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An early warning criterion for the prediction of snowmelt-induced soil slope failures in seasonally cold regions

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Abstract

In Hokkaido, Japan, soil slope failures occur frequently during the snow melting season. These slope failures are triggered by the excess amount of water derived from snowmelt and rainfall. For the prediction of snowmelt-induced soil slope failures in seasonally cold regions, an early warning criterion is required. The existing Japanese early warning criteria for sediment disasters, i.e., the relationship between the 60-min cumulative rainfall and the Soil Water Index (SWI), the effective rainfall index etc., consider the influence of rainfall and the time-dependent random moisture of the soil. However, these criteria do not consider the soil moisture contributed by the snowmelt water. In this study, therefore, the applicability of the existing early warning criteria to predict snowmelt-induced soil slope failures is examined. An empirical method to quantify the amount of snowmelt water is presented. Various scenarios of conceptual soil slope failures are studied using numerical simulations under different magnitudes of rainfall and snowmelt water. As a result, a revision is introduced for the SWI and the effective rainfall index, adding the amount of snowmelt water to that of rainfall, and slope failure scenarios are studied. Based on the results, a new early warning criterion, the Effective Precipitation (EP) index, is introduced. It is found that the new failure criterion performs well for the prediction of snowmelt-induced soil slope failures.

Keywords: Snowmelt water; Seasonally cold regions; Soil slope stability; Soil water index; Effective rainfall index; Early warning systems (IGC: E06/E09/E13)

1. Introduction

In seasonally cold regions, the climate effects, i.e., freeze–thaw action and snowmelt water infiltration, affect the moisture content of the soil (Ishikawa et al., 2015). The snowmelt water infiltrates into the soil ground over a long period. This results in a large amount of surface water which may trigger landslides and debris flows (Nakatsugawa et al., 2015). The stability of soil slopes in seasonally cold regions is very sensitive to the amount of snowmelt water, and this stability cannot be properly judged if the effect of the snowmelt is ignored (Siva Subramanian et al., 2017). Many studies have been done to standardise an early warning criterion to predict the oncoming slope disasters in snowy cold regions using metrological data, i.e., rainfall and snowmelt water, etc. (Okimura and Ichikawa, 1985; Berris and Harr, 1987; Singh et al., 1997; Williams et al., 1999; Matsuura, 1998, 2000; Matsuura et al., 2005, 2008, 2013; Nakatsugawa et al., 2015). According to many of the above-mentioned studies, the Japanese early warning criteria, i.e., the Soil Water Index (SWI), the effective rainfall (ER) index, etc.,

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need to be revised for the prediction of slope failures in seasonally cold regions. These criteria do not consider the soil water content supplied from snowmelt. Compared to the hourly rate of rainfall precipitation, the hourly rate of snowmelt water is relatively very small. However, the snowmelt process is continuous during the thawing season resulting in a constant supply of water to the soil surface. The indistinct infiltration behaviour of snowmelt water has been studied by many researchers (Komarov and Makarova, 1973; Matsuura, 1998; Ishida et al., 2000; Iwata et al., 2011). The snowmelt infiltration process is affected by many factors, such as soil temperature, soil freezing depth, the water content of the soil before winter and the depth of the snow cover (Iwata et al., 2011). Due to the presence of a thick snow cover, most of the soil ground beneath snow will experience a shallow freezing depth. Komarov and Makarova (1973) showed that a shallow freezing depth induces a large amount of snowmelt water infiltration. Matsuura (1998) compared the hourly rate of snowmelt water with rainfall precipitation over a mountainous region in Busuno, Japan, and found that the maximum hourly rate of snowmelt water was 15 mm/h. This maximum value of snowmelt water is much less than that of rainfall. Due to these facts, there is a possibility of the continuous infiltration of snowmelt water into the soil. As snowmelt water infiltration is continuous and its effects on soil slope instabilities are distinct, the above-mentioned criteria, SWI and ER, fail to predict the oncoming soil slope failures and debris flows due to the larger predetermined threshold for heavy rainfall. For these reasons, a method to quantify the hourly rate of snowmelt is necessary so that it can be incorporated into these early warning criteria. Based on this background, a criterion which can be used for the early warning of soil slope failures and debris flow disasters is proposed in this study. Two case studies of soil slope failures occurring in Hokkaido are studied. The applicability of the existing early warning systems is studied by applying those criteria to the case studies. An empirical method to estimate the hourly snowmelt rate is presented. A new early warning criterion to predict the snowmelt-induced soil slope failures in seasonally cold regions is introduced. The applicability and the validity of the new criterion are examined through detailed parametric numerical simulation studies.

