SLOPE-SCALE SNOWPACK STABILITY DERIVED FROM MULTIPLE SNOWMICROPEN MEASUREMENTS AND HIGH-RESOLUTION TERRESTRIAL FMCW RADAR SURVEYS

Hans-Peter Marshall*[1,2], Christine Pielmeier[3], Scott Havens[1], Frank Techel[3]
[1]Boise State University, Center for Geophysical Investigation of the Shallow Subsurface, Boise, ID, USA
[2]Cold Regions Research and Engineering Laboratory, Hanover, NH, USA
[3]WSL Swiss Federal Institute for Snow and Avalanche Research SLF, CH-7260 Davos Dorf, Switzerland

ABSTRACT: Slope-scale stability assessments from SnowMicroPen (SMP) profiles and from remote sensing techniques would support avalanche forecasting operations, as they provide the ability to quantitatively estimate snow properties much faster than traditional methods. Stability information can be gathered more objectively and representatively with these new techniques than with standard stability tests, however signal interpretation remains challenging. Previous SMP studies have related SMP-derived snow properties at failure planes to observed point-scale (compression test) stability and rutschblock-scale stability. The goals of this study are to relate SMP derived properties to rutschblock test results (93 sites) as well as to extended column test (ECT) results and to include information about all layers in the SMP-stability classification scheme. Measurements at 61 different sites are used for the comparison with ECT results. 15 sites from the Swiss Alps and 10 from the Colorado San Juan Mountains, USA with up to 35 nested SMP measurements are used in the slope-scale analysis. A FMCW radar survey, taken coincident with a slope-scale SMP survey, shows the potential for obtaining additional information about the slope-scale variability of layer thicknesses. While radar profiles can not directly estimate strength, they can be used to quantify the variability of overburden stress and continuity of stratigraphy.

KEYWORDS: Snow cover, Snow cover stability, Snow stability evaluation, Micro Penetrometer, Mechanical properties, Avalanche forecasting, Remote sensing, Radar

1. INTRODUCTION

Most forecasting operations around the World base their assessment of snowpack stability on manual snowpack profiles and stability tests as well as on observations of avalanche activity and weather. In Switzerland, the rutschblock test is currently the preferred stability test. In the USA, the extended column test (ECT) has recently become the preferred stability test. The snow properties and the stability test result, which is an index of snow stability for skier triggering, are the most important parameters for the assessment of current snowpack conditions, an important basis for forecasting the regional avalanche danger.

Schweizer and Jamieson (2003) and Schweizer et al. (2007, 2008) showed the significance of observed snow properties at failure interfaces with respect to snowpack stability. Winkler and Schweizer (2009) and Schweizer and Jamieson (2010) analyzed the performance of different stability tests where the rutschblock test (RB) and the extended column test (ECT) are more reliable in predicting snowpack instabilities than the compression test (CT). The assessment of snowpack stability from an automated, objective snow probe has been the objective of several studies during the last decade.

The SnowMicroPen (SMP), a high-resolution automated penetrometer for snow, which measures penetration resistance or snow hardness at the grain scale (Schneebeli and Johnson, 1998), was mostly used in these attempts. The physical theory to characterize snow properties from the SMP signal was first

* *Corresponding author address:* Hans-Peter Marshall, Boise State University, Idaho, USA; tel: (208) 426-1416; fax: (208) 426-3888; email: hpmarshall@boisestate.edu.

developed by Johnson and Schneebeli (1999). It describes three basic micro-structural parameters: the structural element length *(L)*, the deflection at rupture *(δ)* and the rupture force *(f)*. From these, mechanical parameters can be derived, which can be related to stability. In the following years, Sturm et al. (2004), Marshall (2006) and Marshall and Johnson (2009) improved the theory, increasing the accuracy of the micro-structural and micro-mechanical estimates.

