MEASURING THE MECHANICAL PROPERTIES OF SNOW RELEVANT FOR DRY-SNOW SLAB AVALANCHE RELEASE USING PARTICLE TRACKING VELOCIMETRY

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ABSTRACT: Particle tracking velocimetry (PTV) is a measurement technique widely used to determine displacement and velocity fields from video recordings. It is largely nonintrusive and capable of simultaneously measuring the state of deformation over an entire cross section of a sample. PTV has been used in field and laboratory experiments since the mid-1990s to study snow deformation and fracture. Initial studies focused primarily on documenting weak layer collapse and crack propagation velocities. However, recent technological and computational advances allow researchers to determine essential mechanical properties relevant to the processes involved in snow slab avalanche release. Indeed, PTV has been used to estimate the effective elastic modulus of the slab, weak layer specific fracture energy, crack propagation distance and speed, and the friction between the slab and the bed surface after fracture. In this contribution, we will give an overview of over 500 field experiments performed in Canada, USA, and Switzerland over the last 15 years, with an emphasis on relating derived snow mechanical properties to commonly observed snow cover characteristics. For instance, our results suggest that crack propagation speed, which increases with slab density, strongly correlates with crack propagation distance. Furthermore, crack face friction, which determines the critical slope angle at which an avalanche releases, is affected by the hardness differences across the weak layer. While PTV has improved our understanding of the fundamental processes involved in snow fracture, we will also highlight topics that have received little attention to date.

KEYWORDS: snow mechanical properties, avalanche release, Particle Tracking Velocimetry, snow stability

1. INTRODUCTION

For avalanche forecasting, information on the presence and properties of buried weak layers and overlying slabs is of crucial importance, especially in the absence of avalanche activity. To this end, manual field measurements, such as snow profiles and stability tests, are widely used to identify and evaluate the properties of potential weak layers. While correlations with avalanche probability have been established (Schweizer and Jamieson, 2007; van Herwijnen and Jamieson, 2007a), the subjectiveness of some of these manual field measurements, such as hand hardness, does not allow the establishment of a clear and direct link with the material properties of snow. To better evaluate snow slope stability, measurements of snow mechanical properties are thus required.

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Over the years, numerous methods have been developed to obtain objective snow measurements. For instance, in 1936 Haefeli introduced the Rammsonde (Gubler, 1975), a simple portable probe used to obtain a hardness index through a vertical section of the snowpack. Another well-known example is snow density, typically measured by extracting and weighing a defined volume of snow using a density cutter (e.g. Carroll, 1977; Proksch et al., 2016). With technological advances, new in-situ measurement techniques have recently been introduced to objectively describe the stratigraphy of a natural snowpack. These include near infrared photography (Arnaud et al., 2011; Matzl and Schneebeli, 2006), the snow micro-penetrometer (Schneebeli and Johnson, 1998), micro-computer tomography (Coléou et al., 2001; Schneebeli and Sokratov, 2004) or contact spectroscopy (Painter et al., 2007). While these methods provide new insight into the microstructure of snow and its physical processes with unparalleled detail, interpretation of the data remains complicated, in particular with regards to snow stability (e.g. Bellaire et al., 2009; Floyer and Jamieson, 2009; Reuter et al., 2015). Measurements obtained from fracture mechanical field experiments are therefore preferred.

In the past, the focus was largely on measuring weak layer shear strength, as avalanche release was mostly approached by considering the balance between weak layer strength and the stress exerted by the overlying slab (Föhn et al., 1998; Jamieson and Johnston, 2001; Perla et al., 1982). However, it was well known that such an approach is insufficient since avalanche release is a fracture mechanical problem, which requires assessing the crack size at which the energy available for crack growth exceeds the energy needed to extend the crack (e.g. McClung, 1981). With the first fracture mechanical measurements (Kirchner et al., 2002; Kirchner et al., 2000; Schweizer et al., 2004) and concurrent theoretical and numerical developments (Heierli et al., 2008; Sigrist and Schweizer, 2007) a change of view regarding crack propagation occurred. In particular the development of the Propagation Saw Test (PST; Gauthier and Jamieson, 2006; Sigrist and Schweizer, 2007; van Herwijnen and Jamieson, 2005), a fracture mechanical field test used to measure the critical crack length r_c for crack propagation, has led to a more widespread appreciation of the fracture mechanical nature of avalanche release.

