SIMULATION OF LIQUID WATER INFILTRATION INTO LAYERED SNOWPACKS USING MULTI-DIMENSIONAL WATER TRANSPORT MODEL

Hiroyuki Hirashima[1]*, Satoru Yamaguchi[1] and Yoshiyuki Ishii[2]

[1]Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Prevention, Nagaoka, JAPAN
[2]Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan

ABSTRACT: In this study, simulations of liquid water infiltration into layered snowpacks were performed using a multi-dimensional water transport model. The characteristics of water infiltration at the interface of different snow layers were estimated by performing sensitivity experiments using fluctuating grain sizes and constant snow density. Sensitivity simulations with fluctuating snow densities and a constant grain size were also carried out. In addition, four patterns of initial water conditions, i.e., dry snow, wet snow, wet snow above dry snow, and dry snow above wet snow, were tested.

Simulation results showed that preferential flow formed in dry snow, whereas liquid water infiltrated relatively homogeneously in wet snow. In addition, water ponded at the interface of fine over course snow layers because of the capillary barrier effect. However, a capillary barrier did not always form at the interface of fine over coarse snow layers when the difference in grain size between the layers was small. On the other hand, there was the case that the liquid water ponded at the interface of coarse over fine snow layers in the case of wet snow above dry snow. Validation using laboratory experiments to ensure the results from these simulations are robust will be conducted in the future.

KEYWORDS: numerical model, liquid water movement, capillary barrier, preferential flow, sensitivity analysis

1. INTRODUCTION

Liquid water movement in a snowpack affects the arrival time of water at the snow base and occasionally leads to full-depth avalanche release. Preferential flow is an important process to estimate the arrival time of liquid water at snow bases because it accelerates the vertical movement of liquid water. However, liquid water sometimes ponds at the interface between layers, which have different snow densities or grain sizes due to capillary barriers. The blockage of liquid water by ice layers also causes water ponding. Capillary barriers and ice layers delay the vertical movement of liquid water. In an experiment conducted by Waldner et al. (2004), water ponded at the interface of fine over coarse snow layers due to a capillary barrier and then moved through the preferential flow path. Despite the importance of the influence of preferential flow, it is difficult to reproduce the formation of preferential flow in numerical snowpack models because most of these models are one-dimensional. Recently, a multi-dimensional water transport model for snowpacks was developed by Hirashima et al. (2014a) to reproduce preferential flow. Their model was based on the experimental results of Katsushima et al. (2013). In the study of Hirashima et al. (2014a), validation was performed for a single-layer column, which has the same mean density and grain size. The model developed by Hirashima et al. (2014a) reproduced the experimental results of Katsushima et al. (2013) fairly well. However, real snowpack has multiple layers of snow with different densities and grain sizes. Therefore, studies using simulations and laboratory experiments of water infiltration for different snow layers are needed. In this study, sensitivity analyses of liquid water movement at the interface between snow layers with different densities, grain sizes and liquid water contents were performed in the focus of the formation of preferential flow and the capillary barrier.

The goal of this study is to obtain parameters of the influence of preferential flow in order to implement the numerical snowpack model. Results of simulations using a combination of the numerical snowpack model SNOWPACK and the multi-dimensional water transport model are presented in an accompanying manuscript as another approach (Hirashima et al., 2014b)

* *Corresponding author address:*
Hiroyuki Hirashima, Snow and Ice Research Center, NIED, Maeyama, Suyoshi-machi, Nagaoka-shi, Niigata-ken, Japan 940-0821;
tel: +81-258-35-8932; fax: +81-258-35-0020;
email: hirasima@bosai.go.jp

2. SIMULATION METHOD

Details of the multi-dimensional water transport model are provided in Hirashima et al. (2014a). In the present manuscript, the equations used in the model are only referenced. Models of liquid water movement in porous media commonly use Richards' equation and the Darcy-Buckingham law. Capillary pressure gradients and hydraulic conductivity are needed to solve these equations. Although the equation parameters depend on porosity, pore shape, pore connectivity, size distribution, and tortuosity, they are frequently estimated from a combination of snow density and grain size (Jordan et al., 2008). Relationships between capillary pressure, water content, grain size and snow density have been determined by Yamaguchi et al. (2012) using a gravity drainage column experiment. In addition, relationships between saturated hydraulic conductivity, snow density and grain size were estimated by Calonne et al. (2012), who considered snow microstructure. Unsaturated hydraulic conductivity can be estimated using the van Genuchten-Mualem model (van Genuchten, 1980; Mualem, 1976). Consideration of water entry suction is necessary to reproduce preferential flow. Water entry suction was measured and formulated as a function of grain size by Katsushima et al. (2013), and using their formulas, Hirashima et al. (2014a) developed a multi-dimensional water transport model.

In this study, sensitivity experiments using two-dimensional simulations were performed using this multi-dimensional model with the following conditions: the grid sizes were set to 1 cm; the simulation area was 23 cm high and 20 cm wide; the water supply rate was 20 mm/h, and two layers were set (one at the upper 10 cm and one at the lower 10 cm). Katsushima et al. (2013) and Hirashima et al. (2014a) set the wet snow layer at the top to consider the filtering effect of wet snow. In the current simulation, the wet snow layer was also set at the top 3 cm. Hereafter, the snow layer of the top 3 cm, upper 10 cm and lower 10 cm are referred to as the top, upper and lower layer, respectively. The grain size and dry snow density of the top layer were the same as those of the upper layer. A schematic of the simulation area is shown in Fig. 1. This model requires a condition setting for heterogeneity to reproduce heterogeneous water infiltration. In this study, a heterogeneity value of 20% of the mean value was used for the grain sizes.

The characteristics of water infiltration at the interface were estimated by performing a sensitivity experiment. In the sensitivity experiment, the grain sizes in the upper and lower layers were fluctuated from 0.6 to 3.0 mm at 0.3-mm intervals with a constant dry snow density of 400 kg/m^3. In another sensitivity experiment, dry snow densities were fluctuated from 200 to 500 kg/m^3 at 50 kg/m^3 intervals with a constant grain size of 1 mm. Simulations of four patterns of the initial water condition were tested: 1) wet upper and lower snow layers, 2) dry upper and lower snow layers, 3) wet upper layer above a dry lower layer, 4) dry upper layer above a wet lower layer. The main difference between dry and wet snow is whether the water entry suction is affected. Dry snow affects the water entry suction because it is difficult to infiltrate liquid water into a dry snow layer. This leads to the formation of preferential flow and affects the characteristics of the capillary barrier.

In the initial setting, heterogeneities were provided using random numbers. As a result, the simulation results sometimes differed due to the random number sequence, even with the same mean density and grain size (e.g., differences in the number of preferential flow paths). In this study, five different random number sequences were used to generate the five patterns of heterogeneities. In other words, simulations were performed five times using the same mean snow conditions and different random number sequences. In the analysis of these results, some parameters (described later) were estimated. The average values of the parameters for the five simulations were calculated and used as the results of this sensitivity experiment. The influence of the random number sequences on the simulation result was reduced by averaging the five results.

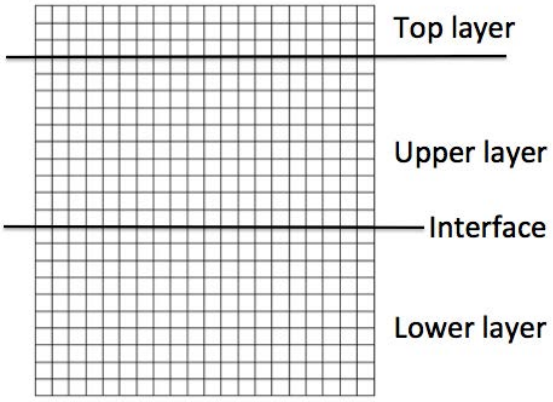


Fig. 1: Schematic of the simulation area used in this study.

In the sensitivity experiments, three indices were used to quantify the characteristics of water infiltration:

1) The difference in the volumetric water content between the upper and lower layers. The water content of the grids nearest the interface of the upper and lower layers was compared.

2) The thickness of the water ponding layer. When the average water content at an arbitrary height in the upper layer was more than double the average water content at the top of the upper layer, this was regarded as the water ponding layer.

3) The arrival time of water at the snow base from the beginning of the water supply.

