OBSERVATION OF FINGERING FLOW AND LATERAL FLOW DEVELOPMENT IN LAYERED DRY SNOWPACK BY USING MRI

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ABSTRACT: Fingering flow develops due to the infiltration of snow meltwater or rain water into dry snowpack. The width, spacing, and areal coverage of the fingering flow path and occurrence of capillary barriers have been demonstrated using dye tracer experiments that were conducted at the field and in cold laboratories. However, the initial shape and temporal development of fingering and lateral flows are unclear because a vertical or horizontal section of snow is needed to observe them. To examine this, we carried out non-destructive observations of fingering flow development and capillary barriers in layered snow in a cold laboratory using Magnetic Resonance Imaging (MRI) via 3-dimensional rapid imaging method. μCT was also used to associate the water flow phenomena with the snow microstructure. The snow column was directly sampled in the vertical direction using the infiltration column from a natural snow-pack without breaking the layered structure of the snow. The experimental results showed that fingering flows developed in all of the snow samples. Fingering flow path increased and lateral flow developed through the continuing water supply. The small discontinuity of pore size and snow density in the vertical direction acted as capillary barriers and induced a lateral flow. These results showed that the persistence of a fingering flow path and an increase in the number of flow paths are important phenomena in understanding the infiltration of water into dry snow, which are needed develop snowpack models that include water moving processes. Detailed information on the heterogeneity of pore distribution and snow microstructures in layered snowpack are needed to understand the water flow phenomena in a natural snowpack.

KEYWORDS: Fingering flow, Lateral flow, Capillary barrier, MRI, μCT

1. INTRODUCTION

The complex nature of the movement of liquid water in snowpack is one of the reasons that makes it difficult to evaluate snowpack instability that leads to wet snow avalanches and runoff from snowpack. Spatial variations in water flow and snow properties appear as a result of developing fingering flow. Fingering flow that has a diameter of several centimeters develops due to the infiltration of snow meltwater or rain water into dry snowpack (Marsh and Woo, 1984). A lateral flow forms at the boundary between a fine layer over a coarse layer and functions as a "capillary barrier" (Wakahama, 1963; Jordan, 1996). The width, spacing, and areal coverage of the fingering flow path and occurrence of capillary barriers have been demonstrated using dye tracer experiments that were conducted at the field (Marsh and Woo, 1984; Williams et al., 2010) and in cold laboratories (Waldner et al., 2004; Katsushima et al., 2013; Avanzi et al., 2016). Numerical simulation models of fingering flow were developed and validated using these experimental results (Hirashima et al., 2017; Leroux and Pomeroy, 2017). However,

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the initial shape and temporal development of fingering and lateral flows are unclear because a vertical or horizontal section of snow is needed to observe them. Also, it remains unclear as to how much difference in snow micro-structures is required for the formation of capillary barriers.

To examine this, we carried out non-destructive observations of fingering flow development and capillary barriers in layered snow in a cold laboratory using Magnetic Resonance Imaging (MRI) via 3-dimensional rapid imaging method. µCT was also used to associate the water flow phenomena with the snow microstructure.

2. METHODS

Infiltration experiments were conducted inside the RF coil of an MRI system at a cold laboratory where air temperature was controlled at 0 °C in National Research Institute for Earth Science and Disaster Resilience, Shinjo Cryospheric Environment Laboratory. The snow column was directly set in the RF coil. Aqueous copper sulfate solution (5 mmol/l) was used for the MRI contrast agent. Water was constantly supplied to the snow sample surface at a point source via a peristaltic pump (SJ-1220Ⅱ-L, Atto Co., Tokyo, Japan) at a rate of approximately 4-6 mm h^{-1}. A wet thin cotton gauze was placed at the top of the snow column to buffer the droplet impact and horizontally diffuse water.

The experiments were performed using the dry snow of decomposing and fragmented precipitation particles (DF). It was directly sampled in the vertical direction using the infiltration column from a natural snowpack without breaking the layered structure of the snow. We selected uniform dry snow layers that do not have flow paths and layer differences in the vertical direction. An acrylic infiltration column that has an inner diameter of 36 mm and a height of 100 mm was used for the experiments. The thickness of the column wall and edge was 0.8 mm and 0.3 mm, respectively. The edge was sharpened to be as sharp as possible for easy sampling.

