On how to measure snow mechanical properties relevant to slab avalanche release

Benjamin Reuter*, Martin Proksch, Henning Loewe, Alec van Herwijnen and Jürg Schweizer
WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

ABSTRACT: The release of a slab avalanche is preceded by a sequence of fractures. The main material properties relevant for the fracture processes are the specific fracture energy of the weak layer as well as the effective elastic modulus and the density of the overlying slab layers. Recent advances in measurement techniques and data processing now allow us to objectively determine these snowpack properties. At the micro-scale, the three dimensional structure of snow samples is obtained from snow micro-tomography (µCT). By modelling the mechanical behaviour based on the snow microstructure, the elastic properties are derived. At the macro-scale, fracture mechanical field tests with particle tracking velocimetry (PTV) allow observing the in-situ fracture behaviour. Specific fracture energy and slab effective elastic modulus are derived from PTV measurement by fitting an analytical beam equation to the observed deformation field. High resolution snow stratigraphy data are obtained from field measurements using the snow micro-penetrometer (SMP). The SMP bridges the gap between both scales since it provides micro-structural information for all layers within the snow cover. Using these three techniques, we compiled a dataset of the mentioned material properties. In many cases we were able to apply at least two of the methods to the same sample. The results show that the different measurement and analysis techniques provide comparable values for fracture energy, effective elastic modulus as well as density, even though the measurements were performed at different scales. With reliable methods to determine the key parameters describing the fracture process now being available, snow instability modelling based on either snow cover simulations or spatial field measurements can be envisaged.

KEYWORDS: snow microstructure, snow mechanical properties, snow fracture, snow stability evaluation, avalanche release

1 INTRODUCTION

Snow slab avalanche release involves a sequence of fractures including failure initiation, meaning the formation of an initial crack in the weak layer beneath the slab, and crack propagation, which finally leads to the detachment of the snow slab (Schweizer et al., 2003).

For both processes, properties of the slab layers and the weak layer are important (van Herwijnen and Jamieson, 2007). For failure initiation, the density and the elastic properties of the slab and the strength of the weak layer are believed to be the important properties. For crack propagation, the critical cut length, as it would be measured in a propagation saw test (Gauthier and Jamieson, 2006), is considered the relevant measure for crack propagation propensity. The critical cut length can be modelled (Heierli, 2008) using the density and the elastic properties of the slab and the specific fracture energy of the weak layer, which is the resistance to crack propagation (Sigrist and Schweizer, 2007).

Density is measured in the field with reasonable precision by weighing a snow sample of a given volume. With respect to snow instability modelling, the effective elastic modulus is probably the most delicate of the mentioned parameters, since experimental values of the effective modulus for seasonal snow spread over at least two orders of magnitude (Mellor, 1975). Misinterpretation can therefore lead to large errors. The effective modulus and the specific fracture energy can be determined by particle tracking (PTV) from propagation saw test (PST) experiments (van Herwijnen and Heierli, 2010). However, the procedures are elaborate and hinder collection of much data during one day.

The snow micro-penetrometer (SMP) (Schneebeli and Johnson, 1998) offers an alternative. From the force signal, which is recorded within short time without having to dig a snow pit, mechanical properties can be derived. As SMP signal interpretation is still in the early stages, parameters derived from SMP signals have not yet been validated. Our aim is therefore to investigate the reliability of SMP-derived quantities by comparison with the corresponding properties derived from micro-computer tomography (µCT) and particle

* *Corresponding author address:* Benjamin Reuter, WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland
tel: +41 81 417 0347; email: reuter@slf.ch

tracking velocimetry (PTV). For this, we have compiled two datasets (PST-SMP and µCT-SMP dataset) that allow a direct comparison of SMP-derived quantities with the two other established methods.

2 METHODS

2.1 Experimental data

The PST-SMP data set consists of field measurements that were conducted in the Swiss Alps around Davos on six days during three seasons (2010-2011 to 2012-2013). On each of these days, SMP measurements were taken next to PSTs, allowing for direct comparison.

The µCT-SMP dataset consists of natural and artificial snow samples taken in the winters of 2009-2010 and 2010-2011. From the center of the snow samples, one µCT sample (1 cm^3) was extracted and up to four SMP measurements were taken around the location of the µCT sample.

