ON THE RELATIONSHIP BETWEEN WATER INFILTRATION AND SNOWPACK STRUCTURE

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ABSTRACT: The type of wet-snow avalanche varies with the circumstances of water infiltration caused by snowpack structures consisting of various snow-grain types. To clarify the nature of water infiltration within snowpack on a slope, we carried out a field experiment to evaluate the relationship between water infiltration and snowpack structure. In the field experiment, water that was colored yellow by fluorescent dye was sprayed onto the surface of natural snowpack for 1 h at a rate of 30 mm/h. Water infiltration was then observed by snow-pit observations that were carried out over a period of 4 h at intervals of 1 h, beginning from the start of the water spraying. In the case of snowpack that had rounded fine grains below the freezing point on a slope, water tended to flow along snow layers and/or a water-ponding layer to lower part of slope but did not reach the bottom of the snowpack. However, in the case of snowpack that consisted of melt-form coarse grains at the freezing point on the slope, water flowed along the water-ponding layer, also penetrated vertically, and reached the ground surface. The results of the experiment also showed that water within snowpack reached the ground faster on level ground than on a slope. Therefore, these suggest that differences in water infiltration through snowpack between level ground and slope have to be considered when estimating avalanche occurrence by using a numerical model.

KEYWORDS: water infiltration, snowpack structure, inclined snow layer, rain on snow

1. INTRODUCTION

Rain-on-snow events will cause disasters such as wet-snow avalanches and floods due to runoff of much water from snowpack on slopes. For estimating the disasters and evaluating the damages caused by these events, knowledge of liquid water infiltration through snowpack is one of important factor. For example, Conway and Raymond (1993), Trempeter (2008) and Conway et al. (2009) suggested that types of wet-snow avalanches, which are surface and/or full-depth avalanches, depend on difference of liquid water infiltration through snowpack cause by snow stratigraphy such as snow grain types and size.

The liquid water infiltration through snowpack has been studied by laboratory experiments using natural snow blocks (e.g., Sugie et al., 2000; Waldner et al., 2004; Yamaguchi et al., 2012) and field experiment using dye tracer (e.g., Wakahama, 1975; Nomura, 1994; Schneebeli, 1995; Peitzsch et al., 2008), and numerical simulations (e.g., Wankiewicz, 1979; Katsushima et al., 2013; Mitterer et al., 2011; Hirashima et al., 2013) based on theoretical examinations (e.g., Colbeck, 1978; Jordan et al., 2008). Hydrological response of snowpack under rain-on-snow events has also been examined in both the field observations and numerical analysis (e.g., Singh et al., 1997; Kohl et al., 2001). However, there is no experiment concerning on the relation between liquid water infiltration and snow stratigraphy in inclined snowpack on natural slope including of liquid water penetration to the bottom of snowpack.

To clarify the nature of liquid water infiltration through snowpack on a slope, we carried out a field experiment using a dye tracer. In particular, we paid attention to the relationship between liquid water infiltration and snow stratigraphy and the difference in its relation between snowpack on level ground and slope.

2. METHODS

Field experiments were conducted at Jozankei (43° 1.9’ N, 141° 7.7’ E, 400 m a.s.l.) in Sapporo, Japan. Slope in gradient of about 30° is closed near to level ground. In the field experiment, liquid water that was colored yellow by fluorescent dye was sprayed onto the surface of natural snowpack for 1 h at a rate of 30 mm/h, which correspond to 4 liters per minute. The rate of rainfall in the experiment is greater than that in the actual rain-on-snow events in Japan (Matsushita and Ikeda, 2011; Hirashima et al., 2013) based on theoretical examinations (e.g., Colbeck, 1978; Jordan et al., 2008).
The spraying area is 4 m in width and 2 m in length, and colored water was sprayed in angle of 90° from two nozzles which were installed in height of 1 m from snow surface (Fig. 1 and Fig. 2). To maintain the constant amount of spraying water as the rate of 30mm/h, reducing valves and flow-meters for each nozzle were installed in pump used in the experiments. Water infiltration within snowpack was then observed by snow-pit observations that were carried out over a period of 4 h at intervals of 1 h, beginning from the start of the water spraying. In the snow-pit observation, snow temperature and density were measured at vertical intervals of about 10 cm or at each snow layer. Snow grain type and size (Tbl. 1) were also observed in the snow-pit observation before water spraying. The field experiments were carried out four times in 2013 and 2014 for various snow stratigraphies (Tbl. 2).

