CORRELATING SNOW MICRO-STRUCTURE WITH SNOW SHEAR STRENGTH

Eric R. Lutz[1],*, Karl W. Birkeland[1,2], Kalle Kronholm[1], Kathy Hansen[1], and Richard Aspinall[2]
[1] Department of Earth Sciences, Montana State University, Bozeman, Montana
[2] USDA Forest Service National Avalanche Center, Bozeman, Montana
[3] Department of Geography, Arizona State University, Tempe, Arizona

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EXTENDED ABSTRACT

Researchers and avalanche forecasters have used an array of probes over the years to quickly analyze snow structure with the goal of better predicting avalanches (Bader et al., 1939; Bradley, 1968; Dowd and Brown, 1986; Schneebeli and Johnson, 1998; Mackenzie and Payten, 2002). However, none of this work has rigorously correlated the probe data to avalanches. Stability tests, on the other hand, have been correlated to avalanche potential (Föhn, 1987; Jamieson, 1999; Birkeland and Johnson, 1999). Birkeland et al. (*in press*) identified a significant correlation between the shear strength and the maximum penetration resistance of the weak layer, as recorded using the SnowMicroPen (SMP), a constant-speed penetrometer that records 250 resistance measurements per millimeter. It was rationalized that the increase in maximum resistance demonstrates strengthening of the strongest bonds within the weak layer, which are critical to weak layer strength (Birkeland et al., in press). Our research attempts to improve techniques for analyzing the SMP signal in order to more conclusively determine where, within and/or adjacent to the weak layer, the strengthening is actually occurring, and then to correlate the changes with strengthening trends.

We analyze data collected in January, 2002 in southwestern Montana at the Lionhead area (Landry et al., 2002; Birkeland et al., in press). Observations focused on monitoring the evolution of a buried surface hoar layer that had initially formed between December 21st and 26th and then subsequently been buried on December 27th. For a detailed description of the snowpack development, see Landry (2002). The Quantified Loaded Column Test (QLCT) was utilized to measure in situ strength of the weak layer (Landry et al., 2001). Micro-structural hardness profiles were acquired using the SMP (Johnson and Schneebeli, 1999; Schneebeli et al., 1999). On the first day, 83 SMP profiles and 30 QLCT measurements were obtained, while on the second day, 128 SMP profiles were recorded with 48 QLCTs.

Using moving windows statistical operations, several resistance variables, in the form of *statistical profiles*, were derived from the SMP measurements, including several measures of central tendency and spread. Each position in a statistical profile represents a statistic that was derived from a section of the SMP signal the size of the sensor head. The width of the moving window was equal to the length of the sensor head (4.33 mm) and contained approximately 1050 resistance readings within each window. To limit data redundancy without compromising its quality, a window spacing of 20 measurements (0.08 mm) was used, which was determined to be the signal's correlation length using semi-variance analysis. Non-parametric descriptors were most intensively analyzed, since the SMP signal is generally non-normally distributed.

To compare hardness and stratigraphic characteristics between plots, values were obtained from the statistical profiles at five stratigraphic positions, including the weak layer center, the upper and lower substratum boundaries, and the transitions between the boundaries and the weak layer. To characterize the size of the weak layer the *separation distance* between the superstratum and the substratum boundaries was calculated. The slab thickness was calculated for each SMP profile. All SMP-derived variables were then tested for significant changes and for spatial structures that can account for variation of stability test results.

Several SMP-derived variables possessed significant correlations with shear strength and stability. The separation distance decreased significantly from 1.9 cm to 1.6 cm, signifying a

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* *Corresponding author address:* Eric R. Lutz, Montana State University, Bozeman, MT 59717; tel: 406-994-5678; fax: 406-994-6923; email: elutz@montana.edu

12.8% decrease in thickness, coinciding with the observation that the weak layer thinned markedly between observation days, from 2 cm to 1 cm (estimated to the nearest centimeter). No plot-scale trends or local spatial structures were evident in the separation distance, supporting the concept that, on fairly uniform slopes like the ones sampled, weak layer thickness is randomly distributed around a slope mean. When compared with the stability results these findings quantitatively support previous research that weak layer strengthening is accompanied by weak layer thinning (Davis et al., 1996; Jamieson and Schweizer, 2000). They support the conceptual model proposed by Jamieson and Schweizer (2000) that the strengthening of buried surface layers is in part due to surface hoar penetration of the substratum.

Two general trends occurred in the hardness characteristics of the weak layer, including softening of the upper transition and superstratum and hardening of the weak layer, lower transition, and substratum. The softening corresponds well with Landry's (2002) snow profile observation: "slab softer...barely cohesive" (Landry, 2002:246), which was caused by faceting due to a large temperature gradient present during the sampling period (Landry, 2002). More relevant to stability, significant hardening occurred at the middle and lower positions in those variables that describe the higher resistance values, including the 90th and 98th percentiles, and the maximum is indicative of bond strengthening or densification. This increase in hardness coincides with the increase in shear strength at the plot-scale, supporting previous research that identified the lower boundary of the weak layer as the critical location for strengthening (Davis et al., 1996; Davis 1998; Jamieson and Schweizer, 2000). In addition, strengthening at the lower transition and substratum positions conforms with the conceptual model proposed by Jamieson and Schweizer (2000), that due to hoar crystal penetration into the substratum, more surface area is made available for bonding with the substratum. These results also augment the findings of Birkeland et al. (in press), by showing that the increase in hardness occurs within the weak layer itself and at the boundary with the substratum.

Spatial analysis of these variables revealed significant correlations between stability test results and the maximum resistance of the lower transition, which at plot 1 accounted for 22.1% of the variation in the size-corrected strength measurements. At both plots, a significant increase in the coefficient of variation at all weak layer positions implied that the weak layer became more variable at the scale of the sensor head, potentially due to the degradation of surface hoar due to aging. Slab thickness possessed significant inverse correlations with the coefficient of variation at the substratum boundary and positive correlations with hardness variables, suggesting that thicker slabs result in harder, more consistent (i.e. less variable) boundaries between the weak layer and the substratum.

The moving window statistical operations developed and employed in this study enabled hardness characteristics of a weak layer to be analyzed at multiple stratigraphic positions. The main findings conclude that weak layer thinning and hardening within the weak layer and its boundary with the substratum coincides with weak layer strengthening. Slab thickness appears to positively affect the hardness of the lower boundary and inversely affect its variation. Both the classical and spatial analysis support the conceptual model that critical weak layer strengthening occurs at the base of the weak layer, where surface hoar crystal contact the substratum.

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