle block (Fig. 1).

Physical tests were conducted on core samples that consisted of weathered mudstone and were assumed to be part of the slip surface, and the grain size distribution and consistency properties were determined (Table 1). In most landslides of Neogene sediments, the clay content exceeds 50% near the slip surface. However, in the landslide studied, the slip surface contained large amounts of fine sand and gravel, and the clay content was only 44%. The consistency properties of the specimens showed clay soil with a high liquid limit (CH) that exceeded 50% and a plastic limit that was above curve A in the plasticity chart.

This is an active landslide that has shown significant displacement almost every year. In the case of a reactivated landslide, which has travelled a long distance, the ring shear test is the most appropriate test. Therefore, a ring shear test, where the remolded sample is normally used, was conducted to determine the residual strength near the slip surface. The test sample was prepared from the core specimen, and the coarse fraction was removed by passing the soil through a 425- μm sieve. It was then remixed and molded into a ring having an external diameter of 150 mm, inner diameter of 100 mm and thickness of 20 mm. The specimen was tested by applying normal loads of 200, 150, 100 and 50 kPa under consolidated drainage conditions and shearing speed of 0.02 mm m^{-1} . We have confirmed that the water content of the test specimen is not significantly different from the natural water content of the core specimen.

The properties of the specimen used in this ring shear test were $\omega_L = 70.1\%$ and $IP = 45.3\%$. According to Scheffler and Ullrich (1981), cohesive soils with similar characteristics are shown to have a constant residual strength at a shear rate of 0.0076–0.076 mm m^{-1} . In addition, Skempton (1985) and Stark and Eid (1994) adopt 0.01 and 0.018 mm m^{-1} as the shear speed, respectively. Furthermore, Suzuki et al. (2000) reported that the residual strength is stable with a kaolin clay at 0.05 mm m^{-1} or

Table 1 Soil parameters of the core samples

Parameters		
Liquid limit	ω_L (%)	70.1
Plastic limit	ω_P (%)	24.9
Plasticity index	IP (%)	45.3
Content ratio of grain size (<2 μm)	(%)	44.0
Cohesion	c' (kPa)	4.41
Internal friction angle	ϕ' ($^\circ$)	11.36
Wet unit weight	γ_t (kN m^{-3})	19.5
Saturated unit weight	γ_{sat} (kN m^{-3})	20.1

less. Based on the previous studies mentioned before, we set the shear speed to 0.02 mm m^{-1} .

The stress–strain curve obtained is shown in Fig. 10. The cohesion and internal friction angle were determined as $c_r' = 4.42 \text{ kPa}$ and $\phi_r' = 11.36^\circ$, respectively. Since the internal friction angle was larger than the mean inclination of the slip surface, which was about 9.5° , the snow load should have acted to increase the safety factor and suppress landslide displacement. The soil tests showed the suppressing effect of the snow load.

Stability analysis of the actual slope

The slope was modeled (Fig. 11), and a stability analysis based on the simplified Janbu method was conducted using the results of the soil tests. The slip surface was estimated from the results of a boring survey and the data monitored by the borehole displacement gauges. The ground water level was estimated based on the monitored pore-water pressure values. The parameters used for the stability analysis are shown in Table 1.

The stability was first calculated for no snow load by using $c_r' = 4.42 \text{ kPa}$ and $\phi_r' = 11.36^\circ$, which were obtained from the ring shear test. The resultant safety factor was $F_s = 1.17$, which meant sufficiently stable. After applying a snow load of 13.75 kN m^{-2} , which is equal to the maximum snow load, the safety factor increased by about 2% and became 1.19. The snow loads were estimated based on the results of a snow survey conducted using a snow sampler. This was because the internal friction angle was larger than the mean inclination, as discussed in the previous section.

Since the landslide continued moving even during the snow cover period, F_s should be 1.00 or smaller. By assuming that the safety factor was 0.998 at the time when the maximum snow load was recorded and ϕ_r' was always 11.36° , the cohesion c_r' was calculated backward, which gave $c_r' = 1.59 \text{ kPa}$. Using this cohesion value, the change in safety factor every 15 days during the continuous snow

cover period was calculated based on the monitored snow load values (Fig. 12). The calculation well reproduced the increase in safety factor by the increase in snow load.

On the other hand, the actual displacement rate of the landslide decelerated as the safety factor increased. In contrast to the research presented by Ishii et al. (2012), we believe that it is difficult to correlate the relationship between the safety factor, calculated using the limit equilibrium method (LEM), and the rate of landslide displacement. However, the displacement rate becomes 0 when the safety factor is greater than 1.0. In this paper, we attempt to clarify the relative effect of snow load on landslide stability.

When calculated using the aforementioned parameters of c_r' and ϕ_r' , a snow load of 13.75 kN m^{-2} increased the safety factor by at least 4%. Backward calculation of the snow load that would result in $F_s = 1.00$ gave 14.07 kN m^{-2} . However, even when a snow load of 16.20 kN m^{-2} was recorded in the winter of 1994/95, the landslide mass did not stop completely but continued to show displacement of 0.15 mm d^{-1} . Therefore, the actual internal friction angle is likely to be smaller than 11.36° .

