THE INFLUENCE OF NEAR-SURFACE WARMING ON SLAB STIFFNESS AND CRACK PROPAGATION PROPENSITY

Benjamin Reuter*, Jürg Schweizer
WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

ABSTRACT: Near-surface warming by either an increase in air temperature or radiation is believed to have a significant effect on dry-snow slab avalanche formation. However, it is unclear how and to which degree warming promotes instability. We have therefore quantified surface warming with respect to the contributing meteorological processes and investigated in situ the fracture behavior under conditions of surface warming. The relevant energy fluxes at the snow surface were partly measured and partly modeled with the snow cover model SNOWPACK and used to determine the energy input into the snowpack. To determine the effect of surface warming on slab properties, we derived the stiffness of snow layers from penetration resistance measurements on nine field days with the snow micro-penetrometer. On eight of these days propagation saw test experiments were performed at the same time and compared to the energy input at the snow surface. Moreover, the specific fracture energy of the weak layer, which in combination with the slab properties controls crack propagation propensity, was determined by means of finite element modeling. A reduction in stiffness by a factor of about 2 was observed in near-surface snow layers when the energy input at the surface exceeded 300 kJ m^{-2}. Meanwhile, weak layer properties showed no trend. Softer slabs were found to cause shorter cut lengths in propagation saw test experiments – suggesting that surface warming increases crack propagation propensity. For the first time the effect of surface warming on instability has been quantified. The results demonstrate a subtle influence of surface warming on snowpack stability. It is suggested that a pre-existing weakness and considerable energy input are required that surface warming may promote instability.

1. INTRODUCTION

Avalanche forecasting services frequently predict a rise in avalanche danger in the course of the day due to day-time warming. We found the corresponding wording in about 20% of the bulletins issued for the Swiss Alps in the months of November to March when typically dry-snow conditions prevail. High avalanche activity is occasionally reported on days just after a snowfall followed by an increase in air temperature.

Crack propagation is the ultimate step in the chain of events preceding the detachment of a slab (Schweizer et al., 2003). Crack propagation may drive the initial failure to a size that a slab is created which will slide down-slope if friction is overcome (van Herwijnen and Heierli, 2009). In order to assess the crack propagation propensity of the snowpack it is common practice to perform field tests such as the PST (Gauthier and Jamieson, 2006; Sigrist and Schweizer, 2007) or the ECT (Simenhois and Birkeland, 2006) and interpret the observed results in regard to slab avalanche release probability.

The crack propagation propensity in any material depends on its mechanical properties and their interaction. Snow is a rather warm material given that observed snow temperatures range not far below the melting point. It seems clear that this close to a thermo-dynamical phase transition an increase in snow temperature will result in a drastic change of the mechanical properties of snow (e.g. Schweizer and Camponovo, 2002). A decrease of stability due to warming of the dry snowpack has often been discussed among practitioners and researchers (e.g. Schweizer and Jamieson, 2010). Exner and Jamieson (2008) found a lengthening of the stress bulb below a skier under warming suggesting a wider zone of influence of a skier at depth.

The objective of our study was to find out whether a change in PST results on days with significant daytime warming can be observed and if so, how the key mechanical parameters change. Therefore, we derived three quantities: the stiffness of slab layers, the fracture energy of the weak layer and the critical cut length. These quantities were compared to the energy input at the snow surface.

2. DATA COLLECTION AND ANALYSIS

In the course of a single day with significant day-time warming, we performed a series of prop-

---

Corresponding author address: B. Reuter,
WSL Institute for Snow and Avalanche Research
SLF, Flüelastrasse 11,
CH-7260 Davos Dorf, Switzerland;
tel: +41 81 4170347; fax: +41 81 4170110;
email: reuter@slf.ch

agation saw tests in conjunction with snow micro-penetrometer (Schneebeli et al., 1999) measurements on sunny slopes in the surroundings of Davos, Eastern Swiss Alps (Fig. 1).

In total we performed 168 PSTs on nine days on different slopes. In at least three adjacent pits (Fig. 1), we measured penetration resistance along with crack propagation characteristics approximately every hour. In each pit one PST was performed approximately every hour. At the lower end of each PST block a penetration resistance profile was recorded with the SMP. Additionally, a transect of penetration resistance profiles had been taken at the beginning to record the initial state of the snowpack for reference. In the end we have performed at least four SMP and PST measurements per pit on a given slope on a specific day. The maximum daytime warming at a depth of 10 cm and at the depth of the weak layer were derived from shaded snow temperature measurements. A detailed description of the measuring procedure is given in Reuter and Schweizer (2012).

PSTs were performed as described in Gauthier and Jamieson (2008) with a column length of 120 cm up-slope and the ends of the column cut slope perpendicular. We recorded slab thickness, slope angle, critical cut length and type of fracture arrest. With the PST fractures are not only classified in propagating and non-propagating fractures, but the cut length which is a continuous quantity is recorded. Hence, the PST is more likely to respond to small changes in crack propagation propensity than other tests. The data obtained from PST measurements were used together with the stiffness obtained from the SMP measurement to calculate the specific fracture energy of the weak layer as described by Sigrist and Schweizer (2007).