### Table 1: Class for snow grain type and size

<table>
<thead>
<tr>
<th>Grain Size</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.5mm</td>
<td>a</td>
</tr>
<tr>
<td>0.5-1mm</td>
<td>b</td>
</tr>
<tr>
<td>1-2mm</td>
<td>c</td>
</tr>
<tr>
<td>2-4mm</td>
<td>d</td>
</tr>
<tr>
<td>4mm &lt;</td>
<td>e</td>
</tr>
</tbody>
</table>

### Table 2: Summary of conditions during experiments

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Weather</th>
<th>Air Temperature (°C)</th>
<th>Temperature of Sprayed Water (°C)</th>
<th>Inclination of Snow Surface (°)</th>
<th>Inclination of Ground Surface (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24 Feb. 2014</td>
<td>fair</td>
<td>-0.4 - 3.3</td>
<td>9.8</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>19 Mar. 2013</td>
<td>cloudy</td>
<td>-2.6 - 3.2</td>
<td>5.0</td>
<td>19</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>23 Apr. 2013</td>
<td>fair</td>
<td>9.4 - 10.7</td>
<td>9.8</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>9 Apr. 2014</td>
<td>fair</td>
<td>10.4 - 11.7</td>
<td>11.0</td>
<td>17</td>
<td>23</td>
</tr>
</tbody>
</table>

### 3. RESULTS

Table 2 shows weather conditions, air temperatures, sprayed water temperatures and inclinations of snow surface and ground surface at each experiment. Results of the experiments are summarized as follows.

#### 3.1 Experiment 1

Figure 3 shows the snow stratigraphy before water spraying and the water-ponding layer after water spraying on both the level ground and the slope. Figure 4 indicates the photographs of the cross-section of snowpack after water spraying. Figure 5 also shows the vertical profiles of snow temperature and density before water spraying and at 2 hours later from start of water spraying.

Snow temperature in whole of snowpack before water spraying was below 0 °C (Fig. 5). Although there were melt-form coarse grains below 120 cm in height on the level ground, snowpack over 120 cm in both the level ground and the slope were consisted of the same snow grain types, which are precipitation particles and rounded fine grains (Fig. 3). In particular, snowpack near the surface was covered by new snow precipitation particles.
In the snowpack on the level ground (Fig. 4a), the surface of snowpack greatly sank like a bowl-shaped depressions in places, and sprayed liquid water ponded at the boundary between the fine and the coarse textured layer (due to both the capillary barrier and the hydraulic barriers) and flowed down vertically through finger flows to the bottom of the snowpack. Conversely, on the slope (Fig. 4b), snow surface depression occurred uniformly in the sprayed area, and sprayed water did not infiltrate below the deepest water-ponding layer which was formed at boundary between fine grains over coarse grains (not shown in Fig. 3) but flowed to the lower part of the slope along the water-ponding layer.

Therefore, the result of this experiment indicates that significant difference in liquid water infiltration within snowpack between the level ground and the slope exists. In the case of snowpack that consisted of precipitation particles and rounded grains below the freezing point on the slope, liquid water tended to flow along snow layers and/or water-ponding layer and did not reach the bottom of the

Fig. 3: Snow stratigraphy before spraying water on (a) level ground and (b) slope in the experiment 1 on 24 February, 2014. Arrows indicate the locations of water-ponding layers after spraying water. Symbols of snow grain type and sighs of grain size are shown in Tbl. 1.

Fig. 4: Photographs of cross-sections of snowpack after the spraying water on (a) level ground and (b) slope in the experiment 1 on 24 February 2014.

Fig. 5: Vertical profiles of snow temperature $T$ and density $\rho$ before spraying water and at 2 hours later from start of spraying water on (a) level ground and (b) slope in the experiment 1 on 24 February 2014.
snowpack. In addition, the bowl-shaped depressions of the snow surface and the finger flow which were formed in the snowpack on the level ground did not occur in snowpack on the slope.

3.2 Experiment 2

The results of the experiment 2 are shown in Fig. 6, Fig. 7 and Fig. 8 in the same as the experiment 1. In the snowpack on the slope before water spraying, snow temperature below 240 cm in height from the ground surface was below 0 °C but snow temperature over 240 cm was nearly 0 °C (Fig. 8b). Conversely, in the snowpack on the level ground, snow temperature in whole of the snowpack before water spraying was already about 0 °C (Fig. 8a). However, significant difference in snowpack structure between the level ground and the slope did not be observed (Fig. 6). Snowpack consisted of the rounded fine grains and melt-form coarse grains.

Fig. 6: Snow stratigraphy on (a) level ground and (b) slope in the experiment 2 on 19 March 2013. Details of information are the same as that in Fig. 3.

Fig. 7: Photographs of cross-sections of snowpack at 2 hours later from start of spraying water on (a) level ground and (b) slope in the experiment 2 on 19 March 2013.

Fig. 8: Vertical profiles of snow temperature $T$ and density $\rho$ before spraying water and at 2 hours later from start of spraying water on (a) level ground and (b) slope in the experiment 2 on 19 March 2013.
In the snowpack on the level ground at 2 hours later from start of water spraying (Fig. 7a), many water-ponding layers were formed and water flowed down to the bottom of snowpack through the finger flows which was thicker than that in the experiment 1. In contrast, in the snowpack on the slope (Fig. 7b), water flow was impeded by the boundary of melt-form coarse grains over rounded fine grains (due to the hydraulic barriers caused in the condition of high water flux indicated by Wankiewicz (1979)) in deep of about 30 cm from the snow surface, and the water flowed along inclined the water-ponding layer and did not reach the bottom of the snowpack. In addition, the water-ponding layer in the snowpack on the slope corresponded to the boundary of snow temperature 0 °C (Fig. 8b).

