QUANTITATIVE SNOW STRATIGRAPHY AND STABILITY DERIVED FROM HIGH-RESOLUTION PENETROMETRY

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ABSTRACT: Precise measurements of snow structural parameters and stratigraphy are essential to understand and model snow physical processes, in particular with respect to avalanche formation. However, most snow measurements are limited in spatial resolution and by extensive measurement times, and therefore lack practicability for avalanche professionals. The snow micro-penetrometer (SMP), a portable, high-resolution penetrometer allows recording vertical profiles of the penetration resistance quickly and reliably, but so far it was not possible to interpret these profiles with regard to stability. We combine a recently developed statistical model to derive the major snow structural parameters and a new method to derive snow stability parameters solely from SMP measurements. We demonstrate the potential of this combined approach by analyzing a 28 m long transect through Alpine snow at the Steintälli, Davos, Switzerland. The transect consisted of 47 SMP measurements which were made perpendicular to a small ridge, thus capturing a classic terrain feature with changing snow depth. The derived structural and stability parameters were in agreement with independent measurements from snow profiles and stability tests. Modeled critical cut length were smaller in the areas with larger snow depth, where the higher load of the slab appeared to be the main driver. The weak layer was located at the transition towards depth hoar at the base of the snowpack, which was consistently present throughout the whole length of the transect. Our approach provides a valuable starting point for further modeling efforts, such as finite element simulations of snow stability at the slope scale.

KEYWORDS: stratigraphy, microstructure, spatial variability, snow instability.

1. INTRODUCTION

To investigate the physical nature of avalanche formation, research has to deal with several different topics. Apart from a sound theoretical understanding of the fracture processes, the measurement of the relevant parameters in the field is essential, but also cumbersome. In recent years, Sigrist and Schweizer (2007) and Heierli et al. (2008) helped to improve our understanding of fracture related processes significantly, and also the development and interpretation of snow measurement methods (Löwe and van Herwijnen, 2012; Schneebeli and Johnson, 1998) made essential progress. However, the critical point is still to put the theory of fracture into practice, which requires the objective measurement of snow structural *and* mechanical parameters in the field.

Therefore we take advantage of two of the most recent techniques and combine the approach of Proksch et al. (2014), to derive snow structural parameters with the work of Reuter et al. (2013), to derive snow mechanical parameters efficiently in the field. Both methods rely on the SnowMicroPen (Schneebeli and Johnson, 1998), a field-suited snow penetrometer specifically designed to obtain high resolution profiles at fast acquisition times. This allows us to derive a quantitative, two-dimensional stratigraphy of the snow cover without digging and to track the spatial distribution of weak layer and slab properties.

Sturm et al. (2004) as well was Kronholm (2004) characterized the spatial variability of the snow cover by multiple SMP measurements, but both studies were restricted to measured penetration resistances. The ability to derive snow structural and mechanical parameters from the SMP therefore provides additional room for analysis, in particular with respect to snow stability.

We demonstrate the potential of the combined approach by a SMP transect through the Steintälli, Davos, Switzerland. The transect ran perpendicular to a small ridge, thus capturing a classic terrain feature with changing snow depth. We discuss the

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spatial patterns of the derived snow mechanical parameters and interpret them in the view of the derived 2D stratigraphy.

2. METHODS

2.1 Field measurements

The snow micro-penetrometer (SMP) has been used in various field studies and offers quick and reliable measurements of penetration resistance at millimeter resolution (Bellaire and Schweizer, 2011; Kronholm et al., 2004; Reuter and Schweizer, 2012; Sturm et al., 2004). On 13 February 2014, we measured a transect consisting of 47 SMP measurements with 50 cm spacing in the Steintälli above Davos at 2415 m. In a distance of 15 m from the first SMP measurement, a manual snow profile was measured, including snow density measurements with a standard 100 cm^3 density cutter. In total six propagation saw tests (PST) (Gauthier and Jamieson, 2006) were performed at distances 5.0 m, 14.5 - 15.0 m and 19.0 m from the first SMP measurement.

2.2 Derivation of snow structural parameters and stratigraphy

The penetration force signal measured by the SMP can be inverted in terms of microstructural parameters (Löwe and van Herwijnen, 2012) such as the element size *L,* which represents the typical distance between two rupturing ice structures. As recently presented by Proksch et al. (2014), this procedure allows to link the SMP force signal to snow structural parameters, such as density and correlation length. They developed a statistical model to derive snow structural parameters solely from SMP measurements. After calibration with micro-computed tomography, they reported an overall accuracy of 11% and 16% for snow density and correlation length, respectively.