3. RESULTS AND DISCUSSION

The differences in the water content of the upper and lower grids, the thickness of the water ponding layer, and the arrival time at the snow base are shown in Fig. 2, 3 and 4, respectively. The results presented in Fig. 2 and 3 occurred 90 minutes from the beginning of the water supply and represent a steady-state situation after the liquid water arrived at the snow base. In Figs. 2, 3 and 4, the x-axis is the grain size (mm) of the lower layer. The grain sizes of the upper layer were expressed using individual line charts. In Fig. 2, the difference in the water content is shown on the y-axis; positive values indicate a larger volumetric water content in the upper layer compared with the lower layer. There was a capillary barrier effect when the grain sizes of the upper layer were smaller than the lower layer.

3.1 Wet snow layers

The simulation results for wet snow layers are presented in Fig. 2a, 3a and 4a. When the grain size of the upper layer was 0.6 mm, a large quantity of water ponded due to the strong effect of the capillary barrier even if the difference in grain size between the upper and lower layer was small. When the grain size of the lower layer was larger than 1.5 mm, grids just above the interface were almost saturated (Fig. 2a) and the water ponding layer was more than 4 cm thick (Fig. 3a). Despite this, grain growth changes rapidly when snow contains liquid water, especially when the grain size is very small, and therefore this situation is considered a rare occurrence. If the grain size of the upper layer was larger than 1.5 mm, water did not pond at the interface even if the grain size of the lower layer was 30 mm.

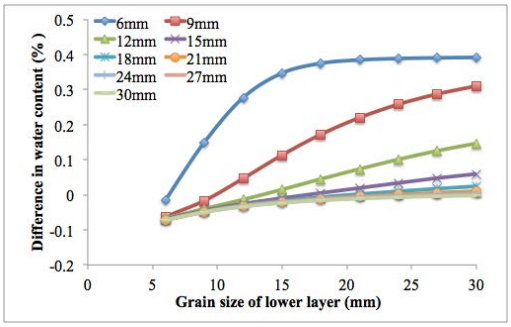
The arrival time of liquid water at the snow base was significantly affected by the grain size of the upper layer (Fig. 4a). When the grain size is small, snow has low hydraulic conductivity and large suction. The smaller grain size of the upper layer led to water ponding due to the capillary barrier. The small grain size delayed the arrival of liquid water at the snow base.

The grain size of the lower layer can affect water movement through its effect on hydraulic conductivity and suction, where a smaller grain size leads to a longer arrival time of liquid water. In addition, the capillary barrier is affected where a smaller grain size prevents water ponding and leads to a shorter arrival time. Since these are opposite effects, the relationship between the grain size of the lower layer and the arrival time of liquid water at the snow base did not show a consistent increase or decrease.

3.2 Dry snow layers

The simulation results for dry snow are presented in Figs. 2b, 3b, and 4b. These results exhibited trends that were similar to the wet snow although the effect of the capillary barrier was somewhat smaller (compare Figs 3a and b). The water content distribution, however, was different from wet snow.

The water content distributions for initially wet and dry snow are shown in Fig. 5. The same grain size, density and random number sequence was used to generate heterogeneity. In the case of initially dry snow (Fig. 5a), liquid water moved through the preferential flow path. At the interface of the upper and lower layers, a water-saturated area formed around the intersection of the preferential flow path and the interface between the upper and lower layer. Then, liquid water infiltrated into the lower layer before the water-saturated area dispersed to all horizontal grids above the interface. The water-saturated area around two preferential flow paths were not connected because water does not easily infiltrate into surrounding dry snow due to the effect of water entry suction. In the case of initially wet snow, the amount of liquid water in the ponding area was smaller than in the initially dry snow (Fig. 5b).



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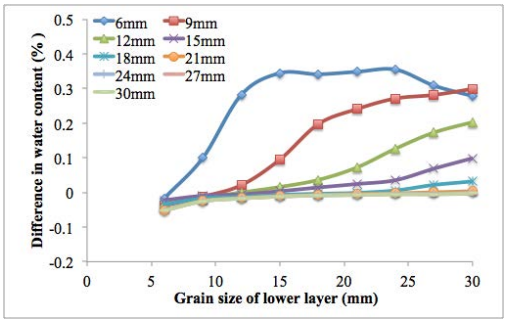

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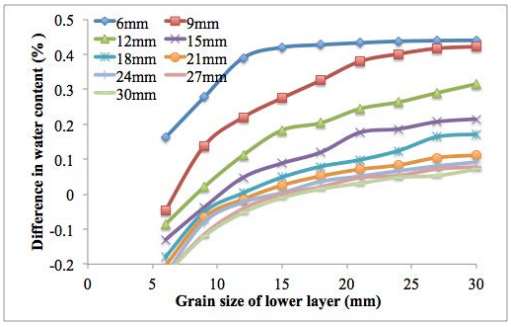

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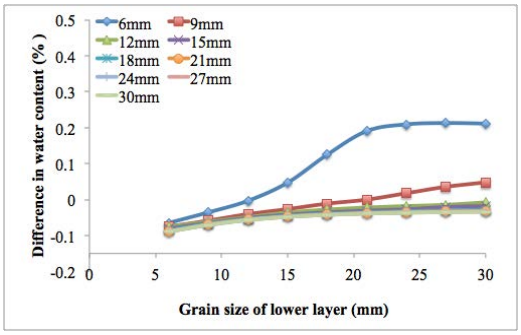

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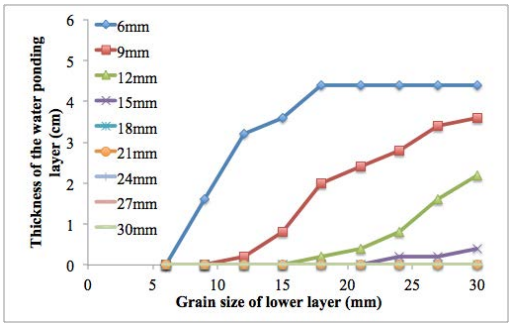
Fig. 2: The difference in the water content between the upper and lower grids of the interface (a: wet snow, b: dry snow, c: wet snow over dry snow, d: dry snow over wet snow).



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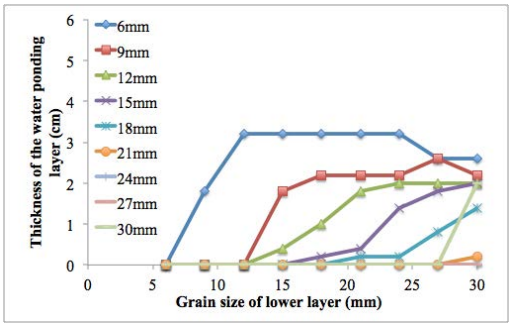

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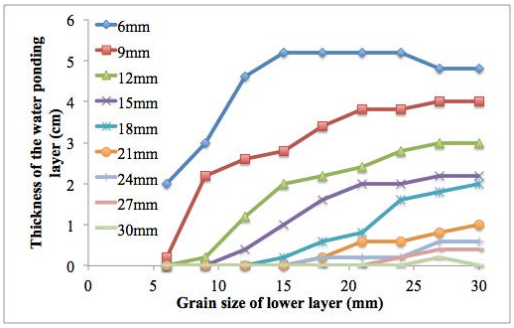

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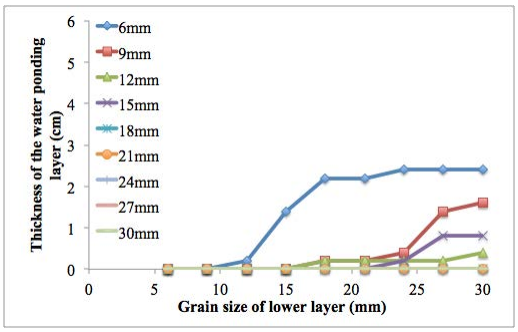

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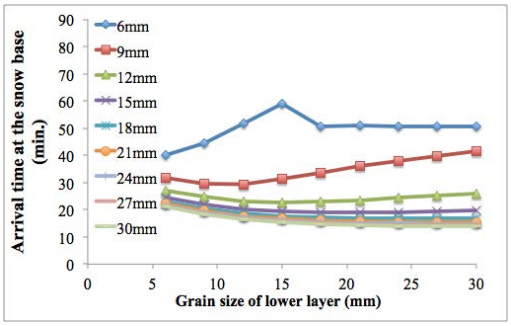
Fig. 3: Thickness of the capillary barrier. The threshold of the determination of the capillary barrier was a water content in the upper layer that was twice the water content in the top of the upper snow layer (a: wet snow, b: dry snow, c: wet snow over dry snow, d: dry snow over wet snow).