Pielmeier and Schweizer (2007), and Pielmeier et al. (2006) applied the 1999 and 2006 versions of the theory in statistical approaches to predict the stability of known RB failure interfaces from the SMP signal. The classification accuracies were between 65% and 70%. Bellaire et al. (2009) introduced a statistical approach based on Johnson and Schneebeli (1999) that yields 75% classification accuracy to predict the stability of RB and CT failure interfaces. Pielmeier and Marshall (2009) proposed a statistical classification model based on Marshall and Johnson (2009), where the best SMP parameter to predict RB stability was the micro-scale strength of the weak layer. When combined with the SMP-estimated mean density of the slab layer, the classification accuracy was 85%. They also showed that removing low quality SMP signals or increasing the number of SMP measurement at the RB scale improved the accuracy further.

During 2009 and 2010, our SMP field surveys were taken to the slope-scale, combining multiple RB and ECT tests as well as FMCW radar surveys. Based on a large dataset taken at three different scales (point, RB and slope scale) and on the results at the RB scale, this study explores how well slope-scale snowpack stability, as estimated from RB and ECT tests, can be predicted from SMP measurements. With the combination of SMP and FMCW radar surveys we illustrate the potential of using remote sensing techniques for understanding the variability of snowpack stratigraphy and stability.

2. DATA AND QUALITY

2.1 Data

A total of 93 surveyed sites from 2002-2010 are the basis of the analysis:

a) Point-scale sites, where hand profiles and RB tests were combined with only one SMP measurement, were examined in Switzerland, mainly in the Canton of Graubünden from 2002-2006 (n=32). Details on the experimental design are given in Pielmeier and Schweizer (2007).
b) Rutschblock-scale sites, where hand profiles, RB and ECT tests were combined with up to seven SMP measurements, were surveyed in Graubünden (n=36) during the winter 2007/08. Details on the experimental design are given in Pielmeier and Marshall (2009).
c) Slope-scale sites, where hand profiles, RB and ECT tests and radar surveys were combined with up to 35 SMP measurements, were surveyed in Colorado, USA (n=10) during January 2009 and in Switzerland, mainly in the Canton of Graubünden (n=15) during the winter 2009/10. The experimental design is shown in Fig. 3.

All locations were chosen for the operational assessment of regional avalanche danger. Altitudes range between 1800 and 3700 m a.s.l. and the slope angles range between 24° and 40°. The majority of the profiles were taken on north facing slopes (NW-N-NE: 60%, SE-S-SW: 22%, E: 7%, W: 11%). Figure 1 shows the range and frequency of the 93 observed snowpack types (Schweizer and Lütschg, 2001). The observed rutschblock scores range from 1 to 7, the ECT results range from full propagation to no propagation.

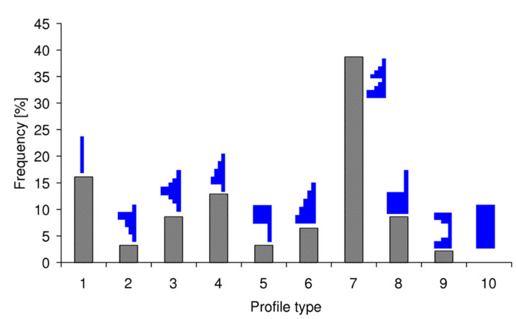

Fig. 1: The distribution of the 93 snow profiles in terms of profile types (blue icons). There is a fair balance between profiles with weak basal layers (type 1-5, 44%) and consolidated basal layers (type 6-10, 56%).

2.2 SMP data quality

At the 93 sites there are 888 SMP measurements available for analysis. These were qualitatively checked for obvious signal errors (Pielmeier and Marshall, 2009; Lutz, 2009) and classified into four quality categories (Table 1).

Table 1: Categories/distribution of SMP quality.

Quality	*Type of SMP signal error*	*N [%]*
Q1	None	594 [67%]
Q2	Trend or offset in absolute SMP force	231 [26%]
Q3	Dampened or disturbed SMP force micro-variance	14 [2%]
Q4	Both, Q2 and Q3	49 [6%]

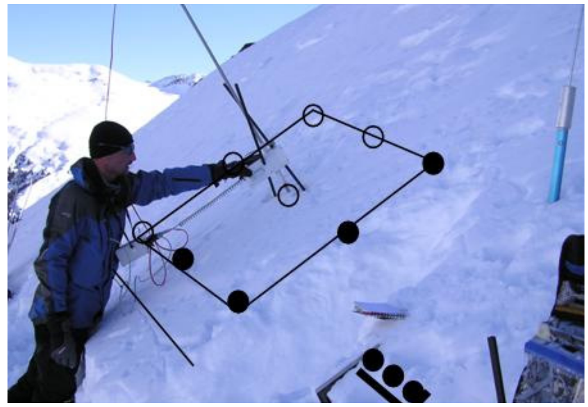

Fig. 2: Seven SMP measurements are taken around and in the center of the RB area, up to three at the manual profile.

