Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Cold Regions Science and Technology 37 (2003) 233–241

cold regions science and technology

www.elsevier.com/locate/coldregions

Snowpack properties for snow profile analysis

Jürg Schweizer[a,*], J. Bruce Jamieson[b]

[a] Swiss Federal Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland
[b] Departments of Civil Engineering and Geology and Geophysics, University of Calgary, 2500 University Drive NW, Calgary, AB, Canada T2N 1N4

Received 1 September 2002; received in revised form 31 January 2003; accepted 2 July 2003

Abstract

A Swiss–Canadian data set of over 400 snow profiles from skier-triggered slopes and slopes that were skied but not triggered was contrasted to derive statistically relevant differences that can be used in snow profile interpretation. The critical weakness was identified either by the adjacent avalanche, rutschblock test or compression test. A failure layer and failure interface was identified in each profile. For discriminating between stable and unstable profiles, univariate analysis revealed the importance of the rutschblock score, failure layer hardness, failure layer grain size as well as difference in grain size and hardness across the failure interface. These same variables were used in two multivariate classification methods, which suggest that approximately 65% of profiles can be correctly classified with or without the stability test score.

Keywords: Snow cover profile; Avalanche forecasting; Avalanche formation; Snow cover stability; Snow stability evaluation; Skier triggering

---

1. Introduction

Observing and recording the snow stratification and subsequently performing a snow stability test provides direct evidence on snowpack stability (McClung and Schaerer, 1993). Therefore, snow profiles with stability tests are widely used for stability evaluation and avalanche forecasting, besides other observations, e.g. on avalanche occurrence. However, it should be noted that decisions on snow stability should never be based on one single profile and/or stability test since substantial snowpack variability might hinder extrapolation. So far, snow profile interpretation is lacking objectivity. The interpretation scheme proposed by Schweizer and Wiesinger (2001) is based on experience rather than data. Although unstable profiles seem to have specific characteristics, as shown by Schweizer and Jamieson (2001), it is presently unclear whether these characteristics are unique for unstable profiles or present in most profiles.

To our knowledge, the only comparison of stable with unstable profiles was performed so far by Ferguson (1984). She compared profile data from three different continents and several snow climates. Employing cluster analysis and pattern recognition techniques did not conclusively discriminate between stable and unstable profiles.

---

* Corresponding author. Tel.: +41-81-417-0164; fax: +41-81-417-0110.

E-mail address: schweizer@slf.ch (J. Schweizer).

0165-232X/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0165-232X(03)00067-3

In the present study, we contrast a data set of over 400 snow profiles from skier-triggered slopes and slopes that have been skied but not triggered to derive statistically relevant differences. The analysis is focused on skier triggering and only dry snow conditions are considered. These limitations follow from the fact that in Europe and North America most avalanches that cause fatalities are dry slabs triggered by people (Atkins and Williams, 2001; Jamieson and Geldsetzer, 1996; Tschirky et al., 2001).

Since for most of our stable profiles a stability test (rutschblock or compression test) was made beside the profile, the primary weakness in the snowpack is known as well as the stability test result. Although we show that the rutschblock score itself is a strong predictor, we also show that other profile parameters have similar classification power, and that classifications can be made with and without considering the rutschblock score, resulting in about the same classification accuracy. In fact, considering other snowpack parameters beside the rutschblock score helps to minimise false stable predictions (McCammon and Schweizer, 2002).

In order to derive statistically relevant differences that can be used in snow profile interpretation, we will compare stable to unstable profiles country by country as well as for the combined data set by applying univariate and multivariate methods.

2. Data

We explore two samples of snow profiles, one from Switzerland and one from Canada. For each country, we have “unstable” profiles from the slope adjacent to skier-triggered avalanches that have been observed usually 1 day after the release, and about the same number of “stable” profiles taken from avalanche starting zones that were skied but not triggered. The profiles from these slopes were gathered during various field studies for avalanche research or for stability evaluation purposes. The data were collected during the winters 1988–1989 to 2001–2002. For all profiles, the primary weakness is known. Either it was the failure plane of the skier-triggered avalanche or it was identified as the layer with the lowest stability score in a rutschblock test (Föhn, 1987) or compression test (Jamieson, 1999). In total, 208 cases from Switzerland and 216 cases from Canada were analysed as shown in Table 1.

