IMPROVEMENTS IN THE APPLICATION OF THE SnowMicroPen TO DERIVE STABILITY INFORMATION FOR AVALANCHE FORECASTING

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ABSTRACT: Local snowpack measurements and local stability tests are currently the basis for the assessment of snowpack stability in most avalanche warning operations. The SnowMicroPen (SMP), a high-resolution penetrometer for snow, measures penetration resistance of snow. In order for SMP measurements to be useful for stability evaluation (or avalanche forecasting purposes), stability information needs to be derived from the SMP signal. It was shown that structural and mechanical parameters derived from the SMP signal for known (or manually observed) failure interfaces were related to snowpack stability. The dataset contained 66 parallel SMP and manual snow profiles with stability tests from five winter seasons 2001-02 to 2005-06 in Switzerland. It was balanced between stable (35) and unstable (31) profiles. The manual failure layer determination in the SMP signal was improved. Micro structural and mechanical parameters were derived from the SMP signal using two models describing the interaction of the SMP tip with an idealized snow structure. The parameters from the improved model are compared with snow stability data for the first time. The new model slightly improved the results of the statistical analysis and the classification accuracy of a failure interface from a SMP profile. The analysis confirms the potential of the SnowMicroPen operational use in avalanche forecasting services.

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

1. INTRODUCTION

Manual snow profiles combined with snowpack stability tests are still 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 could be classified correctly (Schweizer and Jamieson 2003, Schweizer et al., 2005. 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 tested in Swiss avalanche forecasting operations over the last five winter seasons. Occasionally, SMP measurements were taken parallel to avalanche forecaster's snow profiles and stability tests. Pielmeier et al. (2005) derived indicators of instability from the SMP signals at failure interfaces found from stability tests from a three-year dataset (2001-02 to 2003-04). These indicators were the failure layer micro structural length and hardness, the difference in structural length across the failure interface and the failure layer macro elastic modulus. It could be shown, that the cross-validated accuracy of classification into stable or unstable failure interfaces gained from these SMP parameters was comparable to the classification accuracy from manual profile parameters (about 65 %).

In this study the analysis is applied to a five-year dataset (2001-02 to 2005-06) that is balanced between stable and unstable failure layers. The results of the three-year dataset (2001-02 to 2003-04) are compared to the results of the five-year dataset (2001-02 to 2005-

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06). Furthermore, parameters from an improved snow mechanical model by Marshall (2006) and Marshall and Johnson (in prep.) are also considered. The results are compared with the results from the Johnson and Schneebeli (1999) model used previously.

2. DATA

To classify the manual snow profiles, the threshold sum approach, derived from McCammon and Schweizer (2002), was used for stability classification. In cases where five or more parameters were in the critical range (Table 1) at the failure interface (i.e. threshold sum ≥ 5), the manual profile was classified as 'unstable'; otherwise it was classified as 'stable' (Schweizer et al., 2005).

Table 1: Critical ranges of Rutschblock score, mechanical and textural parameters of a potentially unstable failure interface.

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

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 several SMP measurements. At least one vertical and one slope perpendicular SMP measurement were taken adjacent to the manual profile. The SMP measurement used for the numerical analysis was the slope perpendicular measurement closest to the manual profile (Figure 1).

The five-year dataset (2001-02 to 2005-06) included 66 failure interfaces with 47 % unstable interfaces, hence it is nearly balanced (Table 2). The previously used, three-year dataset (2001-02 to 2003-04) consisted of 49 failure interfaces, with only 28 % unstable failure interfaces.

Figure 1: SMP profiling parallel to the manual snow profile and the stability test (Photo: SLF/A. Raez).

Table 2: Five-year dataset: 66 failure interfaces, of which 47 % were classified as 'unstable'.

Profile type	Stable	Unstable
Flat field	12	7
Slope	23	24

During the winter seasons 2004-05 and 2005-06, the number of SMP measurements with signal drift was significantly reduced after the SMP was modified in early winter 2004-05. A silicone O-ring with a very low shear modulus has been placed between the tip and the cone to prevent freezing of the tip in the cone. The analysis of reference measurements in homogenous snow showed no significant differences in SMP signals (Schneebeli, personal communication 2005).

3. METHODS

3.1 Manual snow profiles

The manual snow 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.