Since the internal friction angle is directly related to the normal load (Eq. 1), the increase in effective normal stress must be considered when designing groundwater drainage works (Enokida 2001). The effect of snow load may be overestimated depending on the value of the internal friction angle. To investigate the effect of internal friction angle on the stability of the slope, the cohesion was calculated backward by assuming a safety factor of 0.998 on the day that recorded the maximum snow load and changing the internal friction angle from 12° to 8° . The parameters were then used to calculate the change in safety factor, which is shown in Fig. 13. Snow load should have a significant effect because the landslide displacement decelerated during the continuous snow cover period. However, the landslide did not stop moving even under large loads of $14\text{--}16 \text{ kN m}^{-2}$. Therefore, it is likely that the internal friction angle of the landslide investigated is smaller than the value obtained from the ring shear test and

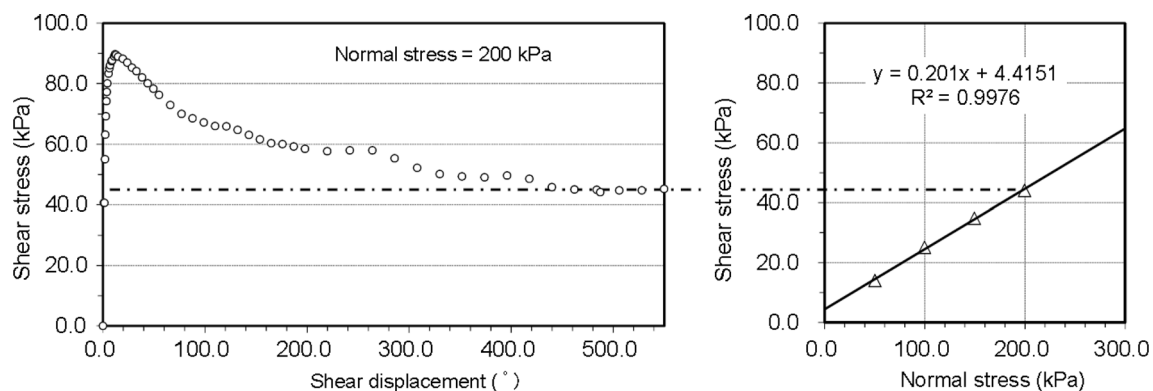


Fig. 10 Results of ring shear test

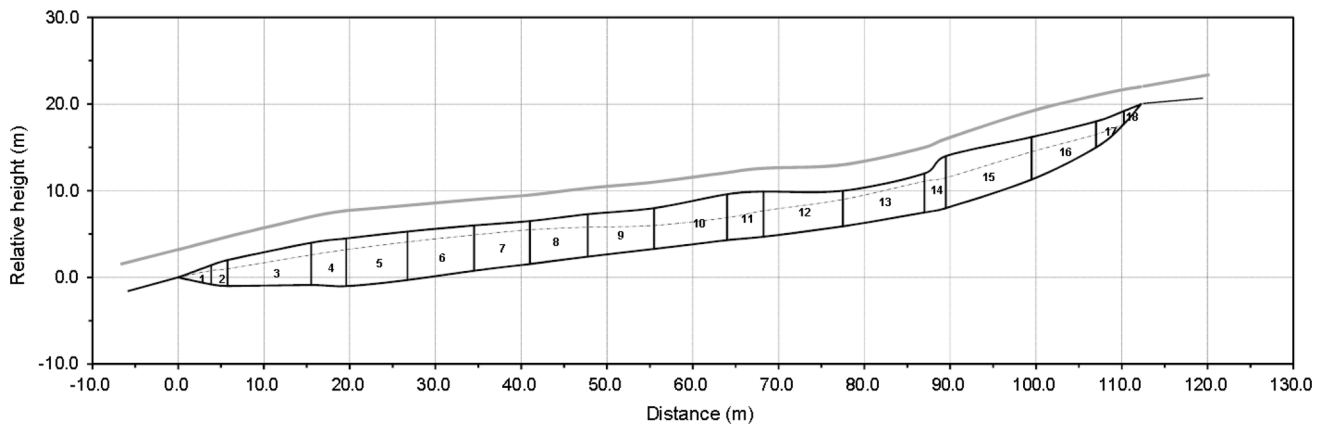


Fig. 11 Profile of the landslide analyzed for slope stability

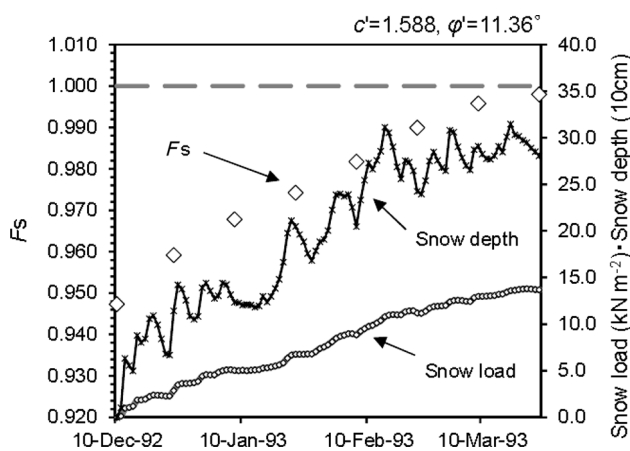


Fig. 12 Change in snow depth, snow load and safety factor

more similar to the mean inclination of the slip surface. The form of the slip surface in the landslide, which is flat rather than arc-shaped, could be one of the reasons why the displacement does not stop completely.

