THE EFFECT OF SNOWPACK WARMING ON THE STRESS BULB BELOW A SKIER

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ABSTRACT: Skier induced stresses are believed to penetrate deeper into the snow pack with increasing snow temperatures, and hence initiation of a fracture in a weak layer becomes more likely. To date, no measurements exist to quantify or validate the temperature effect on the stress bulb below a skier. In this study we present first results of two-dimensional measurements of the skier induced stress distribution. Thin, 5 x 5 cm, capacitive pressure sensors were placed in a snow pit wall below a standing skier. To factor in the effect of temperature changes, the measurements were conducted before and after one to two-day warming periods. Increasing temperatures of the near-surface layers altered the shape of the stress bulb, but so far we have not observed a substantial increase in depth. In some cases, warming and softening of the near-surface layer resulted in deeper ski penetration and stronger bending of the ski, distributing the skier's weight over a longer distance. Therefore, the stress bulb lengthened, but did not gain in depth. A widening stress bulb may overcome the critical length necessary to initiate AND propagate a fracture in a weak layer.

KEYWORDS : Snowpack stability, snowpack warming, avalanche forecasting, skier stress, skier triggering

1. INTRODUCTION

According to experience and observations, slab avalanches can become more prone to skier triggering with daytime warming. Harvey and others (2002) found that in 20% of 128 avalanche accidents in the Swiss Alps, daytime warming was the only factor contributing to avalanching. On those days, no significant amount of new snow or recent wind loading was reported. The fact that on days selected for their study four or more accidents happened, indicates that skiers did not just hit random trigger points. In a survey in western Canada, numerous avalanche practitioners associated unexpected avalanches with warming (Exner and Jamieson, 2008).

McClung and Schweizer (1999) argued that stiff surface layers are softened by warming temperatures, and as result applied dynamic loads (e.g. skier, explosives) penetrate deeper and are more likely to exceed critical deformation and stress values necessary for avalanche release. Their findings were derived from shear strength experiments at different temperatures. Wilson and others (1999) showed that skier induced deformation on a weak layer increased after the surface layer warmed, even if the weak layer was not directly reached by the warming. This result is based on finite element modeling applied to realistic snow packdata. Both studies did not take into account how warming related changes of the distribution of the skier's weight along the ski may influence stresses and deformation. To date, no field measurements exit to fully validate the effect of daytime snowpack warming and a skier load on stress, deformation and stiffness changes.

In this paper we present measurements of the distribution of normal stress below a skier and its warming related changes. A case study demonstrates how daytime heating changed the shape of the two-dimensional (2D) stress bulb. Further, we discuss potential implications for skier triggering and how our findings relate to warming induced changes of stress, deformation and stiffness.

2. METHODS

To measure the normal stress under a skier we placed capacitive pressure pads (2 mm thick, 5 x 5 cm in surface area) in the side of a pit wall below a skier (Fig. 1). The sensors, which were mounted at the tip of a thin aluminium sheet (Fig. 2) were pushed 30 cm into the sidewall of the snow pit, parallel to the snow surface.

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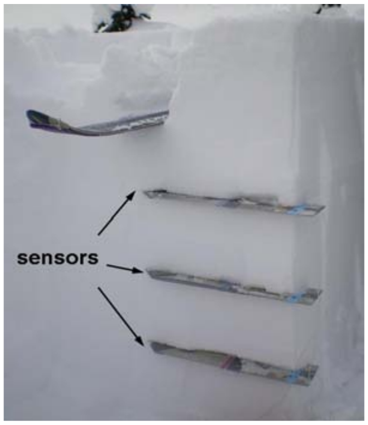


Figure 1: After the measurements, the sensors were dug out to determine their distance below the ski. In this photo, the sensors are located at the tip of the insertion plates below the ski.

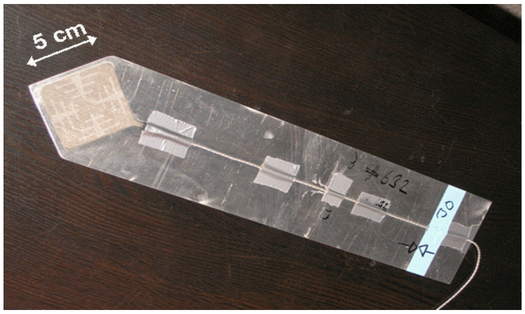


Figure 2: Capacitive pressure pad (5x5 cm) mounted at the pointed end of a 30 cm long aluminium insertion plate.

