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The response of pore water pressure to snow accumulation on a low-permeability clay landslide

Takashi Okamoto[a,*], Sumio Matsuura[b], Jan Otto Larsen[c], Shiho Asano[a], Kazutoki Abe[d]

[a] Forestry and Forest Products Research Institute, 1 Matsunosato, Tsukuba, Ibaraki 305–8687, Japan
[b] Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611–0011, Japan
[c] University Centre in Svalbard, P.O. Box 156, N-9171 Longyearbyen, Norway
[d] College of Bioresource Sciences, Nihon University, 1866 Kameino, Fujisawa, Kanagawa 252–0880, Japan

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ABSTRACT

A snowpack is known to affect landslide stability as the snow loading changes. Furthermore, the snowpack can have effects on the hydrological behavior in the landslide mass. To clarify the response of pore water pressure to snow loading, continuous field-based monitoring of hydraulic and meteorological factors in landslides was conducted for a deposit of extremely low-permeability "quick clay" in Mid-Norway. The pore water pressure increased during every snow-covered period. The pressure exhibited little response to meltwater and/or rain, but corresponded closely to changes in snow accumulation. The increase in pore water pressure during the snow-covered period was considered to be excess pore water pressure generated by undrained snow loading on the extremely low-permeability quick clay. The pore water pressure displayed a positive linear relation with the snow load, and the ratio of the increase in the pore water pressure to the snow load (ru_{snow}) was 0.49–0.53. These values show that approximately half of the snow load contributed to the excess pore water pressure. Continuous field-based monitoring was also conducted for another landslide in relatively high-permeability deposits in Japan, where the pore water pressure showed a relatively low ru_{snow} of about 0.15 and a different timing of the pressure peak. This comparative result indicates that the response characteristics of pore water pressure to the snow loading are strongly affected by the permeability of the landslide mass. Although the excess pore water pressure generated by the snow load theoretically had a negative effect on the slope stability, the value of excess pore water pressure at the monitored landslide was relatively too small to affect its stability.

1. Introduction

Landslides located in snowy regions are strongly affected by snow conditions as well as by rainfall. Snow influences landslide stability and movement in many different ways (Fig. 1); the most common trigger related to snow is snow melting (Fig. 1 (A)). Rapid snow melting caused by sudden warming or rainfall on snowpack is a major factor in landslide occurrence because of the resulting increase in pore water pressure at the sliding surface (Coe et al., 2003; Wieczorek, 1996). Cases of snowmelt-triggered landslides have been reported in snowy regions around the world (e.g., Chigira and Chiba, 1998; Gokceoglu et al., 2005; Naudet et al., 2008).

Snow loading is also a significant factor influencing slope stability (Fig. 1 (B)). When snow accumulates on a slope, the snow load generates both total stress (Fig. 1 (C)) and shear stress (Fig. 1 (D)). Nakamura and Shiraishi (1973) monitored landslide movement during snow-covered periods and observed an increase in landslide activity during the early snow-covered period. Matsuura et al. (2003) reported that a landslide became inactive with an increase in snow accumulation, based on their field monitoring at the Busuno landslide in Japan with a maximum snow depth of 5 m. Okamoto et al. (2008) analyzed infinite slope stability with the addition of a snow load term, and suggested that the snow load had both positive and negative effects on slope stability, depending on the gradient and internal friction angle of the sliding surface.

In contrast, several studies have reported the possibility that the snow load acts not only on the sliding surface, but also on the pore water pressure in the landslide mass (Fig. 1 (E)). Maruyama (1993) observed an increase in pore water pressure during mid-winter at the Sarukuyoji landslide in a heavy snow region in Japan. Matsuura (2000) observed similar fluctuations in pore water pressure during the same period at the Busuno landslide, Japan. Both studies suggested the possibility that the snow load generated excess pore water pressure. However, previous studies provided qualitative descriptions of

* Corresponding author.
E-mail addresses: okataka@ffpri.affrc.go.jp (T. Okamoto), matsu03@scs.dpri.kyoto-u.ac.jp (S. Matsuura), shiho03@ffpri.affrc.go.jp (S. Asano), kazuab@brs.nihon-u.ac.jp (K. Abe).

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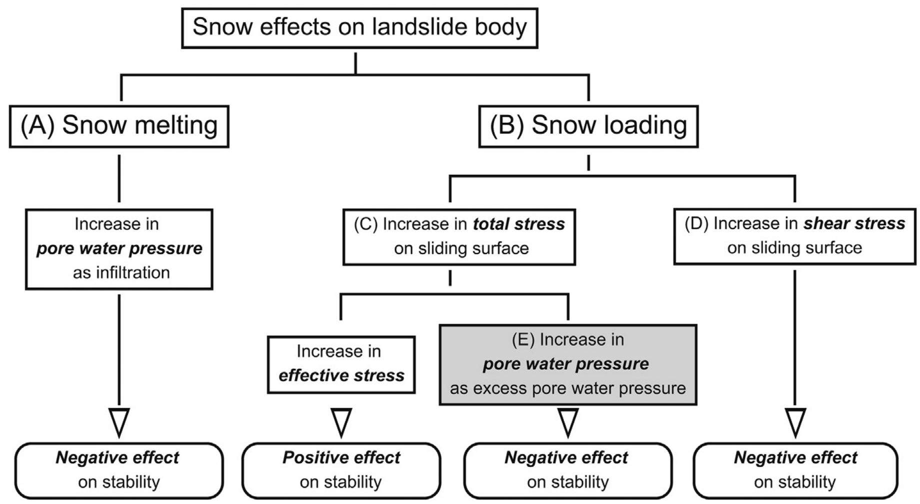