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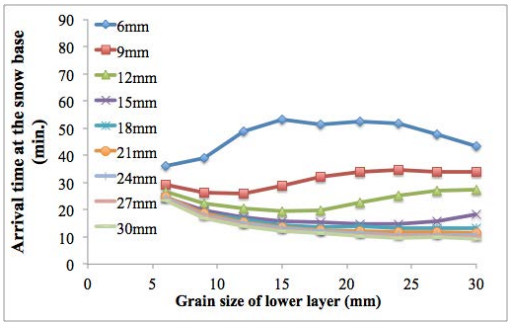

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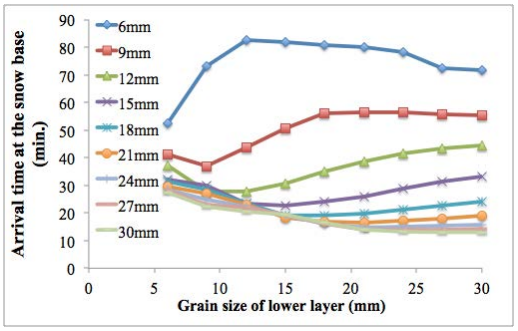

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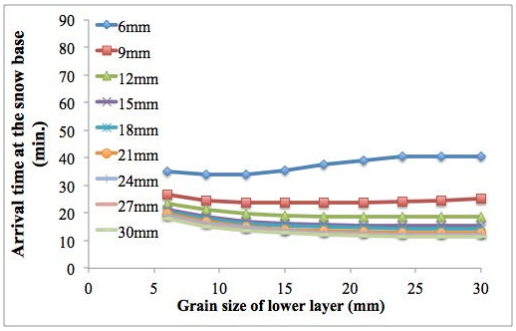

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Fig. 4. The arrival time of liquid water at the snow base for each simulation (a: wet snow, b: dry snow, c: wet snow over dry snow, d: dry snow over wet snow).

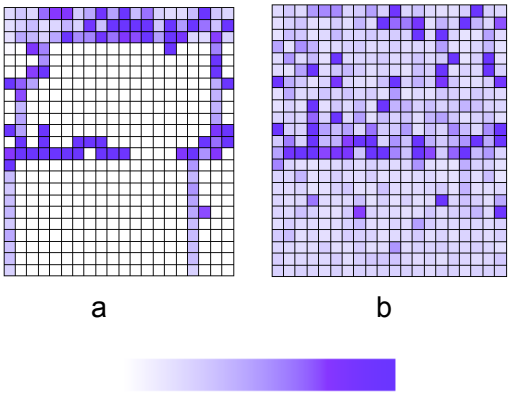

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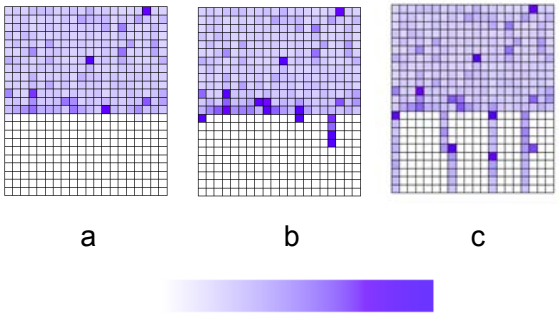
Fig. 5 Comparison of liquid water distribution for initially wet and dry snow. Both simulations are for fine (0.9mm) over coarse (1.8mm) snow layers. (a) initially dry (b) initially wet.

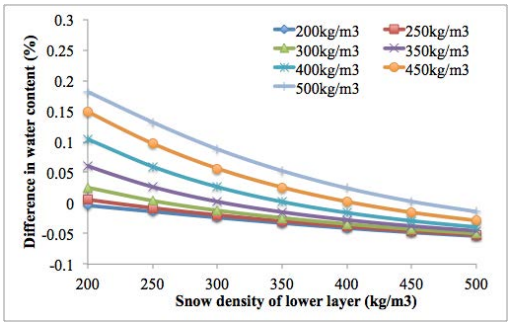


a b c

Fig. 6 Temporal change in the water content distribution for the case of coarse wet (2.1 mm) over fine dry (1.8 mm) snow layers. (a) before the formation of preferential flow, 11 minutes after the start of the water supply (b) just after the formation of preferential flow, 15 minutes (c) after development of sufficient preferential flow, 60 minutes.

3.3 Mixed dry and wet snow layers

In the case of wet snow above a dry snow layer, significantly mode water ponded at the interface compared with other cases (see Fig. 2c and 3c). The effect of the capillary barrier was greatest in this case because it is difficult for liquid water to infiltrate into lower dry snow whereas it is relatively easy for liquid water to disperse in the surrounding upper wet snow. Consequently, it took longer for the liquid water to arrive at the snow base, especially when the grain size of the upper snow layer was small (see Fig. 4c). Furthermore, there was a unique case that liquid water ponded even when the grain size of the upper layer was larger than



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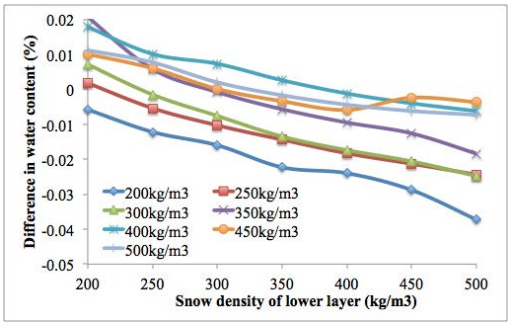

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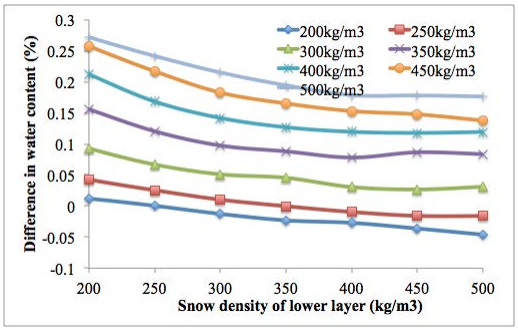

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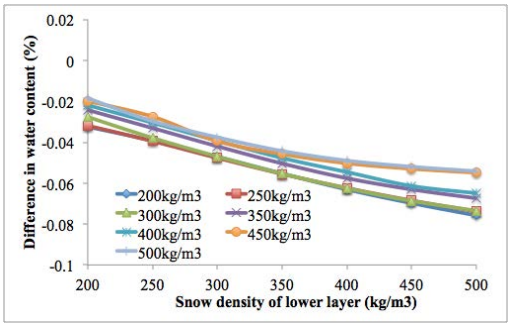

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Fig. 7 The difference in the water content between the upper and lower grids of the interface with fluctuating snow densities (a: wet snow, b: dry snow, c: wet snow over dry snow, d: dry snow over wet snow).

that of the lower layer (see Fig. 3c; e.g., 2.1 mm in the upper layer and 1.8 mm in the lower layer).

Water infiltration under this condition is shown in Fig. 6. When the difference in grain size between the layers was small, liquid water did not easily infiltrate into the lower layer due to the influence of water entry suction (Fig. 6a). After that, a preferential flow path formed in the dry snow layer (Fig. 6b) and the water content gradually decreased. Even after the preferential flow formed, the water content immediately above the interface was greater than in the other upper layer grids because the water pass was restricted in the preferential flow path at the interface.

In the case of dry above wet snow layers, water rarely ponded (see Fig. 3d), in contrast to the case of wet above dry snow layers (compare with Fig. 3c). Even in this case, water ponded at the interface if the grain size of the upper layer was very small (0.6 mm, see Fig. 3d). If the difference in grain size between the layers was not that great, water did not pond. Consequently, the arrival time of liquid water at the snow base was shorter than in the other cases (see Fig. 4d).

3.4 Sensitivity tests with fluctuating snow density

The difference in the water content at the interface of snow layers is shown in Fig. 7 for fluctuating snow density and a constant grain size. Liquid water ponded when the snow density of the upper layer was greater because dense snow has a larger suction than low density snow. The relationship between snow density and suction is the opposite of the relationship between grain size and suction (Yamaguchi et al., 2012). However, water ponding in this case is rare because the snow density of the upper layer is usually smaller than the lower layer. Therefore, the difference in snow density is considered to mitigate the capillary barrier effect in fine over coarse snow.

The sensitivity simulations showed that patterns of water infiltration are complex. These results suggest that more simulations and validations using laboratory experiments are necessary for the parameterization of the effect of the capillary barrier and preferential flow. These types of experiments will be conducted in future studies.