A skier standing on one ski loaded the snowpack directly over the sensors (Fig. 3). After each single measurement (short horizontal lines in Fig. 3) the skier walked off the pit wall, the sensor was placed in new position, and the skier loaded the sensor again. The measurements were done from bottom to top (10 – 20 cm spacing) to preserve the snow pack above.

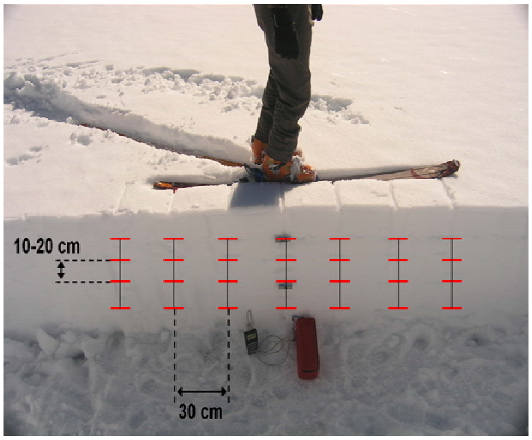


Figure 3: Experimental set up for 2D stress measurements below a skier. The horizontal lines mark the positions where the sensors were pushed into the pit wall. The case contains a Campbell Scientific CR1000 data logger with a keyboard attached.

The horizontal spacing between the vertical arrays was 30 cm. One set of measurements was conducted in the morning before a warming period and the second set during the maximum of the warming period in the afternoon. Manual temperature profiles were measured every 1 – 2 hours to monitor snowpack temperatures. Ski penetration was determined by measuring the depth of the ski track above each vertical array after each set of measurements.

3. DATA SET

In this paper we present data from four warming events in the spring of 2008 from locations in the mountains of western Canada. Table 1 provides an overview of snow pack and temperature conditions on those days. Results of the full 2D stress distribution will be discussed later in case study (April 11-12).

Table 1: Overview of all four warming cases presented in this study. Snow type classification according to Colbeck and others (1990).

Date	***Location***	***Avg. snow density [kg/m^3] (upper 50 cm /50-100 cm)***	***Hand hardness (upper 50 cm/50-100 cm)***	***Duration of warming period***	***Major snow types (upper 50 cm/50-100 cm)***	***Min/Max air temp [°C]***
March 22	Rogers Pass (Mt. Fidelity)	160 / 299	1F- P / P-P+	8 am – 2 pm	decomposed (2a) / small rounded (3a)	-8.2 / -3.9
March 28	Rogers Pass (pass area)	239 / 393	1F – P / P	9 am – 4 pm	mixed forms (3c) / mixed forms (3c)	-10 / -1.7
April 2	Kananaskis (Burstall trailhead)	225 / 300	4F-1F / P	8 am – 4 pm	facets (4a), melt freeze crusts (9e) / depth hoar (5a)	-21.5 / -1.6
April 11-12	Kananaskis (Burstall trailhead)	292 / 310	1F-P / 1F	9 am (0411) – 4 pm (0412)	facets (4a) / facets, depth hoar(4a, 5a)	-3.9 / 7.3

4. HOW DOES THE PIT WALL AFFECT STRESS DISTRIBUTION?

The stress measurement procedure used in this study may not reproduce the realistic stress distribution due to influence of the pit wall. Near the pit wall, the measured stresses may be higher than they would be in an undisturbed ‘full’ snowpack, which would allow the skier’s weight to spread over a larger area. To evaluate the effect of the pit wall comparison measurements were conducted, in which the sensors were placed 1 m beyond a 50 cm wide pit wall at the end of a 2 m long trench (Fig. 4). We assumed this set up is close enough to an undisturbed ‘full’ snowpack. However, results from two sets of comparison measurements were not conclusive. On March 16, the sensors 30 cm from the pit wall yielded slightly higher stress values compared to the sensors 100 cm from the pit wall (Fig. 5a), whereas March 15 showed opposite results (Fig. 5b). The two comparison experiments were done on different locations and elevations, hence different snow pack properties may have influenced the apparently contradictory results. However, for this initial study we assumed that measuring the stress 30 cm from an exposed pit wall is sufficiently close to realistic conditions that qualitative warming related changes are not affected. More test measurements are planned to fully evaluate the influence of the pit wall.