Today, failure initiation and crack propagation are seen as two fundamental processes in dry-snow slab avalanche release (e.g.Schweizer et al., 2003; van Herwijnen and Jamieson, 2007b). Recent work has shown that the relevant snow properties, i.e. the effective elastic modulus of the slab and the weak layer specific fracture energy, can be estimated by combining SMP measurements with finite element simulations (Reuter et al., 2015) or from particle tracking velocimetry (PTV) analysis of PSTs (van Herwijnen et al., 2016). However, thus far the focus has been mainly on quasi-static loading conditions up to the onset of crack propagation, and the importance of dynamic crack propagation has only recently been recognized (Birkeland et al., 2014; Gaume et al., 2015; Schweizer et al., 2014). One of the main differences is that during dynamic crack propagation crack size is an unknown function of time and material resistance to crack propagation generally increases with crack speed. In addition, inertia effects become important as the excess energy is converted to kinetic energy (Anderson, 2005). Furthermore, as the crack propagates, the weak layer progressively collapses (van Herwijnen and Jamieson, 2005; van Herwijnen et al., 2010) and the slab eventually comes into frictional contact with the bed surface (Simenhois et al., 2012; van Herwijnen and Heierli, 2009). Thus, after the onset of crack propagation, crack speed, weak layer collapse and crack face friction are important parameters.

Focusing on fracture mechanical properties of snow has clearly improved our understanding of avalanche release over the last decades (e.g. Schweizer et al., 2016). There is a need for a method to measure the relevant mechanical properties of snow in the field. The PTV method, which consists of analysing the displacement of the snow slab from video recordings of field experiments, provides just that. In this study, we present measurements from over 500 PTV field experiments to measure the effective elastic modulus of the slab, the specific fracture energy of the weak layer, weak layer collapse, crack propagation speeds and crack face friction.

2. METHODS

2.1 Field experiments

Failure initiation, crack propagation and slab sliding were recorded in various field experiments (Fig. 1). In order to visualize the deformation of the slab during the experiments, a cross section of the snow cover was completely exposed by shoveling. Black round markers were inserted in the snow above the weak layer in a regular grid pattern with a typical distance of 10 to 15 cm (Fig. 1). Markers were sometimes also inserted in the snow below the weak layer. A digital camera was then mounted on a tripod to record a video of the experiment. The majority of the experiments were recorded on low-cost consumer digital cameras at frame rates ranging from 15 to 240 frames per second (fps), although we also used action cameras and even smart phone cameras. In some field experiments we also used special high-speed cameras with frames rates up to 1000 frames per second (fps). At each test site, a snow profile was also performed to obtain information about hand hardness, crystal type, crystal size, layer thickness and density of the snow layers (CAA, 2007; Greene et al., 2010).

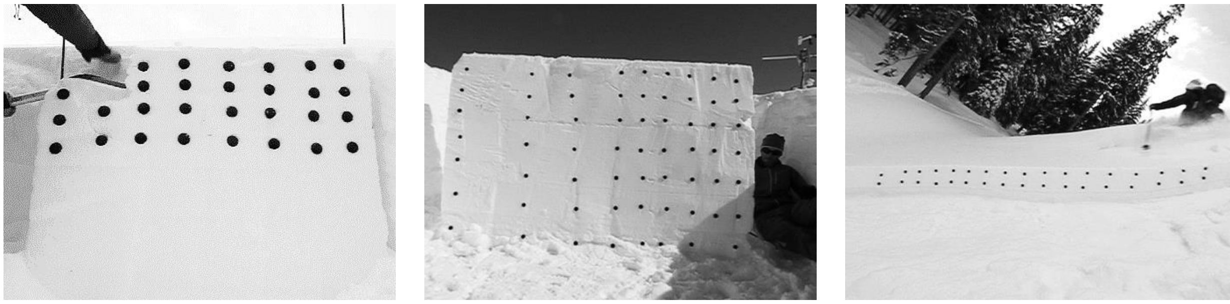

Figure 1: Video recordings of various field experiments, including ECTs (left), PSTs (middle) and skier-tested slopes (right), were analyzed using PTV to investigate weak layer fracture and crack face friction. Black markers were inserted in the snow to measure the displacement of the snow during the experiment.

