# APPLICATION OF THE SNOWMICROPEN TO DERIVE STABILITY INFORMATION FOR AVALANCHE FORECASTING

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ABSTRACT: Snowpack measurements and stability tests are currently the basis for snowpack stability assessment in most avalanche warning operations. The SnowMicroPen, a high-resolution penetrometer for snow, measures snow hardness. In order to be useful for an operational warning service, stability information needs to be derived from the SMP signal. 39 SnowMicroPen profiles (25 on slopes, 14 on flat sites) were taken together with manual snow profiles and stability tests, such as Rutschblock and compression tests. The data are from three winter seasons of the years 2001-02 to 2003-04 in the Swiss Alps. The manual profiles were classified as stable or unstable according to their stability test score and failure interface properties. Based on the manual observations the failure interfaces were identified in the SMP profiles and possible indicators of stability were derived from it. The distinct indicators of stability were the failure layer micro structural length and hardness, the difference in structural length between the failure layer and adjacent layer and the failure layer macro elastic modulus. The prediction accuracy of stable or unstable failure interfaces gained from SMP parameters is close to the prediction accuracy from manual profile parameters (about 65 %). A next step is to predict stability from a SMP measurement without a priori information on the failure interface. If this is can be done successfully and reliably, avalanche warning operations could definitely benefit from the instrument.

Keywords: snowpack stability, avalanche forecasting, snow profile, mechanical properties, snow hardness

## 1. INTRODUCTION

Manual snow profiles combined with snowpack stability tests are currently the most reliable snowpack records considered for stability evaluation in avalanche forecasting (McClung and Schaerer, 1993). Schweizer and Jamieson (2003) provided a stability classification method based on the Rutschblock score and failure interface properties. With their classification model, it was estimated that 65 % of the manual profiles can be classified correctly (Schweizer and Jamieson 2003). These results show the significance of the mechanical and structural properties of the failure interface in respect to snowpack stability.

The SnowMicroPen (SMP), a high resolution snow penetrometer (Schneebeli and Johnson, 1998) has been introduced in Swiss avalanche forecasting operations. This instrument measures the penetration resistance of snow fast and at high resolution (Schneebeli et al., 1999, Pielmeier and Schneebeli, 2003). Since the winter of 2002-03, the Swiss avalanche forecasting service tested the applicability of the SMP. Avalanche forecaster's snow profiles and stability tests were complemented by SMP measurements. The project aimed at SMP training, technical improvement and data collection. The main focus of this study is to explore whether and how the SMP profile is related to snowpack stability. Since snowpack stability is related to failure interface properties and the SMP signal includes structural and mechanical information at high resolution it was expected that stability can also be predicted from the SMP profile.

To test this hypothesis, we analyzed the combined SMP and manual snow profiles with the stability tests and determined the significant SMP parameters indicating stability. The results are compared to those of the manual profile classification (Schweizer and Jamieson, 2003, Schweizer et al., 2004).

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## 2. DATA

The original dataset from the winter seasons of 2002-03 and 2003-04 consisted of 47 profiles. However, in 14 cases significant

SMP signal drift made the profile unusable for the analysis. The erroneous signal drift was attributed to melt or condensation water affecting the SMP force sensor during the measurements. Improved sealing of SMP tip shaft and cables as well as new ventilation holes in the shaft and careful drying were applied to counteract the drift problem and to reduce the number of defective records. The remaining 33 snow profiles with 39 failure interfaces were complemented by 6 snow profiles with 10 failure interfaces originally collected to study spatial variability during the winter seasons of 2001-02 and 2002-03 (Kronholm, 2004).

Finally, the dataset consisted of 39 snow profiles with 49 failure interfaces (Table 1). Most of the profile locations were chosen for the operational assessment of regional avalanche danger. The profiles consisted of a manual profile, a stability test and a SMP measurement. The SMP profile was taken slope perpendicular, adjacent to the manual profile (Figure 1).