Fig. 1. Diagram of snow effects on landslide stability. The focus of this study is indicated by the shaded box.

observed cases, but did not address the fluctuations and response characteristics of pore water pressure. An increase in pore water pressure caused by the snow load had a negative effect on the slope stability. Assessment of the mechanism by which increased pore water pressure causes landslides is significant for landslide risk assessment in snow-covered regions.

We established a landslide research site in Norway, where there is a deposit of extremely low-permeability "quick clay", and have been conducting field-based monitoring of hydrological factors, including pore water pressure, at 15-min intervals since 1997 (Okamoto et al., 2004). From the monitored results, we detected an increase in pore water pressure in response to snow accumulation during a three-year period. The response was more obvious than that reported in previous studies. Here, we describe the detailed process of pore water pressure response to snow accumulation and discuss its response characteristics by comparison with other landslides with different geological backgrounds.

2. Research site

2.1. Quick clay

Quick clay is found mainly in Scandinavia and eastern Canada. This type of sediment is highly sensitive clay that was originally deposited in marine or brackish waters. The clay was subsequently elevated above sea level during the postglacial isostatic uplift. After its emergence, quick clay lost almost all interparticle forces because of leaching of pore-water salt from marine sediment by groundwater flow (Rosenqvist, 1953). Therefore, the skeletal structure can easily collapse as a result of changes in stress caused by landform alteration or construction activity; the quick clay then liquefies, which can cause serious clay slides (Geertsema et al., 2006; L'Heureux et al., 2012). Torrence (1996) defined quick clay as soil exhibiting sensitivity > 30 and remolded shear strength of < 0.5 kPa based on the falling-cone test (Rajasekaran and Narasimha Rao, 2004). Karlsrud et al. (1984) conducted an undrained triaxial compression test, and described the extremely fragile behavior of quick clay as follows: the peak resistance was reached at an axial strain of only 0.3% and the shear resistance was reduced to 50% of the peak strength with a strain of 3%. In contrast, Karlsrud et al. (1984) also reported for quick clay that the loss in shear resistance after the peak was reached was entirely related to an increase in pore pressure.

2.2. Roesgrenda landslide

We established a research site for landslide monitoring in Roesgrenda in Mid-Norway (latitude 63.5°N, longitude 11.5°E), 60 km northeast of Trondheim. A topographic map of the research site is provided in Fig. 2. The landslide area is on a slope along the Helgåa River at an altitude of 50–100 m above sea level [a.s.l.]. Although three relatively large-scale landslides (> 10,000 m^3 in volume) occurred in 1995 and 1996, only small- to medium-scale shallow landslides (< 3000 m^3 in volume and < 30 m in length) were found during our monitoring between 1997 and 2001 (Table 1). The landscape of the scarp is shown in Fig. 3. The slope of the scarp spreads out in a bowl shape with a steep inclination of 30–40°. At the bottom of the scarp is a gentle talus slope (10–20°) that was formed by deposition of collapsed soil. A geological profile of the site is shown in Fig. 4. The base rock is Paleozoic strata overlain by a 10-m-thick layer of moraine deposits, a 25- to 30-m-thick quick clay layer, and then a 10-m-thick layer of river deposits consisting of clay, silt, and gravel. The crown and upper flat area above the scarp are covered in coniferous forest. A brownish-red forest topsoil is found at the ground surface with a depth of < 0.5 m. The physical properties of the quick clay and river deposits in the site are listed in Table 2. The water content (w) of the quick clay is 25.1%, which exceeds its liquid index (w_L) of approximately 16% (Kristoffersen, 1999), indicating that the quick clay is in a fragile condition. The saturated hydraulic conductivity (K_{sat} [m/s]) of the quick clay was estimated to be 10^{-9} to 10^{-12} m/s (Larsen, 2002; Long, 2005), which is extremely low. The K_{sat} of the river deposits has not been measured; however, it is assumed to be greater than that of the quick clay because a small amount of groundwater is discharged from the thin sand layer within the river deposits. The K_{sat} value of the topsoil at the research site is not known; however, the K_{sat} values of forest topsoils are similar, independent of the geological characteristics, and are widely recognized to be approximately 10^{-3} to 10^{-5} m/s from laboratory permeability tests (e.g., Hayashi et al., 2006; Noguchi et al., 1997). These values are significantly larger than that of quick clay. Usually, snow falls from October to April, and the maximum snow depth is approximately 1 m. From 1988 to 2002, the mean annual temperature in Trondheim (Risvollan, 85 m [a.s.l.]) was 4.9 °C and the mean annual precipitation was 1003.5 mm/year (Thorolfsson, 2007).

3. Observations

In November 1997, we initiated continuous monitoring at the Roesgrenda landslide research site at 15-min intervals using an automated data collection system (Okamoto et al., 2004). Our targets were