3.1 *SnowMicroPen profiles*

A similar procedure was performed on the SMP profiles to calculate the layer properties at the failure interfaces. By superimposing the manual profile and the stability test result with the SMP profile, the failure interface was pinpointed in each SMP profile. A failure layer (FL_{smp}), a transitional layer (TL_{smp}) and an adjacent layer (AL_{smp}) were manually chosen (Pielmeier et al., 2005). To facilitate the precise location of the failure interface in the SMP signal, vertical SMP measurements were also considered and found to be helpful.

The following mechanical and structural properties of the 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) and 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.

Parameters, based on the model by Johnson and Schneebeli (1999) and applied by Kronholm (2004), were: FL_{smp} structural length (LN_{99}) and size (LS_{99}), absolute and relative difference in LN_{99} and LS_{99} between FL_{smp} and AL_{smp}, FL_{smp} macro elastic modulus$_{99}$ and macro compressive strength$_{99}$.

Parameters based on the snow mechanical model by Marshall (2006), which is an improvement on Sturm et al. (2004) and is described in detail in Johnson and Marshall (in prep.) were: FL_{smp} micro stiffness ($kmicro_{06}$), FL_{smp} and AL_{smp} number of involved elements, absolute and relative differences in number of involved elements between FL_{smp} and AL_{smp}, FL_{smp} structural length (LN_{06}) and size (LS_{06}), absolute and relative differences in LN_{06} and LS_{06}, FL_{smp} micro and macro compressive strength ($Smicro_{06}$, $Smacro_{06}$) and elastic modulus ($Emicro_{06}$, $Emacro_{06}$).

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 correlation analysis on the significant parameters we used discriminant analysis. 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 from the learning dataset and compared the results to Pielmeier et al. (2005).

4. RESULTS

4.1 *Univariate analysis of SMP profiles*

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

Table 3: Stable-unstable comparison of significant SMP variables. The level of significance (p-value) of the univariate analysis (U-test) is given. The uncorrelated variables are indicated with *.

SMP parameter	p-value
*FL mean hardness	0.001
*Absolute difference in mean hardness	0.005
*AL number of elements	0.005
*FL structural size, model 2006, LS_{06}	0.029
*Relative difference in number of elements	0.048
FL number of elements	0.001
FL macro compressive strength ($Smacro_{06}$)	0.001
FL structural length, model 1999, LN_{99}	0.044
FL texture index, TI	0.045

The FL_{smp} mean hardness ($p = 0.001$) is the most significant SMP parameter to classify between stable and unstable failure interfaces. Further, the absolute difference in mean hardness between FL_{smp} and AL_{smp} ($p = 0.005$) and the new parameter AL_{smp} number of involved elements ($p = 0.005$) are also highly significant. The FL_{smp} structural size (LS_{06}) ($p = 0.029$) is more significant than the FL structural length (LN_{99}) ($p = 0.044$). A further significant parameter is the relative difference in number of involved elements between FL_{smp} and AL_{smp}. ($p = 0.045$). The distributions of the five significant and uncorrelated SMP variables (Table 3, indicated with *) are shown in Figures 2, 3 and 4.
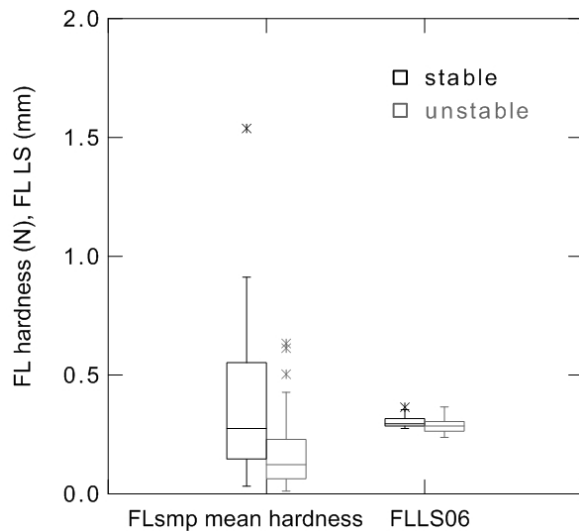
Figure 2: The distributions of the FL_{smp} hardness (N stable/unstable 35/31, p-value 0.001) and the FL_{smp} structural size LS_{06} (N stable/unstable 30/30, p-value 0.029).
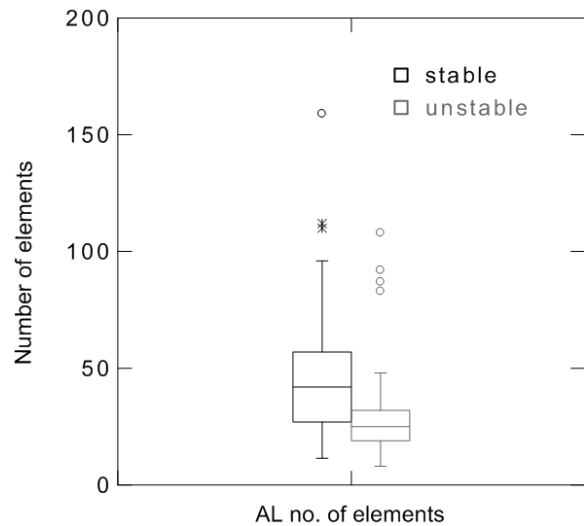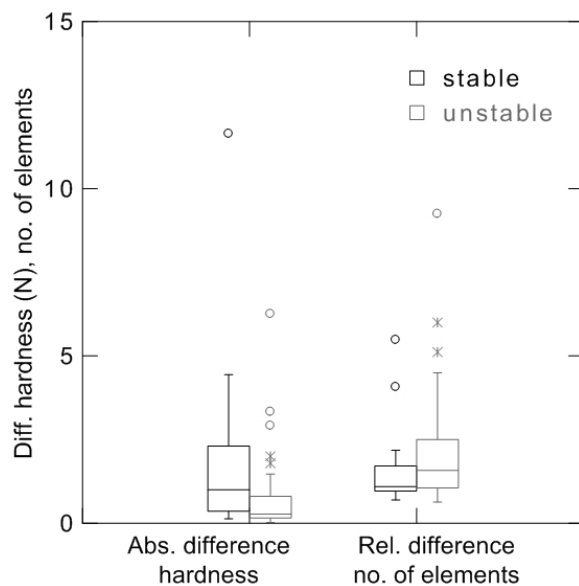