2.2 Particle tracking velocimetry (PTV)

Particle tracking software (Crocker and Grier, 1996) was used to analyze the images of the experiments. PTV is a measurement technique widely used in fluid mechanics to determine displacement and velocity fields from video recordings (e.g. Adrian, 1986). It is largely nonintrusive and capable of simultaneously measuring the state of deformation over an entire cross section of a sample. PTV was first used in snow to analyze a video sequence of a fracture in a small column field test (Schweizer et al., 1995). This was likely the first photographic record of weak layer collapse during fracture. In their comprehensive study on weak layer fracture using PTV, van Herwijnen and Jamieson (2005) showed that weak layers collapse is very common and they also measured crack propagation speeds. Since then, various studies have used PTV to investigate weak layer fracture, fracture propagation and crack face friction (Bair et al., 2012; Simenhois et al., 2012), and to study the mechanics of the Extended Column Test (van Herwijnen and Birkeland, 2014).

The basic idea behind particle tracking is to identify spherical particles in each image of the video recording to track their position with time. High contrast particles with a fixed diameter are best suited to ensure adequate tracking results. By 'connecting the dots' between subsequent images, the trajectories of the particles can be determined, and thus snow displacement can be measured during the experiment.

The displacement of a marker in slope parallel and slope normal direction (u_x, u_y) was calculated as the departure from its initial position (x_0, y_0), the average position of the marker prior to movement. From these measured displacements, we then derived various mechanical parameters related to fracture in snow:

- *Prior to crack propagation* in a PST, the unsupported part of the slab bends as the saw advances through the weak layer. By analyzing the displacement of the markers in the slab up to r_c, van Herwijnen et al. (2016) recently showed that using the formulation of Heierli et al. (2008) for the mechanical energy of the system it is possible to estimate the effective elastic modulus of the slab E^* and the specific fracture energy of the weak layer $\mathrm{w_f}$.
- *During fracture*, the weak layer collapses and the slope normal displacement u_y of subsequent markers exhibits a time delay proportional to the distance between the markers. This time delay was used to determine the crack propagation speed c (van Herwijnen and Jamieson, 2005). Furthermore, the total collapse height u_y^{WL} after weak layer fracture was also determined.
- When the slab slides down the slope *after weak layer fracture*, the slope parallel acceleration of the slab is constant. The magnitude of the acceleration a_x, calculated as the second time derivative of the slope parallel displacement $a_x = {\partial^2 u_x}/{\partial t^2}$, was used to determine the coefficient of friction μ (van Herwijnen and Heierli, 2009).

Thus, by simply inserting black plastic markers in the snow and recording a video of field experiments, it is possible to determine the displacement of the snow, estimate mechanical properties of the slab and the weak layer, measure crack propagation speed and determine the amount of crack face friction.

3. RESULTS AND DISCUSSION

The results presented in this work consist of both new and previously published data (Bair et al., 2014; Bair et al., 2012; Bair et al., 2013; Birkeland et al., 2014; Gaume et al., 2015; Simenhois et al., 2012; van Herwijnen and Birkeland, 2014; van Herwijnen et al., 2016; van Herwijnen and Heierli, 2009; van Herwijnen and Heierli, 2010; van Herwijnen and Jamieson, 2005; van Herwijnen et al., 2010). They were obtained from 566 video recordings of various field experiments at 149 different sites in Canada, USA and Switzerland between 2002 and 2016. The experiments consisted of Compression Tests (CT), ECTs, PSTs and a few skier-tested slopes. Here we summarize the main findings and refer the reader to relevant studies for more details.