2.2 Snow micro-tomography

µCT scans were performed with a nominal resolution (pixel size) between 10 µm for new snow samples and 25 µm for depth hoar. The height of the scanned volume ranged between 2.56 mm for new snow and 10 mm for depth hoar. The attenuation image (grey scale image) resulting from each scan was filtered using a Gaussian filter (σ = 1 voxel, kernel half-width = 2 voxel) and then segmented into a binary image. The segmentation was performed in order to match the density of the binary image with the density of the snow sample. The elastic moduli were computed from segmented µCT images by finite element modelling (Garboczi, 1998). For the following discussion, we neglect the micro-structural anisotropy of snow and focus solely on the results for the vertical Young's modulus, simply referred to as elastic modulus henceforth. Neglecting differences between horizontal and vertical directions is consistent with the underlying assumption of the PTV analysis where the slab is considered as a laminate made of mechanically isotropic layers. The validity of this assumption in view of the existing micro-structural anisotropy of snow remains to be discussed in the future.

2.3 Snow micro-penetrometry

With the help of the SnowMicroPen (SMP), which is a high-resolution snow penetrometer being driven into the snow cover at constant speed, it is possible to measure the penetration resistance of snow layers. The density was derived from the median penetration resistance within a moving window of 2.5 mm based on the work by Pielmeier (2003). The specific fracture energy was determined by integrating the penetration force throughout the weak layer. The effective modulus was calculated from the average slab density based on quasi-static uniaxial compression experiments (Scapozza, 2004).

2.4 Propagation saw test and particle tracking

All PST experiments (Gauthier and Jamieson, 2008) (Sigrist and Schweizer, 2007) had the same dimensions (cross-slope width: 0.3 m, up-slope length: 1.2 m), but had slope normal, rather than vertical, column ends. A crack was cut into the weak layer in up-slope direction with a 2 mm thick snow saw until a self-propagating crack started at a critical cut length r_c. Numerous black markers were inserted in the snow above and below the weak layer and experiments were recorded with a video camera. The particle tracking velocimetry (PTV) method for analyzing PSTs uses the horizontal and vertical displacements of each marker in the slab to derive the mechanical strain energy of the beam for a given crack length. An analytical expression relating the mechanical strain energy with the effective modulus and the crack length allows deriving the bulk effective modulus of the slab and the specific fracture energy of the weak layer (van Herwijnen and Heierli, 2010).

3 RESULTS AND DISCUSSION

To build a bridge between the micro and the macro scale, we first show that two independent methods (µCT, SMP) produce similar values of snow density. In the following, we provide support that also effective moduli derived with snow micro-penetrometry are reliable by presenting comparisons with both, µCT-derived elastic modulus and PTV-derived effective modulus. Eventually, we address the specific fracture energy and compare SMP with PTV-derived values.

4.1 Density

Twenty seven snow samples were both scanned in the µCT and tested with the snow micro-penetrometer. Snow density was obtained from the ice volume fraction of the binary µCT images and from SMP penetration resistance measurements. Snow densities derived from the SMP signal compared well with those obtained from the µCT (Figure 2).

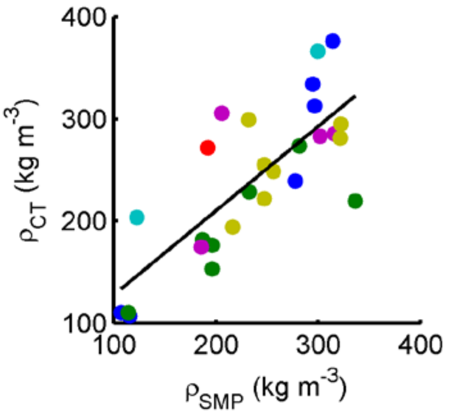

Figure 2: µCT and SMP-derived density with linear regression for 27 snow samples (r=0.78, p<0.01) covering a broad range of different snow types (colour coded, see Figure 4).

4.2 Effective modulus

From µCT images, the elastic modulus is computed by means of finite element modelling. The derived elastic modulus clearly increased with increasing ice volume fraction (density) in Figure 3, for the same data as shown in Figure 2, except for one data point.

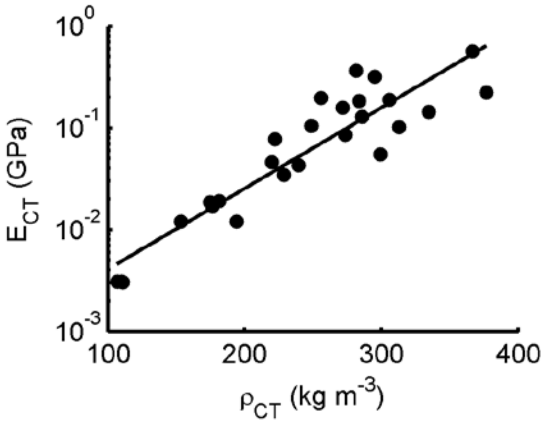

Figure 3: Elastic modulus in relation to density for 26 snow samples, both computed from µCT. The line represents an exponential relationship (r=0.92).