Table 1
Characteristics of data sets used: number of profiles

Country	Stable	Unstable
Switzerland	105	103
Canada	99	117

3. Methods

In the following two paragraphs, the variables used for contrasting stable to unstable profiles (Table 2) are very briefly described. Most are standard snowpack observations (CAA, 2002).

Elevation, slope angle and aspect were measured at the profile site. Snow cover properties were classified according to Colbeck et al. (1990). Layer thickness, grain type, grain size, hand hardness index and snow temperature were recorded. Occasionally for the Swiss, and consistently in the Canadian profiles, average slab density was measured. In addition, average properties for the slab (snow temperature and hardness) were derived, and the grain type was classified as nonpersistent, persistent (Jamieson and Johnston, 1995) or crust. The load above the weak layer or interface was calculated from slab density and thickness. Hand hardness for individual layers was indexed from 1 to 6 for Fist (F), Four-Finger (4F), One-Finger (1F), Pencil (P), Knife (K) and Ice (I), respectively. Intermediate values were allowed, e.g. 1–2 or 2+. Snowpack consolidation or hardness distribution within the snowpack was classified according to the hardness profile types given in Schweizer and Lütschg (2001). For the Canadian profiles, failure layer strength as determined with the shear frame (Jamieson and Johnston, 2001) and failure layer age since burial was recorded for many layers.

Rutschblock tests were performed as described in Schweizer (2002). The rutschblock score was supplemented for the Swiss profiles with the type of release (either whole block, part of the block or only an edge) and the type of fracture (either smooth, rough or irregular) (Schweizer, 2002). Compression tests scores in the ranges 0–5, 6–13, 14–16, 17–18,

Table 2
Stable–unstable comparison of snow profile variables for Swiss, Canadian and combined data sets. For each variable, distributions from stable and unstable profiles are contrasted (*U*-test, cross-tabulated), and the level of significance is given. Very highly significant variables ($p < 0.001$) in the combined data set are given in bold with three asterisks. One asterisk denotes very highly significant variables that showed only up in either the Swiss or the Canadian sample

Variable	Switzerland					Canada					Combined		
	Stable		Unstable		*p*	Stable		Unstable		*p*	Stable	Unstable	*p*
	N	Median	*N*	Median		*N*	Median	*N*	Median		Median	Median	
Elevation (m)	105	2520	103	2470	0.40	99	1990	117	2015	0.41	2270	2190	0.30
Slope angle (°)	105	35	103	37	0.18	99	37	117	38	0.41	36	37	0.11
Aspect	105	N	103	NE	0.28	99	E	117	E	0.17	NE	E	0.74
***__RB score__	105	5	70	3	<0.001	99	6	95	3	<0.001	5	3	<0.001
*Snow depth (cm)	105	153	103	115	<0.001	89	258	107	250	0.72	186	187	0.24
*RB release type	71	partly	27	full	<0.001	–	–	–	–	–	–	–	–
RB fracture type	51	clean	28	clean	0.032	–	–	–	–	–	–	–	–
*Hardness profile type	105	3, 6, 7	103	7, 4, 1	<0.001	99	6	117	6	0.62	6, 7	6, 7	0.001
Slab hardness	105	2 (4F)	103	1–2	0.075	89	2.3 (4F+)	113	1.8 (4F −)	0.01	2 (4F)	1.8 (4F −)	0.003
Slab thickness (cm)	105	39	103	52	0.001	99	50	117	44	0.03	45	47	0.63
Slab temperature (°C)	104	−5.5	92	−5.0	0.43	98	−5.15	108	−5.2	0.79	−5.5	−5.0	0.45
Slab density (kg m^{-3})	24	200	31	204	0.48	89	149	113	130	0.01	160	141	0.07
Bridging (hardness) (cm)	105	68	103	86	0.053	89	110	113	82	0.006	84	84	0.47
Load (kPa)	24	0.69	31	0.88	0.12	89	0.75	113	0.61	0.022	0.74	0.67	0.17
*FL grain type	105	4, 3, 2	103	4, 5, 7	<0.001	99	7, 2, 4	117	7, 2, 4	0.51	4, 2, 7	7, 4, 2	0.001
***__FL grain size (mm)__	105	0.75	103	1.5	<0.001	97	1.75	116	2.375	0.001	1.1	2	<0.001
***__FL hardness__	105	1–2	103	1 (F)	0.002	89	2 (4F)	104	1.7 (4F −)	<0.001	2 (4F)	1 (F)	<0.001
FL thickness (cm)	105	6	103	3	0.038	99	1	117	1	0.16	3	1.5	0.15
FL temperature (°C)	104	−4.5	91	−3.5	0.156	69	−4.2	95	−4.5	0.13	−4.4	−4.0	0.94
*FL shear strength (kPa)	–	–	–	–	–	82	1.48	105	0.77	<0.001	–	–	–
FL age (day)	–	–	–	–	–	39	13	66	11	0.02			
AL grain type	105	3, 4, 6	103	4, 3, 6	0.017	84	3, 2, 6	105	3, 2, 6	0.17	3, 6, 4	3, 4, 6	0.10
AL grain size (mm)	105	0.625	103	0.75	0.036	66	0.75	83	0.75	0.84	0.75	0.75	0.09
AL hardness	105	3 (1F)	103	3 (1F)	0.015	99	3.7 (P −)	116	3 (1F)	0.007	3 (1F)	3 (1F)	0.96
AL thickness (cm)	105	6	103	5	0.945	99	11	117	10	0.135	8	8	0.53
*Difference grain type	105	np/np	103	p/p	<0.001	84	np/np	105	p/np	0.58	np/np	p/np	0.01
***__Difference grain size (mm)__	105	0.375	103	1.0	<0.001	66	1.5	82	2.425	0.08	0.5	1.1	<0.001
***__Difference hardness__	105	1.3	103	2	<0.001	89	1	104	1.5	0.005	1	1.7	<0.001
Interface temperature grad (°C)	104	−4.3	91	−4.0	0.80	–	–	–	–	–	–	–	–
Layering	102	h/s	96	h/s	0.96	81	s/h	98	s/h	0.65	s/h	s/h	0.82