The correlation length is a classic metric of porous media such as snow and considered as objective length scale of the snow microstructure. Thin dendrites or decomposed particles show small correlation length values, whereas larger structures such as depth hoar or melt forms show larger values.

2.3 Derivation of snow stability parameters

Besides the snow structural parameters, Reuter et al. (2013) derived and validated snow mechanical properties from SMP measurements., *Reuter et al*. [2014] presented a framework to model the critical cut length based on SMP derived slab density (Proksch et al., 2014), bulk effective modulus (Schneebeli and Johnson, 1998) and weak layer fracture energy (Reuter et al., 2013).

The modeled critical cut length is a measure of crack propagation propensity analogous to the cut length measured in a propagation saw test.

3. RESULTS

3.1 SMP derived density

First we compare SMP derived and manually measured snow densities (Figure 1). Two SMP signals close to the manual snow profile were averaged and compared to the manually measured densities of the layers in the snow profile. The two measurement techniques were in good agreement. The SMP density is derived with a vertical resolution of 1.25 mm revealing even smallest density variations, which the density cutter did not resolve.

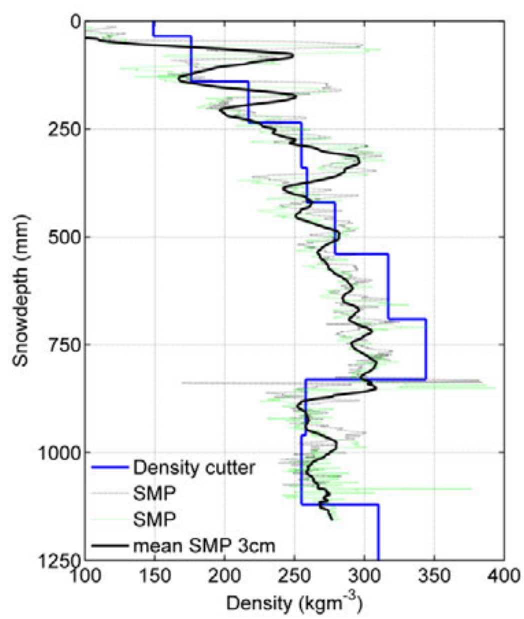

Figure 1: *Density measured by density cutter (black) and SMP (green and grey). The black line is the average of two neighboring SMP measurements.*

3.2 2D Stratigraphy

The repeated SMP measurements provided the 2D quantitative stratigraphy of the transect in terms of correlation length (Figure 2) and density (Figure 3c). The transect was made perpendicular to a small ridge with a transition from smaller snow depth at the ridge (0-10 m distance) towards larger