We used an upright open MRI system using permanent magnets that have 1.5 T of static magnetic field intensity (MR Technology Inc., Tsukuba, Japan) to non-destructively visualize the water distribution in snow samples (Adachi et al., 2012). The development of water movement over time was obtained from the 3-D water distribution data at 2.5-minute intervals at a spatial resolution of 0.4 mm and pixels of 128 × 128 × 128 with the 3-dimensional rapid imaging method using the Gradient Echo sequence with Compressed Sensing (Lustig et al., 2007). The 3-D distortion correction for MRI images was used to reduce image distortion that caused by magnetic field distortion.

3-D snow microstructure data that are obtained by X-ray µCT (µCT 35, SCANCO Medical AG, Switzerland) was used to evaluate the association between water flow phenomena and snow properties. For the snow microstructure measurements, another snow sample was taken from the same snow layer as the sample used in the MRI experiment. This data were taken at a spatial resolution of 20 µm. Profile data of pore size diameter in the Z direction were obtained from the horizontal slice data of snow using the Watershed method of ImageJ/Fiji software (Schindelin et al., 2012). Snow density profiles were also obtained from these data. The moving averages of the profile data over 0.4 mm were used for analysis.

3. RESULTS

3.1 Observations of water flow using MRI

The time series of water distribution over the duration of the experiment is shown in Figure 1. In the case of fingering flow (a), horizontal diffusing and ponding of water occurred at the upper part of the column where there was a capillary barrier during the early stages of the experiment. After that, fingering flow suddenly appeared and divided the flow into two near the center of sample. The diameter of fingering flow path was not constant in the Z-direction. It appears that the dimension of fingering flow was affected by the snow property and the upper and lower layering. After approximately 25 minutes, another fingering flow was newly formed from the top of the sample through the dry part of sample. The flow paths became complicated due to flow ponding and division at the boundaries of the capillary barrier.

In case of the capillary barrier (b), the flow was more complicated compared to the fingering flow (a). The fingering flow formed in the layers between the capillary barrier boundaries. The lateral flows formed on several layer boundaries of the capillary barriers after reaching the fingering flow. At least three significant capillary barrier boundaries appeared within the imaging range of 51.2 mm in the height direction. As a result, water reached most parts of snow column.