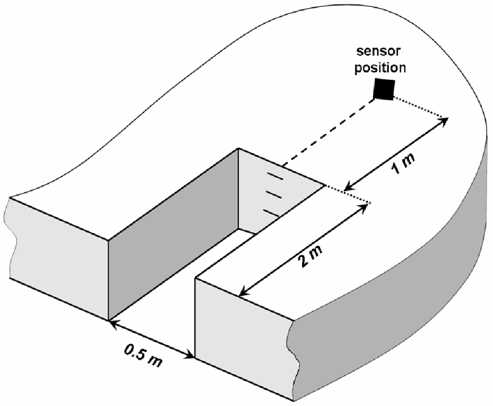
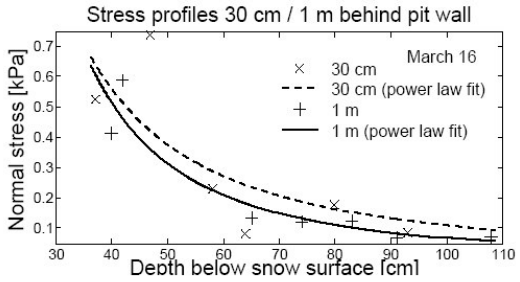
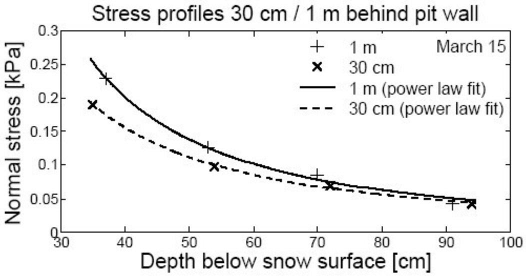


Figure 4: This schematic (not to scale) demonstrates the set up which we assume allows a stress distribution close to a ‘full’ snow pack. The sensors were pushed 1 m into the pit wall at the end of a 2 m long trench. The results of this set up were compared to the standard measurements (see Fig. 5)



a.



b.

Figure 5: Stress measurements with the sensor placed 1 m (sold line) and 30 cm (dashed line) into the pit wall from March 16 (**a**) and March 15 (**b**). Note the higher spread of data points on March 16, probably due irregularities in the snowpack.

5. RESULTS

After showing the depth of warming and stresses below mid ski for all four experiments (see sections 5.1 and 5.2), detailed measurements are presented for April 11-12 in section 5.3. For all other cases stress measurements over the full length of the ski were not available and cannot serve to evaluate 2D changes of the full stress bulb.

5.1 Depth of warming

The increase in snowpack temperatures during the warming period for all cases is summarised in Fig. 6. The depth of the warming layers ranged from approximately 20 cm, on days with weak daytime warming, to 40 cm on days with the strongest warming (April 11-12). Below this depth, no significant temperature changes were observed. For the duration of the warming periods see Table 1. The wide spread in daytime warming (8℃ to 24℃) can mainly be attributed to varying cloudiness and wind speed.

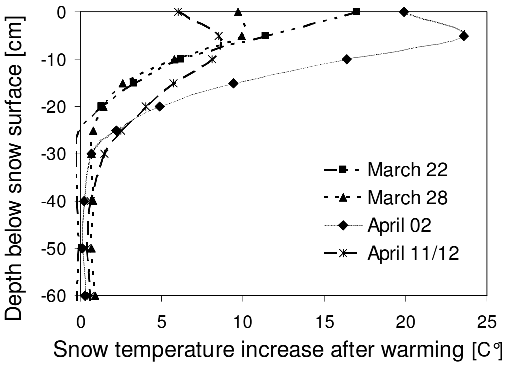


Figure 6: Temperature increase of the snowpack for all four warming events.

5.2 Stress changes below mid ski

The depth below the snow surface where substantial stress changes (> 0.1 – 0.2 kPa) occurred was approximately 35 cm for all cases (Fig. 7). Factoring in ski penetration, this depth ranged from approximately 20 cm to 25 cm below the ski. The depth of the warming layers was similar. In most cases, except for March 28, the stress under the middle of the ski decreased after the warming period. Below approximately 35 cm no significant stress changes were observed, indicating that the absolute depth of the stress bulb changed little with warming snow surface temperatures. The strongest stress decrease on April 02 occurred in the experiment with the strongest daytime warming. In all other cases, no correlation between stress change and temperature increase was obvious.

