The effect of daytime warming on snowpack creep

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ABSTRACT: Snowpack warming is, besides loading by precipitation and wind-transport, one of the major triggers contributing to natural avalanche release. Established release mechanisms for spontaneous slab avalanches strongly depend on deformation rates in weak layers, which are affected by temperature changes. Once a critical rate is exceeded snow exhibits strain softening and ultimately brittle fracture. Failure of a weak layer is an important prerequisite to slab avalanche release. Critical slope parallel deformation rates may be reached in weak layers on sufficiently steep slopes due to increased creep in the overlying slab, which is heated by solar radiation. Using time lapse photography during the transition from cold mornings to warm sunny afternoons, we monitored vertical and slope parallel displacements of markers on a vertical snow profile on steep slopes. In a case study we present time series of displacements that showed increased snowpack creep and slope parallel deformation rates during solar heating of the near surface layers.

KEYWORDS: Snowpack creep, daytime warming, stability, field measurements, avalanche forecasting.

1 INTRODUCTION

Snow that accumulates on the ground is in constant motion. Important factors governing snowpack creep and settlement are snow metamorphism, gravity and temperature (McClung and Schaerer, 2006, p. 75) .

On an inclined slope the gravitational pull causes slope parallel movement and deformation along snowpack layers. Fixed objects, such as lift towers and avalanche defence structures need to be designed to withstand potentially destructive forces of a downward creeping snowpack (Larsen, 2000; McClung, 1983).

On a smaller time and length scale, changes in slope parallel deformation rate largely contribute to spontaneous slab avalanche release. Snow can adjust to low deformation rates without weakening. Once a critical rate is exceeded snow exhibits strain softening and ultimately brittle fracture, that may propagate along a weak layer. Temperature changes strongly affect the rheological and mechanical behaviour of snow and therefore the stability of a layered snowpack. (Bartelt and Christen, 1999; McClung and Schweizer, 1999).

Avalanche forecasters observed natural slab avalanches directly after exposure to solar radiation (B. McMahon, pers. communication, 2008) and ski guides in mechanised ski operations in western Canada experienced considerably decreasing stability while skiing sun exposed runs several times (Exner and Jamieson, 2008). Presumably, solar heating of the surface layers increased the slope parallel deformation rate above a critical value.

Creep measurements from a number of studies are available over multiple days for a settled snowpack (McClung, 1980; Caselli, 2004). Other studies investigated snowpack creep during melting focusing on wet spring avalanches (Trautman et al., 2004) and changes in creep rate with the onset of rain in low density snow (Conway et al., 1996).

We are more interested in a dry, low density snowpack and short term changes of creep during daytime warming. Using time lapse photography we measured accelerated snow-pack creep in a case study on March 21, 2009.

2 STUDY SITE

The creep measurements were conducted at Mt. Fidelity study site in Glacier National Park, BC, Canada. Weather and radiometer data were available from a nearby automatic weather station. The experiment was set up on a 48°, east-facing slope in a forest opening at approximately 1900 m. Total snow height was 315 cm, which is about average for this time of year and elevation in an area with its characteristic transitional snow climate (McClung and Schaerer, 2006, p. 23). Typically, hand hardness increases gradually with depth to about finger to pencil hardness in the mid and

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lower snowpack with usually rounded grains (Canadian Avalanche Association, 2007).

3 EXPERIMENTAL SETUP

Approximately 5 cm long toothpicks were pushed in the near surface layers of a slope parallel snow pit with a vertical spacing of 3 - 4 cm (Figure 1). The tips of the toothpicks were painted black for better contrast to the surrounding snow. To monitor the movement of the toothpick tips, which was assumed to follow snow creep, a camera was mounted on a tripod at a distance of approximately 1.5 m viewing the toothpick profile perpendicularly from the side. Time lapse images were taken with an interval of 15 min. The camera was set up just after dawn, while air and snowpack temperatures, and therefore snow creep, were still at their minimum. The time lapse images were continued until 6 pm, well after the maximum of daytime warming was reached in the afternoon.