3. METHODS

3.1 Field methods

Manual snow profiles were taken according to the International Classification for Seasonal Snow on the Ground (Fierz et al., 2009). Adjacent to the manual profile, one RB test (Föhn, 1987) and two ECTs (Simenhois and Birkeland, 2009) side by side were taken. Close to the manual profile, two slope perpendicular and one vertical SMP measurement were taken. Up to six SMP measurements were taken at the perimeter and one in the center of the real rutschblock area (Figure 2). The four additional areas surveyed on a slope, the so called "nests", each have two ECTs back to back as shown in Figure 3. In each nest, up to six SMP measurements were taken at the perimeter and one in the center of the virtual rutschblock area (3 m^2). The nests were spaced up to 10 m from the central point of the manual profile.

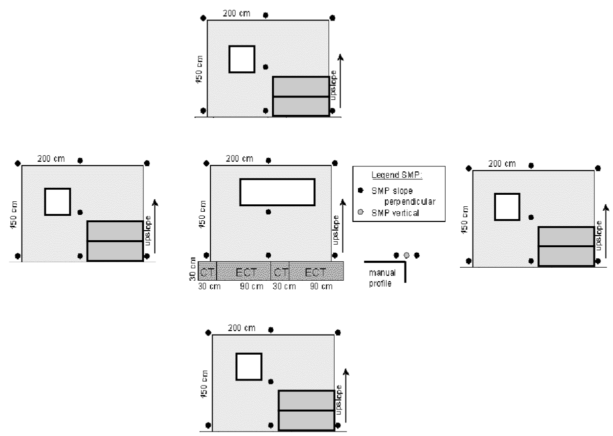

Fig. 3: Sampling design of the slope-scale surveys in the USA (n=10), where in the center, one manual profile was taken along with one RB, two ECTs side by side and seven SMP measurements in the real RB area. The four outer "nests" are distanced up 10 m. In each nest, two ECTs back to back and seven SMP measurements in the virtual RB are sampled. The design of the surveys in Switzerland (n=15) is slightly different because the position of the nests is shifted to the outer corners of the slope.

In this study, the weak layer depth and the stability were determined by the rutschblock test. The RB score (1 to 7), release type (whole block vs. partial break/edge) and fracture surface character (clean vs. rough/irregular) were observed (Schweizer, 2002). ECT results were separately examined and compared to SMP measurements.

During the field campaigns in the U.S., a portable microwave radar was used to measure snow stratigraphy and depth in the study region (e.g. Marshall et. al., 2007; Marshall and Koh, 2008).

3.2 Analysis methods

Stability classification

Unstable and stable profiles were classified according to a) the RB scores and b) the ECT results. Profiles are classified unstable with RB scores 1 to 3 independent of release type and RB score 4, if release type is whole block. Profiles are classified stable with RB score 4, if release type is partial break and RB scores 5 to 7 independent of release type.

While the RB score is a measure of fracture initiation, the ECT test measures fracture propagation. We investigate the relationship between SMP measurements and the ECT result to test if the SMP measurement also contains information about fracture propagation. For this analysis, the ECT result is considered unstable if there is full propagation within 1 tap of fracture initiation, and stable otherwise (Simenhois and Birkland, 2009).