3.1 Failure initiation and the onset of crack propagation

Progressively sawing the weak layer in a PST results in bending of the slab (van Herwijnen et al., 2016). On average, the slope normal displacement at the critical cut length decreased from 0.65 mm at the free end of the PST to 0 at a distance of $2r_c$ (Fig. 2). These results show that the snow slab typically deformed up to a distance of $2r_c$. To better represent the transition to crack propagation in PSTs this means that the column should be sufficiently long to ensure that the free upslope end of the column does not influence test results. Based

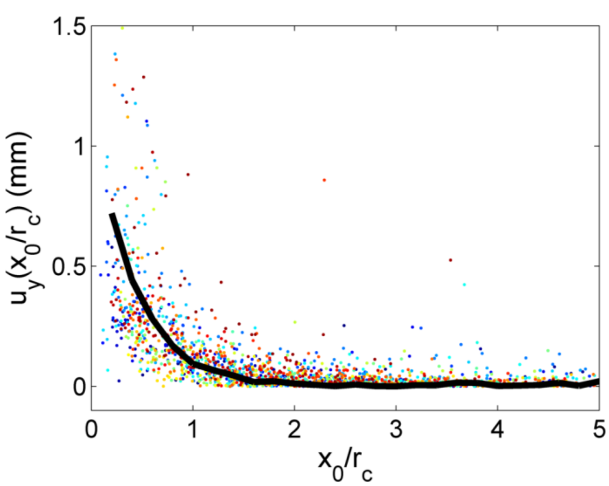

Figure 2: Slope normal displacement u_y with normalized distance x_0/r_c (n = 243; each color represent one test) at the critical cut length r_c. The mean slope normal displacement of all experiments is depicted by the thick black curve.

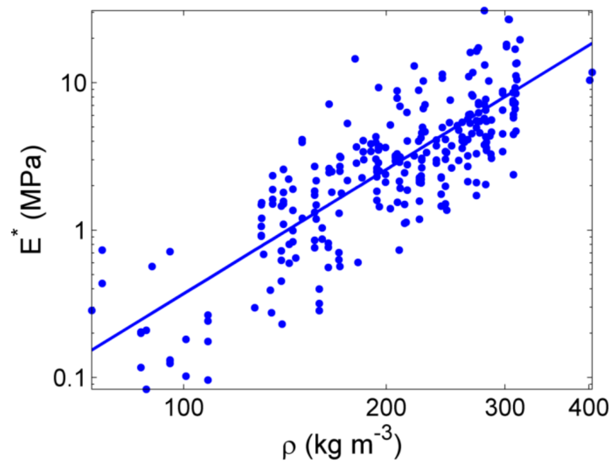

Figure 3: Effective elastic modulus of the slab E^* with density ρ (n = 272; dots). The power law $E^*(\rho) = 0.93\rho^{2.8}$ provided a reasonable fit to the data (blue line).

on the observed displacements, r_c should not exceed one third of the column length, in line with recent results from numerical simulations of the PST (Bair et al., 2014; Bair et al., 2013; Gaume et al., 2015).

Prior to crack propagation, the mechanical energy of the slab - weak layer system can be computed from the measured displacement field (van Herwijnen et al., 2016). By fitting an adjusted analytical expression from Heierli et al. (2008) to the derived mechanical energy, the effective elastic modulus of the slab and the weak layer specific fracture energy can be derived.

The effective elastic modulus ranged from 0.08 to 31 MPa and increased with mean slab density according to a power law relationship $E^*(\rho) = 0.93\rho^{2.8}$ (van Herwijnen et al., 2016)(Fig. 3). PSTs in which the crack propagated to the end of the column had significantly higher E^* values (median of 4 MPa) than when the fracture arrested (median of 1.9 MPa), in line with recent experimental and numerical results (Gaume et al., 2015; Schweizer et al., 2014).

Weak layer specific fracture energy ranged from 0.06 to 2.7 J m^{-2} and increased with increasing load (not shown). Some of the w_f values we obtained were comparable or higher than typical values for ice (~ 0.5 – 2 J m^{-2}). This suggests that the values we obtained are effective values; thus a substantial fraction of the potential energy in PSTs is dissipated and may not be available to drive crack expansion. Therefore, future improvement will include accounting for visco-plastic effects in