Table 1: Used data sets: number of failure interfaces

| *Profile type* | *Stable* | *Unstable* |
|---|---|---|
| Flat field | 12 | 4 |
| Slope | 23 | 10 |

## 3. METHODS

### *3.1 Manual snow profiles*

The manual profiles were taken according to the guidelines of the International Classification for Seasonal Snow on the Ground (Colbeck et al., 1990). The Rutschblock test (Föhn, 1987) was performed on slopes. At flat profile locations, the compression test was used and its test score was converted to a Rutschblock score according to Jamieson (1999). Based on the stability test the failure layer ($FL_{man}$) and the adjacent layer ($AL_{man}$) across the failure interface were defined. For each $FL_{man}$ and $AL_{man}$ the hand hardness, grain size, grain shape and layer depth were used for the analysis. Also, the absolute grain size difference and hardness difference across the failure interface were used.

The threshold sum approach as proposed by McCammon and Schweizer (2003) was used for stability classification. In case five or more criteria of the list in Table 2 were fulfilled at the failure interface (i.e. threshold sum $\geq 5$), the manual profile was classified ‘unstable’ (Schweizer et al., 2004). Otherwise it was classified ‘stable’.

Figure 1: Right after SMP profiling the manual snow profile and the stability test were taken adjacent to the SMP profile.

Table 2: Critical ranges of Rutschblock score, mechanical and textural parameters of a potentially unstable failure interface (Schweizer et al., 2004).

| *Parameter* | *Critical range* |
|---|---|
| Rutschblock score | < 4 |
| Grain size difference | ≥ 0.75 mm |
| Grain size | ≥ 1.25 mm |
| Hardness difference | ≥ 2 hardness indices |
| Hardness | ≤ 1-2 |
| Grain shape | Facets, depth hoar or surface hoar |
| Layer depth | ≤ 1 m |

### *3.1 SnowMicroPen profiles*

A similar procedure was performed on the SMP profiles to calculate the layer properties at the failure interfaces. By superposing the manual profile and the stability test result with the SMP profile, the failure interface was pinpointed in each SMP profile. We used a manual layer definition procedure similar to Birkeland et al. (2004) and Kronholm et al. (2004). Since the SMP profile is not a discrete but a continuous record of the snow properties, the failure interface was defined not in two layers, as done in a manual profile, but in three layers: failure layer ($FL_{smp}$), transitional layer ($TL_{smp}$) and adjacent layer ($AL_{smp}$).

The following mechanical and structural properties of the so defined SMP layers were calculated: $FL_{smp}$ thickness, $FL_{smp}$ mean hardness, absolute and relative hardness difference between $FL_{smp}$ and $AL_{smp}$, $FL_{smp}$ texture index (Schneebeli et al., 1999), absolute and relative texture index difference between $FL_{smp}$ and $AL_{smp}$. The relative differences are the ratio of the $AL_{smp}$ parameter and the $FL_{smp}$ parameter. The force discontinuities in the transitional layer were fitted with a linear and a robust linear model. The modeled force gradients of the transitional layers were also analyzed.

Further structural and mechanical SMP parameters studied, based on the model by Johnson and Schneebeli (1999) and applied by Kronholm (2004), were: the $FL_{smp}$ structural length (LN) and size (LS), the absolute and relative difference in LN and LS between $FL_{smp}$ and $AL_{smp}$, the $FL_{smp}$ macro elastic modulus and macro compressive strength.

To compare the SMP data from the stable and unstable profiles we used the non-parametric Mann-Whitney U-test to decide whether two distributions were different based on a level of significance of $p = 0.05$. For multivariate analysis the classification tree method was used (Breiman et al., 1984). From the results of the classification tree we calculated the predictive power of the significant SMP variables.

## 4. RESULTS

### *4.1 Univariate analysis of SMP profiles*

The results of the statistical analysis of the significant SMP parameters for the stable and unstable profiles are shown in Table 3.