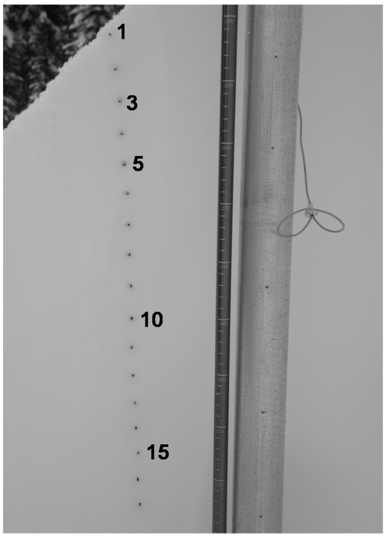

Figure 1. *Toothpick profile on a slope parallel pitwall, avalanche probe as length-scale reference, and stationary aluminium post with black reference points. The profile points with numbers were selected for a more in-depth analysis.*

For length scale reference an avalanche probe with the cm-scale facing the camera was pushed into the snowpack next to the tooth pick profile (Figure 1). To analyse the movement of the toothpick tips reliable reference points were necessary. The silver aluminium post in Figure 1 (3 m x 4 cm diameter) with black dots along its length was rammed vertically into deeper, consolidated layers of the snowpack. We assumed snow creep of those deeper layers, and therefore the movement of the pole was negligible compared to the displacement of the toothpicks in the near-surface layers.

We estimated the total sources of error in a toothpick position to be approximately 0.3 - 0.5 mm.

4 CASE STUDY MARCH 21

Before the experiment was started early morning of March 21, 30 cm of dry snow fell in the previous 72 hrs, and 12 cm during the previous night. For details about hand hardness, grain size and type, and density in the top 50 cm of the snowpack, where the toothpicks were placed see Figure 2. Initial snowpack temperatures ranged from -6 °C at the surface to -4 °C at a depth of 50 cm.

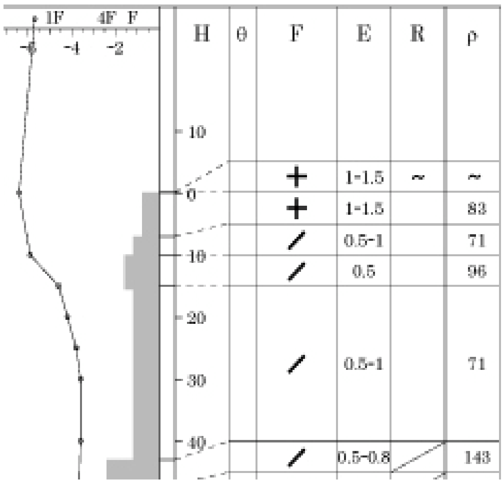

Figure 2. *Temperature profile (solid line), hand hardness, snow height (H), grain type (F) and size (E), and density (ρ) of the upper snowpack (Canadian Avalanche Association, 2007), where the toothpicks were placed.*

Figure 3 shows half-hourly creep profiles (solid lines) and trajectories of every odd-numbered toothpick tip (dotted lines). For the following analysis we selected profile points at 0.9, 5.3, 10.1, 22.5 and 34.0 cm depths on the initial profile at 6:15 am (profile point numbers 1, 3, 5, 10 and 15 in Figure 1 and 3).

Weather and snowpack conditions only allowed high resolution creep measurements until 9:15 am. After this time with penetrating solar radiation and rising air temperatures above freezing the toothpicks started to melt out and did not follow the natural creep of the snowpack (Figure 4). However, total vertical settlement could still be determined over the full duration of the experiment (Figure 5).

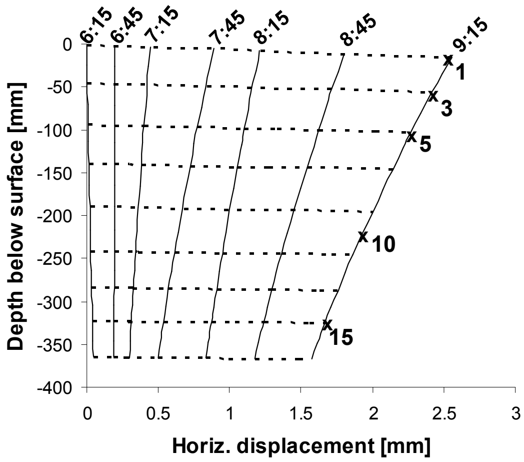

Figure 3. *Half-hourly creep profiles (solid lines) and trajectories (dashed lines) of odd-numbered profile point. The numbers (1, 3, 5, 10 and 15) are selected profiles points for further analysis. Note the different scales on both axes.*