19–20 and >20 taps were converted into comparable rutschblock scores 2, 3, 4, 5, 6 and 7, respectively (Jamieson, 1999).

Special attention was given to the primary weakness as revealed by the avalanche release or a stability test. We followed a partly new approach. In the majority of the cases (53%), the fracture is reported to be at the boundary (interface) between two adjacent layers. The softer of the two layers we consider then as the "failure layer" (FL); the layer across the failure boundary as the "adjacent layer" (AL). If the failure interface is not reported, we assume the failure interface to be the boundary with the larger hardness or grain size difference, or in case of no difference for the upper and lower layer, we chose the lower layer as adjacent layer. Accordingly, the failure layer is sometimes below, and sometimes above the adjacent layer, or in other words the fracture occurred at the upper or lower boundary of the failure layer. Consistently following the procedure to assign the failure and adjacent layers as described above, in case it was not reported, did not bias the analysis. If the group of *reported* failure interfaces is compared to that of *assumed* failure interfaces, no difference could be found in regard to whether the failure layer is above or below: $p = 0.27$ for the Swiss, $p = 0.16$ for the Canadian sample (Mann–Whitney *U*-test described below). The hardness and grain size differences across the failure interface were considered (Schweizer and Jamieson, 2001), as well as the temperature gradient. For analysis, the grain type in the failure and the adjacent layer was summarized as nonpersistent, persistent or crust. The variable "Layering" describes the hardness change at the failure interface: "hard over soft" (h/s), or "soft over hard" (s/h). To check whether bridging is of importance, a variable "Bridging" was derived by multiplying slab hardness with thickness.

To compare stable to unstable data, we used primarily the nonparametric Mann–Whitney *U*-test to decide whether two distributions were different based on a level of significance of $p = 0.05$. The Kruskal–Wallis *H*-test, a generalization of the *U*-test, was applied to compare more than two independent samples. Nonparametric tests were applied since they are independent of population distributions and associated parameters, i.e. they do not require that restrictive assumptions be made about the shape of a distribution. They are especially valuable in dealing with nonnumerical (ordinal and nominal) data. Comparing categorical variables such as grain type or profile type, the distributions were compared by cross-tabulating the data and calculating the Pearson χ^2 statistic. The χ^2 test is as well a nonparametric test to compare samples of nominal (frequency) data (Sanders, 1995; Spiegel and Stephens, 1999). These test statistics computed for each variable individually might not be independent due to possible correlations between variables. Therefore, in addition, multivariate analysis methods that use all variables simultaneously, were applied.