The $FL_{smp}$ structural length ($p = 0.008$) was the most significant SMP parameter to classify between stable and unstable failure interfaces. Further, the $FL_{smp}$ hardness ($p = 0.028$), the $FL_{smp}$ elastic modulus ($p = 0.034$) and the absolute difference in structural length between $AL_{smp}$ and $FL_{smp}$ ($p = 0.040$) were significant. The ranking of the significant SMP parameters was similar to the ranking of the significant manual profile parameters. Measures of FL structural dimension were in both cases most significant indicators of instability followed by measures of FL hardness. Compared to the results from manual profiles, the difference in FL hardness across the failure interface was not a significant variable in the SMP profiles. The distributions of the significant SMP variables are shown in Figures 2 and 3.

Table 3: Stable-unstable comparison of significant SMP variables. The sample size (N) and the level of significance (p-value) of the univariate analysis (U-test) are given.

| *SMP parameter* | *N stable* | *N unstable* | *p-value* |
|---|---|---|---|
| FL hardness | 34 | 14 | 0.028 |
| FL structural length | 32 | 13 | 0.008 |
| Absolute difference structural length | 32 | 13 | 0.040 |
| FL macro elastic modulus | 31 | 13 | 0.034 |

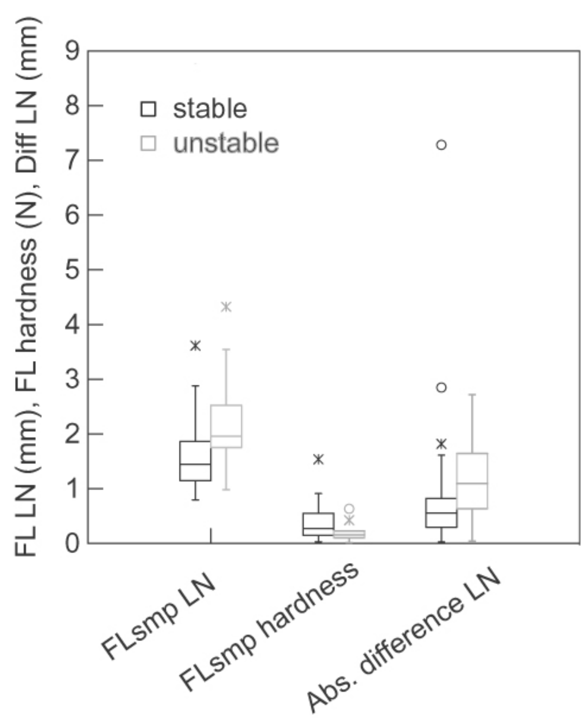


Figure 2: The distributions of the $FL_{smp}$ structural length (LN), the $FL_{smp}$ hardness and the absolute difference in structural length (LN) across the failure interface compared for stable and unstable profiles.

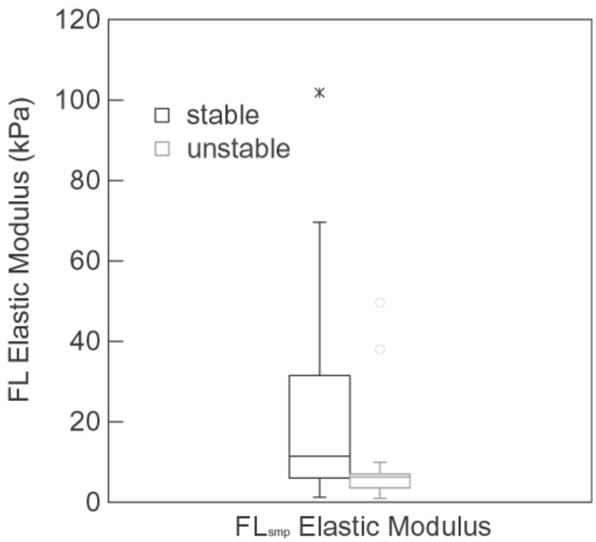


Figure 3: The distribution of the $FL_{smp}$ elastic modulus compared for stable and unstable profiles.