4. SUMMARY

Sensitivity experiments were carried out with fluctuating grain size or snow density to analyze the characteristics of the formation of the capillary barrier and preferential flow path. Simulated results

showed that preferential flow formed in the initially dry snow whereas the liquid water infiltrated relatively homogeneously in the initially wet snow. In addition, water ponded at the interface of fine over course layers due to the effect of the capillary barrier. These results are consistent with the trends obtained in laboratory experiments in other studies.

The capillary barrier did not always form at the interface of fine over coarse snow layers especially when the difference in grain size was small. On the other hand, depending on the initial water condition, there was an event where water ponded at the interface of coarse over fine snow layers.

These sensitivity results need to be validated using laboratory experiments in the near future, which will provide a guide to estimate the effect of the capillary barrier and preferential flow on a natural snowpack. The results from laboratory experiments will be parameterized to implement a numerical snowpack model. Therefore, the challenge is to develop a method to convert simulated heterogeneous water transport into a simple equation. In addition, an improved water transport model with increased accuracy (described in Hirashima al. (2014a)) will be available in the future works. A combined simulation using the numerical snowpack model SNOWPACK and this model can be used to estimate the potential of this model to improve the numerical snowpack model (Hirashima et al., 2014b).

ACKNOWLEDGEMENTS

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THE EVOLUTION OF THE 2014 'DAMALANCHE' FACET LAYER OF SOUTH-CENTRAL AND SOUTHEAST ALASKA

Donald Sharaf [1,2] and Michael Janes[3]

[1]Valdez Heli-Ski Guides, Valdez, AK, USA
[2] American Avalanche Institute, Victor, ID, USA
[3]Alaska Electric Light and Power, Juneau, AK, USA

ABSTRACT: The 2014 mid to late season snowpack in the Eastern Chugach Range of Alaska presented challenges and learning for the heli-ski operations around Thompson Pass, and in the bigger picture the entire Chugach Range and mountains of SE Alaska. The rain event that triggered the widespread avalanche cycle on January 24 and 25, 2014 was known as the "Damalanche" cycle for the Dam that it created on the Lowe River at the mouth of Keystone Canyon. This event, by itself, was not a serious problem further into the winter, but the saturated snowpack that resulted fostered the growth of near-surface facets (via melt-layer recrystallization or "DW faceting") that grew to the size of 5mm depth hoar grains in 'favored' locations. This layer, dubbed the "Damalanche Facets" went through a fascinating period of building, dormancy, activity, dormancy and reactivation. A similar layer formed in SE Alaska and some of the similarities will be addressed. Through more than two months of direct observation we saw varying degrees of strength, propagation and friction; universally poor structure; and widespread continuity of the weak layer. This paper addresses the formation and evolution of the dam facets, lessons learned for forecasting and guiding, and thoughts for tracking similar layers into the future.

KEYWORDS: near-surface faceting, Alaska, avalanche forecasting, melt-layer recrystallization.

1. INTRODUCTION

Alaska is often referred to as a land of extremes. In an avalanche-forecasting context, Alaska does see similar snow grain growth, avalanche cycles, and weak layer types that are found in many other mountain ranges around the world. However, the frequency of encountering different avalanche conditions and the varied nature of them is truly impressive. The 2013/2014 winter season was a classic case of a season that blended elements of a true continental climate in November and December 2013, pursued by a wet slide cycle triggered by 'biblical' rains (Fitzgerald 2014), and then a trip back into the deep freeze for most of January and February 2014. The resulting snowpack was what forecasters encountered as helicopter skiing season started in the Eastern Chugach Range of South-Central Alaska. A similar snowpack existed down in the Coast Range of SE Alaska. (Fig.1)

The intent of this paper is to follow the evolution of the 'Damalanche Facets ' from the point they were developing, through the time they became active, a short period of dormancy, a longer active avalanche cycle, and on to the point they were removed from the snowpack (in this case as melt water). This evolution reinforced recent research pertaining to avalanche release (cited within the paper) and the conclusions at the close of the paper will help illustrate the lessons learned.

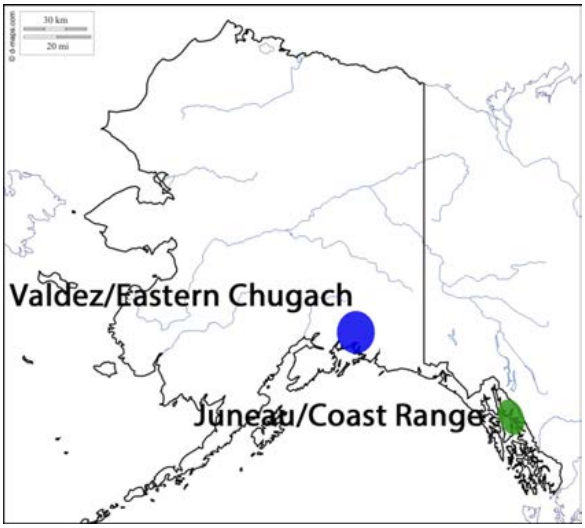

Fig. 1: Map of Study Areas

* *Corresponding author address:*
Don Sharaf,
email: dsharaf1224@gmail.com

2. SEASON HISTORY

The mountains of South Central Alaska (specifically the Chugach Range) are far removed from the mountains of SE Alaska (specifically the Coast Range and Chilkat Range). Despite the 700+ kilometers that lie between the regions, the snowpacks can be quite similar. A review of the season histories that led up to the period of study will show some of the similar events that led to the weak layer formation. Statham et al (2012) track the evolution of weak layers from formation to activity to dormancy to inactivity or extinction. That terminology will be used throughout the narrative that follows.

2.1 Tough Times on Thompson Pass (Eastern End of the Chugach Range)

Thompson Pass is known as one of the snowiest places in the world having recorded over 2500 cm of snowfall in a single season. The winter of 2013/2014 did not come close to that total despite a strong start in November. A mid-month storm brought close to a meter of snow, but in the next week no new snow fell, the snowpack shrunk to 30cm, and temperatures dipped as low as -29°C. As expected the snowpack became faceted and depth hoar began developing in some areas. Storms in latter November, mid-December, and around the Winter Solstice weren't enough to keep the snowpack from continued faceting.

A short New Year's storm followed by moderate temperatures through January 11th did little to change the existing snowpack structure of depth hoar and assorted hard wind slabs. Near suicidal skiers in Valdez perked up when snow began to fall on January 13th and a moisture-rich feed started to set up from Hawaii. 75cm fell between January 13-16 bringing the total snow depth to a season high (thus far) of 165cm. On the 17th the Pineapple Express kicked in and snow changed to rain. Turnagain Pass (160 km to the west) caught the brunt of the early part of this Tropical push (Fitzgerald 2014), but the new snow around Thompson Pass rapidly settled as it became rain-soaked. As Turnagain Pass absorbed more and more rain over the 18th and 19th the Eastern end of the Chugach returned to snow with another 33cm falling. What followed on the 21st- 23rd of January will remain in infamy in Valdez for generations.

2.2 The Damalanche Event – Valdez/Thompson Pass

Rain began on Thompson Pass on January 21 and continued through the 24th. Recording instruments failed to record accurate rainfall amounts on Thompson Pass, but the Valdez NWS station (40 km away and at sea level) recorded over 279 mm during that period. The results were impressive, to say the least, with avalanches to size D4.5 between Valdez and Thompson Pass and a widespread wet slab avalanche cycle to the north of Thompson Pass that ran on all aspects below 1525m. The huge avalanche that came out of Snowslide Gulch dammed the Lowe River and effectively closed the Richardson Highway (the only road to Valdez) for 12 days. This avalanche led to the name "the damalanche" and all the variations that followed. (Carter and Carter, 2014). On the 24th the Thompson Pass station saw a rain snow mix where a total of 10cm of new snow fell on the rain-saturated snowpack. This is the snow layer that is thought to be what morphed into the Damalanche Facets that is the focus of this paper.

From January 25 to the 27th, the temperatures stayed unseasonably warm, remaining above freezing in the mountains and reached +5°C at Thompson Pass on the 26th. Cooling followed on the 27th of January and there was no new snow until February 12th. That period was marked by generally clear skies, temperatures down to -25°C, generally light winds and very little settlement within the snowpack as the surface snow faceted and the rain-soaked snow gradually froze into a thick crust (knife + hardness).