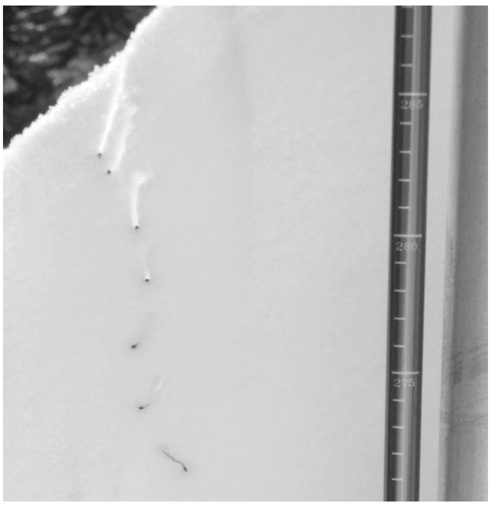

Figure 4. *After 9 am the toothpicks started to melt into the snowpack in irregular patterns and were useless for creep analysis.*

4.1 Total vertical settlement

Figure 5 shows the total vertical settlement and settlement speed measured at the snow surface over the course of the day. The snowpack settled a total of 16 cm by the end of the experiment at 6 pm. Vertical settlement speeds increased from initially 2 mm/hr to 8 mm/hr from the coldest morning temperatures before sunrise with increasing solar radiation and air temperatures until 9:15 am (Figure 6). The variations in settlement speed between 6:45 am and 9:15 am are due alternating shading and insolation of the study site by sparse trees while the sun was still at low angles in early morning.

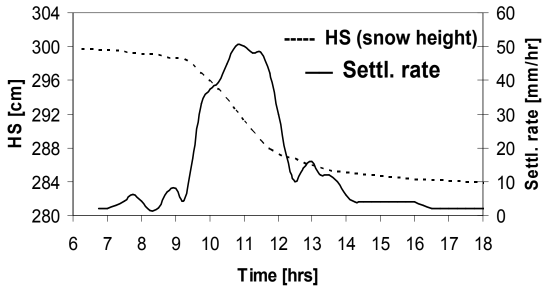

Figure 5. *Total snow height HS (dashed line) and settlement rate (solid line) during the course of the day of March 21.*

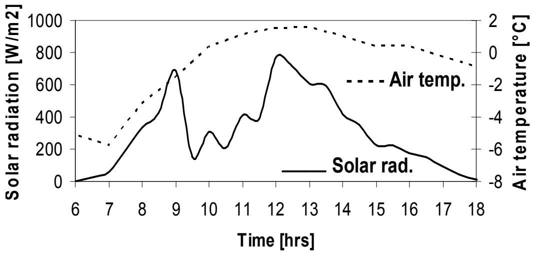

Figure 6. *Air temperature (dashed line) and direct solar radiation (solid line, averaged over 30 min) on March 21.*

Measured solar radiation did not reflect the variations since the radiometer was located in a nearby weather station with unobstructed sky view. After 9:15 am settlement speed rapidly jumped to maximum values of 50 mm/hr, followed by a strong reduction to 15 mm/hr until 12:30 pm. After 12:30 pm settlement speeds reduced to 2 mm/hrs with the sun leaving the east facing study site in the early afternoon hours. Obviously, although insolation between 9 and 12 am was reduced by thin, high clouds, air temperatures rising above freezing and the remaining solar input were sufficient to cause the high settlement rates after 9 am (Figure 6).

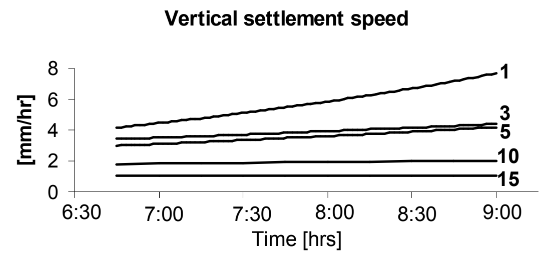

Figure 7. *Vertical settlement speeds on various depth levels on March 21. The numbers on the right refer to selected profile points in Figure 1 and Figure 3.*

A closer look at the vertical settlement speed between 6:45 am and 9:00 am, the time period for which detailed creep data are available (Figure 7), reveals a depth dependence of vertical settlement speed gain over time. Vertical settlement speed of the top layer (profile point 1) doubled with daytime warming from 4 mm/hr to 8 mm/hr. In deeper layers (profile points 3 and 5) a rise of approximately 1 mm/hr was observed, whereas the deepest layers (10 and 15) remained fairly constant during the observation period until 9:15 am.