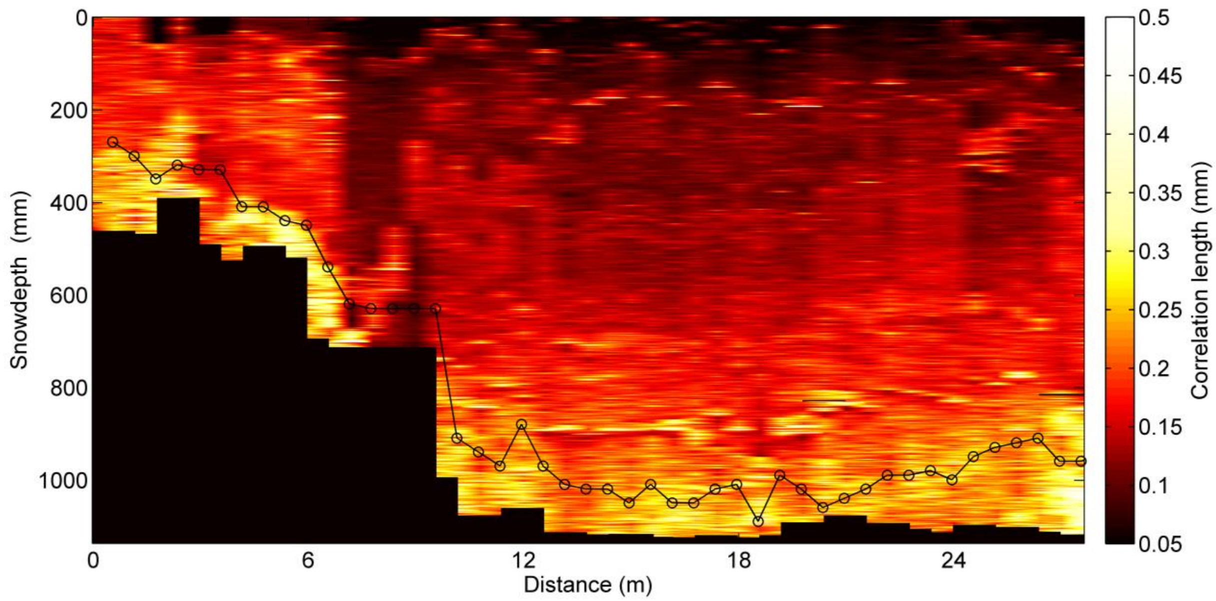

Figure 2: 2D correlation length stratigraphy of the Steintälli transect extending from a ridge (0 - 10 m) into a bowl (10 - 28 m), derived from 47 neighboring SMP measurements. The weak layer (black circles) and maximum measured depth (black) are indicated. The position of the weak layer corresponds well with the transition towards the depth hoar fundament with large correlation length (yellow).

snow depth in a small bowl next to the ridge (10-28 m distance).

The stratigraphy represented a typical mid-winter snowpack at an Alpine site (2415 m). The depth hoar layer at the base of the snowpack (Figure 2, values larger than 0.25 mm) was overlain by layers of smaller faceted crystals and small rounded grains and partly decomposed and fragmented precipitation particles with low values of correlation length towards the surface. The weak layer was located at the transition from depth hoar to smaller faceted crystals (black circles), and was visually determined in each SMP measurement according to the manual snow profile and stability test results. At 10 m distance the transect ran from a small ridge into a bowl. The slab height increased from 30 cm to 1 m, covering the depth hoar, which was close to the surface at the ridge, with a thick slab in the bowl.

The areas at the ridge showed less pronounced layering (Figure 3c) due to stronger wind exposure, causing frequent erosion of the layers. The more wind-sheltered bowl showed higher accumulation and more pronounced layering, as well as a larger amount of recently fallen snow (low densities, deep red to black) near the surface of the snowpack.

3.3 Snow mechanical properties

The critical cut length modeled from all SMP signals along the transect is presented in Figures 3a and 3b. Figure 3a is completed by the bulk effective modulus and the load of the slab, Figure 3b additionally includes the specific fracture energy of the weak layer.

The critical cut length was significantly lower in the bowl area indicating a higher propensity for a crack to propagate. The weak layer fracture energy, however, was just slightly lower in the bowl area (excluding the distributed areas from 7 m to 9 m) (Figure 3b).

The SMP derived critical cut lengths were qualitatively in agreement with the results obtained from propagation saw tests (PST) (Figure 3b). Smaller modeled critical cut lengths corresponded to full propagation to the end of the column (Figure 3b, PST END), whereas larger modeled cut length at the ridge corresponded to slab fracture (Figure 3b, PST SF).