Figure 3: The distribution of the absolute difference in hardness between FL_{smp} and AL_{smp} (N stable/unstable 35/31, p-value 0.005) and the relative difference in number of involved elements between FL_{smp} and AL_{smp} (N stable/unstable 30/30, p-value 0.048).

Figure 4: The distribution of the AL_{smp} number of involved elements (N stable/unstable 29/27, p-value 0.005).

4.2 Multivariate analysis

For the prediction of our categorical dependent variable (stable/unstable) we used the classification tree method. We selected the five dependent variables that were uncorrelated and statistically significant in the univariate analysis (Table 3, variables indicated with *).

The classification tree split with the dependent SMP variable and the value where it was most balanced when discriminating between stable and unstable. The tree hierarchy and the splitting values are shown in Figure 5. From this analysis, SMP failure interfaces were predicted to be unstable if

a) FL_{smp} LS_{06} < 0.275 mm

or b) FL_{smp} LS_{06} >= 0.275 mm and FL_{smp} hardness < 0.114 N

or c) FL_{smp} LS_{06} >= 0.275 mm and FL_{smp} hardness >= 0.114 N and the absolute difference in hardness between FL_{smp} and AL_{smp} is < 0.680 N.

The classification tree calculated with manual profile parameters (Schweizer and Jamieson, 2003) resulted in the following splitting parameters: on the first level it split with the difference in grain size across the failure interface and on the second level it split once with the FL_{man} hardness and once with the difference in hardness across the failure interface. With the five-year dataset we obtain an 81 % classification accuracy (not cross-

validated). The false stable prediction rate is 30 % and the false alarm rate is 10 %. Compared to our previous study (Pielmeier et al., 2005) the overall accuracy of prediction could be slightly improved.
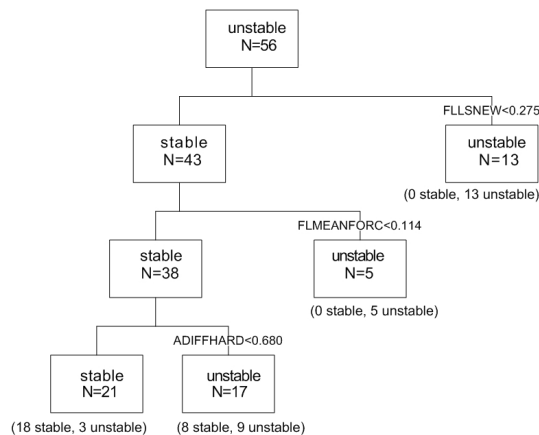

Figure 5: Classification tree for stable/unstable dataset (N = 56). The not cross-validated classification accuracy is 81 %.