As a relationship between the µCT and SMP-derived densities (Figure 2) was found and the elastic modulus is computed from µCT images with good precision (Figure 3), we may also compare SMP-derived effective and µCT-derived elastic moduli in order to give the first support for the reliable derivation of effective moduli from snow micro-penetrometry.

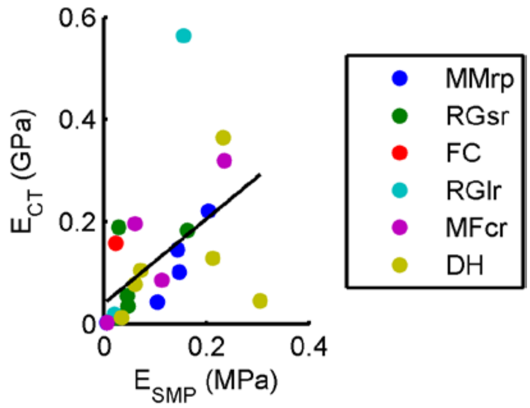

Figure 4: SMP-derived effective and µCT-derived elastic moduli (r=0.54, p<0.01) for 26 samples, colours indicating different snow types as shown in Figure 2.

Although there is a shift of three orders of magnitude between the absolute values of the effective moduli derived with µCT and SMP, both properties are clearly related (p<0.01; Figure 4). The striking difference between the two moduli stems from visco-elastic and plastic deformation occurring at the tip of the snow micro-penetrometer, whereas for the finite element modelling based on the µCT images, linear elastic behaviour is assumed.

The deformation during a PST, is not purely elastic either, hence values for the effective modulus obtained with the PTV method are in the same range as SMP-derived values (Figure 5). Overall, the agreement of the effective modulus from the PTV method with the effective modulus from the average, SMP-derived slab density is fairly good.

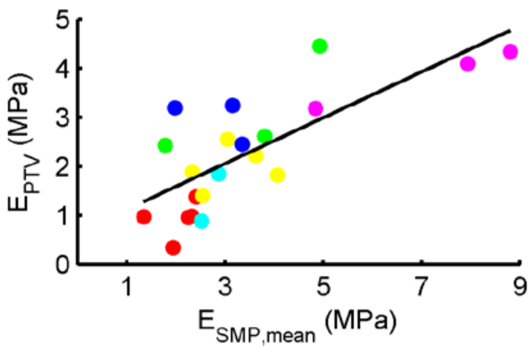

Figure 5: Effective modulus derived from the SMP signal (mean density) and effective modulus derived from PTV (r=0.83, p_{slope}<0.01), colours indicating field experiments in the same loaction but on different days.

The SMP-derived effective modulus was calculated from the average density of the slab neglecting stratigraphy, i.e. the sequence of the layers and their properties. With the PTV method, some stratigraphic information is implicitly preserved. One could therefore argue that the differences stem from the average slab density used in the SMP method. However, by accounting for the stratigraphy with finite element simulations, the correlation coefficient did not change considerably. In fact, the finite element simulations showed that changes in the effective modulus due to stratigraphy are within the uncertainty of the PTV method (about 30%). Thus, the effect of layering can probably not be resolved with our data.

4.3 Fracture energy

The specific fracture energy, the crucial property of the weak layer, describes the amount of energy needed to expand a crack over a given distance through the weak layer. The specific fracture energy derived from the SMP signal compared reasonably well with the fracture energy derived from PTV (Figure 6). The presented values of the specific fracture energy were in the same range as the values reported by Schweizer et al. (2011) who performed finite element simulations to model the bending behaviour of the entire system consisting of slab, weak layer and basal layer. Our results suggest that SMP signal analysis provides realistic values of specific fracture energy.

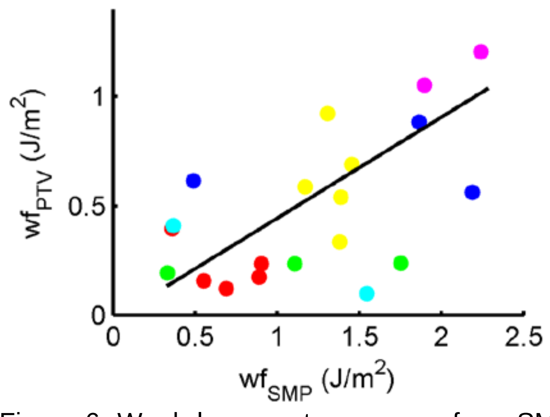

Figure 6: Weak layer rupture energy from SMP being in line with PTV-derived fracture energy (r=0.64, p_{slope}<0.01).