2. Soil slope instabilities in seasonally cold regions

In this study, many cases of soil slope failures occurring in Hokkaido, Japan have been examined. Table 1 summarizes a list of sediment disasters occurring during the thawing season in Hokkaido from 1999 to 2013. For example, on 07-04-2013 (dd-mm-yyyy), at 11:20 A.M., a slope failure happened along National Highway Route 230 in Hokkaido, Japan, as shown in Fig. 1(a). Sapporo City of Hokkaido and Setana, a town in the Hiyama subprefecture of Hokkaido is connected through this highway. The slope failure occurred along an embankment of the roadway with a size of 44 m in length and 19 m in height and 11,000 m^3 of sediments flowed downward to the foot of the slope, as shown in Fig. 1(a). Field investigations confirmed that the slope failure was induced by the combined action of heavy rainfall and snowmelt water (Hokkaido Regional Development Bureau, 2014). A nearby meteorological telemetry maintained by the Ministry of Land, Infrastructure, Transport and Tourism, Hokkaido Regional Development Bureau (MLIT) as shown in Fig. 1(a) recorded 92 mm of cumulative rainfall and 31 mm of cumulative snowmelt on 07-04-2013. The data were collected from the meteorological telemetry situated most near the disaster site, as depicted in Fig. 1(a). The snowmelt water was not measured physically using a snow lysimeter, etc. The amount of snowmelt water (SM) directly corresponds to the snow water equivalent (SWE), the reduced snow depth (SD) and the density of the snow (ρ_{sn}). On average, previous studies have shown that the maximum density of snow (ρ_{sn}) in Hokkaido is 500 kg/m^3 (Abe and Shimizu, 2009). Based on this, the amount of snowmelt water was estimated from the snow depth data recorded at the telemetry as half the amount of the reduced accumulated depth of the snow on 07-04-2013, according to the following relationship:

$$SM = \frac{\rho_{sn}}{\rho_w} \times \Delta SD \quad (1)$$

Table 1
List of sediment disasters occurring and recorded in snowy cold regions of Japan (after Iwakura et al., 2010).

S. No.	Date of occurrence (dd-mm-year)	City	Type of sediment-related disaster	Cause
1	01-04-1999	Lee County	Landslide	Snow melting
2	14-04-1999	Otaru City	Landslide	Rainfall and snow melting
3	15-04-1999	Shakotan-gun	Landslide	Snow melting
4	18-04-1999	Kamikawa-gun	Landslide	Snow melting
5	01-05-2000	Nakayama Pass	Landslide	Rainfall and snow melting
5	22-02-2004	Western County	Landslide	Rainfall and snow melting
6	22-02-2004	Western County	Sediment discharge	Rainfall and snow melting
7	17-03-2004	Western County	Debris flow	Rainfall and snow melting
8	17-03-2004	Kodaira County	Landslide	Rainfall and snow melting
9	30-04-2007	Otaru City	Debris flow	Snow melting
10	02-05-2007	Otaru City	Landslide	Snow melting
11	01-05-2012	Nakayama Pass	Sediment discharge	Rainfall and snow melting
12	07-04-2013	Nakayama Pass	Embankment collapse	Rainfall and snow melting