SIMULATING LIQUID WATER INFILTRATION - COMPARISON BETWEEN A THREE-DIMENSIONAL WATER TRANSPORT MODEL AND A DUAL-DOMAIN APPROACH USING SNOWPACK

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ABSTRACT: In this study, we compared the performance of a three dimensional (3-D) water-transport model and the physics-based multi-layer SNOWPACK model with a dual-domain approach for preferential flow, to simulate water infiltration by preferential flow. We used data from three experiments to validate our models: liquid-water profiles and preferential-flow patterns around capillary barriers, measured in cold laboratories (Avanzi et al., 2016); water-sprinkle experiments measuring discharge amounts in the field (Ishii et al., 2014); and infiltration experiments in nature-identical snow with simultaneous measurements of wet-snow metamorphism, measured using micro-computed tomography, (Avanzi et al., 2017). Qualitatively, the dual-domain approach of SNOWPACK produced similar patterns of water infiltration to the 3-D model. However, percolation speed in preferential channels, the position of the water-ponding layer, and the simulated time when the transition from preferential to matrix flow occurred differed between the two models. We show that the 3-D model yields good agreement with laboratory experiments and field observations. Our results also suggest that the 3-D model could be used to enhance the accuracy of the SNOWPACK model's simulation by refining the parameters of the dual-domain approach. Such improvements enhance the ability of SNOWPACK to simulate liquid-water infiltration in snow, thereby enhancing its ability to predict the formation of wet-snow avalanches.

KEYWORDS: Liquid-water movement, numerical snowpack model, preferential flow, 3-D water transport model.

1. INTRODUCTION

Wet-snow avalanches are closely related to the processes by which liquid water infiltrates snowpack, which follow two mechanisms: matrix flow and preferential flow. Although most numerical snowpack models include only matrix flow, preferential flow is a key mechanism because it allows water to quickly reach deep-lying weak layers. Therefore, prediction of the timing and depth of the release of wet-snow avalanches requires accurate simulation of preferential flow. Two approaches have been generally used to reproduce preferential flow; the first is to use a three-dimensional (3-D) water-transport model (Hirashima et al., 2014, 2017), and the second is to use a dual-domain approach for preferential flow implemented into the physics-based multi-layer SNOWPACK model (Wever et al., 2017). Another example of multi-dimensional model is discussed in Leroux and Pomeroy (2017).

Each model has specific advantages and disadvantages. For example, the 3-D model explicitly resolves individual flow paths, yet has high computational cost. SNOWPACK, on the other hand, considers the most relevant processes governing seasonal snow cover development, is computationally relatively efficient, but only describes preferential flow in a parameterized way. Therefore, a comparison of the SNOWPACK and 3-D models is important to guide improvements in the accuracy of liquid-water infiltration simulations by numerical snowpack models that feature preferential flow. In this study, we compared simulations using these two models of water infiltration by preferential flow. We benchmarked the differences that we observed in the simulations of the water-infiltration process between the two models against validation data obtained from both laboratory and field experiments. The results from the study provide useful information for improving these models.

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2. MODELS

2.1 3-D water transport model

The 3-D water transport model used in this study was developed by Hirashima et al. (2014) and reproduces preferential flow of liquid water in snow by defining a grid of 3-D voxels and considering horizontal and vertical water flux, heterogeneity, and water entry suction parameterized by Katsushima et al. (2013). The model fully reconstructs flow-path patterns through snow and has been shown to correctly reproduce preferential flow. The disadvantages of this model are that it is computationally intensive and includes only wet-snow metamorphism, neglecting snow compaction and other relevant seasonal processes. This makes the 3-D model unsuitable for operational use for avalanche prediction at this stage, but suitable for reproducing detailed infiltration processes and useful for providing information to improve the SNOWPACK model. The 3-D model can also be used in a 2-D mode.

2.2 SNOWPACK model with dual-domain approach

The dual-domain approach of the SNOWPACK model considers both water infiltration via preferential flow paths and matrix flow by parameterizing preferential flow areas in one dimension. This approach is useful for operational avalanche prediction, but the current one-dimensional parameterization of preferential flow paths requires further validation. Therefore, it is important to compare the SNOWPACK and 3-D models to improve the accuracy of liquid-water infiltration simulations by numerical snowpack models that feature preferential flow.

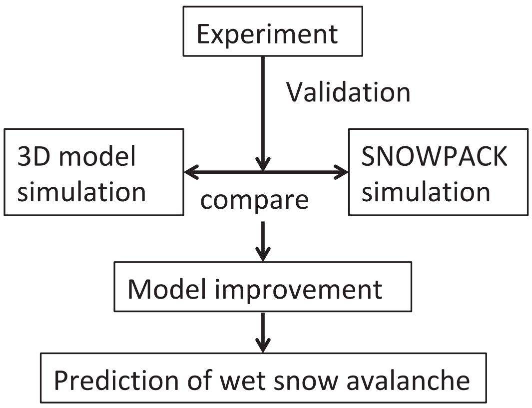


Fig.1. Method used in this study.