Discriminate analysis and classification tree methodology are used for the multivariate analysis. The discriminant analysis provides linear functions of the variables that "best" separate cases into the two groups of stable and unstable profiles. The variables in the linear function are selected in a forward or backward stepwise manner. At each step, the variable enters that contributes most to the separation of the groups or removes the variable that is least useful (Flury and Riedwyl, 1988).

Classification analysis is used to produce an accurate classifier and/or to uncover the predictive structure of the problem, i.e. to give simple characterizations of the conditions, in terms of the variables, that determine whether a case is in one group rather than another. Tree structured classifiers are constructed by repeated splits of subsets of the data set into two descendant subsets, beginning with the data set itself. An ordinary least square loss function was used to optimize the splits. The minimum proportion reduction in error for the tree allowed at any split was set to 0.02. The same value was used as minimum split index value allowed at any node (Breiman et al., 1984).

4. Results

The Swiss and the Canadian samples are first compared in Table 2. We then report on the univariate analysis of the combined data set and the multivariate analysis with classification methods: discriminant analysis and classification trees.

4.1. Univariate analysis of Swiss profiles

In the Swiss sample, RB score, snow depth, RB release type, hardness profile type, failure layer grain type and size, and differences in grain type, grain size and hardness were very highly significant variables, i.e. for each variable the two groups of stable/unstable profiles were statistically different with $p < 0.001$. Therefore, these variables were significant indicators of instability. Unstable profiles had shallower snow depth, failure layers were softer and consisted of larger, primarily persistent grains. Across the failure interface, unstable profiles showed a larger difference in grain size and hardness, and most frequently persistent grain types in both the adjacent and the failure layer were present. Not surprisingly, the stable profiles had a higher RB score (median: 5) compared to the unstable profiles (median: 3). In the majority of the cases (85%) of the unstable profiles, the whole rutschblock released, whereas in the stable profiles, partial release ("below skis" or "only an edge") was more frequent (76%).

Still highly significant were slab thickness and failure layer hardness. Unstable profiles showed larger slab thickness and softer failure layers than stable profiles.

4.2. Univariate analysis of Canadian profiles

In the Canadian sample, only three variables were very highly significant: RB score, failure layer hardness and shear strength. Still highly significant ($0.001 \leq p \leq 0.01$) were two variables that also showed as important in the Swiss profiles: failure layer grain size and difference in hardness across the failure interface. In addition, unique to the Canadian sample, slab hardness, slab density and consequently bridging as well as adjacent layer hardness were also highly significant. Unstable profiles had lower density and hardness, and accordingly less bridging effect. Adjacent layer hardness was less in the unstable group than in the stable group.

4.3. Univariate analysis of combined Swiss and Canadian profiles

Comparing significant variables in the combined Swiss and Canadian data set suggests that snow depth is only important as long as it is relatively low and differences in snow depth are accordingly rather large. This follows from wind deposits that are much more irregular as long as there is some terrain roughness. Accordingly, the profile type that describes general snowpack consolidation is only important as long as the snowpack is not too deep and differences in snowpack are relatively large. In case of slab hardness and density, the Swiss sample showed the same trend (softer slab for unstable) as the Canadian for the hardness, but no trend at all for the density. The trends in slab thickness were contrary in regard to instability: thicker slabs in the Swiss and thinner in the Canadian sample. The discrepancy in failure layer grain type that was very highly significant in the Swiss sample, but not at all in the Canadian sample where surface hoar dominates both the stable and unstable groups, is likely due to the predominance of this type of failure layer in the Columbia Mountains of Western Canada and maybe partly due to Canadian sampling preferences. Consequently, there is also no significant difference in grain size across the failure interface in the Canadian sample.

Combining the two samples might be questionable in view of the differences described above. However, doing so hopefully reveals the most significant variables independent of snow climate. These were RB score, failure layer grain size and hardness and differences in grain size and hardness across the failure interface (Fig. 1). Except for the grain size difference, these variables were highly significant in both the Canadian and the Swiss samples. The difference in grain size across the failure interface was not a significant variable in the Canadian sample, but showed the same trend as in the Swiss sample: larger grain size difference in the unstable group than in the stable group.