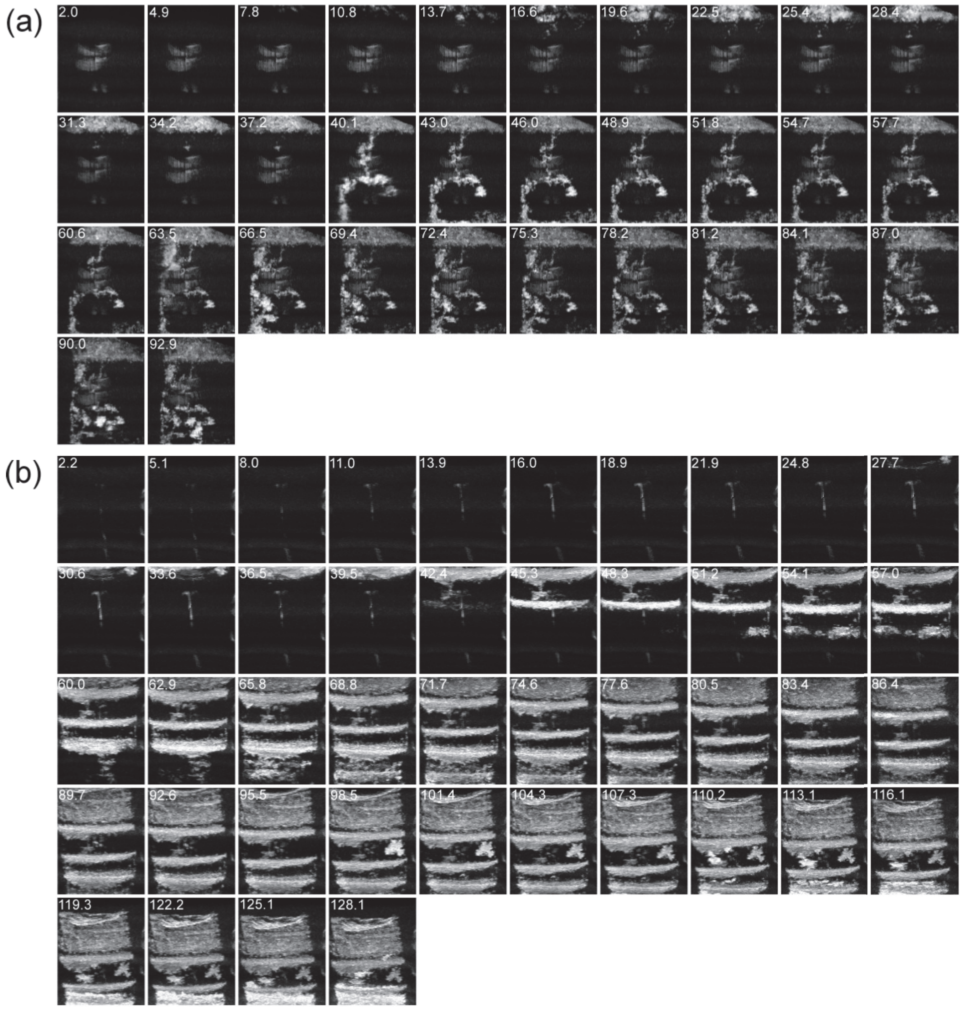

Figure 1: Time series of water distribution visualized by MRI at intervals of 2.5 minutes at 14.4 mm – 65.6 mm from the bottom of the sample: (a) fingering flow (snow type = DF, bulk snow density=155 kg m^{-3}, water flux=4.5 mm h^{-1}) and (b) Capillary barrier (snow type = DF, bulk snow density=181 kg m^{-3}, water flux=6.7 mm h^{-1}). Numbers in the upper left of panels show the time from the start of infiltration in minutes. Maximum Intensity Projection (MIP) was used to visualize 3-D data to 2-D. White pixels show high brightness corresponding to high water content, and black pixels show where the signal from the water cannot be detected corresponding to dry areas. Pixels that are located outside of the snow column were trimmed to remove the false echo from the cooling tube in the RF coil.

Figure 2 shows the equivalent circular diameter of cross-section of fingering flow path in the case of fingering flow (a). It was estimated from the MIP images that is stacked from infiltration start to each time. Binary image of that were created by using Maximum Entropy thresholding method. Averaged diameter of 1st and 2nd fingering flow path were approximately 4 mm. There was no significant changing in the shape and widening the diameter of flow once fingering flow developed. An increasing diameter of 1^{st} fingering flow was observed from 78 minutes, but it seems to be due to rapid snow-settlement by wetting.

3.2 Comparison with snow microstructure data

The profiles of average pore diameter, snow density (obtained using X-ray μCT), and average brightness (obtained using MRI) are shown in Figure 3. Snow density tended to decrease and the pore size tended to increase in the Z direction in case of both (a) and (b). In case of the fingering flow (a), there were two significant fine-over-coarse layering in the upper part (z = 45.2–41.2 mm) and near center (z = 23.2–21.8 mm) of the snow column. This layering corresponds to capillary barrier boundaries that were observed via MRI. The difference in pore size and density was 81 μm and 24 kg m^{-3}, respectively, for the upper part and 43 μm and 19 kg m^{-3}, respectively, for the central part. The differences in the upper part of sample are smaller compared with that of the central part. Smaller differences also existed in the other parts; however, these were not significant compared with that of the capillary barrier boundaries.

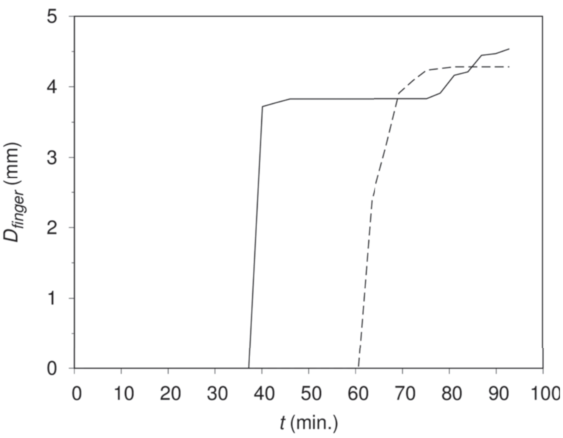

Figure 2: Equivalent circular diameter of cross-section of fingering flow path at the center of an imaging range for the Z direction (z = 25.6 mm) in the case of fingering flow (a). Line shows the diameter for 1st fingering flow and dash line shows the 2nd fingering flow.

