HOW DO YOU STRESS THE SNOWPACK?

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ABSTRACT: In the majority of fatal avalanches, skiers and snowmobilers apply load to the snowpack which triggers the initial failure in a weak layer. Understanding how the stress from a dynamic surface load transmits through the snowpack can help people avoid situations where they can trigger slab avalanches. Capacitive sensors were used to measure this stress within the mountain snowpack. The three main variables affecting stress transmission through the snowpack investigated in this paper are the type of loading, depth and properties of the snowpack. A decrease in stress was observed with increasing depth. At specific depths, snowmobiles added more stress than skiers did, thus increasing the probability of initiating a fracture in a weak layer and releasing a slab avalanche. The increased penetration depth of snowmobiles into the snowpack compared to skiers is the primary reason for this increase in stress. Falling skiers added about 3 times more stress than typical skiing. Skiers added about 1.5 times more stress than snowboarders. A decrease in stress was observed with increasing depth. Supportive surface layers created a "bridging effect" that spread stress out laterally and decreased the depth to which it penetrated.

KEYWORDS: Dynamic stress, localized dynamic loading, snowmobile, snow stability, avalanche forecasting, snowpack stratigraphy

1. INTRODUCTION

Most of the fatalities caused by snow avalanches result from people triggering the avalanches themselves (Harvey et al., 2012; Jamieson et al., 2010)! Backcountry skiing, snowmobiling, snowboarding, etc. results in localized dynamic loading applied to the snowpack, which can initiate failures in weak layers and possibly trigger avalanches. This loading imparts stress to the snowpack and depends mainly on: a) the type of trigger creating the load and b) the medium that the resulting stress travels through. Does the skier weigh 50 kg with 120 mm skis underfoot or is he (she) a researcher doing a faceplant with a 30 kg pack of instruments? Is the snowmobile making a blinding powder turn in 50 cm of fresh snow or ripping up a steep slope on a supportive spring crust? Understanding how the stress from these different loading types transmits through the mountain snowpack may help people avoid situations where they can trigger avalanches.

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Increased snowmobile recreation in the mountains and modern snowmobiles allows riders easier access to avalanche terrain, resulting in an increase of snowmobile avalanche fatalities. Snowmobiles accounted for 27% of all avalanche fatalities in Canada between the years of 1997 and 2007, whereas between 2001 and 2010 they accounted for 42%. Further, in 2009 and 2010 snowmobiles have accounted for 73% and 50% of all avalanche fatalities, respectively (Canadian Avalanche Centre, 2011). Snowmobiles are heavier than skiers, load a larger area and travel faster uphill, yet the induced stresses within the snowpack have not been measured. Finally, there has been much work performed on improving slope stability evaluation for skiers (e.g. Föhn, 1987), but little has been done to investigate how snowmobiles affect slope stability.

Föhn (1987) made the first attempt to solve the problem of how localized dynamic loading affects slope stability. He introduced a skier stability index that modeled the skier (or snow machine) as a static load applied to an elastic and isotropic snowpack. Jamieson and Johnston (1998) further improved this index by including the effect of skier penetration into the snowpack and the effect of microstructure of the weak layer on its shear strength. Since then, finite element modeling has been used to further understand the static stresses imparted to a layered snowpack by LDL (e.g. Schweizer, 1993; Jones et al., 2006; Habermann et al., 2008). However, the dynamic nature of the loading coupled with the viscoelastic-plastic deformation of the snowpack creates a complicated mechanics problem, which when modeled as a static problem, results in large uncertainty.

To improve the modeling and tackle the complexities with dynamic loading, load cells were used to measure the dynamic stresses induced by skiers within the snowpack (Schweizer et al., 1995a; Schweizer et al., 1995b; Camponovo and Schweizer, 1997). They showed that stress decreased with depth, less stress was measured below hard layers ("bridging") and that measured dynamic loading imparts more stress to the snowpack compared to static loading. Camponovo and Schweizer (2001) used the same load cells to measure the size of a skier's zone of influence capable of initiating fractures in weak layers. It was found to be relatively small, approximately 0.3 – 0.5 m^2, for depths relevant for skier triggering. These data supported, in accordance with earlier finite element calculations, that skiers are able to trigger slab avalanches by directly initiating a brittle fracture within a weak layer or interface. The findings by Schweizer et al. (1995, 2002) are based on a limited data set, did not include the dynamic stress induced by snowmobiles and were limited to qualitative statements about the effects of snowpack stratigraphy.

This paper presents numerous dynamic measurements of stress within the snowpack induced by skiers, snowboarders and snowmobiles and examines how snowpack structure affects the transmission of this stress.