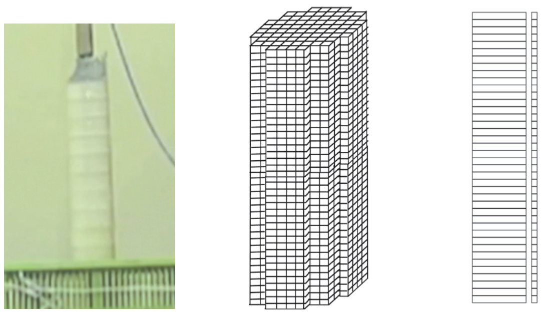
3. SIMULATIONS

3.1 Simulation of water infiltration into layered snow

Liquid-water profiles and preferential-flow patterns around capillary barriers were measured in cold-laboratory experiments by Avanzi et al. (2016). To this end, nine layered snow samples were artificially sieved in acrylic cylindrical containers. The height of each cylinder was 20 cm; its diameter was 5 cm. Each sample was composed of two layers: a 10-cm thick upper layer and an 8- or 10-cm-thick lower layer. All samples were characterized by finer-over-coarser layering, which aimed to reproduce capillary barriers. The three classes of snow grain size were fine (0.25–0.5 mm), medium (1.0–1.4 mm), and coarse (2.0–2.8 mm). Three water input rates were investigated: 10, 30, and 100 mm h^{-1}. In total, nine experiments were performed. The experimental configuration is shown in Fig. 2a.

The simulations aimed to replicate these experiments are described in detail in Hirashima et al. (2017). We performed 3-D simulations, using the same area for each simulation and 5-mm voxels (Fig 2b). The snow densities, grain sizes, and rates of water supply were set to the same values as those in the laboratory experiments. Grain-size heterogeneities were set to 20% of the median grain size following the approach of Hirashima et al. (2014), who used the data of Katsushima et al. (2013). Heterogeneity of snow density was not provided in the simulation. As in the laboratory experiments, the grain-size combinations in the simulation were fine-over-coarse, fine-over-medium, and medium-over coarse snow.

Simulations with the SNOWPACK numerical snowpack model were also implemented to simulate the dynamics observed during these laboratory experiments. In this study, we used SNOWPACK with the dual-domain approach (Wever et al., 2016) to simulate temporal changes in the water-content profiles for both the matrix and preferential flow areas (Fig. 2c). The resolution of the SNOWPACK model was set to 5 mm to match that of the 3-D model.



a b c

Fig. 2. Schematic of capillary-barrier experiments: a) photograph of experimental set-up; b) simulation in 3-D model; c) simulation in SNOWPACK model, with the grid on the right showing preferential flow.

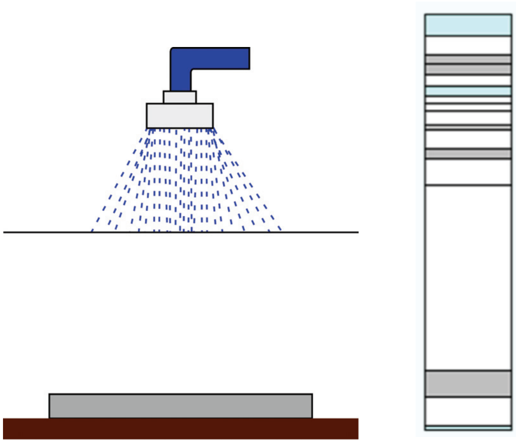


Fig. 3. Sprinkle experiment: (a) schematic figure of experimental configuration; (b) profiles of snow in sprinkle experiment in 2012 (light blue: extremely wet, gray: wet with coarse grains, white: dry with fine grains).

3.2 Simulation of water-sprinkle experiment

Water-sprinkle field experiments measuring discharge amounts were performed in a previous study (Ishii et al., 2014, Fig 3a) four times in Moshiri, Hokkaido, Japan, during the snowmelt periods of 2012 and 2013. Hirashima et al. (2016) performed reproduction simulations for these field observations using the water-transport model in its 2D mode (computational reasons). The measured profiles for snow density and grain size were used as initial data. The water supply amount was set to be equal to that in the field experiment (approximately 30 mm/h for 6 h). The same reproduction simulation was also performed using the SNOWPACK model. In our comparison of the two models, we focused on the water-transport process and discharge characteristics.

