APPLICATION OF A NUMERICAL SNOWPACK MODEL TO ESTIMATE FULL-DEPTH AVALANCHE DANGER

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ABSTRACT: Many full-depth avalanches occur in temperate, snowy regions such as the northern part of Honshu, Japan. Such avalanches threaten infrastructure and communication lines in mountain communities. Despite these threats, numerical snowpack modeling has mainly focused on dry-slab avalanche danger. Predicting wet snow avalanches has been difficult because of model oversimplification of the water transport process in snow. Recently, however, a water transport model for snow was developed using the experimental results of a gravity drainage column experiment and the van Genuchten-Mualem model. This model was incorporated into the larger numerical model, SNOWPACK. This study attempted to estimate full-depth avalanche danger in terms of slope stability using a modified SNOWPACK model. In the simulation, liquid water pooled at the boundary between snow and ground during a melt or rain period. The water then infiltrated the soil. During liquid water pooling, a low stability index was calculated at the bottom layer of snow.
In cooperation with local governments, we gathered information on full-depth avalanches and compared it with the result of the modified SNOWPACK model. This comparison showed that the natural stability index at the snowpack bottom is a useful factor for estimating full-depth avalanche danger by implementation of the water transport scheme.

KEYWORDS: SNOWPACK model, water transport, full depth avalanche

1. INTRODUCTION

Many full-depth avalanches occur in temperate, snowy regions such as the northern part of Honshu, Japan. Such avalanches threaten infrastructure and communication lines in mountain communities. Numerical snowpack modes are useful tools for estimating avalanche danger. However, in the past, numerical snowpack modeling has mainly focused on dry-slab avalanche danger (Lehning et al., 2004, Hirashima et al., 2009). Full depth avalanches are associated with the existence of free water at the interface between the snow and ground surface (McClung and Clarke, 1987). Free water at the bottom of the snowpack affects the friction between snow and ground and the shear strength of bottom-layer snow. It also decreases the viscosity at the bottom of the snow slab. This free water is supplied by rain, snowmelt near the surface due to solar radiation and warm air, and snowmelt at the bottom due to stored heat in the ground. Rain and meltwater near the snow surface take some time to percolate through the snowpack. According to Clarke and McClung (1999), full-depth avalanche release responds to rainfall and snowmelt events within 12-24 hours. Therefore, estimation of the water percolation rate is important for predicting the release of a full-depth avalanche.
However, the water transport process has been oversimplified in many numerical snowpack models (Durand et al., 1999; Bartelt and Lehning, 2002). In such models, when liquid water exceeds the residual water content, excess water percolates to the layer below. On the other hand, some snowpack models have focused on the water transport process (Jordan et al., 1999; Katsushima et al., 2009). Hirashima et al. (2010) developed a water transport model using van Genuchten's (1980) model based on a gravity drainage column experiment (Yamaguchi et al., 2010) and incorporated it in the SNOWPACK model, which has been developed by SLF. This modified model reproduced the capillary barrier. In the present study, this model was applied to predict full-depth avalanches. First, the simulated runoff amount at the bottom layer was compared with lysimeter measurements at observation point because the incoming liquid water at the bottom

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relates significantly to the release of a full-depth avalanche. Subsequently, the snow stability index and runoff amount were simulated at the avalanche release zone.

2 VALIDATION OF SNOWPACK STRATIGRAPHY AND RUNOFF AMOUNT

2.1 Method

Meteorological and snow observation data have been obtained every year since 1964 at the field site of Snow and Ice Research Center, Nagaoka, Japan. Observed meteorological data were used as input data for the SNOWPACK model, and a simulation was carried out for winter 2009/2010. This study used two types of models. One was the unmodified version of SNOWPACK in which the water transport process was calculated with a simple scheme (Bartelt and Lehning, 2002). The other was a modified version that included a water transport model based on a gravity drainage column experiment (Hirashima et al., 2010). Precipitation amount was also used as input data to estimate the amount of rain. For the simulation, the rainfall catch ratio of Yokoyama et al. (2003) was used to correct the precipitation amount as follows:

