A multi-dimensional water transport model to reproduce the preferential flow in a snowpack

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ABSTRACT: Modeling of liquid water transport in snowpack is important for the prediction of wet snow avalanches. In this study, a multi-dimensional water transport model for snowpack was developed to reproduce preferential flow. Darcy’s law and the van Genuchten model were used to simulate water movement. Parameters for the van Genuchten model were determined as functions of snow density and grain size based on a previous gravity drainage column experiment. Water-entry suction was newly considered for the case of liquid water infiltrating into dry snow. The result of a previous infiltration-pattern laboratory experiment was used to validate the model. The simulated result reproduced the experimental formation of preferential flow fairly well. The model was then applied to simulate water movement in layered snow for both initially dry and initially wet snow. In the initially dry snow, preferential flow dominated, but in the initially wet snow, water infiltrated homogeneously. Capillary barriers had a large effect on the travel time from the snow surface to the snow base, especially in the initially dry snow. Simulations considering the slope effect were also carried out. The results indicated that, compared to level ground, the slope had larger layers of ponded water caused by capillary barriers, which resulted in longer travel times to the snow base.

KEYWORDS: water transport in the snowpack, numerical model, preferential flow, slope effect.

1 INTRODUCTION

Infiltration of liquid water into the snowpack is an important process for wet snow avalanches. Wet-snow full-depth avalanches tend to occur when liquid water arrives at the snow bottom (McClung and Clarke, 1987). In addition, wet slab avalanches often occur when liquid water reduces the shear strength between adjacent snow layers (Kittelmann, 1984). Thus, the transport of liquid water affects snow stability and sometimes results in a wet snow avalanche. Modeling of liquid water transport in the snowpack is therefore important for predicting wet snow avalanches.

The water transport process in porous media is classified into two regimes, matrix flow and preferential flow. Past studies of water movement in snowpack have mainly addressed matrix flow, for example, measurements of permeability or hydraulic conductivity (Shimizu, 1970; Colbeck and Davidson, 1973; Sugie and Naruse, 2000), and measurements of capillary pressure (Colbeck, 1974; Yamaguchi et al., 2010, 2012). Modeling with numerical snowpack models has also mostly considered water transport by focusing on matrix flow (Jordan, 1995; Hirashima et al., 2010). Nevertheless, some multi-dimensional models for water transport have been developed (Illangasekare et al., 1991; Daanen and Niever, 2009). These have considered snow temperature and ice layers but have generally not included the formation of preferential flow. However, the importance of preferential and lateral flow for realistic simulation of the snowpack has been pointed out (Gustafsson et al., 2004; Waldner et al., 2004). Recently, Katsushima et al. (2013) measured water entry suction in the snowpack and observed the formation of the preferential flow. In the present study, a new multi-dimensional water transport model in snowpack was developed. The purposes of this study were 1) to develop a multi-dimensional model to reproduce the formation of preferential flow, 2) to validate the model using the result of the laboratory experiment by Katsushima et al. (2013), and 3) to apply the model to water movement in layered snow on level ground and on a slope.

2 DEVELOPMENT OF THE MULTIDIMENSIONAL MODEL

In our earlier study (Hirashima et al., 2010), a one-dimensional water transport model was developed. The main limitation of the one-dimensional model was the inability to consider heterogeneous water transport and the slope effect. This limitation was a serious drawback for the prediction of wet snow avalanches. Therefore, a multi-dimensional model for water transport...
transport was developed to resolve this limitation. In the multi-dimensional model, voxel grids were considered and water fluxes were calculated by Darcy’s law for the x, y, and z axes. Suction was determined by using the van Genuchten (1980) model, the parameters of which were determined as a function of snow density and grain size based on the result of the gravity-drainage column experiment by Yamaguchi et al. (2012). Saturated hydraulic conductivity was determined as a function of snow density and grain size based on the method of Shimizu et al. (1970). Unsaturated hydraulic conductivity was calculated based on the van Genuchten-Mualem model. For simulation on a slope, the gravity vector of Darcy’s equation was deconstructed into directions normal to and parallel to the slope.