Elevation, aspect and slope angle shows no difference between stable and unstable profiles. This suggests that the above results are not depending on

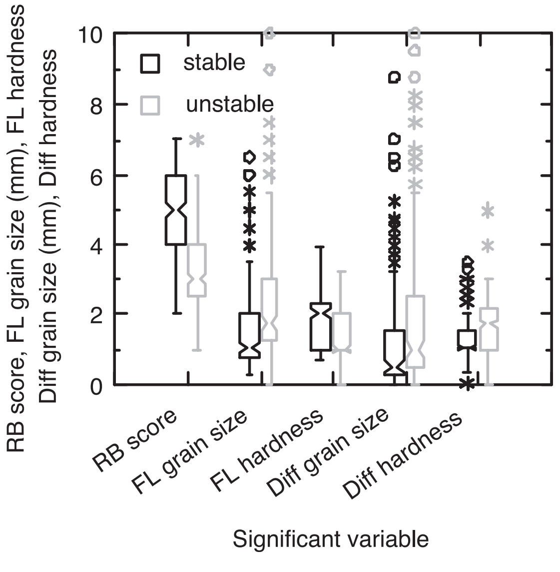

Fig. 1. Contrasting stable and unstable profiles from Canada and Switzerland for the five most significant variables: RB score, failure layer grain size, failure layer hardness, difference in grain size and difference in hardness across failure interface. For each variable, stable data is on the left and unstable on the right given. Boxes span the interquartile range from first to third quartiles with a horizontal line showing the median. Notches at the median indicate the confidence interval ($p < 0.05$). Whiskers show the range of observed values that fall within 1.5 times the interquartile range above and below the interquartile range. Asterisks show outliers, open dots show far outside values.

terrain factors, i.e. that sampling sites were independently chosen. In addition, there are a few snowpack variables worth mentioning that obviously do not differentiate between stable and unstable snowpack. These are slab thickness, slab temperature, failure layer temperature and temperature gradient across the failure interface. In addition, adjacent layer properties vary too widely to reveal significant differences.

4.4. Multivariate analysis of combined Swiss and Canadian profiles

For the multivariate classification, we use discriminant analysis and classification trees. For both approaches, we have pre-selected the variables from Table 2 based on the number of cases available for analysis, on the physical meaningfulness and on the significance in the univariate analysis. Accordingly, we used six variables for the multivariate analysis ($N = 291$): RB score, slab hardness, failure layer grain size, failure layer hardness, difference in grain size and difference in hardness across the failure interface. Backward and forward selection did not affect the result. For both discriminating procedures, the three variables RB score, failure layer grain size and difference in hardness across the failure interface showed up as the variables that best separate profiles into stable and unstable groups. With this classification model in 68% of the cases, the profiles were correctly classified. This score is calculated by the jackknifed procedure that removes and replaces one case at a time. If the discriminant analysis is repeated with only these three best variables, the number of cases available for analysis increases to $N = 347$ and the classification accuracy is still 68%.

When omitting the rutschblock score ($N = 332$), the forward separating procedure revealed the difference in hardness across the failure interface, the failure layer grain size and the slab hardness as best separators which resulted in a jackknifed classification score of 64%. The backward procedure found, in order of decreasing importance, the differences in hardness and grain size across the failure interface, the slab hardness and the failure layer hardness as best separators with 65% correct classifications.

In addition to the six variables chosen above for the discriminant analysis, we added the variable failure layer grain type (simply “persistent” or “nonpersistent”) for the classification tree analysis. The tree classification revealed rutschblock score and difference

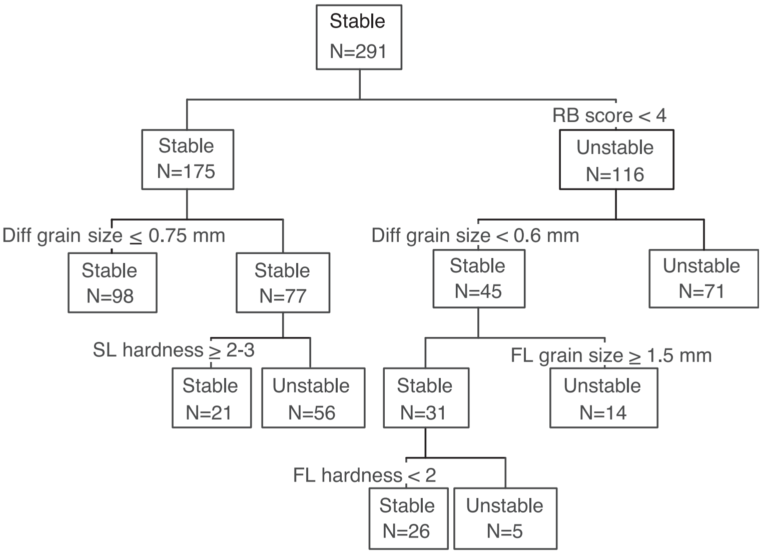

Fig. 2. Classification tree for combined stable/unstable data set ($N = 291$). Classification accuracy was 78%. Data set contains rutschblock score as independent variable.