3.3 Low water infiltration rates over a long period

In the experiments described in Section 3.1, the liquid-water supply rate was greater than 10 mm/h, and while the duration of each experiment was less than 3 h (see data in Avanzi et al. 2016). Each experiment ended when liquid water arrived at the snow base. This period was too short for observing the potential migration, or expansion, of preferential-flow paths. In contrast, Avanzi et al. (2017) performed longer experiments (up to about 2 weeks) using a low melting rate. In their experiments, they sieved three relatively large blocks of snow (50 x 50 x 30 cm) and subjected these blocks to controlled melt, or melt-freeze, using a heating plate; snow subsequently gradually melted. The protocol for a melt-only experiment (namely, an experiment without refreezing) consisted of about 6-7 hours of forced heating with the plate and about 17-18 hours of isothermal conditions at 0°C without the plate. This protocol was repeated for about 2 weeks. Wet-snow metamorphism was measured during the experiment using X-ray micro-CT (see Avanzi et al 2017 for details).

The reproduction simulations were performed using both the 3-D model (here again in the 2D mode for computational reasons) and SNOWPACK. The snowmelt rate was estimated to be 0.66 mm/h based on the decrease in the amount of snow during each cycle. Since the 2-D model does not consider snowmelt, liquid water was supplied at the rate of 0.66 mm/h for 7 h, after which the water supply was set to zero for 17 h. The simulation area in the 2-D model was 10 × 30 cm rather than 50 × 30 cm, again for computational reasons. The voxel size was set to 5 mm. The SNOWPACK simulation was performed using the same conditions.

4. RESULTS AND DISCUSSION

4.1 Simulation of water infiltration in layered snow

The output of the SNOWPACK model is usually shown as temporal 1-D snow profiles for various variables (Bartelt and Lehning, 2002). The 3-D model also shows the horizontal distribution of the liquid water content. To perform a direct comparison between the two models in this study horizontal water distribution was also estimated for the SNOWPACK model simulations by considering the amount of water in both matrix and preferential flow areas.

As an example, Fig. 4 shows the results of the fine(0.4 mm) - over - medium (1.4 mm) capillary-barrier experiment with a 10-mm water supply. Both simulations showed liquid water infiltrating along a preferential flow path (Fig. 4a, e) and subsequently ponding at the layer boundary, which is consistent with experimental observations. Such an effect was obtained because of preferential flow, which allowed water to move in small paths and to reach deeper locations even when most of the upper layers of snow remained dry. The water-ponding layer thickened until a preferential flow path formed in the lower layer (Fig. 4b, f). In the SNOWPACK model, during the process of liquid-water ponding at the layer boundary, infiltration as matrix flow also started (Fig. 4f). In the 3-D model, after preferential flow formed in the lower layer, the preferential flow

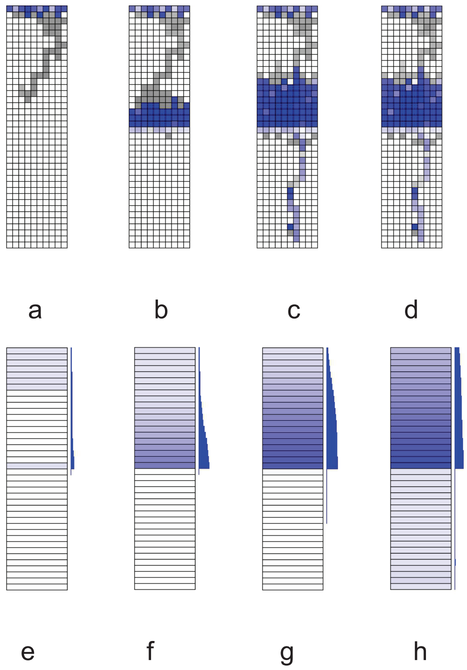


Fig. 4. 3-D (a–d) and SNOWPACK (e–h) model simulations of one of the capillary-barrier experiments (fine-over-medium with 10 mm/h supply). In SNOWPACK, the box on the left shows the liquid water content in the matrix-flow and in the preferential flow zones (right). In the 3-D model, the blue scale represents liquid water content (see e.g. Hirashima et al. 2017 for details). The capture time is at 15 (a, e), 60 (b, f), 110 (c, g) and 180 (d, h) min after the start of water supply.

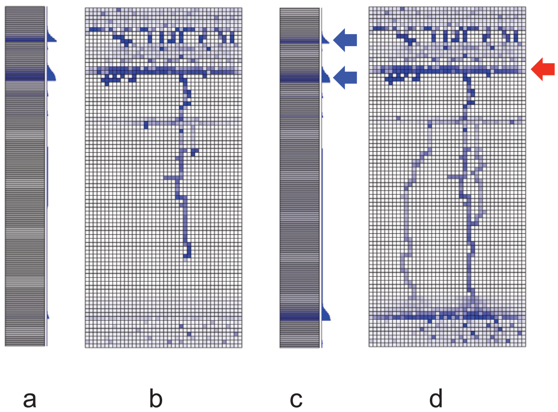


Fig. 5 SNOWPACK (a, c) and 2-D (b, d) model simulations of the 2012 sprinkle experiment. In SNOWPACK, the box on the left and right line shows the liquid water content in the matrix-flow and in the preferential flow zones, respectively. In the 3-D model, the blue scale represents liquid water content. The capture time is at 80 (a, b) and 250 (c, d) min after the start of the water supply.