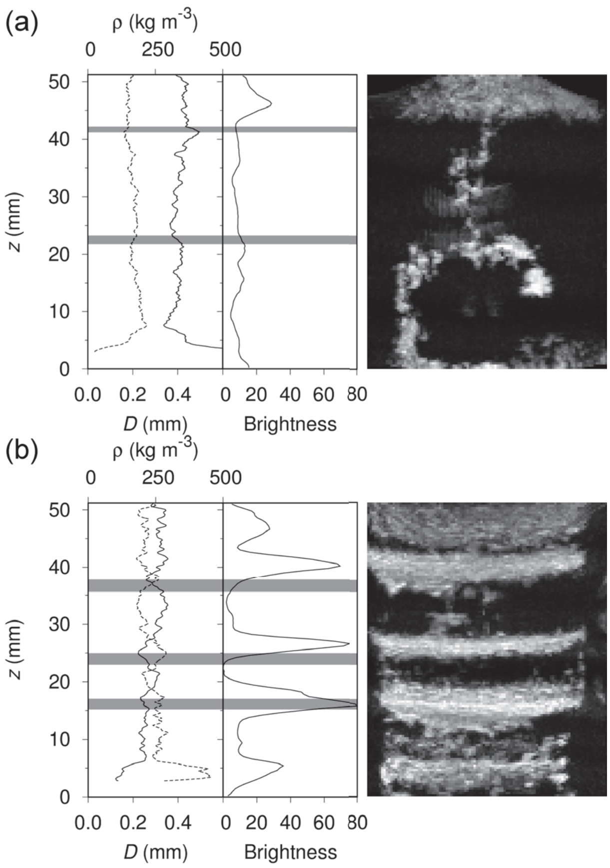

Figure 3: Comparison between profiles of averaged pore diameter, snow density (obtained by X-ray µCT) and averaged brightness (via MRI): (a) Finger-ing flow experiment, at 43 minutes after beginning water supply, (b) Capillary barrier experiment, at 69 minutes. The lines on the left of the figures show pore diameter, and the dashed line shows snow density. Gray colored area show capillary barrier boundaries.

In case of the capillary barrier (b), there were a lot of small and large layer differences within a small area of the sample. The differences in pore size for significant water ponding at the upper (z = 37.7–35.6 mm), central (z = 24.9–23.0 mm), and lower (z = 17.0–15.2 mm) parts were 77, 50, and 38 µm, respectively, and that of density were 67, 42, and 28 kg m^{-3}, respectively.

4. DISCUSSIONS

MRI observations revealed an increasing number of fingering flow paths through the continuing water supply. There were no significant changes in the shape and diameter of the flow once fingering flow developed. This experimental result reveal the same phenomena as that observed in the 2-D infiltration experiment on dry sand (Glass et al., 1996).

The mechanism for fingering flow persistent in dry sand is explained by the existence of the water-entry capillary pressure required for initial wetting and the hysteresis behind the fingering flow path (Glass et al., 1996; Liu et al., 1994). The water-entry value for dry snow was also measured in experiments involving fingering flow (Katsushima et al., 2013). It appears that the persistence of fingering flow path and increase in the number of flow paths are both important factors to understand water infiltration into dry snow and to develop a snowpack model that includes water moving processes.

These experiments also demonstrated that capillary barrier boundaries appear on the layer boundary even with small differences in snow property. These differences are smaller than those observed in previous studies (Waldner et al., 2004; Avanzi et al., 2016). The small discontinuity of pore size (40 µm) and snow density (20 kg m^{-3}) in the vertical direction acted as a capillary barrier and induced a lateral flow. The degree of pore size difference between the upper and lower layers may influence the temporal development of flow patterns, such as fingering and lateral flows. Moreover, the diameter of fingering flow path was not constant in the Z-direction. Smaller differences of pore size also existed in the fingering flow layer. It seems that diameter of fingering flow is affected by not only the snow property but also the surrounding snow layering. These results demonstrated that detailed information on the heterogeneity of the pore distribution and snow microstructures in layered snowpack are needed to understand the water flow phenomena in a natural snowpack.

5. CONCLUSIONS

Flow patterns during infiltration into dry layered snow were non-destructively observed using MRI at a cold laboratory. Fingering flows developed in all of the snow samples. Fingering flow path increased and lateral flow developed through the continuing water supply. The small discontinuity of pore size and snow density in the vertical direction acted as capillary barriers and induced a lateral flow. These results showed that the persistence of a fingering flow path and an increase in the number of flow paths are important phenomena in understanding the infiltration of water into dry snow, which are needed develop snowpack models that include water moving processes. Detailed information on the heterogeneity of pore distribution and snow microstructures in layered snowpack are needed to understand the water flow phenomena in a natural snowpack.

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