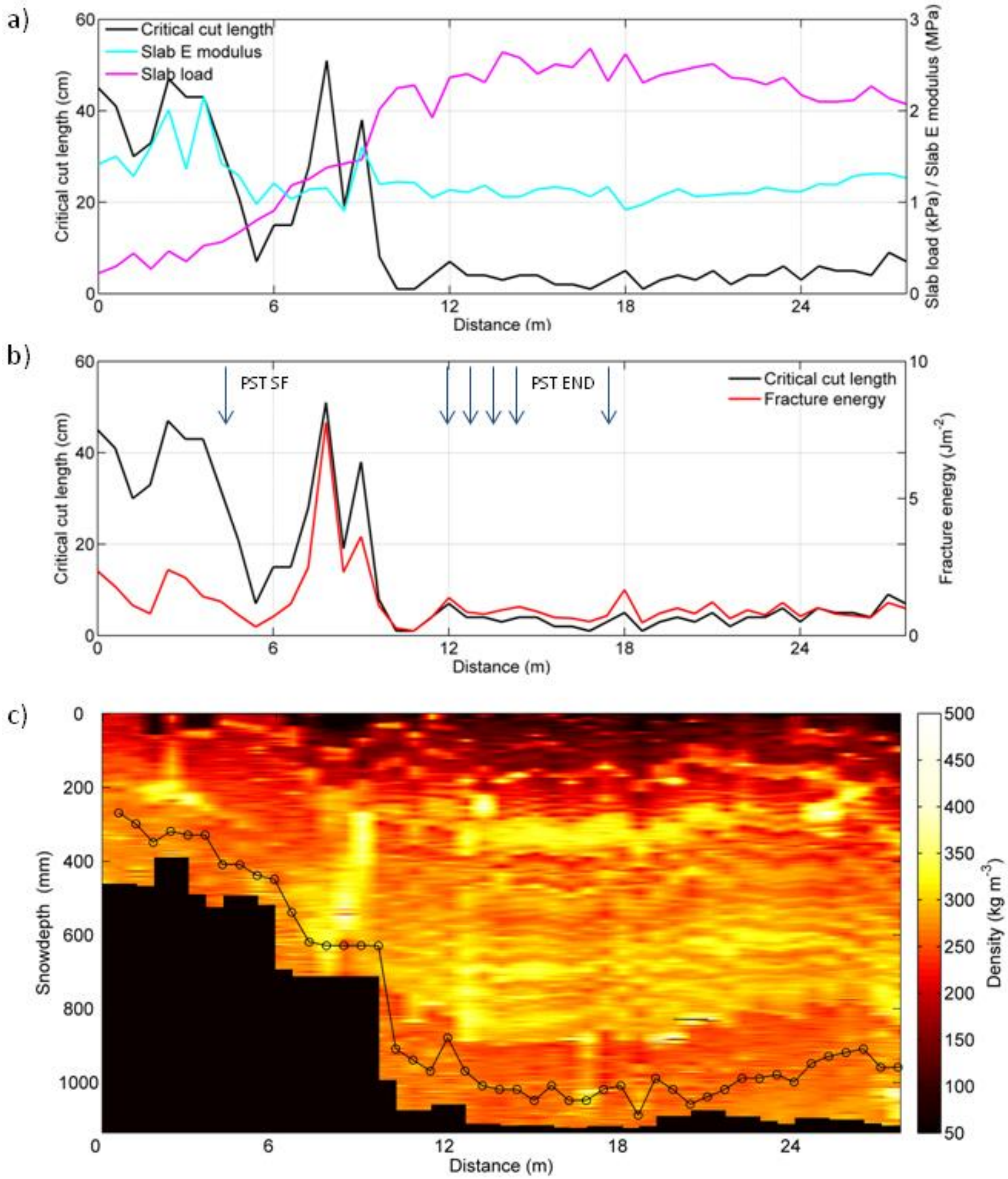

Figure 3: Snow mechanical properties (a, b) and density stratigraphy (c) of the Steintälli transect extending from a ridge (0 - 10 m) into a bowl (10 - 28 m), derived from 47 neighboring SMP measurements: a) modeled critical cut length and slab properties (load and effective modulus) along the transect, b) modeled critical cut length and specific weak layer fracture energy along the transect, as well as results from propagation saw tests (arrows) c) 2D density stratigraphy with weak layer (black circles) and maximum depth measured by the SMP (black).

4. DISCUSSION

4.1 2D Stratigraphy

The layering was less visible in the correlation length stratigraphy than in the density stratigraphy. The variations in density were not represented by variations in correlation length, in particular at snow depths smaller than 90 cm in the bowl. Below a depth of 90 cm, however, snow density remained almost constant, but the correlation length increased significantly indicating the transition to depth hoar and the position of the weak layer. This fact corroborates the approach of Proksch et al. (2014), namely that it is possible to derive two independent measures, the density and an objective length scale (the correlation length) from SMP measurements.

The depth hoar layer at the base of the snowpack was consistently present through the whole length of the transect (Figure 2). This result is in line with Kronholm et al. (2004), who could identify their weak layer in all SMP measurements, showing that weak layers can be spatially persistent features on the slope scale.

The 2D stratigraphy plots also revealed unavoidable disturbances of a frequently used field site by old ski tracks, stability tests or manual profiles. The areas between 7 m and 9 m distance were disturbed throughout the whole measurement depth by old stability tests, which is why we excluded this area from further interpretation. The density peaks in the upper layers at 3 m and 25 m distance were supposed to be old ski tracks, but do not affect our analysis.