path extended and arrived rapidly at the snow base (Fig. 4c). In contrast, the SNOWPACK model required more time for the preferential flow path to extend, and there was a delay in its arrival at the snow base (Fig. 4g). In the 3-D model, after the preferential flow arrived at the snow base, the water ponding layer stopped expanding (Fig. 4d), whereas in the SNOWPACK model, water ponding continued even after arrival of the liquid water because the infiltration rate in the lower layer was too low. This step was then followed by the onset of matrix flow in the lower layer (Fig. 4h). Comparison of the arrival times (as shown in Hirashima et al., 2017) of the two models showed a delay in the arrival time in the SNOWPACK model. Similar trends were observed for other simulations.

4.2 Simulation of field experiment

Fig. 5 shows an example of the simulation performed to replicate the sprinkle experiment in 2012, here again using both the SNOWPACK and 2-D models. The water-content distributions at 80 min (a and b) and 250 min (c and d) after the start of water-sprinkle experiment are shown. Both simulations showed water infiltrating as matrix flow in wet-snow layers and as preferential flow in dry-snow layers (Fig. 5 a, b). Although water ponding occurred in both simulations, its position differed between the two models. SNOWPACK showed water ponding at the interface of the finer-dry-over-coarser-wet snow layers (blue arrow in Fig. 5 c). In contrast, the 3-D model showed water ponding at the interface of the coarser-wet-over-finer-dry snow layers (red arrow in Fig. 5 d). Although capillary force is usually stronger in finer snow grains, water infiltration is less into dry snow than into wet snow due to both water entry suction and unsaturated conductivity. Hence, the position of water ponding differed between the two models; the actual position requires confirmation by laboratory experiments or field observations. However, the 3-D model produced better agreement for runoff. The delay of simulated runoff by the 3-D model and SNOWPACK with respect to the observed one was about 30 and 80 min, respectively. The observed timing was 80 min on average.

4.3. Low water infiltration over a long period

Fig. 6 shows the liquid water distribution at 27 and 150 h for the cold-laboratory two-week experiment. The 2-D model initially produced one preferential flow path (Fig. 6b). The area of the preferential flow path increased by more than 40% after 6 days (Fig. 6d). Although the SNOWPACK simulation showed the formation of

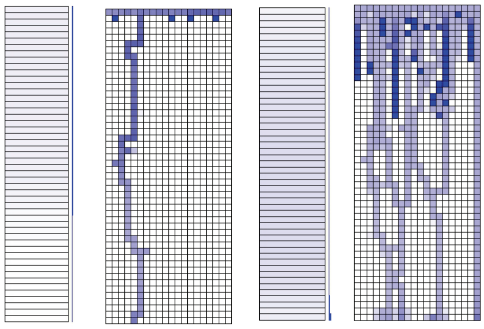


Fig. 6. SNOWPACK (a, c) and 2-D (b, d) model simulations of the long, low intensity, cold-laboratory experiment. In SNOWPACK, the box on the left and right line shows the liquid water content in the matrix-flow and in the preferential flow zones, respectively. In the 3-D model, the blue scale represents liquid water content. The capture time is at 1,600 (a, b) and 9,000 (c, d) min after the start of the experiment.

preferential flow, infiltration by matrix flow started earlier and all the snow quickly became wet (Fig. 6 a, c).

5. SUMMARY

To the best of our knowledge, this is the first study to compare the SNOWPACK and 3-D models under various experimental conditions. Qualitatively, SNOWPACK simulations using the dual-domain approach showed similar patterns of water infiltration to those of the 3-D model. However, our study also revealed the following differences between the models: the water transport rate by preferential flow was lower in SNOWPACK; matrix flow formation and transition to wet snow occurred more rapidly in SNOWPACK; and water ponded at layer transitions characterized by different grain size properties (finer-dry-over-coarser-wet snow layer in SNOWPACK, coarser-wet-over-finer-dry in the 3-D model.) The 3-D model replicated the laboratory experiments with greater accuracy than did the SNOWPACK model. However, this does not necessarily indicate that the 3-D model always reproduces the actual processes accurately, and more laboratory experiments or field observations are necessary. Our results suggest that the 3-D model could be used to improve the accuracy of the SNOWPACK model by refining the parameters used in the dual-domain approach. Such improvements could enhance the ability of SNOWPACK to simulate liquid-water infiltration into snow, thereby improving its ability to predict the formation of wet-snow avalanches.

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