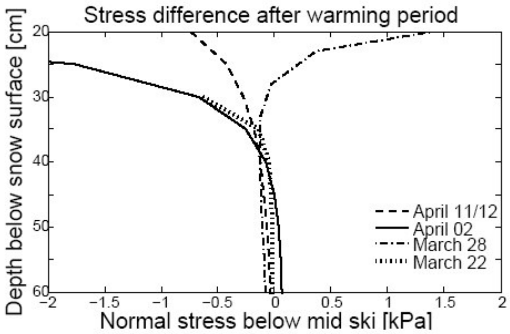
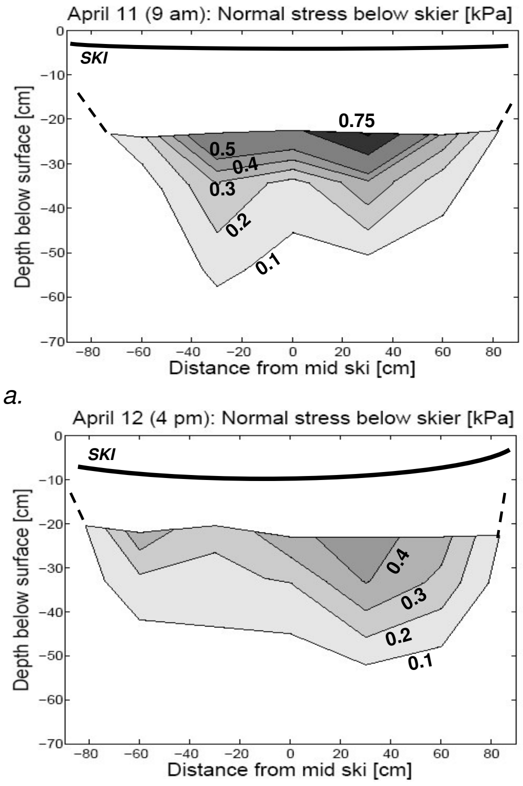


Figure 7: Changes of normal stresses during the warming period. Negative values indicate stress decrease, positive values stress increase.

5.3 Case study of 2D stress distribution (April 11-12)

Fig. 8a and 8b show the 2D stress distribution below a skier before and after the warming period of April 11/12. The solid line above the stress bulb indicates the penetration and bending of the ski. No measurements in white area directly below the ski are available due to limited performance of the pressure sensors measuring in the compacted snow below the ski.



a.

b.

Figure 8: 2D normal stress distribution before (**a**) and after (**b**) the warming period from April 11 (9 am) to April 12 (4pm). The white area below the ski and the first values at a depth of approximately 20 -22 cm are due to limited performance of the sensors measuring the stress in the compacted snow below the ski. The thick solid line (ski) indicates ski penetration and ski bending.

Before the warming (Fig. 8a) normal stresses (down approximately 22 cm) up to 0.75 kPa were observed. Maximum stresses in the same depth after warming were just above 0.4 kPa (Fig. 8b), indicating that the skier's weight was distributed over a wider distance. The overall shape of the stress bulb widened after the warming, but did not gain in depth. The width of two selected stress contour lines (0.1 and 0.2 kPa), before and after the warming, are shown in Figure 9. The 0.1 kPa contour line was up to 30 cm wider in the top 45 cm of the snowpack after the warming period. The 0.2 kPa line gained up to 20 cm in width in the top 35 cm. The width of the 0.3 kPa contour line did not change substantially with increasing temperature (not shown in Fig. 9). The intersection of the curves with the x-axis (depth below surface) give maximum depths of the specific contour lines. The depth of the 0.2 kPa line did not change substantially, and the depth of the 0.1 kPa curve decreased by approximately 5 cm.

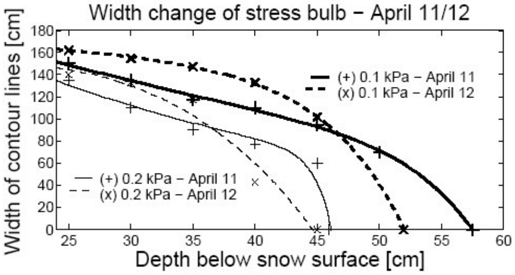


Figure 9: Width of two selected stress contour lines (0.1 kPa and 0.2 kPa) before (solid line) and after the warming period (dashed line). The dashed and dotted curves are exponential fits.

After the warming, ski penetration (see solid lines in Fig. 8a and 8b) at the middle of the ski (2.5 cm to 8 cm) increased more compared to the tip and tail of the ski (1 cm to 6 cm at tail, 1 cm to 2.5 cm at tip), causing a stronger bending of the ski. Therefore, the skier induced normal stresses spread out more evenly along the ski (Fig. 11 illustrates this behaviour).