$$P = P_0\,(1+mU) \quad (1),$$

where P_0 is the measured precipitation amount, P is the precipitation amount used as input data for the SNOWPACK model, and U is the observed wind speed at the height of 3.5 m above the surface. The coefficient m values for the warm water-type precipitation gauge are 0.346 and 0.0856 for snow and rain, respectively.
The simulation results were compared with manual observation data. As mentioned in the introduction, the amount of liquid water arriving at the snowpack bottom is an important factor for predicting full-depth avalanches. As the liquid water amount arrived at the bottom, the runoff amount was observed using a lysimeter with a area of 9 m^2. Simulated runoff data were compared with the lysimeter-observed data. The comparison results are described below.

2.2 Results

Figure 1 presents the simulated snow types. Much of the snow is melt forms even in midwinter, because of the temperate climate of Nagaoka (Yamaguchi et al., 2007, Hirashima et al., 2010). Figure 2 presents the observation results, which

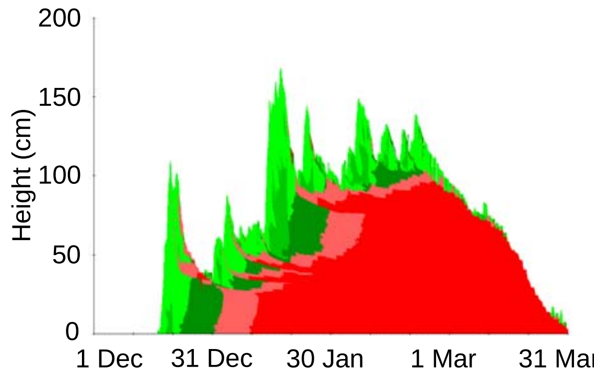

Fig. 1 Simulated snow types at Nagaoka in winter of 2009/2010

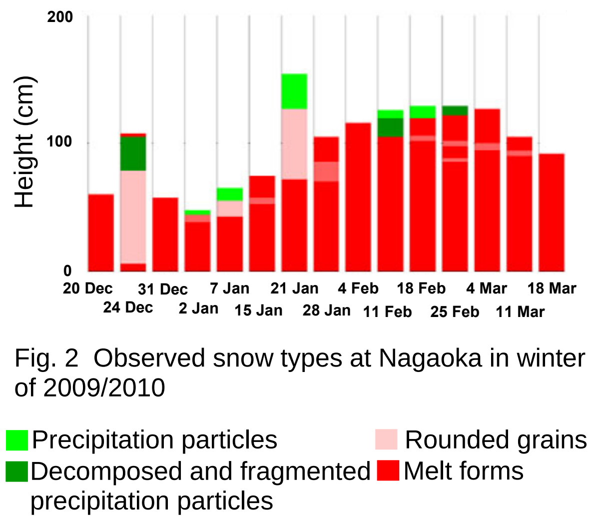

Fig. 2 Observed snow types at Nagaoka in winter of 2009/2010

also shows much of the snow as melt forms.
In Figure 3, observed and simulated runoff amounts are compared. Runoff was seen for whole winter (Fig. 3a). The observations show that the runoff amount increased in daytime and then gradually decreased following a water reduction curve at night. This water reduction curve was not reproduced in the unmodified SNOWPACK model (see blue line in Fig 3b).
Water content profiles simulated by the modified and unmodified SNOWPACK models are shown in Figure 4. In the unmodified SNOWPACK, the runoff amount was zero until the water content of all snow layers became the residual water content. When the water content had the same value as the residual water content, the runoff amount had the same value as the snowmelt amount. Therefore, the unmodified SNOWPACK model did not consider the deposition and infiltration of liquid water in the snowpack in excess of the residual