2.3 February 2014 on Thompson Pass

As February progressed a layer of near-surface facets formed over the surface of the rain-soaked snow from late January. The snow that fell following the rains of January 22-24 changed by a near-surface faceting process know as melt-layer recrystallization (Birkeland 1998). The extent to which the upper layer of the snowpack had been saturated by rain would help determine the duration of the faceting. Essentially, until the rain-soaked layer froze into a rain crust it would remain at 0°C and be the heat source for the snow above. Thicker layers of saturated snow could drive the vapor pressure gradient for longer. Thinner layers of snow overlying the saturated snow also increased the temperature gradient. Between these two drivers of melt-layer recrystallization there was an ideal elevation band for facet formation (Jamieson and Langevin, 2004). Too low (<600m) and there was just rain with no storm-ending snow. Too high (>1525m) and the thickness of the new snow inhibited large gradients from forming. After seventeen days the drought ended and from February 13th to the 18th a slab started to build atop

the Damalanche Facets leading to the first avalanche cycle on that layer.

Heli-ski operations on Thompson Pass often start with several days to a week of time without a helicopter, allowing time to set-up the base, ski tour, and start a base-line for avalanche forecasting. Forays into the "backyard" starting on February 24th revealed a cranky loud snowpack. Gaining elevation, whumphs increased from localized collapses of a few meters to long running collapses that sent jets of snow up around alders 20 meters away. Cracks were ubiquitous on any slope >20° and previously collapsed snow was collapsing again as we traveled on it. The saving grace for stability was that the slab from the mid-February snows had faceted (this time via diurnal recrystallization) and seemed capable of supporting propagation, but low slab stiffness may have kept the friction high enough at the slab/weak layer interface to prevent avalanche release. Regardless, it was clear that the Damalanche Facets would again be a big problem with subsequent snowfall. Ski tours explored 600-900 meters above the base (elevation 497m), but the arrival of helicopters would soon show the distribution of the Damalanche Facets across the different climatic zones and elevations that are used in daily operations.

2.4 "Beware the Ides of March"

The snowpack continued talking to us through the end of February, but on March 2nd the Damalanche Facets got their second load. No new snow fell, but strong northeasterly winds created localized hard slabs 40-100 cm deep along the Thompson Pass Corridor. In mid-elevation cross-loaded terrain the collapses started propagating even further (up to 60 meters) and some of the whumphs became sonic booms. Careful terrain management kept guides and clients out of trouble, but several skier triggered avalanches occurred with a now stiffer slab sitting on top of the Damalanche Facets As operations moved further afield we found that the damalanche facet layer was unusually continuous across all aspects and elevations between 600m and 1525m. That being said there was one zone where the facet layer was the most reactive and that area became a "supermodel" for much of March (i.e. you can look, but don't touch). Small avalanches (R1 to R3, D1 to D2) continued to be remotely and directly triggered by skiers and riders through March 10th, but natural activity seemed to stop by March 4th. On one occasion one of the authors skied up to a flat area that whumpfed loudly. Seconds later a second guide skied past and collapsed the area a second time.

A big storm was forecasted for March 12th and 13th and the hope was that the "crush and flush" might lessen the challenges of the Damalanche Facets.. The storm failed to meet the estimated water amounts, but 40-50cm of mid density snow fell in the Thompson Pass Area. Following three no-fly days, the carnage visible on the 14th was impressive, but not inspiring. Few areas had large-scale natural activity, but there were pockets scattered everywhere between 600 and 1525m averaging 40-70cm in depth. Curiously, despite the natural cycle and ongoing skier triggers, an artillery shoot to protect the Richardson Highway produced virtually no results. Location appeared to be hugely important and it seemed that the typical target points were not the best ones for this slab weak layer combo. Low elevation shots were seemingly the only results from that mission.

Although natural activity seemed to stop by March 14th, human triggered avalanches continued for the next week and a half, including some impressive remote triggering from as far as 400 meters away. By March 25th human triggered avalanches had come to a close, ECT results were mixed with some propagating and some not; and friction was seemingly increasing as more results were resistant planar. The structure remained horrible and an occasional collapse kept the guides wary, but we were starting to guide more complex terrain and feel good about it.

2.5 April showers…Not so much

By the start of the April the snow surface was haggard. Various wind events had trashed many slopes. The only saving grace was that diurnal near-surface faceting and surface hoar formation (a layer known as the equinox facets) had improved the skiing in areas that were less wind affected. By April 6th it had been 18 days since the last snowfall, but 10-15cm of fresh snow dressed up the skiing nicely that day.

On April 7th the only avalanche that stepped down to the Damalanche Facets occurred. This incident is discussed in section 4.3 that addresses slab warming effects. The last suspected propagation events from that layer of facets were three separate collapses from three different lower elevation slopes on April 10th. The primary active weak layer for early to mid-April was the shallowly buried Equinox Facets and Surface Hoar. As far as we could tell there were no further avalanches to the Damalanche Facets until the very end April

despite above freezing temperatures that arrived after April 17th.

2.6 May – The Shed Cycle cometh

Dormant doesn't mean removed or extinct. Late April/early May marked the start of the shed cycle and the advent of wet slides. On May 4th, the Valdez Avalanche Center noted a wet slab that had likely initiated in the Damalanche Facets and subsequently stepped down to the ground. That avalanche initiated in terrain that was in the heart of the Damalanche Facet terrain (900m and along the Thompson Pass Corridor). There were probably many more avalanches ascribed to this layer as the snowpack continued to go isothermal, but observations became very limited after the heli-operations closed for the season. As one guide stated "You know when I'll trust that layer?… When it's in the river."

2.7 Early Season in Southeast Alaska

The 2013/2014 season in northern portion of Southeast Alaska started out on the dry side in November but picked up substantially in December with well above normal snowfall at sea level. A fairly typical "maritime" December and early January yielded small avalanche cycles. None of this would matter in the end when the reset button was hit Jan 14-16th when a cooler storm was followed by a warm, wet storm that brought 75-100mm of rain up to 4000'. Again very little activity resulted other than small (up to R2D2) slides due to a generally moist and previously rain-tempered snowpack. Some small bouts of light precip followed on the 17-20th with fluctuating temps bringing mixed wet snow and rain into start zones (457m-914m). Record-breaking warm temps ensued on the 22nd-24th (Juneau Airport at sea level) but this time with lighter precipitation. Freezing levels rose to 1828m at the Juneau Icefield weather stations. The rain events in SE Alaska failed to produce a significant full depth cycle as it had in the Chugach, but by months-end the snow surface was remarkably similar; a rain-saturated snowpack with a thickening surface crust. On Jan 29th a small amount of new snow fell at mid elevations. On the 30-31st clear skies allowed radiation cooling despite near freezing air temps and a thin surface crust formed above the wet new snow.

2.8 February 2014 in Southeast

February started dry and cool and faceting in the near-surface layer began in earnest. Temperatures close to, but below freezing coupled with radiation cooling resulted in a strong near-surface gradient. Light to Moderate winds and cool temps continued through Feb 9th when a "Taku" wind event (resulting from an Arctic outbreak) dropped temperatures and the strong wind stripped the developing facets from many exposed locations. As the winds eased and the next storm approached, light dry snow buried the faceting layer. Feb 13-15th then saw an additional 50cm of new snow that started dry and gradually became moist at mid elevations. This thaw (to 762m) was short lived and resulted in a few small direct action slides within storm layers. As temps cooled 30-40cm of dry snow fell on top of the denser snow between Feb 16-18th. On the 17th, hollow cups were widespread between 457m and 914m in Troy Bowl on Douglas Island. Propagation was present but was resistant and compression tests also showed high friction results. In this area, however the slab was only 20-40cm. On the following day, while conducting fieldwork south of Juneau where heavier snowfall dominates, things got interesting. Areas previously stripped by outflow winds showed no signs of faceting above the January crust. But after landing on a ridge at Arthur Peak (~40km SE of Juneau) the 2nd person exiting the helicopter triggered a collapse cracked the whole ridge and riddled the lower start zone with cracks releasing two separate R2/D2 slabs. Later that day while descending Mt Jumbo on Douglas Island, a ski cut resulted in a similar R2/D2 release. On the 22nd, a crew from Alaska Powder Descents experienced nearly a dozen remote triggers on the backside of Mt. McGinnis on the mainland. The day started when the helicopter remotely triggered a R2/D2 slide while landing on the ridge. Subsequent testing showed ECTP SC's. The last part of February saw a warm dry spell last until March 7th. Warm temps and clear weather led to people skiing as if they had nothing to lose. Testing during this period backed up the lack of artificially triggered slides; ECT's and PST's in areas that showed propagation in February now showed low propagation potential (ECTN's) and long critical cut lengths.