In a study of water transport in soil, Hillel and Baker (1988) suggested that the water ponding process caused by the water-entry value is a key process for the formation of preferential flow. Therefore, water-entry suction was considered in our model when liquid water infiltrated dry snow. In this study, residual water content was used as the threshold value to distinguish dry snow from wet snow. When water moved into a grid of dry snow, the water flux, \( q_x \), was calculated as

\[
q_x = \begin{cases} 
K \left( \frac{h_{we} - h_1}{\Delta x} \right) & (h_{we} > h_1) \\
0 & (h_{we} \leq h_1)
\end{cases},
\]

where \( K \) is the hydraulic conductivity, \( h_{we} \) is the water entry suction of dry snow, \( h_1 \) is the suction of the grid of inflow source, and \( \Delta x \) is the grid size.

Water-entry suction was determined based on the experiment of Katsushima et al. (2013), which indicated that the water-entry suction of dry snow was about 1 cm larger than that estimated by the formula of Baker and Hillel (1990). Thus, the water-entry suction for dry snow was increased by 0.01 from the formula of Baker and Hillel (1990).

3 SIMULATION RESULT AND DISCUSSION

3.1 Reproduction simulation of the laboratory experiment

Katsushima et al. (2013) conducted two laboratory experiments regarding the formation of preferential flow. One was the capillary pressure experiment in which suction was measured by tensiometer just above the interface between wet snow and dry snow. In that study, the minimum suction value was measured just before infiltration of the liquid water into the dry snow. The second experiment was an infiltration pattern experiment in which flow patterns were observed by using a dye tracer. In the present study, we conducted numerical experiments to reproduce the experiments of Katsushima et al. (2013).

Table 1 shows the snow densities and grain sizes used in the experiments. Katsushima et al. (2013) used four types of snow with different grain sizes ranging from 0.23 to 1.46 mm. In their laboratory experiment, a column of snow with a height of 27 cm and diameter at base of 5 cm was used. The top 2 cm was initially wet.

In this study, two-dimensional simulation was carried out to make the water infiltration viewable. The grid size was set to 1 cm on a side. The simulation area had a height of 27 cm and a width of 20 cm (Fig. 1). The initial snow densities and grain sizes were the same as the values shown in Table 1. Heterogeneous properties were incorporated to make the water movement non-uniform. Normal random numbers were generated for each grid and used to fluctuate the snow density and grain sizes. In this simulation, the standard deviations of the frequency distributions for snow density and grain size were 1% of the mean values. The initial volumetric water content was 4% for the upper 2 cm and 0% for the lower 25 cm. Liquid water was supplied at the top grids at a rate of 20 mm per hour.

As an example, the temporal change in the

<table>
<thead>
<tr>
<th>grain size (mm)</th>
<th>density (kg/m³)</th>
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<tr>
<td>Sₘ</td>
<td>0.23</td>
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<tr>
<td>Sₘ</td>
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<td>1.054</td>
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<td>Sₘ</td>
<td>1.463</td>
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Table 1 Snow parameters used in the laboratory experiment and reproduction simulation.

Fig. 1. Temporal change in volumetric water content distribution for sample Sₘ after the start of the water supply. (a) 12 min, (b) 15 min, (c) 16 min
volumetric water-content distribution of the SL sample is shown in Fig. 1. The temporal change in suction just above the interface between wet and dry snow (second to top grids) is shown in Fig. 2. At first, the liquid water that was supplied did not infiltrate the dry snow but ponded just above the interface between the wet and dry snow (Fig. 1a). As the water was ponded there, suction continued to decrease (point a in Fig. 2). When the suction at the wet snow attained a value lower than the water-entry suction of the dry snow, water began to infiltrate the dry snow (Fig. 1b). After infiltration began, the liquid water infiltration progressed, lengthening the preferential flow path (Fig. 1c). At this time, the liquid water just above the interface moved horizontally to the entrance of the preferential flow path. After preferential flow formed, the suction increased (points b and c in Fig. 2) and then maintained a steady value. This increment of suction is called capillary overshoot and is a requirement for formation of preferential flow (Baker and Hillel, 1990). Katsushima et al. (2013) also observed capillary overshoot in their laboratory experiment.