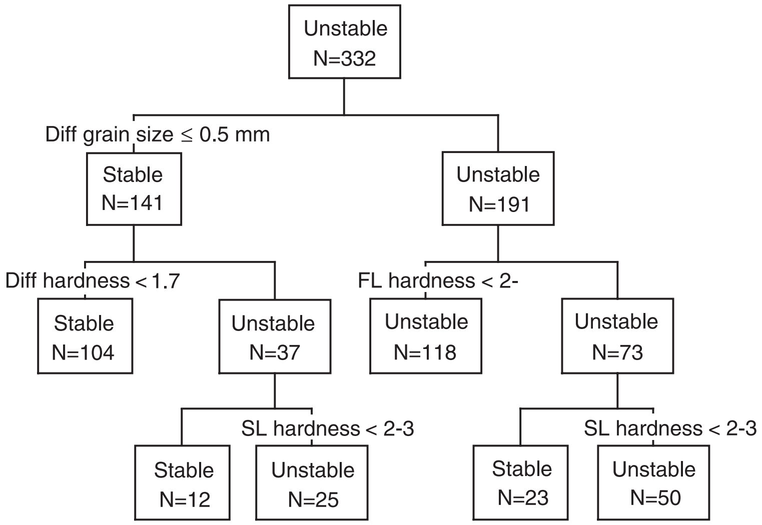

Fig. 3. Classification tree for combined stable/unstable data set ($N=332$). Classification accuracy was 74%. Data set does not contain rutschblock score as independent variable.

in grain size as the best separators, followed by failure layer grain size, failure layer hardness and slab hardness (Fig. 2). Only failure layer grain type was not used in the two trees as separating variable. The overall classification accuracy was 78%. However, as the same data were used to compute the tree and evaluate its classification accuracy, this value is too optimistic. If the rutschblock score is not used as independent variable, the classification accuracy decreases to 74%. In that case, difference in grain size and difference in hardness were the best separators followed by failure layer hardness and slab hardness (Fig. 3).

Table 3
Parameters of instability and proposed "unstable" ranges for snow profile classification for Swiss, Canadian and combined data sets. Variables listed in order of decreasing importance in classification methods

Parameter	Critical range		
	Swiss	Canadian	Combined
Rutschblock score	< 4	< 3.5	< 4
Difference in grain size (mm)	≥ 0.875	≥ 5	≥ 0.75
Failure layer grain size (mm)	≥ 1.5	–	≥ 1.25
Difference in hardness	≥ 2	≥ 1.7	≥ 1.7
Failure layer hardness	≤ 1.3 (F+)	< 1.7 (4F −)	≤ 1.3 (F+)

Finally, the classification tree method provided cut values that discriminate stable and unstable profiles for the five very highly significant variables. These cut values are given in Table 3 for the Swiss, the Canadian and the combined data set. With each variable, except with the failure layer grain size for the Canadian sample, a classification accuracy greater than 50% can be achieved.

5. Discussion

The different methods applied consistently reveal that that the following parameters are indicators of snow instability: soft slabs, large and persistent grains in a soft failure layer, large difference in grain size and hardness across the failure interface and low rutschblock scores. These variables all have a clear physical relation to dry snow slab avalanches triggered by skiers. Softer slabs increase the skier stress and strain at the depth of the failure layer. Large and persistent grains produce particularly weak failure layers due to poor bonding, and as hardness is related to bonding as well, low hardness of the failure layer also favours instability. A large difference in grain size across the failure layer indicates poor bonding between the layers. A large difference in hardness promotes stress/strain concentrations at the layer boundary. Finally, lower rutschblock scores are obviously related to higher triggering probability (Föhn, 1987).

6. Conclusions

Based on a large data set of stable and unstable profiles from Switzerland and Canada, we have shown that most stable and unstable profiles have distinct characteristics. For the first time, unstable ranges were identified for a few highly significant snowpack parameters that have a clear physical meaning. Some of these cut values (e.g. RB score <4) separating the stable from the unstable group coincide with well-established empirical rules that were so far lacking evidence. Classification methods were used to derive preliminary models to classify snow profiles. The models were not cross-validated yet, but the preliminary results suggest high potential for classification accuracy of about 65–70%. Classification without the RB score as independent variable was nearly as accurate as with the RB score. Accordingly, for the future, we propose to further develop these models into operational support tools for snow profile analysis.