2.9 March in Southeast; Dormancy to Rebirth

After a week of warm, dry weather, March saw 12 days of consecutive precipitation adding 80-120cm of new snow. Fluctuating warm temps kept the snowpack settling and the slab stiffening. Tests on Mar 18 & 21 showed impressive propagation including two 3m long ECTP26Q1 and a PST24/277End. The slab now ranged from 1-2m thick, yet was ~100-200 kg/m³ denser than Feb slab densities. After several more days of dry cool

weather, one of the more impressive slides was remotely triggered by a party of two on Mt Stewart on Douglas Island. This trigger came after at least 8 people had skied one of the lines across the shallowest part of the slope near rocks. The slide was triggered from a relatively flat and treed area 170m from the nearest slide and 400m away from a second slide (Fig. 2). A crown profile the next day documented a dense slab (168-400 kg/m³) ranging from 1-2m thick overlaying rounding mid-pack depth hoar (from melt layer recrystallization). Late March and April turned out to be drier than normal and the faceted layer slowly healed but was still visually identifiable. Storms that affected the region were generally benign and only led to further settlement and rounding of the weak layer. ECT and PST test results backed up this change by trending toward low propagation potential results. Needless to say, with the March 24th slide visible from the Eaglecrest Ski Area chairlifts, skiers were more gun shy than typical.

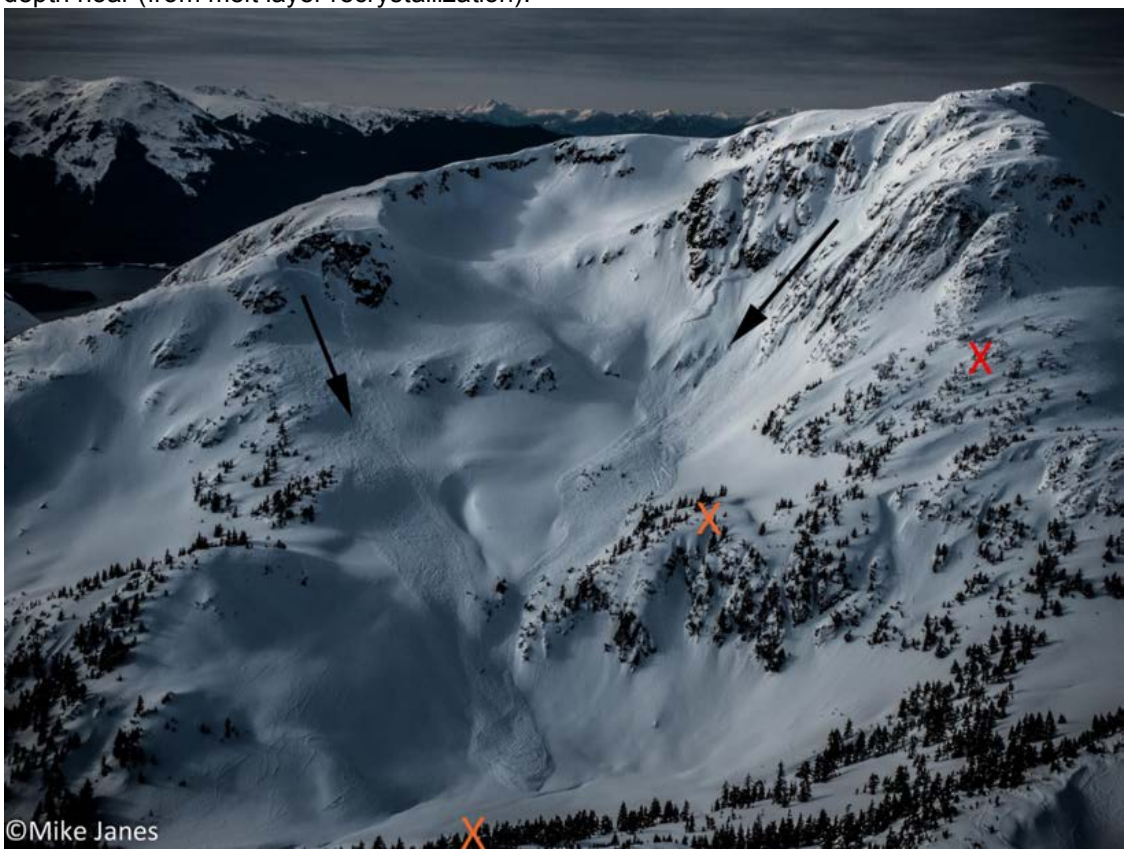

Fig. 2: March 24, 2014 Mt. Stewart Avalanche. The red X (upper right) shows the trigger point and location of other party members (orange X's) as well as the two remotely triggered slides (SS-ASr-R3/D3.5-O) indicated by the black arrows.

3. DEPTH HOAR ON THE SURFACE?!

On occasion, surface and near-surface temperature gradients conspire to create large faceted grains near the surface regardless of the overall depth of the snowpack. In the case of the Thompson Pass Region the Damalanche Facets formed 70 to 150 cm above the ground. Depth hoar seems a misnomer for the larger grains, but that is how they are classified using our existing system. The following sub-sections are a discussion of the grain sizes and types encountered using IACS classifications. (Fierz et al, 2009)

3.1 Grains in the Eastern Chugach

Near-surface faceting is a common process in many ranges, but the resulting facets are generally smaller than 3mm (Birkeland 1998). The Damalanche Facets that formed on the surface of the snowpack from late January to mid-February varied in size by elevation and by distance from the coast. The largest that we encountered were up to 5mm in size and were full-blown depth hoar crystals and varied from cups DHcp ∧ to chains of small depth hoar or large facets DHch ⩓ (up to 3cm in length). At the higher end of where the

Damalanche Facets existed the grains were more commonly 2-3 mm striated facets FCso ▫ and FCsf ⧄ (Fig. 3). As temperatures warmed and the Damalanche Facets were buried more deeply, grain sizes changed little, but the layer started to round, so that grain types became rounded facets FCxr ⍾ and rounding Depth Hoar DHxr ∧.



Fig. 3: 1mm grid. An example (FCso) of one of the many shapes of the Damalanche Facets . Photo by Wendy Wagner

3.2 Grains: Formation in SE Alaska

The grains observed in Southeast Alaska were remarkably similar in both shape and size to those observed in the Chugach. Initial size observations in mid-February were in the 2-4mm range. By early March the size grew to be 3-6mm. In addition, between 457m and 914m the layer was almost always ~2cm thick overlaid by a 3-5mm crust. The most common shape was generally depth hoar cups (DHcp), but regular faceted crystals (FCso) and striated facets were also abundant. While the layer was not present below 457m, it was consistent to 914m. Above 914m it was present as well but was generally a thicker layer with smaller faceted grains and less cupped depth hoar. As loading in late March progressed, the crystals began to round but were still readily identifiable as cupped forms.

4. LESSONS LEARNED AND RE-LEARNED

Unfortunately, we didn't walk away with tremendous new insights into avalanche release, BUT we did gain great experience echoing recent research into avalanche release, propagation, friction, and the influence of warming on propagation.

4.1 Guiding Stategies

Running a heli-ski operation is daunting enough when the stability is good. Looking at the hand that was dealt in late February, we had to figure out where we could go safely as folding was not an option. Fortunately, the owner committed the time and money to do extensive reconnaissance at the start of the season. Most runs were opened and dug on by a team of guides; and soon enough information was gathered to start establishing some trends. As rain-soaked snow was the driving mechanism for the damalanche facet formation, the expectation was that the facets would be less prevalent at our upper elevations (1525m-2400m) where less rain, and more snow, had fallen during latter January at the end of the damalanche event. This proved to be the case and operating at upper elevations became the foundation of our guiding strategy.

Knowing that the largest, and most reactive facets were found between 600m and 1525m, particularly in the circuits closest to our base of operations – we needed to have a way to descend from our upper start zones. We looked closely for our lowest angle terrain with clean run-outs. Terrain traps and large convex start zones were avoided for weeks – even though some of those areas provide our most profitable skiing and often our only skiing when the clouds obscure visibility. Using "defendable" terrain worked well for the operation, but it took time to construct appropriate run-lists in the morning and to achieve buy-in from the guides.