*4.2 Multivariate analysis of SMP profiles*

For the prediction of our categorical dependent variable (stable/unstable) we used the classification tree method. We selected the four independent variables that were statistically significant in the univariate analysis (Table 3). Because of the correlation of $FL_{smp}$ hardness to $FL_{smp}$ macro elastic modulus and compressive strength, only $FL_{smp}$ structural length and hardness were relevant in the multivariate analysis.

The classification tree split with the parameter and the value where it was most balanced when discriminating between stable and unstable from the independent SMP parameters. The tree hierarchy and the splitting values are shown in Figure 4. From this analysis, SMP failure interfaces were predicted to be unstable if $FL_{smp}$ LN ≥ 1.94 mm and $FL_{smp}$ hardness < 0.217 N.

The classification tree calculated with manual profile parameters (Schweizer and Jamieson, 2003) resulted in different splitting parameters. There, the classification tree split on the first level with the difference in grain size across the failure interface. On the second level it split once with the $FL_{man}$ hardness and once with the difference in hardness across the failure interface. The learning set had a 75 % accuracy of prediction, an 8 % false stable prediction rate and a false alarm rate of 15 %. Since an additional dataset for verification was not available, we split the learning set for this purpose in half and used one half as learning set and the other as verification set and vice versa. A reduction of about 10 % in prediction accuracy is usually expected from this procedure. When the complete dataset was randomly split in half, the mean accuracy of prediction was reduced to 67 %. When only the stable dataset was split in half and the unstable was taken completely, the mean accuracy of prediction increased to 76 %. Hence, the accuracy of prediction gained from SMP parameters lies close to the one estimated for manual profile parameters (65 %).

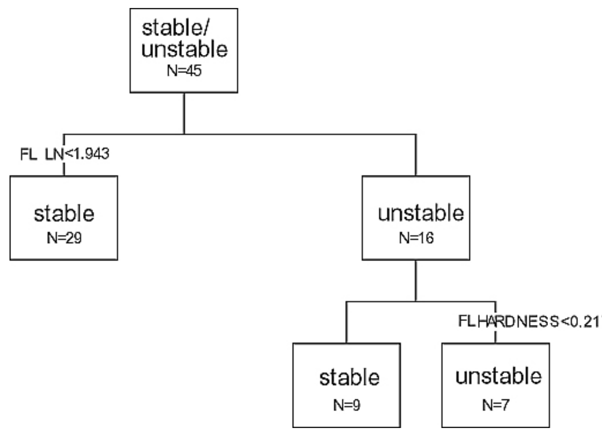


Figure 4: Classification tree for stable/unstable dataset (N = 45). The not cross-validated classification accuracy is 75 %. The dataset contains $FL_{smp}$ structural length and hardness as independent variables.

## 5. CONCLUSIONS

With a small combined dataset of manual and SMP snow profiles, we found the following parameters calculated from the SMP signal of failure interfaces that indicate instability: $FL_{smp}$ structural length, $FL_{smp}$ hardness, difference in structural length across the failure interface and $FL_{smp}$ macro elastic modulus. These parameters are related to the indicators from manual profiles and to dry snow slab avalanches. The classification tree showed that failure layer structural dimension and hardness were not only indicators of stability in manual profiles but also in SMP profiles. The classification tree can be used as preliminary model to classify snowpack stability from a SMP profile. The SMP prediction accuracy of stable or unstable profiles is close to the one gained from manual profiles. Improvements should be made in the SMP failure interface identification and by expanding the dataset primarily with unstable profiles.

A next step is to test how well stability can be predicted from an unclassified SMP profile, i.e. without determining the failure interface by comparison with the manual observation. If a reliable failure interface detection and stability prediction from SMP profiles is possible, avalanche warning operations could benefit from the instrument. SMP signal drift made about one third of the original dataset unusable for the analysis. Improvements in signal drift detection and signal drift reduction will also be necessary to make the SMP an operational field instrument for avalanche warning purposes.

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