Water content distributions after 1 h in all snow samples are shown in Fig. 3. Horizontal section views at a depth of 4 cm from the top of the laboratory experiment of Katsushima et al. (2013) are also shown for comparison. The simulated results showed that a preferential flow path formed for snow samples SM, SL, and SLL (Fig. 3b, c, and d). The liquid water in sample SS did not form preferential flow but instead infiltrated homogeneously (Fig. 3a). Because the water-entry suction for the very fine snow was large, it was easy for water to infiltrate the dry snow. These results correspond with the laboratory experiment of Katsushima et al. (2013) (right photos of Fig. 3). In the laboratory experiment, capillary overshoot was not observed for sample SS, so its water-entry suction was estimated by extrapolation based on other samples.

Comparisons between the simulated and measured suction just above the interface between wet and dry snow are shown in Fig. 4. Except for sample SS, capillary overshoot was observed in both the simulated and measured results. In the simulated results, the timing of capillary overshoot was delayed and the minimum suction values were larger than the measured values. These discrepancies may lead to error in preferential flow formation and have room for improvement. Even so, the trend of
formation of preferential flow path was reproduced fairly well by these simulations.

The travel times of the liquid water from the start of the water supply to arrival at the snow base were 68, 27, 17, and 14 min for samples Ss, Sm, Sl, and Sll, respectively. Therefore, preferential flow shortened the travel time by one-half to one-fifth compared to homogeneous infiltration in these simulations.

3.2 Water infiltration in layered snowpack.

Snow stratigraphy influences the water transport process. Thus, water transport simulations in snowpack of interlaminated fine and coarse snow were carried out. The grid size was set to 1 cm on a side. The simulated area had a height and width of 40 cm. Four 10-cm high layers were configured and numbered from the top as L1, L2, L3, and L4 (Fig. 5). Snow densities were set to 550 kg/m³ for all grids. Grain sizes of the L1, L2, L3, and L4 layers were 1.1, 2.1, 1.1, and 2.1 mm, respectively. The heavy lines in the figure show the boundaries of layers. This simulation also incorporated heterogeneous properties with 1% of standard deviation of the mean values for snow density and grain size. The rate of liquid water supply from the top of the grids was 20 mm per hour. Simulations were carried out with two different initial conditions of water content: initially dry snow with zero water content and initially wet snow with the same moisture as the residual water content. The temporal changes in the liquid water content distributions are shown in Figs. 5 and 6 for the initially dry and wet snow, respectively.

The simulation result of the initially dry snow showed that the liquid water infiltrated through preferential flow paths (Fig. 5a). When the preferential flow arrived at the interface between the overlying fine layer (L1) and coarse layer (L2), downward water movement stopped because of the capillary barrier and the flow started to extend horizontally (Fig. 5b). After an adequate amount of liquid water ponded at the capillary barrier, a preferential flow path formed and vertically transported liquid water at high speed (Fig. 5c). It took less than 30 s from the formation of preferential flow at the top of L2 to arrival at the interface between L3 and L4. The interface between L2 and L3 was a coarse-overfine interface and did not affect the extension of preferential flow. A layer of ponded water formed again at the interface between layers L3 and L4 because of the capillary barrier. The travel time was 62 min from the start of the water supply to arrival at the bottom. The influence of capillary barriers dominated the travel time in this simulation.

The simulation result for the initially wet snow showed that the liquid water infiltrated homogeneously (Fig. 6a). A large water-content layer formed at the boundary between L1 and L2 because of the capillary barrier. However, the water content amount at the capillary barrier was smaller than that of the simulation of the
initially dry snow (compare Figs. 5b and 6b) because the initially wet snow had no effect on water-entry suction. A large water-content layer formed again at the boundary between L3 and L4. In this simulation, the arrival time from the start of the water supply to arrival at the bottom was 42 min. It took about 18 min from the beginning of infiltration into the L2 layer to arrival at the interface between the L3 and L4 layers. Thus, both hydraulic conductivity and the influence of capillary barriers were important for determining the travel time to the snow base.

In this comparison, liquid water arrived faster in the initially wet snow. However, if the heights of the L2 and L3 layers were larger, the travel time became longer in the initially wet snow but differed little in the initially dry snow. Thus, the initially dry snow was affected more extremely than the initially wet snow by the snow stratigraphy.