2. METHODS

To investigate the additional dynamic stress applied to a mountain snowpack by human-induced LDL, single point capacitive sensors were used during the winter of 2009 in Glacier National Park, British Colombia, Canada (Exner, 2012) and near Blue River, British Columbia, Canada in 2011 and 2012.

The general experimental procedure involved digging into the snowpack and performing a manual snow profile including densities (Canadian Avalanche Association, 2007). The profile was used to quantify the snowpack stratigraphy for the area of the experiments. The sensors were mounted to aluminum sheets and inserted 1 m into one of the side walls of the snow profile. The loading was performed on the surface of the snow by either a skier sliding straight downhill dropping their knees over the sensors to simulate a typical ski turn, a snowmobile driving uphill over the sensors or a snowboarder sliding downhill similar to the skier. Figure 1 shows a skier loading the snow surface above the buried sensors.

Although the 2009 experiments were performed on a flat snowpack that was artificially compacted the day prior to experiments, the subsequent experiments were performed on sloped terrain ranging between 16° and 32°. The snowpack was mostly undisturbed soft snow on the surface with rounded grains below (Fierz et al., 2009).

To obtain a stress measurement for each pass of the LDL over the sensors, the difference between the baseline quasi-static stress measurement per sensor (before arrival of the dynamic load) and the peak stress recorded for the dynamic load was extracted. This ensured that only the additional stress due to the LDL was measured and not the initial compression on the sensors from insertion into the snowpack.

3. DATA

In total, three, nine and twelve days were used for data collection in the 2009, 2011 and 2012 seasons, respectively. These 24 days resulted in 1064 measured localized dynamic loading events. We measured and analyzed vertical depth of sensor below undisturbed surface of snow, type of localized dynamic load (e.g. skier, snowmobile, etc.), experiment number, penetration depth of trigger into the snowpack, effective depth (defined as penetration depth subtracted from depth of sensor), snowpack density and snowpack hand hardness.

Figure 1: Skier performing an experiment loading the snow surface above the buried sensors.

4. RESULTS AND DISCUSSION

The measurements displayed in Figure 2 showed that snowmobiles added considerably more stress to the mountain snowpack than skiers did, thus increasing the probability of inducing a brittle fracture in a weak layer and possibility releasing a slab avalanche.

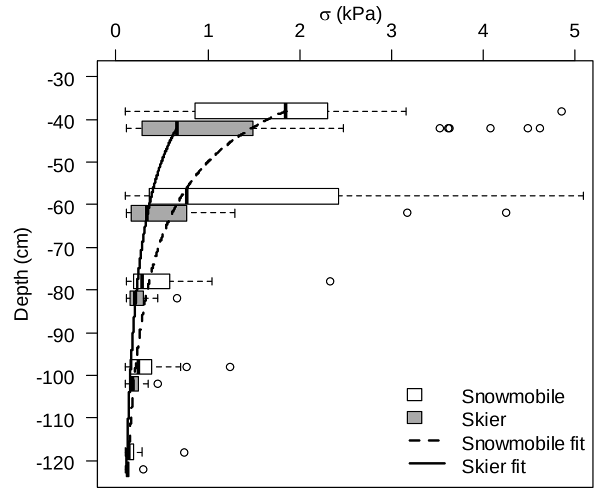

Figure 2: Box plots of stress by absolute depth class for snowmobiles (white) and skiers (grey). Lines indicate the fitted model for snowmobiles (dashed) and skiers (solid). Boxes span the interquartile range. Whiskers extend to 1.5 times the interquartile range. Open circles indicate outliers.

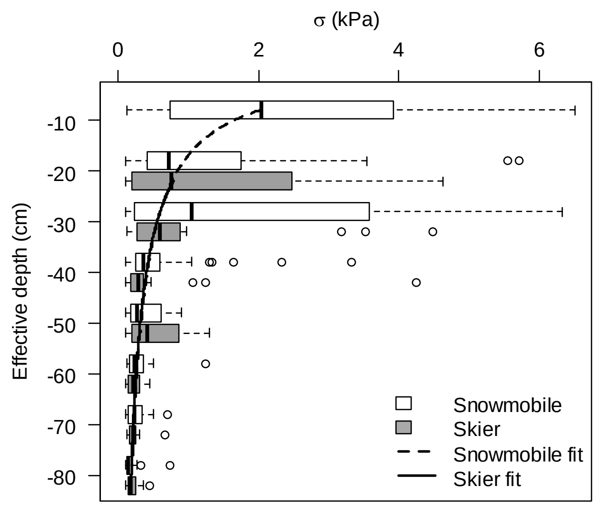

Figure 3: Box plots of measured stress per effective depth (penetration depth subtracted from depth) for snowmobiles (white) and skiers (grey). Lines indicate the fitted model for snowmobiles (solid) and skiers (dashed). Note, the fitted lines overlap each other. Boxes, whiskers and open circles as in Figure 2.