By comparison with the manual snow profile the corresponding snow layers in the SMP signal were identified. Interfaces of layers were picked manually in all SMP signals. The SMP signals were processed with a MATLAB routine based on the work by Marshall and Johnson (2009) in order to extract the stiffness of the layers from the SMP signals.

To calculate the energy input into the snow cover we used the numerical snow cover model SNOWPACK (Bartelt and Lehning, 2002) with the following meteorological input quantities from the closest possible weather station (Fig. 1): incoming shortwave radiation (S_{IN}), reflected shortwave radiation (S_{OUT}), incoming longwave radiation (L_{IN}), snow surface temperature, air temperature, wind speed, wind direction, relative humidity, snow depth. Outgoing longwave radiation (L_{OUT}), the flux of sensible heat (H_S) and latent heat (H_L) were modeled. According to King et al. (2008) the energy flux balance is:

$$dH/dt = S_{in} - S_{out} + L_{in} - L_{out} + H_S + H_L$$

where H is the snowpack's internal energy per unit area. By cumulating the energy fluxes of 15 min intervals over the time span from the first measurement to the measurement later in the day when the PST was performed, the energy input (dH) was calculated. If the sign of dH is positive the snowpack gains energy which means it is warmed, if the sign of dH is negative the snowpack is cooled. This approach allows us to determine the amount of energy which is available to

Figure 1: PST along with SMP measurements have been performed in three pits (1,2,3) each field day. High-quality meteorological data for simulations was taken from an AWS located closest to the field site.

Figure 2: The snow micro-penetrometer (SMP) measures the penetration resistance of snow layers and due to its high resolution sensor allows the derivation micro-mechanical properties.

the snowpack within a certain time. With this integral measure of warming we capture the interaction of the meteorological processes acting on the snow cover. Solely considering air temperature and its change is not sufficient to describe the near-surface warming of snow layers.

3. RESULTS AND DISCUSSION

On all field days a fairly prominent weak layer in the snowpack existed (as found with a CT) and significant daytime warming in the top 10 cm of the snowpack was observed. The maximum day-time snow temperature rise at 10 cm depth was 4.6°C on average, whereas it was only 1.2°C at the depth of the weak layer. Average snow temperature at 10 cm depth and at the depth of the weak layer in the early morning was -7.5°C and -3.9°C, respectively.

We related the stiffness of slab layers, the weak layer fracture energy and the critical cut length to the observed amount of warming. Warming was quantified by the cumulative energy input derived from the surface energy flux balance. The energy input derived from the energy surface fluxes are prone to errors – not least because turbulent fluxes were modeled based on a bulk approach and atmospheric stability assumptions. To each of the energy fluxes contributing to the energy input we assigned an uncertainty and eventually determined the overall uncertainty of the hourly energy input to 40 kJ m^{-2}, which is about 8% of the mean energy input per day.

In order to observe changes in slab stiffness the values derived from SMP measurements performed during the day were related to the nearest reference measurement performed at the beginning of the day. Top layers experienced a more pronounced reduction in stiffness than deeper layers. To reduce the effective modulus of the layers located within the top 5 cm by about 50% an energy input of about 300 kJ m^{-2} was required. The observed reduction in stiffness decreased with layer depth and was not observed in layers located deeper than 20 cm below the surface. This observation agrees with measured snow temperature profiles and confirms that warming of the snow mainly occurs in near-surface layers (e.g. Fierz, 2011).

As snow temperature changes at the depth of the weak layer were small, we expected the specific fracture energy of the weak layer to remain unaffected. The first PST measurement performed in a pit was used as the reference for the measurements later conducted in this pit. In the 168 PSTs we modeled, the critical energy release rate ranged from 0.4 to 2.2 J m^{-2} with a mean of 1.3 J m^{-2}. No trend between warming and the change of critical energy release rate was observed. Hence, we note that the specific fracture energy was largely unaffected by surface warming. This observation is in agreement with the snow temperature measurements that only showed small changes at the depth of the weak layer.

The critical cut lengths measured in the PSTs in the course of a field day were related to the first measurements in the morning. For cumulative energy inputs below about 400 kJ m^{-2} the change of critical cut length varied widely; positive and negative changes were observed. For a cumulative energy input larger than about 400 kJ m^{-2}, however, most cut lengths were shorter than the initial cut length. Notwithstanding considerable scatter a statistically significant trend ($p=0.022$) was found towards shorter cut lengths in PST experiments under surface warming.

Former analyses of contributory factors had shown that warming played a subordinate (or at best controversial) role (e.g. Perla, 1970). This study is the first to quantitatively measure the effect of surface warming on instability. Our results show decreasing values of slab stiffness and critical cut length with ongoing warming in dry snowpacks that have initially contained a potential weakness. As we only examined cases which were favorable to crack propagation and when surface warming was anticipated to play a role, we do not see our results in contrast with previous studies.