The result of the experiment 2 that indicated the difference in infiltration within snowpack between the level ground and the slope will support the result of the experiment 1. However, the depression of snow surface that formed in the experiment 1 did not occur in the experiment 2 because of difference in snow grain type near the snow surface.

### 3.3 Experiment 3

The results of the experiment 3 are shown in Fig. 9, Fig. 10 and Fig. 11. Temperatures of snowpack on both the level ground and the slope before water spraying were approximately 0 °C (Fig. 11).

**Fig. 9:** Snow stratigraphy on (a) level ground and (b) slope in the experiment 3 on 23 April 2013. Details of information are the same as that in Fig. 3.

**Fig. 10:** Photographs of cross-sections of snowpack at 1 hour later from start of spraying water on (a) level ground and (b) slope in the experiment 3 on 23 April 2013.

**Fig. 11:** Vertical profiles of snow temperature $T$ and density $\rho$ before spraying water and at 1 hour later from start of spraying water on (a) level ground and (b) slope in the experiment 3 on 23 April 2013.
Snowpack consisted of most melt-form coarse grains and some rounded fine grains and ice layers also existed in whole of the snowpack (Fig. 9).

In the snowpack on the level ground (Fig. 10a), sprayed water reached the bottom of the snowpack within 1 hour from start of water spraying. In the snowpack on the slope (Fig. 10b), both the flows along the water-ponding layer and in vertical to the lower part of the snowpack existed. The sprayed water within the snowpack on the slope penetrated down step by step but did not reach the bottom of the snowpack. Moreover, finger flows in the snowpack on the slope did not be clear because the gravity will act to the water movement in two directions which are in vertical and along the snow layer.

In the case of snowpack that consisted of melt-form coarse grains and rounded fine grains at the freezing point on the slope, liquid water flowed along a water-ponding layer and also penetrated vertically, but did not reaches the ground surface.

3.4 Experiment 4

The results of the experiment 4 are shown in Fig. 12, Fig. 13 and Fig. 14. Temperatures of the snowpack on both the level ground and the slope before water spraying were approximately 0 °C (Fig. 14). Snowpack consisted of only the melt-form coarse grains except in some part of the snowpack on the level ground (Fig. 12).

Fig. 12: Snow stratigraphy on (a) level ground and (b) slope in the experiment 4 on 9 April 2014. Details of information are the same as that in Fig. 3.

Fig. 13: Photographs of cross-sections of snowpack after the spraying water on (a) level ground and (b) slope in the experiment 4 on 9 April 2014.

Fig. 14: Vertical profiles of snow temperature $T$ and density $\rho$ before spraying water and at 2 hours later from start of spraying water on (a) level ground and (b) slope in the experiment 4 on 9 April 2014.
The sprayed water penetrated vertically and reached the ground surface within 1 hour from start of water spraying in the snowpack on both the level ground and the slope (Fig. 13). In particular, in the snowpack on the slope, water flow along the snow layer did not exist but water penetrated uniformly in mostly vertical. The area of the snowpack on the slope in which water infiltrated was 70 cm from the edge of the area of water spraying in the direction to lower slope (Fig. 13b).

In the snowpack consisted of only the melt-form coarse grain, liquid water can flow down easily within snowpack on the level ground but also on the slope.

4. CONCLUSIONS

To clarify the relationship between liquid water infiltration through snowpack and snow stratigraphy on a slope, we carried out a field experiment by spraying water onto natural snow surface.

The results of experiments showed clearly the differences in water infiltration caused by various snowpack structures on the slope. In the case of snowpack that consisted of rounded fine grains below the freezing point on the slope, liquid water tended to flow along snow layers and/or water-ponding layer to lower part of the slope and did not reach the bottom of the snowpack. However, in the case of snowpack that consisted of melt-form coarse grains at the freezing point on the slope, liquid water flowed along a water-ponding layer, also penetrated vertically, and reached the ground surface. The differences in water infiltration due to snow stratigraphy will affect the type of wet-snow avalanche, such as a surface or full-depth avalanche (e.g., Tremper, 2008; Conway et al., 2009).

The results of the experiments indicated also differences in water infiltration through snowpack and in time required for reaching water at the ground surface between the level ground and the slope. These characteristics of liquid water infiltration through snowpack on the slope have to be considered when estimating avalanche occurrence by using a numerical analysis. However, quantitative evaluation of the liquid water flow along snow layer and the vertical flow through snowpack on slope is a future task.

REFERENCES