However, from simple calculations, the ***static stress*** applied to the ***surface*** of a mountain snowpack are similar for a typical skier (2.6 kPa, from 85 kg skier, 0.32 m^2 area) compared with a typical snowmobile (3.8 kPa, from 350 kg machine and rider, 0.9 m^2 area). The fact that the magnitude of stress added to the snowpack should be similar for skiers and snowmobiles was further evidenced in Figure 3 which showed stress vs. ***effective*** depth. There is no substantial difference between the fitted curves for the skier and snowmobile data. Effective depth is calculated by subtracting penetration depth of the skier (or snowmobile) from the absolute depth into the snowpack. Therefore, Figures 2 and 3 imply that the main variable responsible for the difference in stress added to the snowpack is penetration depth. As observed in Figure 4, snowmobiles penetrated the snowpack about 2 times deeper than skiers, when comparing medians (40 cm for snowmobiles and 20 cm for skiers). The data presented are from varying snowpacks.

It appears that the differences in the dynamic movements between skiers and snowmobiles lead to differences in penetration depth of each (Figure 4), which is responsible for the differences in stress levels within the snowpack. This result agrees with Jamieson and Johnston (1998) who proposed to include ski penetration as an improvement to the skier stability index (Föhn, 1987). Further, the observed decrease of stress with depth in Figure 2 indicates that the closer a buried sensor or weak layer is to the LDL, the more stress will be applied. These results are consistent with dynamic stress measurements on flat terrain (Schweizer et al., 1995a; Schweizer et al., 1995b; Camponovo and Schweizer, 1997) and with calculations for a sloping homogenous elastic snowpack (e.g. Föhn, 1987).

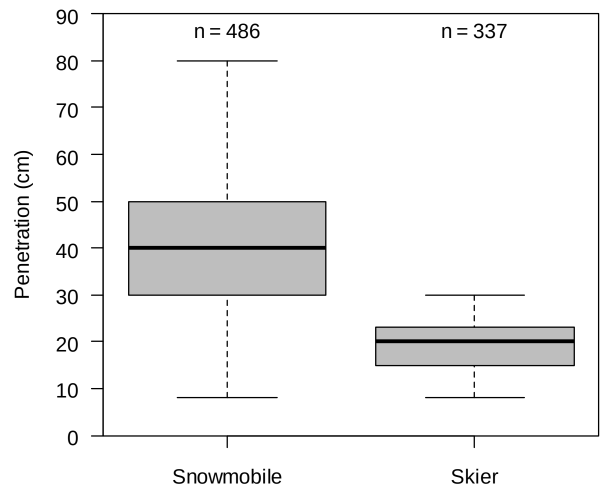

Figure 4: Comparison of penetration depth for snowmobiles and skiers. Boxes, whiskers and open circles as in Figure 2.

If we draw the static stress beneath a snowmobile it takes the shape of a bulb that dissipates with depth, see Figure 5. And, the data presented above indicates the importance of penetration depth on how deep our stress travels into the snowpack. So, these “stress bulbs” start below the depth that we penetrate the snowpack. This is an important point when evaluating the stability of a slope before skiing or riding it. Maybe the tests that we use to evaluate slope stability (e.g. compression and extended column tests) for skiing and snowmobiling should represent this?

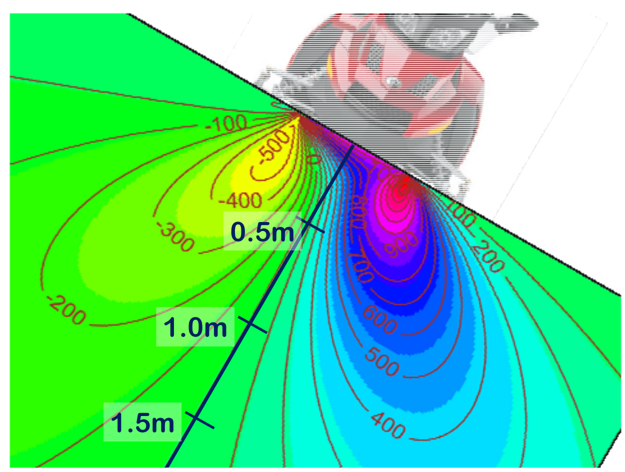

Figure 5: Static shear stress below a snowmobile (Calculations based on Das 1983”)