4. CONCLUSIONS

We related the energy input as a measure of surface warming – calculated from the partly measured and partly modeled surface energy fluxes – to stiffness observed in near surface snow layers and to the critical cut length found in 168 PST experiments.

We observed decreasing values of slab stiffness derived from the SMP penetration force signal with increasing cumulative energy input. The critical cut length in propagation saw test experiments tended to decrease with increasing energy input into the snowpack – though the effect was less pronounced than for the slab stiffness. The critical cut length is an integral measure of the crack propagation propensity. We conclude that the reason for increased crack propagation propensity was increased bending of the slab layers, as we measured a reduction of stiffness, but did not observe a trend in the weak layer fracture energy on days with considerable surface warming. Several hours of medium or high energy input were required for a notable effect on crack propagation propensity. The amount of energy leading to warming can be accumulated by either insolation on a suitably inclined slope or positive adding of turbulent fluxes and radiative fluxes. Hence, estimating warming in the field solely from observed air temperatures or cloud coverage seems challenging and is likely to be error-prone.

Despite the uncertainty arising from the calculation of surface energy fluxes it seems clear that a considerable amount of energy is needed to change slab layer properties and in combination with a pre-existing weakness to promote instability.

ACKNOWLEDGEMENTS

We would like to thank Alec van Herwijnen, Susanna Hoinkes, Jake Turner, Fabiano Monti and Stephan Simioni for their help with the field work.

REFERENCES

Bartelt, P. and Lehning, M., 2002. A physical SNOWPACK model for the Swiss avalanche warning; Part I: numerical model. Cold Reg. Sci. Technol., 35(3): 123-145.

Exner, T. and Jamieson, B., 2008. The effect of snowpack warming on the stress bulb below a skier. In: C. Campbell, S. Conger and P. Haegeli (Editors), Proceedings ISSW 2008, International Snow Science Workshop, Whistler, Canada, 21-27 September 2008, pp. 415-420.

Fierz, C., 2011. Temperature profile of snowpack. In: V.P. Singh, P. Singh and U.K. Haritashya (Editors), Encyclopedia of Snow, Ice and Glaciers. Encyclopedia of Earth Sciences Series. Springer Netherlands, pp. 1151-1154.

Gauthier, D. and Jamieson, B., 2008. Evaluation of a prototype field test for fracture and failure propagation propensity in weak snowpack layers. Cold Reg. Sci. Technol., 51(2-3): 87-97.

Gauthier, D. and Jamieson, J.B., 2006. Towards a field test for fracture propagation propensity in weak snowpack layers. J. Glaciol., 52(176): 164-168.

King, J.C., Pomeroy, J.W., Gray, D.M., Fierz, C., Föhn, P.M.B., Harding, R.J., Jordan, R.E., Martin, E. and Plüss, C., 2008. Snow–atmosphere energy and mass balance. In: R.L. Armstrong and E. Brun (Editors), Snow and Climate: Physical Processes, Surface Energy Exchange and Modeling. Cambridge University Press, Cambridge, U.K., pp. 70-124.

Marshall, H.-P. and Johnson, J.B., 2009. Accurate inversion of high-resolution snow penetrometer signals for microstructural and micromechanical properties. J. Geophys. Res., 114(F4): F04016.

Perla, R., 1970. On contributory factors in avalanche hazard evaluation. Can. Geotech. J., 7: 414-419.

Reuter, B. and Schweizer, J., 2012. The effect of surface warming on slab stiffness and the fracture behavior of snow. Cold Reg. Sci. Technol.: in press, doi: 10.1016/j.coldregions.2012.06.001.

Schneebeli, M., Pielmeier, C. and Johnson, J.B., 1999. Measuring snow micro structure and hardness using a high resolution penetrometer. Cold Reg. Sci. Technol., 30(1-3): 101-114.

Schweizer, J. and Camponovo, C., 2002. The temperature dependence of the effective elastic shear modulus of snow. Cold Reg. Sci. Technol., 35(1): 55-64.

Schweizer, J. and Jamieson, B., 2010. On surface warming and snow instability, International Snow Science Workshop ISSW, Lake Tahoe CA, U.S.A., 17-22 October 2010, pp. 619-622.

Schweizer, J., Jamieson, J.B. and Schneebeli, M., 2003. Snow avalanche formation. Rev. Geophys., 41(4): 1016.

Sigrist, C. and Schweizer, J., 2007. Critical energy release rates of weak snowpack layers determined in field experiments. Geophys. Res. Lett., 34(3): L03502, doi:10.1029/2006GL028576.

Simenhois, R. and Birkeland, K.W., 2006. The extended column test: a field test for fracture initiation and propagation. In: J.A. Gleason (Editor), Proceedings ISSW 2006. International Snow Science Workshop, Telluride CO, U.S.A., 1-6 October 2006, pp. 79-85.

van Herwijnen, A. and Heierli, J., 2009. Measurements of weak snowpack layer friction. In: J. Schweizer and A. van Herwijnen (Editors), International Snow Science Workshop ISSW, Davos, Switzerland, 27 September - 2 October 2009. Swiss Federal Institute for Forest, Snow and Landscape Research WSL, pp. 112-114.