On the other hand, when a landslide experiences large displacement, the shear resistance drops to the residual strength, and the cohesion drops to 0 (Skempton 1985). The internal friction angle ϕ' was calculated for $c' = 0$ by assuming the safety factor during the maximum water equivalent of snow ($F_s = 0.998$), which resulted in 12.66° . However, this value overestimates the effects of the snow load and cannot explain why the landslide did not stop. The apparent cohesion was likely not zero because the ring shear test showed a cohesion value of 4.42 kPa and there should be an edge effect of the landslide. A three-dimensional stability analysis was thus required to assess accurately the edge effect of both the landslide body and the snow cover. An airborne laser survey seems necessary to acquire data on the spatial distribution of the snow cover.

Moreover, the landslide has a slip surface of 5–7 m, which is shallower than the common depth of landslide slip

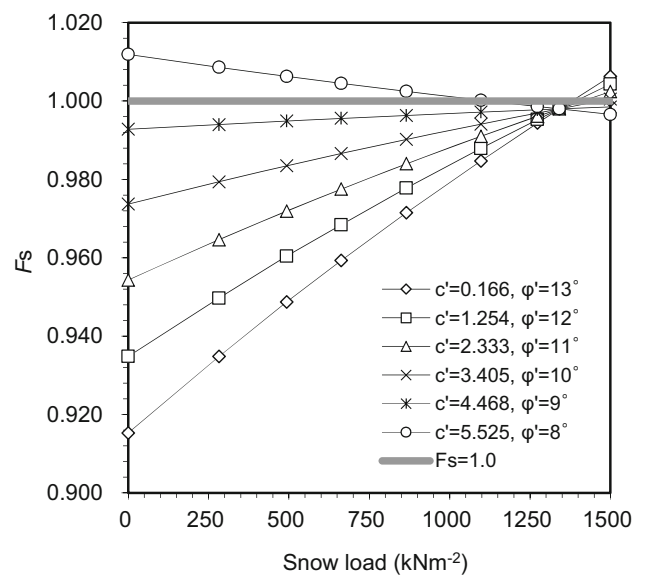


Fig. 13 Relationship between soil parameters and safety factor

surfaces in Japan, which is about 20 m. Therefore, when the mean two-dimensional cross section is considered, snow load has an effect of about 15–20% of the weight of the landslide in this landslide, whereas it is only several percentage points in average-scale landslides. Relatively small-scale landslides that have shallow slip surfaces are likely to receive strong effects from snow cover. On the other hand, landslides of average scale are more greatly affected by the rise in pore-water pressure during the snowmelt period than by the snow load.

Conclusions

The displacement of a reactivated landslide in a snowy region in Japan was monitored for a long period. The displacement dropped sharply during the continuous snow

cover period every year. There were two possible causes: (1) reduction in the amount of water that reached the ground surface (MR) and (2) increase in snow load. The investigation of factors showed that the drop in displacement was more highly attributable to the increase in snow load than to the reduction in MR.

Dynamic analysis based on the limit equilibrium method showed that the effect of the snow load depended on the strength and topographical characteristics of the slip surface. In other words, the increase in snow load increases the effective normal stress and stabilizes the landslide when the internal friction angle is larger than the mean inclination angle of the slip surface, or the internal friction angle is larger than the mean inclination angle of the slip surface in landslides that decelerate due to the increase in snow load. The investigated landslide decelerated as the snow load increased, and recorded the minimum displacement when the water equivalent of snow was the maximum.

A ring shear test of soil samples showed that the internal friction angle was larger than the mean inclination angle of the slip surface. A stability analysis that used the parameters also confirmed that the increase in snow load increased the dynamic stability of the landslide. Given that the landslide did not stop completely even when a snow load of about 16 kN m^{-2} was imposed, the actual internal friction angle was likely to have been similar to the mean inclination angle of the slip surface.

The study showed that a relatively small reactivated landslide is strongly affected by snow load. The size of the landslide is likely to be closely involved. Snow loads of $10\text{--}16 \text{ kN m}^{-2}$ are likely to increase the effective normal stress of relatively shallow landslides that have a slip surface of $5\text{--}7 \text{ m}$. On the other hand, the effects of snow load are smaller in larger landslides, in which the rise in pore-water pressure is likely to be a major cause of the reduction in effective normal stress.

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