Investigating further, Figure 6 shows direct comparisons between skier stress and falling skiers, snowboarders and snowmobiles. The measurements for falling skiers and snowboarders were made on the same days as the subsequent skier measurements, thus ensuring the same snowpack properties. We observed about 3 times more stress when skiers fall, and that skiers add about 1.5 times more stress than snowboarders. The direct comparison between skiers and snowmobiles includes data from 2011 and 2012 over multiple days and varying snowpack properties. When comparing medians, snowmobiles added about 2 times more stress than skiers, which is comparable to the difference in penetration depth (Figure 4).

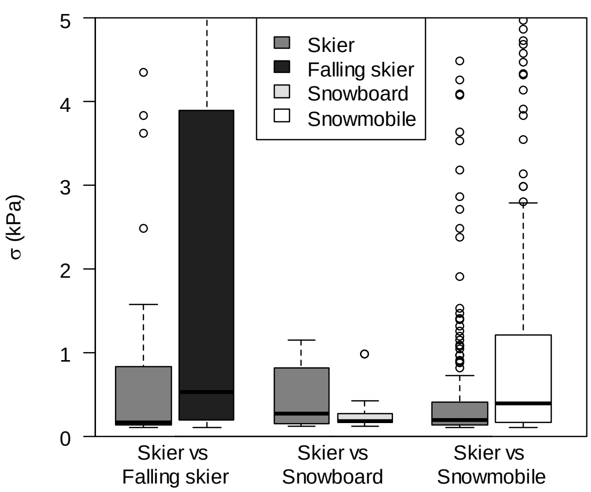

Figure 6: Stress for varying triggers compared to skiers. Boxes, whiskers and open circles as in Figure 2.

The data presented in Figure 7 show the importance of the structure of the snowpack on the impact of LDL. Figure 7 shows higher levels of stress measured at similar depths when the snowpack had an uncompacted surface layer compared to a compacted surface layer. This softer near surface layer allowed more penetration into the snowpack, which resulted in comparable stress being transmitted more deeply. Conversely, the supportive surface layer created a “bridging” effect where stresses were distributed over a larger area, but did not penetrate as deeply into the snowpack. This “bridging” effect was recognized by Camponovo and Schweizer (1997).

The movement of skiers and snowmobiles through an undisturbed snowpack resulted in a large variation between measurements. The main variables analyzed were carefully measured and recorded, but other variables such as ski properties including size and width, speed of skier or snowmobile and mass of skier or rider plus backpack were left out of this analysis. To confirm the validity of the measurements an order of magnitude comparison was performed with previously published measurements. Camponovo and Schweizer (1997) measured a skier weighting a load cell at an effective depth of 20 cm and 30 cm in the snowpack at about 1.8 kPa and 0.6 kPa, respectively. They also presented calculated values for a static line load (500 N m^{-1}) at 20 cm and 30 cm down of 1.6 kPa and 1.0 kPa, respectively. The equation for the fitted line for skier data at 20 cm and 30 cm effective depth in Figure 7 yields 0.77 kPa and 0.55 kPa, respectively.

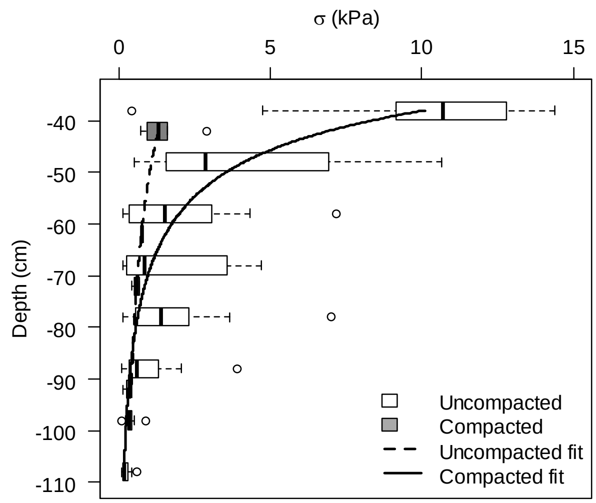

Figure 7: Distribution of stress per depth for snowmobiles. Grey box plots correspond to data collected where the surface of the snowpack was artificially compacted and supported the LDL. White box plots correspond to data collected where the surface of the snowpack was undisturbed, soft and allowed penetration of the LDL (uncompacted). Lines indicate the fitted models. Boxes, whiskers and open circles as in Figure 2.