4.2 Avalanche Forecasting AND Communication

Communicating to a group of guides has often been likened to herding cats. Taking cues from teaching avalanche courses, using 21st century technology, and frequently asking "does this make sense?" were key to communicating the message to the guides at the morning meeting. Videos of pit results, pictures of avalanches (regardless of whether they were natural or human triggered), and plotted pits all helped to illustrate current conditions. Guides who hadn't been in the same areas the previous day could see the nature of the activity, or inactivity, and that led to a better understanding of the distribution, sensitivity, and consequences of the avalanches-du-jour. Plotting the problems on the Probability vs. Consequences graph also helped with run selection prior to firing up the helicopters. (Statham et al, 2010) (Sharaf, 2014)

4.3 Slab warming

The mid-March avalanche cycle showed how reactive the damalanche facet layer could be, but avalanche sizes in the Eastern Chugach were consistently size D2 or smaller. Propagation seemed to self-limit by slab depth and hardness, so that portions of slopes would avalanche, but rarely would involve the entire start zone (typically R3 or less). Following the active cycle of March 12-14 the weak layer went dormant for a large part of the heli-ski season. The game changed on April 7th, when air temperatures at lower elevations rapidly rose above the freezing mark and abundant sunshine characterized the day. In technical terms a non-propagating, dormant, conditionally-unstable snowpack progressed to an active propagating snowpack with only the addition of heat (Simenhois and Birkeland, 2008). In non-tech talk a client triggered a much larger avalanche than had been seen in the past two weeks. Skiing at lower elevations in the heat of the day resulted in a soft slab which wrapped a ridge feature in its entirety (R4) and deposited an impressive debris pile (D2.5). (Fig. 4) A client was caught, but deployed his airbag for a happy outcome. This was the most dramatic involvement for the operation for the season and shows the importance of being wary of warming effects on slabs.

4.4 Structure

On a number of different levels it was fascinating to see the change of the grains over a two month period. As mentioned in section 3.1 and 3.2 the grains varied in size. Conditions were ideal for forming large grains; as one person noted conditions were perfect for prolonged faceting – a long period with a large temperature gradient and a long-lasting heat source in relatively high porosity snow. With those conditions large facets and depth hoar could grow anywhere in the snowpack, even at its surface.

As the snowpack warmed and the Damalanche Facets became buried more deeply they slowly began to round. They rarely decreased significantly in size however, and were easy to discern in pits as a thick layer (5-15 cm thick) of significantly larger crystals than the diurnal near-surface facets and wind slabs that overlay them. Avalanching and propagation appeared to correlate more directly to slab properties (stiffness and depth) than structural changes of the weak layer.

As the Chugach snowpack warmed further into late April, and early May, middle and lower elevations (lower than 1066m**)** became isothermal and the entire snowpack morphed to wet grains of varying sizes. This allowed avalanches to initiate as wet loose slides or wet slabs within the Damalanche Facets and then step down to the ground – through what was previously impenetrable knife-hard rain crust. Until the snowpack became isothermal, the layer of Damalanche Facets could be classified as having four to five structural "lemons" or structural properties conducive to fracture propagation. (McCammon and Schweizer, 2002)



Fig. 4: Photo of the April 7th avalanche where warming seemed to play a pivotal role in accentuating propagation within the Damalanche Facets. The crown was 30-60cm deep, the avalanche ran 350 meters and was classified SS-ASu-R4-D2.5-O

4.5 Strength

Strength as viewed by ECT scores was rarely very low. As slabs were building over the Damalanche Facets scores were consistently moderate (ECT 11-20). ECT results remained in that range well into the dormant period of the facets. Eventually scores moved into the hard range (ECT 21-30), but better indicators of avalanche release were friction observations (fracture character) and whether the crack propagated across the block, or not.

4.6 Continuity

One factor important in avalanche forecasting is the continuity of both the weak layer and the slab. High spatial variability of either can limit propagation and avalanche size. The more continuous the distribution of both the weak layer and the slab, the greater the potential avalanche size. In the

Eastern Chugach the Damalanche Facets exhibited exceptionally good continuity covering all aspects at lower and mid elevations. This distribution provided very few places to hide, or guide. It was fortunate that the March and April storms were few and far between, so slab continuity and depth were less than what was needed for large avalanches (>D3) to occur. Wind events also played into spatial variability of the slabs, as they thinned some areas and deposited in others. The winds also created much stiffer areas of slab and propagation may have self-limited at the slab margins where it became softer.

4.7 Friction

Friction seemed to be slope angle and slab stiffness dependent. Again this seemed to support recent research (Simenhois et al, 2014). Friction is a calculated value, but our surrogates were observations of fracture character and which slope angles would crack, but not release. During the times that the Damalanche Facets became active avalanches rarely started on slopes <35°. Propagation would occur on slopes as gentle as 20° as shown by the abundant cracks in lower angle terrain.

5. CONCLUSION

Avalanche forecasting for such a widespread and sensitive persistent weak layer was one of the best challenges the authors have encountered. The layer demanded respect and constant observation in order to work safely around it. Recent research into fracture propagation, friction, and avalanche release were very helpful in forming theories of what was coming next. The authors are excited for the research to be presented at the 2014 ISSW relating to avalanche release. Avalanche forecasting is a challenging, and humbling, profession that can only improve with fastidious record keeping, abundant field observations, an eye to the science behind it, and a passion for sliding on snow.

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WHAT DO FIELD OBSERVATIONS TELL US ABOUT AVALANCHE DANGER?

Shane Haladuick*, Michael Schirmer, and Bruce Jamieson

Department of Civil Engineering, University of Calgary, Canada

ABSTRACT: The avalanche forecast regions in Canada range from 100 to 30,000 km^2, far larger than the 10 km^2 covered in a typical backcountry day. This difference in scale could cause the danger a recreationist is exposed to, the local avalanche danger, to differ from the regional bulletin. This study examines the relationship between field observations (instability, snowpack, and weather factors), which do not require digging a snow profile, and the local avalanche danger. The results were grouped for analysis by the dominant avalanche character of the day: Loose Dry, Wet (loose and slab), Wind Slab, Storm Slab, Persistent Slab, and Deep Slab. Throughout the past 6 winters we have created a unique dataset of 28 field observations from 425 field days. Univariate and multivariate cross-validated classification trees were built to examine the predictive capability of the observations for the local danger. Storm, Persistent, and Wind Slab avalanche characters had the most field observations correlate significantly with the local danger, and Wet (loose and slab) had the least. Observations of Slab Avalanche Activity, New Snowfall, and Tree Bombing were applicable for the most avalanche characters. Univariate and multivariate classification trees can be useful to recreationists in interpreting critical observations and the combinations of these observations that indicate elevated danger.

KEYWORDS: Local avalanche danger, avalanche character, avalanche forecasting, recreationist

1. INTRODUCTION

On a typical backcountry day, a recreationist ski tours, split boards, snowshoes, or snowmobiles through avalanche terrain. Typically recreationists travel in avalanche terrain less than 20 days per year (Bakermans et al., 2010). Jamieson et al. (2008) estimated a recreationist's area of exposure to avalanche hazard at 10 km^2, which is approximately the area of one mountain drainage. This area is referred to as the local avalanche area, and the avalanche danger rating for this area is the local avalanche danger (D_{LN}).

The Canadian regional avalanche bulletin is an expert assessment of the avalanche danger for a specific region, which range in size from 100 to 50,000 km^2 (Haladuick, 2014). This is not the same as the local avalanche danger (10 km^2). In fact, Jamieson et al. (2006) found that this rating differed from the local avalanche danger rating in 36-43% of cases. The difference in spatial scale is one of the main reasons for the discrepancy. Other reasons include the difference in temporal uncertainty between the local nowcast and the regional forecast, the spatial variability of the avalanche danger (Schweizer et al., 2008), the inaccuracy of available data when the forecast was made (Jamieson et al., 2009), and error by human forecasters or forecasting models (Jamieson et al., 2009). In addition, the regional bulletin is not available in certain areas (Haladuick, 2014).

It is useful for recreationists to use additional sources of information to verify or, potentially, adjust the regional bulletin to their local area. To localize the avalanche danger, professionals and experienced recreationists rely on weather, avalanche and snowpack observations, as well as observations from snow profiles and snowpack tests that require digging a pit. They also rely on their previous experience travelling in similar conditions, and their intuition (Stewart-Patterson, 2008), which has been developed over years of operating in avalanche conditions. By contrast, recreationists usually do not dig pits due to the time and training requirement. They also have less experience operating under similar avalanche conditions and do not have the wealth of experience required to calibrate accurate intuitive decisions. Therefore, non-digging field observations play an important role in the localization of the avalanche danger for recreationists. This study assesses the relationship between field observations and the local avalanche danger for different avalanche characters.

* *Corresponding author address:*
Shane Haladuick, Dept. of Civil Engineering, University of Calgary, Calgary, AB, Canada, T2N 1N4; tel: 1-587-225-9445;
email: smhaladuick@gmail.com

2. METHODS AND DATASET

A typical field day replicated a recreationist's backcountry day. The field team ascended from the trailhead with skis or snowmobile, performing a set of 28 field observations (Table 1) along the way to the decision point. The decision point was the point at which the team decided whether or not to enter more hazardous avalanche terrain. At the decision point the main avalanche character of the day was identified from a list similar to Haegeli et al. (2010) (Figure 1). The field team then descended back to the trailhead, again performing the field observations. At the trailhead they rated the local avalanche danger. The local danger was rated for the vegetation bands that the team members were confident rating, using all of the information available to them.