4.2 Snow mechanical parameters and snow instability

Close to the ridge, modeled critical cut lengths were longer than in the bowl due to low load and either high modulus or high fracture energy. The magnitude of change in the weak layer properties was small compared to the change in cut length, so that the weak layer properties alone seem not sufficient to explain the change of crack propagation propensity in our transect.

Also, the variation of the effective modulus of the slab across the transect was rather low, though decreasing towards the bowl. The shallow snowpack had frequently seen erosion events disturbing the snowpack layering and introducing variation of slab properties. Variations of weak layer properties may have been caused as well by high surface roughness of the ground. This is why we found more variation towards the ridge in slab and weak layer properties. As the combination of slab and weak layer properties finally drives the propensity of crack propagation, these trends and variations are reflected in the critical cut length.

The load of the slab increased significantly from the ridge into the bowl. With a similar magnitude of change compared to the critical cut length, the load of the slab appears as the main driver of snow instability in our example. Still, the critical cut length is the product of slab and weak layer properties which showed small variations; the overall trend can however be explained by the load of the slab.

5. CONCLUSIONS

We derived the 2D stratigraphy in terms of two of the main snow structural parameters, density and correlation length, from a SMP transect in the Steintälli, Davos, Switzerland. The 2D plots of the transect, extending from a ridge into a bowl, revealed the main stratigraphic features with a thick layer of depth hoar near the base throughout the transect and a distinct layering in the bowl area. The weak layer was located at the transition towards the depth hoar layer at the base of the snowpack, which was persistently present through the whole length of the transect.

In addition, snow mechanical parameters were derived as well as a measure of snow instability, the critical cut length. The critical cut length was smaller in the bowl area than near the ridge, mainly driven by an increased load of the slab.

Being able to quantify snow structural and mechanical parameters, we believe that this method is not only useful to improve our understanding, but also to provide a valuable starting point for further research, such as finite element simulations of snow stability at the slope scale.

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REFERENCES

Bellaire, S. and Schweizer, J., 2011. Measuring spatial variations of weak layer and slab properties with regard to snow slope stability. Cold Regions Science and Technology, 65(2): 234-241.

Gauthier, D. and Jamieson, J.B., 2006. Evaluating a prototype field test for weak layer fracture and failure propagation. In: J.A. Gleason (Editor), Proceedings ISSW 2006. International Snow Science Workshop, Telluride CO, U.S.A., 1-6 October 2006, pp. 107-116.

Heierli, J., Gumbsch, P. and Zaiser, M., 2008. Anticrack nucleation as triggering mechanism for snow slab avalanches. Science, 321(5886): 240-243.

Kronholm, K., Schneebeli, M. and Schweizer, J., 2004. Spatial variability of micropenetration resistance in snow layers on a small slope. Ann. Glaciol., 38: 202-208.

Löwe, H. and van Herwijnen, A., 2012. A Poisson shot noise model for micro-penetration of snow. Cold Regions Science and Technology, 70: 62-70.

Proksch, M., Loewe, H. and Schneebeli, M., 2014. Density, specific surface area and correlation length of snow measured by high-resolution penetrometry. Journal of Geophysical Research: in review.

Reuter, B., Proksch, M., Loewe, H., van Herwijnen, A. and Schweizer, J., 2013. On how to measure snow mechanical properties relevant to slab avalanche release. In: F. Naaim-Bouvet, Y. Durand and R. Lambert (Editors), Proceedings ISSW 2013. International Snow Science Workshop, Grenoble, France, 7-11 October 2013. ANENA, IRSTEA, Météo-France, Grenoble, France, pp. 7-11.

Reuter, B. and Schweizer, J., 2012. The effect of surface warming on slab stiffness and the fracture behavior of snow. Cold Regions Science and Technology, 83-84: 30-36.

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

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.

Sturm, M., Johnson, J.B. and Holmgren, J.A., 2004. Variations in the mechanical properties of arctic and subarctic snow at local (1-m) to regional (100-km) scales, Proceedings ISSMA-2004, International Symposium on Snow Monitoring and Avalanches, Manali, India, 12-16 April 2004. Snow and Avalanche Study Establishment, India, pp. 233-238.