There is a substantial decrease in the values measured in this study, but they are comparable to the previous studies. The decrease in measured stress may be due to the greater width of modern skis (less penetration) or the rapid downslope movement in the present study.

5. CONCLUSION

We took measurements to better understand how we stress the snowpack. The results showed that snowmobiles added more stress to the snowpack compared to skiers. The increased penetration depth of snowmobiles compared to skiers is the primary reason for the increase in stress. Skiers added about 1.5 times more stress than snowboarders. Falling skiers added about 3 times more stress.

The results showed a strong decrease of stress levels with increasing depth into the snowpack, which agrees with previous studies (Schweizer et al., 1995a; Schweizer et al., 1995b; Camponovo and Schweizer, 1997). Stiff snowpack layers created a “bridging effect” that reduced the depth at which a given level of stress was measured. This result was recognized in the previous studies (Schweizer et al., 1995a; Schweizer et al., 1995b; Camponovo and Schweizer, 1997).

Understanding the transmission of stress due to localized dynamic loads through a mountain snowpack may help people avoid situations in which they can trigger avalanches. The next stage of this research will be to collect data that shed light on how much snow and of what hardness is needed to effectively bridge a weak layer.

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REFERENCES

Camponovo, C., Schweizer, J., 1997. Measurements on skier triggering. Proceedings of the International Snow Science Workshop ISSW 1996, Banff, Alberta, Canada, 6–10 October 1996. Canadian Avalanche Association, Revelstoke BC, Canada, p.100–103.

Canadian Avalanche Centre, 2011. Avalanche incident report database. http://www.avalanche.ca/cac/library/incident-report-database/view, accessed July 1, 2011.

Canadian Avalanche Association (CAA), 2007. Observation Guidelines and Recording Standards for Weather, Snowpack and Avalanches. Canadian Avalanche Association. Revelstoke, BC, Canada.

Das, B., 1985. Advanced Soil Mechanics. McGraw Hill.

Exner, T., 2012. Field studies of snowpack stress and deformation due to surface loads and temperature effects. PhD thesis, Dept. of Geoscience, University of Calgary, Calgary, Canada.

Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K. and Sokratov, S.A., 2009. The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology 83, IACS Contribution 1, UNESCO-IHP, Paris.

Föhn, P.M.B., 1987. The stability index and various triggering mechanisms. IAHS Publication, 162, 195-214.

Harvey, S., Rhyner, H, and Schweizer, J. 2012, Lawinenkunde. Praxiswissen für Einsteiger und Profis zu Gefahren, Risiken und Strategien. Bruckmann Verlag GmbH, Muenchen. pp.192.

Jamieson, J.B., Haegeli, P. and Gauthier, D., 2010. Avalanche Accidents in Canada, Volume 5: 1997 – 2007. Canadian Avalanche Association, Revelstoke, BC, Canada.

Jamieson, J.B. and Johnston, C.D., 1998. Refinements to the stability index for skier-triggered dry-slab avalanches. Ann. Glaciol., 26, 296-302.

Jones, A.S.T., Jamieson, J.B., Schweizer, J., 2006. The effect of slab and bed surface stiffness on the skier-induced shear stress in weak snowpack layers. In: Gleason, J.A. (Ed.), Proceedings of the International Snow Science Workshop 2006, Telluride CO, U.S.A., 1–6 October 2006, p. 157-164.

Habermann, M., Schweizer, J. and Jamieson, J.B. 2008. Influence of snowpack layering on human-triggered snow slab avalanche release. Cold Reg. Sci. Technol., 54 (3), 176–182.

Schweizer, J., 1993. The Influence of the layered character of the snowpack on the triggering of slab avalanches. Ann. Glaciol., 18, 193-198.

Schweizer, J., Schneebeli, M., Fierz, C. and Föhn P., 1995a. Snow mechanics and avalanche formation: Field experiments on the dynamic response of the snowpack. Surveys in Geophysics 16: 621 – 633.

Schweizer, J., Camponovo, C., Fierz, C. and Föhn P., 1995b. Skier triggered slab avalanche release – some practical implications. Sivardiére, F., ed. Les apports de la recherché scientifique a la sécurité neige, glace et avalanche. Actes de Colloque, Chamonix 30 mai – 3 juin 1995. Grenoble, Association Nationale pour l`Étude de la Neige et des Avalanches (ANENA), 309-315.

Schweizer, J., Camponovo, C., 2001. The skier's zone of influence in triggering slab avalanches. Annals of Glaciology 32: 314-320.