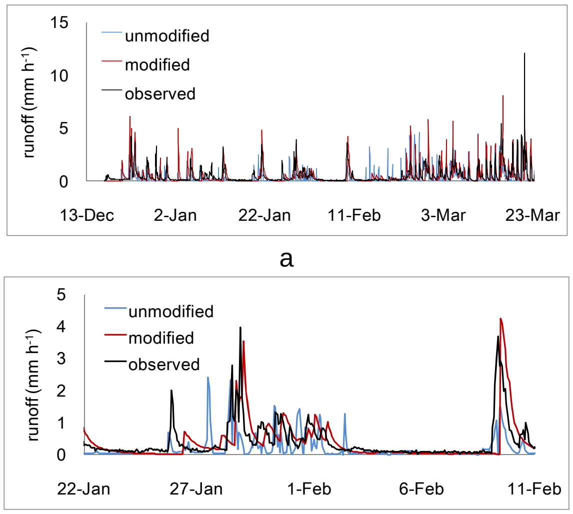

Fig. 3 Observed runoff amount (black line) and runoff amount simulated by the unmodified (blue line) and modified (brown line) SNOWPACK model (a) for full winter and (b) from 22 January to 11 February.

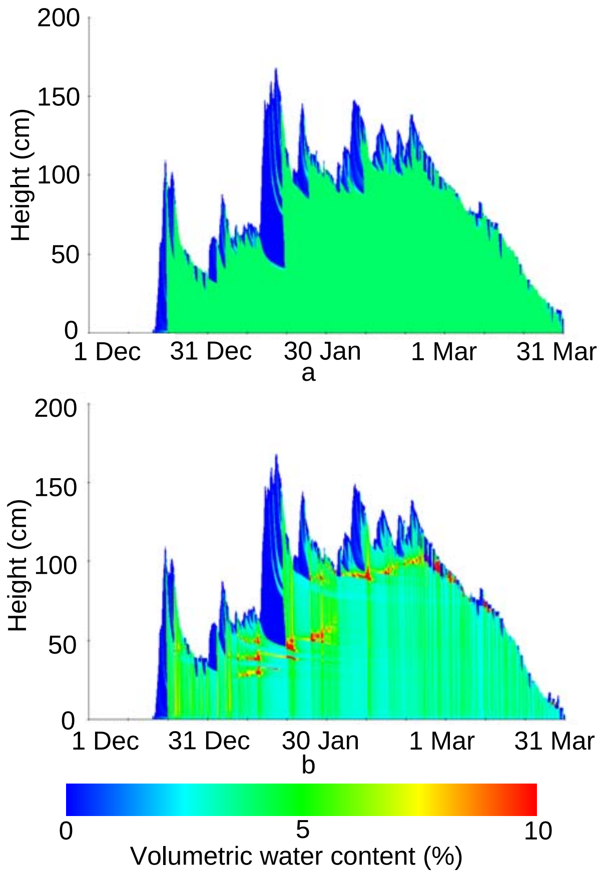

Fig. 4 Simulated volumetric water content at Nagaoka in winter of 2009/2010 (a) by the unmodified SNOWPACK model and (b) modified SNOWPACK model.

water content. On the other hand, the modified SNOWPACK model showed water deposition in the snowpack during snowmelt. Water content increased during the snowmelt period and then decreased gradually (see Fig. 4b). This process resulted in the enhanced reproducibility of the water reduction curve (brown line in Fig. 3b). Therefore, reproducibility of the runoff amount was significantly improved, and the amount of liquid water arriving at the bottom was calculated more accurately in the modified version of the SNOWPACK.

3 APPLICATION FOR PREDICTION OF A FULL-DEPTH AVALANCHE

3.1 A full-depth avalanche in Niigata

Full-depth avalanches occur even in midwinter in Niigata Prefecture. Here, an avalanche that occurred on 23 December 2009 in Nagaoka was modeled, and the simulation result was compared to observed data. Data from the Automated Meteorological Data Acquisition System (AMeDAS) of Japan Meteorological Agency were used as input data for SNOWPACK model. Figure 5 shows the locations of the avalanche and meteorological station.