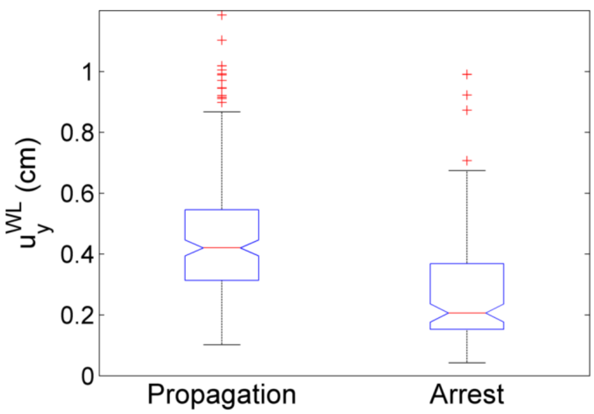

Figure 4: Collapse height u_y^{WL} for experiments in which the crack propagated to the end of the column (*n* = 192; Propagation) and for experiments in which the crack arrested before the end of the column (*n* = 127; Arrest). Whiskers extending to the most extreme data points not considered outliers (crosses) within 1.5 times the interquartile range above the 3rd and below the 1st quartile.

the slab and in the weak layer to refine the results shown here.

3.2 Dynamic crack propagation

Upon reaching the critical crack length in a PST, or the critical loading step in an ECT, a CT or a RB, dynamic crack propagation will occur and the weak layer will collapse. Typical u_y^{WL} values associated with weak layer collapse ranged from 0.04 to 3.1 cm with a median of 0.36 cm. Significantly higher u_y^{WL} values were observed in tests where the crack propagated to the end of the column (median of 0.42 cm) than in tests where the fracture arrested (median of 0.21 cm; U-test: $p < 0.01$; Fig. 4). Similarly, crack propagation speed was significantly higher in tests with full propagation (*n* = 151; median of 30 m s^{-1}) than in tests with fracture arrest (*n* = 75; median of 13.5 m s^{-1}; U-test: $p < 0.01$).

These results suggest that both weak layer collapse height u_y^{WL} and crack propagation speed c are relevant parameters for crack propagation. Indeed, for experiments in which the crack arrested before the end of the column, there was a positive correlation between crack propagation speed and propagation distance (Spearman; $r = 0.56$, $p < 0.01$; Fig. 5). These two parameters are rather unfamiliar to most avalanche practitioners and researchers as they cannot readily be measured in a snow pit. This raises the question: What snow

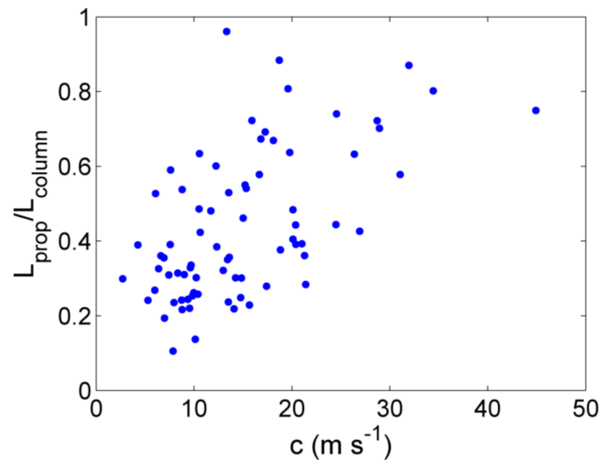

Figure 5: Ratio of crack propagation distance to column length (L_{prop}/ L_{column}) with crack propagation speed (*n* = 75).

cover parameters influence u_y^{WL} and c? Our data suggest that u_y^{WL} mostly relates to weak layer parameters. It somewhat increases with weak layer grain size and with hardness differences between the weak layer and the layers above and below. Crack propagation speed, on the other hand, mostly relates to slab properties, as c correlated with both slab density and E^*. Interestingly, there was also a positive correlation between u_y^{WL} and c, in line with observations by van Herwijnen and Birkeland (2014) and van Herwijnen and Jamieson (2005).

3.3 Crack face friction

After weak layer fracture, the slab comes into contact with the substratum through the weak layer debris and downslope gravitational forces are counteracted by frictional forces. The critical slope angle above which the slab will slide downslope is thus determined by the coefficient of friction μ, which can be measured with PTV (van Herwijnen and Heierli, 2009). Typical μ values in our experiments ranged from 0.32 to 0.88 with a median of 0.58 (critical slope angle of 30°).