SMP signal analysis

By graphically superimposing the manual profile onto the slope-perpendicular SMP measurement that is closest to the manual profile, the layer boundaries at the failure interface are manually delineated (aided by vertical SMP measurements). Furthermore, all SMP measurements from one site were graphically aligned to track the failure interface. The layer definition is according to Pielmeier and Marshall (2009) with the weak layer (WL), the transitional layer (TL), the adjacent layer (AL) and the slab layer (SL). Furthermore, the bed surface layer is delineated, which is the layer below the WL.
The SMP signal is first filtered to reduce signal noise with a static threshold of 0.023 N rupture force based on measurements in air (e.g. Lutz et. al., 2009; Pielmeier and Marshall, 2009).

The calculated SMP parameters based on Marshall and Johnson (2009) are: rupture force (f), deflection at rupture (δ), structural element length (L), force normal to tip (F), probability of contact (P_c), number of elements engaged (N_e), number of elements available (N_a), mean force (F_m), total force at peak (F_T), stiffness (k), micro-scale elastic modulus (E_{micro}), micro-strength (σ_{micro}), measured number of ruptures per mm (N_m) and total number of ruptures (N_T). Also, the texture index (TI) (Schneebeli et al., 1999), the slab layer mean density (ρ) (Pielmeier, 2003), and the depth of the weak layer were calculated.

4. RESULTS

This study builds on the stability classification of Pielmeier and Marshall (2009). The database has been significantly expanded and now includes twice as many sites, and the number of SMP measurements at each site was increased to 36 at many locations. In addition, second failures are also included from both RB and ECT tests.

Future analysis will involve building classification trees separately for RB and ECT tests, as the RB measures fracture initiation and the ECT measures fracture propagation. All listed SMP-estimated variables (Sec. 3.2) will be included as potential predictor variables, and it is likely that the classification will be different for RB and ECT estimated stability.

Based on our previous work, the SMP-estimated micro-strength in the failure layer was the best classifier of stability. As a first step, we therefore begin by examining the relationship between SMP micro-strength of the failure layer and stability, as estimated from RB and ECT tests.

4.1 RB Stability

Figure 4 shows boxplots of the median failure layer micro-strength for both stable and unstable situations, based on the RB score and fracture character. The plot on the left shows the results for all sites where a RB score was available and finite micro-strength was measured by the SMP.

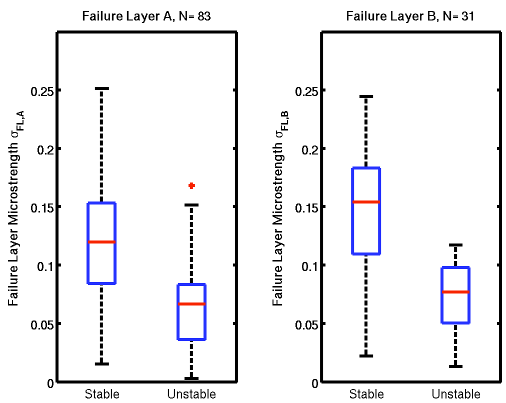

Fig. 4: Failure layer micro-strength, for both stable and unstable RB results. Left plot shows results from the first failure (layer A), and right plot shows results from the second failure (layer B).

At each site, the median failure layer micro-strength is calculated from all available SMP measurements. Some of the sites that were included in the database used by Pielmeier and Marshall (2009) only have 1 SMP measurement, while the more recent sites have up to 36.

4.2 Second failure layer

Building on our previous work, in this study we also examine the results of the second failure, when present. The RB score for the second failure is classified as stable and unstable as before, and the failure layer SMP micro-strength for this second layer is used. The left plot in Figure 4 shows the micro-strength for both stable and unstable situations.

4.3 ECT Stability

Figure 5 shows the micro-strength distribution for stable and unstable ECT conditions: full propagation within one tap of fracture initiation (unstable) and partial or no (full) propagation, or full propagation with more than 1 tap within fracture initiation (stable), for both first and second failure layers. ECT results were taken as the median result from all available tests at a given site.