The meteorological station and avalanche slope differed in altitude. Furthermore, the avalanche slope faced a certain direction and thus received

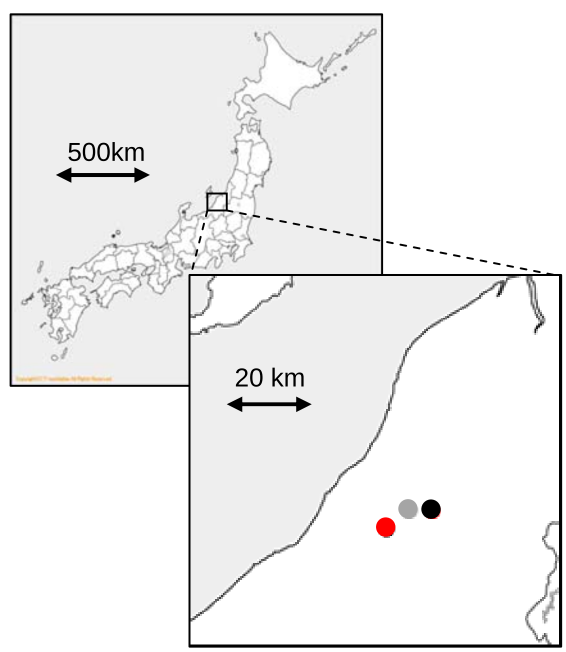

Fig.5 Locations of the meteorological station (gray point), avalanche slope (red point), and Snow and Ice Research Center (black point).