The highest μ values were associated with storm snow weak layers (n = 19; median of 0.78), while lower values were measured for persistent weak layers (surface hoar, facets and depth hoar; *n* = 68; median of 0.57). These results suggest that critical slope angles for avalanche release depend on weak layer type, in line with field observations presented by McCammon (2009). From a physical point of view, the properties of the layers surrounding the weak layer seem more relevant for

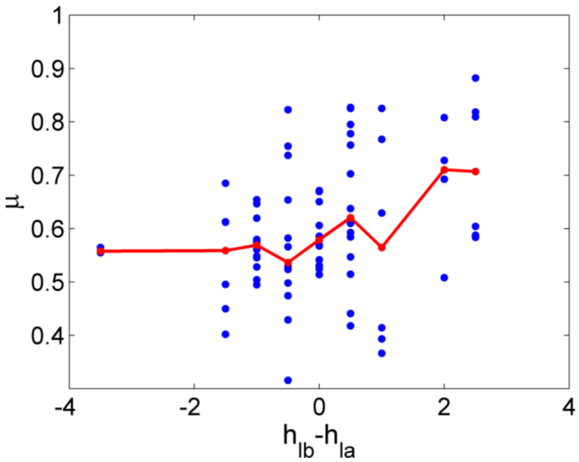

Figure 6: Coefficient of friction μ with the difference in hand hardness index between the layer below the weak layer h_{lb} and the layer above the weak layer h_{la} (n = 82). The median for each hardness difference class are shown with the red line.

the coefficient of friction, as after fracture the weak layer is mostly destroyed by the time the slab and substratum come into contact. This view is supported by our field measurements, which show a significant positive correlation (Pearson: $r = 0.33$, $p < 0.01$) between the coefficient of friction and the hardness difference across the weak layer (i.e. the difference in hand hardness between the layer below the weak layer and the layer above the weak layer; Fig. 6). In other words, the critical slope angle is generally higher for soft slabs sliding on a hard layer than vice versa. This is somewhat intuitive as soft slabs on a hard base will typically erode as they slide on the substratum, thereby requiring more downslope force (steeper slope) to overcome the additional resisting forces.

4. SUMMARY AND OUTLOOK

We presented snow mechanical properties derived from Particle Tracking Velocimetry (PTV) measurements of over 500 field experiments performed in Canada, USA, and Switzerland over the last 15 years. PTV is a technique particularly well suited to study snow fracture in field experiments, since no special equipment is required. A snow saw, a bag of black plastic markers and a modern digital camera with a tripod suffice. The technique allows us to measure relevant snow mechanical properties related to three fundamental stages of avalanche release, namely the onset of crack propagation (effective elastic modulus of the slab and weak layer specific fracture energy), dynamic crack propagation (weak layer collapse height and crack propagation speed) and downslope sliding of the slab after weak layer fracture (coefficient of friction).

The main results are:

- The effective modulus of the slab ranged from 0.08 to 31 MPa and increased with slab density
- Weak layer specific fracture energy ranged from 0.06 to 2.7 J m^{-2} and increased with increasing load.
- Weak layer collapse height was on the order of a few mm and was significantly larger in experiments with full propagation than in experiments with crack arrest.
- Crack propagation speeds were on the order of 10 to 30 m s^{-1} and correlated with crack propagation distance.
- The coefficient of friction was typically around 0.6 (critical slope angle of 30°) and increased with increasing hand hardness difference across the weak layer.

These results constitute the first comprehensive set of measurements of snow mechanical parameters relevant to fracture in snow obtained from field experiments. As such, these measurements provide valuable new insight into the fundamental processes involved in avalanche release, such as the importance of weak layer collapse and propagation speed for dynamic crack propagation. On the other hand, our results also highlight many areas that require more research. For instance, the relatively high weak layer specific fracture energies we obtained show that accounting for visco-plastic effects in the slab and the weak layer is required to better interpret the measured displacements. Furthermore, it still remains unclear how the derived snow mechanical parameters relate to snow cover instability. Nevertheless, encouraged by the results presented here, we are convinced that the PTV method will help us to better understand and eventually predict avalanches in the future.

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