6. CONCLUSION

The statistical analysis to predict stable and unstable failure interfaces from the SMP signal for known failure interfaces was applied to a dataset of 66 manual and SMP snow profiles. The following parameters calculated from the SMP signal of failure interfaces indicated instability: FL_{smp} hardness, difference in hardness between the FL_{smp} and the AL_{smp}, FL_{smp} structural size (LS_{06}). These parameters are related to the indicators for manual profiles and to dry snow slab avalanches.

By including the new SMP parameters based on the improved model of the interaction of the SMP tip with the snow microstructure by Marshall (2006) and Johnson and Marshall (in prep.) into the statistical analysis, the results were slightly improved. The classification accuracy increased from 75 % (Pielmeier et al., 2005) to 81 % (this study). Note that the cross-validated results lie about 10 % below the not cross-validated results. 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 SMP profiles based on failure layer parameters in respect to snowpack stability.

It would be beneficial to further verify the new theory with well-defined laboratory measurements, especially of snow mechanical properties. A larger database might still improve the robustness of the results. SMP signal drift due to tip freezing was greatly reduced by a modification of the measuring tip.

Further steps are the location of potential failure interfaces from SMP measurements, the quantification of the slab properties from the SMP measurement and the development of a SMP stability index. If a reliable failure interface detection and stability prediction from SMP profiles is possible, avalanche warning operations could benefit from the instrument.

Acknowledgements

References

Breiman, L., Friedman, J.H., Olshen, R.A., Stone, C.J., 1984. Classification and Regression Trees. CRC Press, Boca Raton, USA, 368 pp.

Colbeck, S.C., Akitaya, E., Armstrong, R., Gubler, H., Lafeuille, J., Lied, K., McClung, D., Morris, E., 1990. The International Classification for Seasonal Snow on the Ground. International Association of Scientific Hydrology. International Commission on Snow and Ice, Wallingford, Oxfordshire, 23 pp.

Föhn, P.M.B., 1987. The Rutschblock as a practical tool for slope stability evaluation. In: B. Salm and H. Gubler (Editors), Symposium at Davos 1986 - Avalanche Formation, Movement and Effects, IAHS Publ., 162. International Association of Hydrological Sciences, Wallingford, Oxfordshire, U.K., pp. 223-228.

Jamieson, B., 1999. The compression test – after 25 years. Avalanche Rev., 18(1), 10-12.

Johnson, J.B., Schneebeli, M., 1999. Characterizing the micro structural and micro mechanical properties of snow. Cold Reg. Sci. Technol., 30, 91-100.

Johnson, J.B., Marshall, H.P., in prep. Characterization of snow microstructural and micromechanical properties and their scaling to the macro-scale. J. of Glac.

Kronholm, K., 2004. Spatial variability of snow mechanical properties with regard to avalanche formation. Ph.D. thesis, University of Zürich, Zürich, 158 pp.

Marshall, H.P., 2006. Snowpack spatial variability: towards understanding its effect on remote sensing measurements and snow slope stability. Ph.D. thesis, University of Colorado at Boulder, 264 pp.

McCammon, I., Schweizer, J., 2002. A field method for identifying structural weaknesses in the snowpack. In: Stevens, J.R. (Ed.), Proceedings ISSW 2002. International Snow Science Workshop, Penticton BC, Canada, 29 September – 4 October 2002, pp. 477-481.

McClung, D.M., Schaerer, P., 1993. The Avalanche Handbook. The Mountaineers, Seattle, WA, USA, 271 pp.

Pielmeier, C., Schweizer, J., Stucki, T., 2005. Application of the SnowMicroPen to derive stability information for avalanche forecasting. In: K. Elder (Editor), Proceedings ISSW 2004. International Snow Science Workshop, Jackson Hole WY, U.S.A., 19-24 September 2004, pp. 177-181.

Schneebeli, M., Johnson, J.B., 1998. A constant-speed penetrometer for high-resolution snow stratigraphy. Ann. Glaciol., 18, 193-198.

Schneebeli, M., Pielmeier, C., Johnson, J.B., 1999. Measuring snow microstructure and hardness using a high resolution penetrometer. Cold Reg. Sci. Technol., 30, 101-114.

Schweizer, J., Jamieson J.B., 2003. Snowpack properties for snow profile analysis. Cold Reg. Sci. Technol., 37, 233-241.

Schweizer, J., Fierz, C. and Jamieson, J.B., 2005. Assessing the probability of skier triggering from snow layer properties. In: K. Elder (Editor), Proceedings ISSW 2004. International Snow Science Workshop, Jackson Hole WY, U.S.A., 19-24 September 2004, pp. 192-198.

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