3.3 Water infiltration on a slope.

The slope effect is important for modeling water movement because avalanches occur on slopes. However, the slope effect was not considered in the previous one-dimensional numerical model. In the model of this study, the slope effect was considered by deconstructing the gravity vector of Darcy’s equation into directions normal to and parallel to the slope.

In situ intercomparison observations between level ground and slope have been reported in some abstracts of academic meetings in Japan. Kawashima et al. (2009) carried out manual observations on level ground and on a south-east facing slope and showed that the snow stratigraphy on the slope was relatively homogeneous and that melt forms developed earlier than it did on the level ground. Kawashima et al. (2012) compared lysimeter data at the same field and showed that the travel time of the liquid water to the snow base on the slope was longer, within the range of 0 to 9 h, than that on the level ground. They also showed that the trend of longer travel time on the slope was predominant during the early melt season. Ikeda et al. (2012) found in a case example that preferential flow formed in the snowpack on level ground but did not form on a north-facing slope. These studies had the common result that liquid water in the snowpack on the level ground discharged faster through preferential flow paths. Although the influence of slope angle and direction on incoming solar radiation affects liquid water conditions, the mechanistic slope effect is also important. In this study, the influence of the mechanistic slope effect was tested using the new model.

In this simulation, the slope angle was set to 45 degrees. The simulated area was 40 cm for the direction normal to the slope and 80 cm for the direction parallel to it (Fig. 7). The conditions of grain size in each layer, heterogeneity, initial water content, and amount of water supply were the same as in the simulation of level ground described in section 3.2. The boundary condition at the left side and the right side was not an impermeable wall but an antiperiodic boundary. Thus, if liquid water discharged from one side (the right side in this simulation), it flowed to the other side (left side). The temporal changes in liquid water content are shown in Figs. 7 and 8 for the initially dry snow and the initially wet snow, respectively.

The simulation result for the initially dry snow on the slope also showed that liquid water infiltrates through preferential flow paths. When the preferential flow arrived at the interface between the top fine layer (L1) and the subsequent coarse layer (L2), the liquid water stopped because of the capillary barrier and started to move parallel to the slope (Fig. 7a). The thickness of the ponded water layer was larger than that of level ground (compare Figs. 5b and 7b). The ponding resulted in a delay in the formation of preferential flow in layer L2. The time required to form the preferential flow was 58 min compared to 37 min in the simulation of level ground. Much water also ponded at the interface between layers L3 and L4. Consequently, the
4 CONCLUSIONS

A multi-dimensional water transport model in snowpack was developed to reproduce preferential flow. Darcy’s law, van Genuchten’s model, and the results of gravity drainage column experiments and capillary pressure experiments were used to develop the model.

A reproduction simulation was first carried out and validated by comparing with the laboratory experiments of Katsushima et al. (2013). The simulated results reproduced the formation of preferential flow fairly well. Capillary overcompensation was also reproduced qualitatively, but it had some shortcomings quantitatively.

This model was then applied to simulate water movement in a layered snowpack of interlaminated fine and coarse snow. Simulations were conducted for both initially dry and initially wet snow. The simulated result in the initially dry snow showed that the influence of capillary barriers at the interfaces between overlying fine snow layers and underlying coarse snow layers dominated the arrival time of liquid water to the base. On the other hand, in the initially wet snow, the influence of the capillary barriers was smaller and the effect of infiltration length was also important.

Finally, comparison simulations between level ground and slope were carried out. Liquid water in the snowpack on the slope required a longer time to arrive at the snow base than it did on level ground, which was due to larger ponded water layers at the capillary barriers. This effect was particularly substantial in the initially dry snow. These characteristics corresponded with the results of previous observational studies.

This model is a first step in the reproduction of heterogeneous infiltration of liquid water in snowpack. The effects of snow temperature, refreezing of liquid water, and growth of preferential flow channels will be considered to improve the model. Improvements of the water transport model should move the numerical model closer to the goal of prediction of wet snow avalanches.

5 ACKNOWLEDGEMENT

This study was a part of the Research on Advanced Snow Information and Its Application to Disaster Mitigation project. We thank the members of the Snow and Ice Research Center for their advice and discussion. We are grateful to M. Miura, who assisted in our research.

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