Over the past six winters field teams collected data during 425 days throughout the mountains of western Canada. Figure 1 shows the relative frequency of the field days grouped by avalanche character.

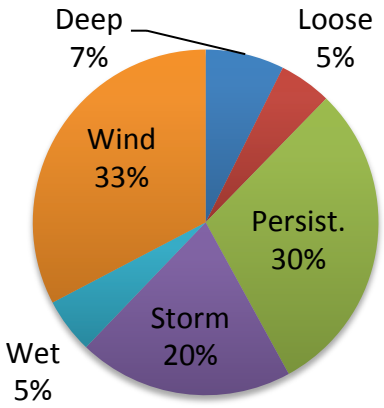

Figure 1: Relative frequency of field days grouped by avalanche character.

Table 1: Field observations and their associated values

Field observation	*Values (ordered low to high rank)*
Current Loose Avalanches	0, 1, 2, 3+
Current Slab Avalanches	0, 1, 2, 3+
Recent Loose Avalanches	none, 24-48 h, <24 h
Recent Slab Avalanches	none, 24-48 h, <24 h
Whumpfing / Shooting Cracks	0, 1, 2, 3+
Cracking at Skis	none, occasional, frequent
Pin Wheeling	0, 1-2, 3+
Tree Bombing	none, occasional, frequent
Hand Shear Resistance	no result, hard, moderate, easy
Hand Shear Character	break, resistant planar, sudden planar
Hand Shear Depth	cm
Snow Surface Condition	dry fresh, settled, sticky, wind stiff, moist / wet coarse, crust
Surface Crust Supportive	yes, no
Surface Crust Thickness	cm
Ski Penetration	cm
Ski Pole Probe	gradually increasing resistance, a hard layer over a soft layer, buried crust (CR), obvious weak layer (WL)
Precipitation	snow: 0, <1, 1, 2, 3+ (cm / h) or rain: light, moderate (according to CAA, 2007)
Wind Speed	calm, light, moderate, strong/extreme (according to CAA, 2007)
Blowing Snow	none, at ridge, below ridge
Wind Scouring	none, 24-48 h, < 24 h
Wind Deposits	none, 24-48 h, < 24 h
Sky Condition	clear, few, scattered, broken, overcast, obscured (according to CAA, 2007)
HN24	cm
HN48	cm
Ta Trend in 24 h	°C, either positive or negative
Ta Warming to 0 °C	yes, no
Overnight Freeze After Thaw	thaw and refreeze, no thaw, thaw and no refreeze

This dataset was analyzed using both univariate and multivariate techniques. The Spearman rank (Walpole et al., 2007, p 690-691) and Kruskal-Wallis (Kruskal and Wallis, 1952) tests were used in a univariate selection process to determine the avalanche character and field observation categories that were significant. Categories significant on both tests were selected for further analysis.

Univariate and multivariate cross-validated classification trees were built based on the results of the selection process. The target variable for the classification trees was a binary version of D_{LN}, for which Low and Moderate danger were categorized as 0, and Considerable and higher were 1. This simplified the interpretation of the results of the trees. Univariate classification trees were built for each of the selected avalanche character and field observation categories. The critical value or criterion from the first split in these trees indicates elevated avalanche danger. Multivariate classification trees were built for each avalanche character, using all of the selected field observations for each character as inputs. These trees show the combinations of field observations that can lead to elevated danger.

Two levels of cross-validation were used to build the trees. The inner level was used to prune the final tree to the best level. The outer level was used to build a 2x2 contingency table (Doswell et al., 1990) of model forecasted results compared to actual observed results. This contingency table was used to calculate the validation parameters for each tree. Five validation parameters were used: percentage correct (PC), true skill score (TSS), probability of detection (POD), probability of false detection (POFD), and false alarm rate (FAR) (Doswell et al., 1990).

3. RESULTS AND DISCUSSION

Figure 2 shows a sample of the results from this study, the multivariate classification tree for Storm Slab avalanche character.

The tree in Figure 2 can be interpreted in the following way. The first field observation selected was HN48, with a criterion of 13 cm or greater. Since this observation was selected first it was the most important observation for Storm Slab, which is not surprising as it is an indication of new snowfall. If there was less than 13 cm of HN48 but there was a 'failure' on the Hand Shear Test then the danger was elevated. This is because a result on the hand shear test means a near surface (top 40 cm) instability exists.

If the HN48 was critical and if there was 28 cm or more Ski Penetration, or 'calm' Wind Speed, or Blowing Snow 'below ridge' then the danger was elevated. The combination of HN48 and Ski Penetration selected days with recent unsettled snow. The sign for Wind Speed was reversed, with 'calm' indicating elevated danger. This is counter intuitive; however, it is due to the interaction between the avalanche character and Wind Speed. Days with higher Wind Speed were probably already filtered out of the Storm Slab dataset by the field team defining the avalanche character and placed in the Wind Slab dataset. The selection of Blowing Snow in the fourth level of the tree shows that the combination of new snowfall and wind transport is still important for Storm Slab.

This tree had a cross-validated PC of 68%; however, it had a relatively low TSS of only 34%. This was because it had a high POFD of 43% relative to the trees built for the other characters. This means that nearly each second time when the actual local danger was Low to Moderate the tree incorrectly predicted the local danger as Considerable or higher. The full results and discussion can be found in Haladuick (2014).

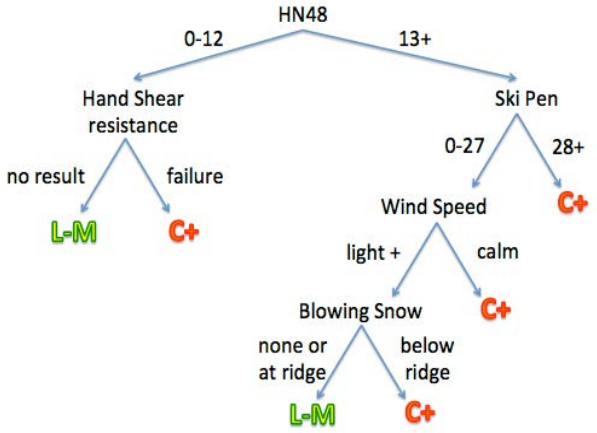

Figure 2: Multivariate classification tree for Storm Slab avalanche character.

The avalanche characters that had the most indications of avalanche danger were Storm Slab, Persistent Slab, and Wind slab, in that order. This implies that these characters are the easiest for a recreationist to localize the danger under, and potentially the easiest to forecast the regional danger under. Conversely, the avalanche character that had the fewest indications of increased danger

was Wet (loose and slab). This indicates that this character is the most difficult for a recreationist to localize the danger under, and potentially the most difficult to forecast.

The field observations that were the most applicable (useful under the most avalanche characters) were Slab Avalanche Activity, New Snowfall, and Tree Bombing. The field observations that were highly specific to certain characters (in bold) were:

- **Deep Slab**: Recent Loose Avalanches, Recent Slab Avalanches, Pin Wheeling, Wind Speed, Blowing Snow, Wind Deposits
- **Loose Dry**: Recent Loose Avalanches, Pin Wheeling, Wind Scouring, T_a Trend in 24 h, lowest CT score (CT)
- **Persistent Slab**: Hand Shear Character, Wind Deposits
- **Storm Slab**: Wind Speed, Blowing Snow, T_a Trend in 24 h
- **Wet**: Recent Loose Avalanches, Pin Wheeling, T_a Trend in 24 h

4. CONCLUSIONS

On 425 days over the past six winters, field teams performed 28 different field observations, rated the local avalanche danger, and identified the main avalanche character across the mountains of western Canada. The field observations were analyzed with respect to their univariate and multivariate relationship with the local danger.

Univariate classification trees showed the critical range of the observations that indicated increased avalanche danger. Multivariate classification trees showed how the field observations can be combined to predict the avalanche danger. Recreationists can use these trees to help interpret their field observations when travelling in avalanche terrain. These trees may also prove useful in future decision support schemes.

Storm, Persistent, and Wind Slab had the most indications of instability. Wet (loose and slab) had the least indications. Slab Avalanche Activity, New Snowfall, and Tree Bombing were the field observations that were applicable to the most avalanche characters.

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