4.2 Slope parallel displacement

In contrast to vertical displacement speeds, slope parallel creep speeds increased over time until 9:00 am at all measured depth levels, although the velocity gain in lower layers was less (Figure 3 and Figure 8). At the top layer (profile point 1), creep speed rose from 0.9 mm/hr to 1.6 mm/hr. The increase gradually decreased with depth, with a gain at the lowest point (profile point 15) from 0.6 mm/hr to 0.9 mm/hr.

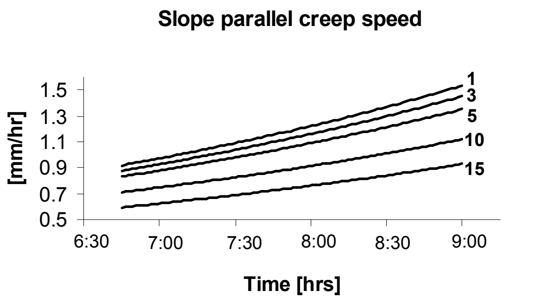

Figure 8. *Slope parallel creep speed on various depth levels. The numbers on the right refer to selected profile points in Figure 1 and Figure 3.*

4.3 Slope parallel deformation rate

Slope parallel deformation rate (shear rate) can be interpreted as the change of slope parallel displacement speed with depth or between adjacent layers (e.g. a weak layer) and therefore is an important indicator for fracture initiation in the slab avalanche release problem.

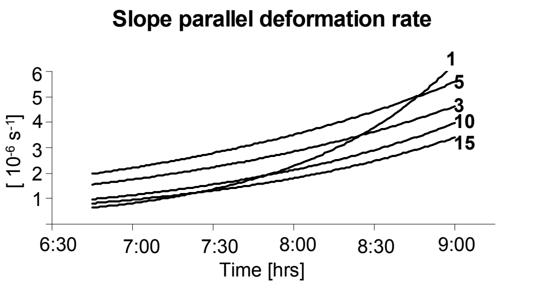

Figure 9. *Slope parallel deformation rate on various depth levels. The numbers on the right refer to selected profile points in Figure 1 and 3.*

During the case study of March 21, slope parallel deformation rates increased in all measured depth levels with exposure to the early morning sun and rising air temperature until 9 am (Figure 9). A clear dependence on depth could not be observed, although the strongest increase was observed at layers close to the surface (0.5 to 5×10^{-6} s^{-1}). In all other (deeper) layers down to approximately 34 cm (profile point 15) we observed rate gains by a factor of approximately 3 - 6 to values of 3 - 5 $\times 10^{-6}$ s^{-1}.

Note the absence of an obvious weak layer in Figure 2 where stress concentration could potentially lead to higher deformation rates.

5 DISCUSSION

The creep measurements during March 21 exhibited accelerating vertical settlement and slope parallel displacement with daytime warming in the morning on a steep east-facing slope with low density, dry storm snow (before 9 am). Air temperatures rising above 0 °C, penetrating solar radiation, low density snow and rising liquid water content may explain the strong and rapid increase of vertical settlement rate after 9:15 am. Conway et al. (1996) pointed out that capillary forces, when liquid water is present cause shrinkage of the snowpack independently of gravity. The irregular melting pattern of the toothpicks (Figure 4) hints at the presence of liquid water. Conway et al. (1996) measured creep rates (mostly due to settlement) up to 90 mm/hr with the onset of rain.

Depending on snow properties, critical deformation rates in shear for brittle fracture usually range from 10^{-4} to 10^{-3} s^{-1} (Schweizer, 1998). The formation of micro cracks in tension was reported to start between 10^{-6} and 10^{-5} s^{-1} by Narita (1983). Compared to those values, the measured increase in shear rate on March 21 suggests failure initiation may be possible with a pre-existing weak layer. Stress concentration at the interface of snowpack layers with different hardness, density or grain size usually causes higher shear rates (Habermann et al., 2007).

In numerous incidents where ski guides reported deteriorating stability (cracking, whumpfing or slab release) of a dry snowpack within hours during intense solar radiation (Exner and Jamieson, 2008) increased creep rates may have contributed to the critical conditions. Snowpack and weather conditions in those cases were quite similar to our case study: steep E to SE facing aspect, first sunny day after a storm in March or April, cold air temperatures (below freezing) in the morning. Our data showed that settlement only increased in the near surface layers, whereas slope parallel displacement increased over time in all measured depths. In other words, settling and compacting of the near surface layers and increased deformation rate on a potentially pre-existing weak layer below may actually create a reactive slab/weak layer combination.

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