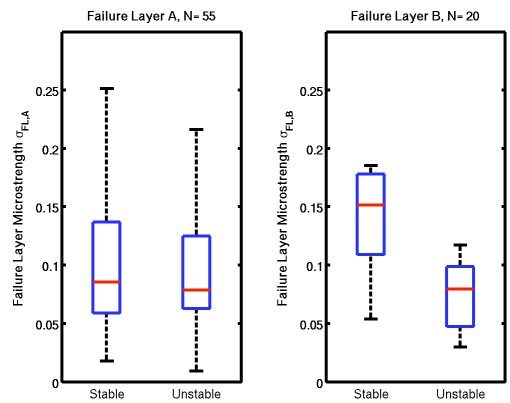

Fig. 5: Failure layer micro-strength distributions, for both stable and unstable ECT results. Left plot shows results from the first failure (layer A), and right plot shows results from the second failure (layer B).

4.4 FMCW radar comparison

A portable microwave radar (e.g. Marshall and Koh, 2008) was used to map stratigraphy at the U.S. sites in 2009, and preliminary results from Senator Beck Basin, Colorado, are shown in Figure 6. The layers show variations at the 100 m scale, and prominent reflections are visible that correspond with major density contrasts, especially crusts. The location of the failure layer is shown with the red line in the right plot of a nearby SMP profile, and corresponds to a strong radar reflection as the layer is adjacent to a crust.

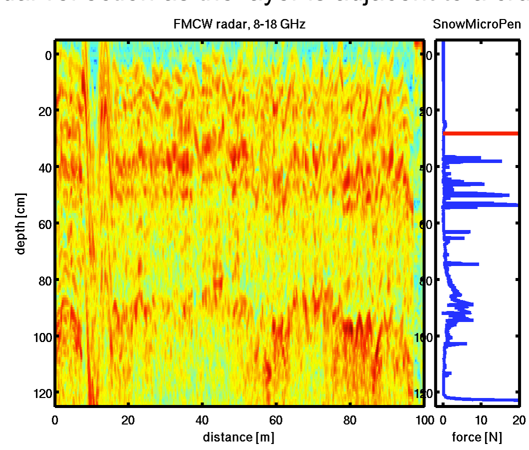

Fig. 6: Comparison of FMCW measurements (left) and example SMP profile (right) at Senator Beck Basin, Colorado.

5. DISCUSSION

This larger dataset covering a wider range of conditions in both Switzerland and the U.S. verified that the SMP can be used to estimate stability, as measured by a RB test, as shown by Pielmeier and Marshall (2009). Building on this study, these results show that the SMP-estimated micro-strength of the second failure layer also can be used to estimate the second RB failure score.

In this study we also present preliminary results from a comparison of failure layer micro-strength and ECT results. It is interesting that the micro-strength can not be used to predict the ECT result for the first failure layer, however the micro-strength of the second failure layer is significantly lower for the unstable condition. We hypothesize that deeper instabilities typically have denser slabs that likely have mechanical properties more likely to propagate a fracture once initiated, and therefore the ECT result is primarily sensitive to weak layer strength. For the first layer, likely the mechanical properties of the slab are also important controlling factors for the test result, and a classification involving slab properties will be necessary.

Note that in both of the above results, all SMP measurements in which the failure layer was visually identified were used, regardless of quality (N=888, Table 1). As shown by Pielmeier and Marshall (2009), Q3 and Q4 signals show lower classification accuracies, therefore we expect the relationship between SMP micro-strength in the failure layer and stability to be even better when the poor quality signals are removed (~8% of the data).

Preliminary results from coincident FMCW radar and SMP tests indicate these two new high-resolution tools provide complimentary information, and can be used together to investigate the role of spatial variability in slope stability.

6. CONCLUSION

The SMP-derived weak layer micro-strength is a good predictor of RB stability, and this was shown to be true for a larger and more robust dataset than that used in our previous work. The second failure layer RB score is also very sensitive to SMP micro-strength of the second failure layer, indicating SMP measurements can also be used to estimate stability of deeper weak layers. ECT results show a relationship to weak layer strength, but only for second failure layers, possibly because deeper layers often are associated with slabs that can propagate fractures. Predicting first failure layer ECT results from SMP measurements will likely require estimates of slab properties, and this will be the subject of future analysis. FMCW radar measurements show reflections from large changes in density, and when failure layers are associated with crusts or large density contrasts, their depth can be measured at high resolution along profiles. This enables estimates of the spatial variability of overburden stress on the failure layer, which is an important aspect of stability.

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