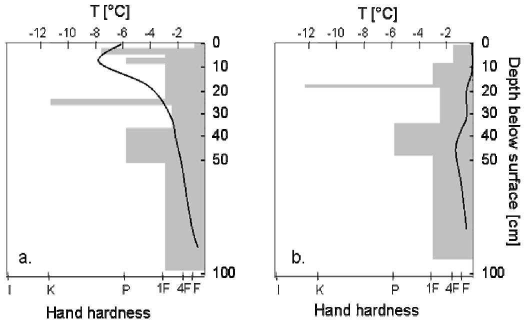
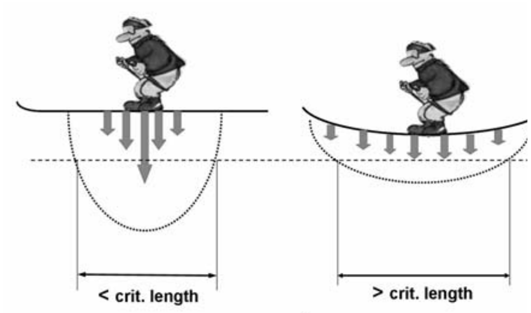


Figure 10: Hand hardness (Canadian Avalanche Association, 2007) and snow temperature (solid curves) before (**a.**) and after (**b.**) the warming period on April 11-12. The height of the snow pack settled from 98 cm to 92 cm. Note the softening in the top 10 cm.

The increasing ski penetration was caused by softening of the near surface layers. A spring-like melt-freeze crust in the top 10 cm of the snowpack turned into a layer of melting snow grains during the warming period. According to Fig. 10 the hand hardness of the top 10 cm decreased from about 1F – P to 4F (Canadian Avalanche Association, 2007). No changes in hand hardness were observed below 10 cm, even though the warming layer reached down to approximately 40 cm. The hand hardness test may not be sensitive enough to pick up smaller changes in hardness.



a. b.

Figure 11: Schematic showing the bending of the ski and magnitude of normal stresses before (**a**) and after (**b**) the surface layer warmed up. The widening stress bulb after the warming period may potentially fracture a weak layer with the necessary critical length for fracture propagation.

6. DISCUSSION AND SUMMARY

The results of this study indicate that depth of the 2D distribution of normal stresses below a skier and parallel to the skis did not increase after warming and softening of the surface layers. For a spring-like snowpack the stress bulb widened and the maximum depth did not change substantially. Deeper ski penetration in the softening surface layer caused stronger bending of the ski, and therefore the skier's weight spread out over the length of the ski, decreasing maximum stresses on the snow surface. Under these conditions, this may overrule the effect of a deepening stress bulb caused by decreasing stiffness of the surface layers due to warming as proposed by McClung and Schweizer (1999) and Wilson and others (1999). However, McClung and Schweizer's conclusions are still valid for a load that does not change its distribution along the snow surface with warming (e.g. explosives, snowmobile). Even for a realistic skier load this concept still may apply, when a hard surface layer only allows for minor ski penetration.

Our results cannot directly be compared to Wilson and others' (1999) results, since we measured normal stresses in flat terrain and they modeled shear stresses on a slope below a skier that was approximated by a constant line load. Potentially, the shear deformation below a realistic skier load (when our results are transferred on a slope) may increase with decreasing stiffness of the surface layers. According to McClung and Schweizer (1999) shear deformation may increase with decreasing stiffness, even though shear stresses do not increase.

Furthermore, a stress bulb that does not deepen with warming surface layers can not contribute to easier fracture initiation (Schweizer and others, 2003). To release a slab avalanche a fracture needs to be initiated and has to propagate along a weak layer (Schweizer and others, 2003). It is believed that a critical length of the initial fracture, which is assumed to be approximately 0.1 to 1 m (Schweizer, 1999), is necessary for propagation. Potentially, the widening stress bulb exceeds this critical length (Fig. 11), which is comparable to the order of magnitude of the width of the stress bulb. This hypothesis is speculative, since no measurements exist to confirm the critical crack size.

Schweizer and others (2004) found in lab experiments that the fracture toughness of snow is temperature dependent. Therefore, a warming related change in fracture toughness may be responsible for a change in propagation propensity even though stresses do not change considerably.

At this point our conclusions cannot be generalized for skier loading of any kind of snowpack. Only a limited amount of warming events, mostly for a spring-like snowpack were available and only static skier loading in flat terrain was considered. More measurements are planned to include a wider variety of temperature ranges and snowpack properties. Measuring skier induced shear stresses on a slope may be problematic with the method we used.

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