Acknowledgements

This study would not have been possible without the fieldwork of numerous people in Switzerland and Canada, including Hans-Jürg Etter, Charles Fierz, Paul Föhn, Stephan Harvey, Roland Meister, Thomas Stucki, Thomas Wiesinger, Jill Hughes, Tom Chalmers, Ken Black, James Blench, Joe Filippone, Michelle Gagnon, Ryan Gallagher, Torsten Geldsetzer, Sue Gould, Crane Johnson, Greg Johnson, Alan Jones, Kalle Kronholm, Paul Langevin, Greg McAuley, Kyle Stewart and Adrian Wilson. Martina Lütschg and Elsbeth Kuriger entered the Swiss data in a database. In Canada, Mike Wiegele Helicopter Skiing, Canadian Mountain Holidays and Glacier National Park provided essential support for the field studies. The Canadian contribution to this study was funded by the BC Helicopter and Snowcat Skiing Operators Association, the Natural Sciences and Engineering Research Council of Canada, Intrawest, Canada West Ski Areas Association and the Canadian Avalanche Association.

References

Atkins, D., Williams, K., 2001. 50 years of avalanche deaths in the United States. Proceedings ISSW 2000, International Snow Science Workshop, Big Sky, Montana, USA, 1–6 October 2000. American Avalanche Association, P.O. Box 1032, Bozeman, MT 59771, USA, pp. 16–20.

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

CAA, 2002. Observation Guidelines and Recording Standards for Weather, Snowpack and Avalanches. Canadian Avalanche Association, Revelstoke, BC, Canada. 78 pp.

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

Ferguson, S.A., 1984. The role of snowpack structure in avalanching. PhD Thesis. University of Washington, Seattle, WA, USA. 150 pp.

Flury, B., Riedwyl, H., 1988. Multivariate Statistics: A Practical Approach. Chapman & Hall, London, UK. 296 pp.

Föhn, P.M.B., 1987. The Rutschblock as a practical tool for slope stability evaluation. IAHS Publ. 162, 223–228.

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

Jamieson, J.B., Geldsetzer, T., 1996. Avalanche Accidents in Canada, 1984–1996, vol. 4. Canadian Avalanche Association, Revelstoke, BC, Canada. 193 pp.

Jamieson, J.B., Johnston, C.D., 1995. Monitoring a shear frame stability index and skier-triggered slab avalanches involving persistent snowpack weaknesses. Proceedings ISSW 1994, International Snow Science Workshop, Snowbird, Utah, USA, 30 October–3 November 1994. ISSW '94, P.O. Box 49, Snowbird, UT 84092, USA, pp. 14–21.

Jamieson, J.B., Johnston, C.D., 2001. Evaluation of the shear frame test for weak snowpack layers. Ann. Glaciol. 32, 59–68.

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.

Sanders, D.H., 1995. Statistics: A First Course. McGraw-Hill, New York. 624 pp.

Schweizer, J., 2002. The Rutschblock test—procedure and application in Switzerland. The Avalanche Review 20 (5) 1, 14–15.

Schweizer, J., Jamieson, J.B., 2001. Snow cover properties for skier triggering of avalanches. Cold Reg. Sci. Technol. 33 (2–3), 207–221.

Schweizer, J., Lütschg, M., 2001. Characteristics of human-triggered avalanches. Cold Reg. Sci. Technol. 33 (2–3), 147–162.

Schweizer, J., Wiesinger, T., 2001. Snow profile interpretation for stability evaluation. Cold Reg. Sci. Technol. 33 (2–3), 188–189.

Spiegel, M.R., Stephens, L.J., 1999. Schaum's outline of theory and problems of statistics. Schaum's Outline Series. McGraw-Hill, New York. 538 pp.

Tschirky, F., Brabec, B., Kern, M., 2001. Avalanche rescue systems in Switzerland: experience and limitations. Proceedings ISSW 2000, International Snow Science Workshop, Big Sky, Montana, USA, 1–6 October 2000. American Avalanche Association, P.O. Box 1032, Bozeman, MT 59771, USA, pp. 369–376.