4.3 Critical crack length

The slab and weak layer properties we discussed above can be integrated into a stability model to compute failure initiation and crack propagation propensity, which can be regarded as predictors for point stability. Figure 6 shows an example of modelled critical cut lengths as a measure for crack propagation propensity. Using 119 quality checked SMP measurements from 13 February 2012 in a basin above Davos, Switzerland, to determine density and effective modulus of the slab as well as weak layer fracture energy, we estimated the spatial distribution of critical cut lengths. Modelled cut lengths tended to be longer on south-facing slopes (~60 cm) than in other aspects (~45 cm). This was in line with stability observations in the field.

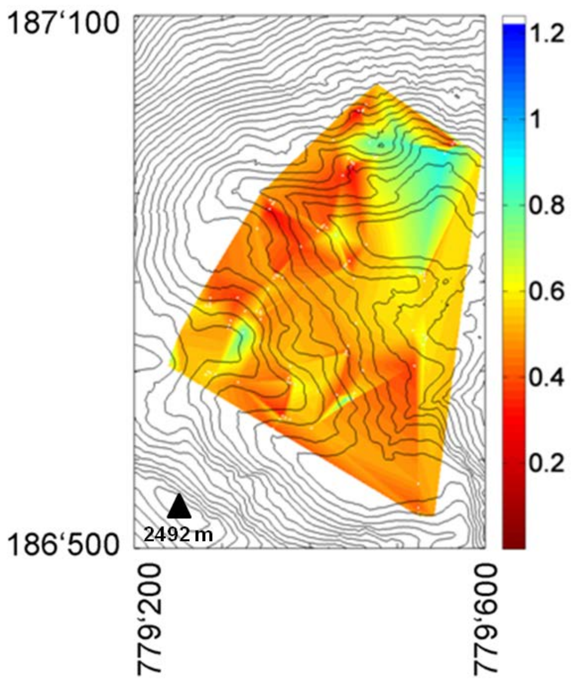

Figure 6: Linear interpolation of the modelled critical cut length (in meters) in the Steintälli above Davos for 13 Feb 2012 (Swiss coordinate grid, in meters; 5 m contour lines).

5 CONCLUSIONS

Objective and fast measurements of snow properties are required to advance snow instability modelling. We presented data acquired with three different methods SMP, µCT and PTV. The shared datasets substantiate the reliability of SMP-derived snow properties.

Snow density was reproduced with the SMP and the data were well in line with the data derived from µCT image analysis for a broad range of alpine snow types.

Accurate characterisation of structure and mechanical properties is a prerequisite for reliable and deterministic snow stability evaluation in the field as well as stability modelling. Our results demonstrate that the snow micro-penetrometer provides us with a method to sample the relevant snow properties quickly and with reasonable precision. All properties needed to model failure initiation as well as crack propagation, namely density and modulus of the slab layers, and strength and toughness of the weak layer can be derived from the SMP signal.

Our results pave the way towards an objective measurement of stability with the SMP. This will foster studies on spatial characteristics of snow instability and help us understand the variable nature of the snowpack and its causes.

REFERENCES

Garboczi, E.J., 1998. Finite element and finite difference programs for computing the linear electrical and elastic properties of digital images of random materials, NISTIR 6269, U.S. Department of Commerce.

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.

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.

Heggli, M., Frei, E. and Schneebeli, M., 2009. Snow replica method for three-dimensional X-ray microtomographic imaging. J. Glaciol., 55(192): 631-639.

Heierli, J., 2008. Anticrack model for slab avalanche release. Ph.D. Thesis, University of Karlsruhe, Karlsruhe, Germany, 102 pp.

Pielmeier, C., 2003. Textural and mechanical variability of mountain snowpacks. Ph.D. Thesis, University of Berne, Berne, 127 pp.

Scapozza, C., 2004. Entwicklung eines dichte- und temperaturabhängigen Stoffgesetzes zur Beschreibung des visko-elastischen Verhaltens von Schnee. Ph.D. Thesis, ETH Zurich, Zurich, Switzerland, 250 pp.

Schneebeli, M. and Johnson, J.B., 1998. A constant-speed penetrometer for high-resolution snow stratigraphy. Ann. Glaciol., 26: 107-111.

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

Schweizer, J., van Herwijnen, A. and Reuter, B., 2011. Measurements of weak layer fracture energy. Cold Reg. Sci. Technol., 69(2-3): 139-144.

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

van Herwijnen, A. and Jamieson, J.B., 2007. Snowpack properties associated with fracture initiation and propagation resulting in skier-triggered dry snow slab avalanches. Cold Reg. Sci. Technol., 50(1-3): 13-22.

van Herwijnen, A. and Heierli, J., 2010. A field method for measuring slab stiffness and weak layer fracture energy, International Snow Science Workshop ISSW, Lake Tahoe CA, U.S.A., 17-22 October 2010, pp. 232-237.