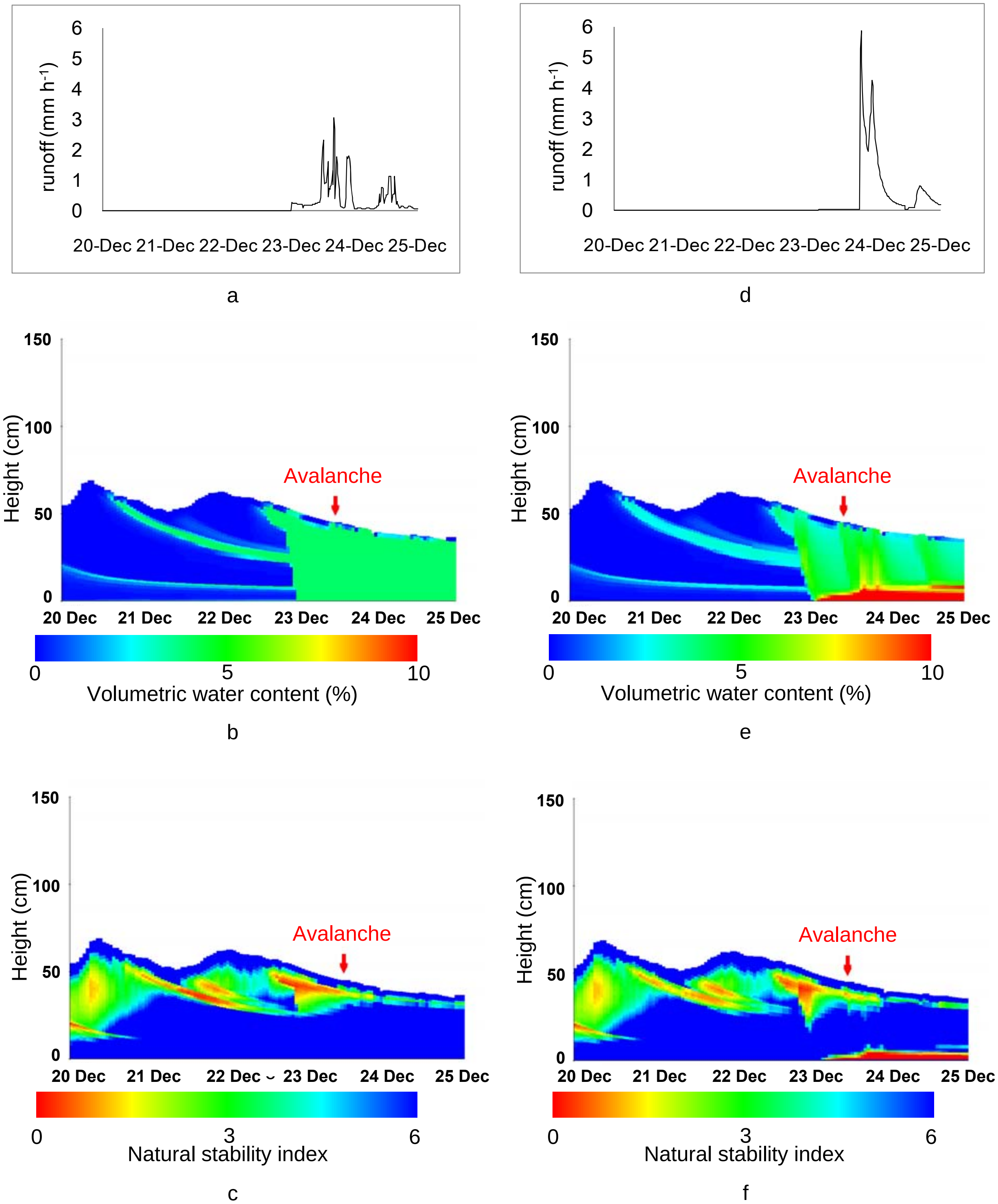

Fig. 6 Simulation by the unmodified (a-c) and modified (d-f) SNOWPACK models for the full-depth avalanche that occurred on 23 December 2009 (the exact time is unknown): (a) and (d) runoff amount; (b) and (e) volumetric water content; (c) and (f) natural stability index.

different solar radiation from that received at a flat area such as the AMeDAS site. To account for these effects, the correction method described by Hirashima et al. (2008) was applied. Air temperature was corrected by considering a lapse rate of 6.5 $\times 10^{-3}$°C m^{-1}. Solar radiation was corrected based on the slope angle, aspect of the avalanche starting zone, solar altitude, and solar orientation on the basis of Funk and Hoelzle's (1992) parameterization. The SNOWPACK simulation was carried out with the avalanche slope shown in Fig. 5.

3.2 Comparison between observed and simulated cases

Figure 6 shows the runoff amount, water content profile, and stability index simulated by the unmodified and modified SNOWPACK models. The modified model showed an increase in water content during the snowmelt period (Fig. 6d), whereas the unmodified model did not show a significant change in water content during the wet snow condition (Fig. 6a). In the modified model, after the water front arrived at the bottom of the snowpack, a water-saturated layer formed at the bottom snow layer, leading to a decrease in the natural stability index of that layer.

As shown in Fig. 6, the timings of stability index decrease and full-depth avalanche release coincided in the modified SNOWPACK model. This result indicates that prediction of full-depth avalanche release would be possible using the modified numerical snowpack model. However, further study and observation are necessary before using the model for practical applications. For example, estimation of water transport from the snow to the ground surface is necessary to accurately simulate the water content and stability index at the bottom of the snowpack. Furthermore, the meteorological data used in the simulation should be observed or estimated near the avalanche slope. In the case shown in Fig. 6, the meteorological station and avalanche slope were about 10 km apart, with a vertical difference of approximately 100 m. Furthermore, although the observed and simulated release timings agreed well for the case shown in Fig. 6, other cases may not show such good agreement.

The advantage of using the modified model is that full-depth avalanche danger can be estimated from the simulated natural stability index. The unmodified version did not show instability at the snowpack bottom, even when the water front arrived at the bottom layer of snow.

4 CONCLUSION

Numerical simulations using modified and unmodified versions of the SNOWPACK model were carried out for an avalanche site in Nagaoka, Japan. Simulated snowpack and runoff data were compared with observed data. In the modified model, runoff reproducibility was obviously improved compared with the unmodified model. Full-depth avalanche danger was also estimated using the modified and unmodified SNOWPACK models. In the modified model, when the water front arrived at the bottom of the snowpack, the natural stability index decreased, and the timing of it was coincident with full-depth avalanche start. Future research steps include improvements to the water transport model and estimation of water transport from snow to the ground surface to allow for more accurate estimation of full-depth avalanche danger.

ACKNOWLEDGEMENTS

We thank the government of Niigata Prefecture for providing the avalanche data. We also thank the members of the Snow and Ice Research Center for their helpful advice and discussions.

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