Available online at www.sciencedirect.com
ScienceDirect
Cold Regions Science and Technology 51 (2008) 112 – 121
cold regions science and technology
www.elsevier.com/locate/coldregions

Snowpack observations and fracture concepts for skier-triggering of dry-snow slab avalanches

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

[a] WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland
[b] SnowPit Technologies, Salt Lake City UT, USA
[c] Department of Civil Engineering, Department of Geology and Geophysics, University of Calgary, Calgary AB, Canada

Received 5 November 2006; accepted 28 April 2007

Abstract

Dry-snow slab avalanche release is generally believed to proceed in three stages: 1) initiation of a local failure (crack), 2) widespread fast propagation of that fracture beneath the slab, and 3) detachment of the slab from its margins. To date, most field stability tests primarily assess the strength of the weak layer and thus relate to the first stage of avalanche release — failure initiation. Field methods that comprehensively evaluate the second stage – fracture propagation – have remained elusive. In this paper, we explore evidence that field estimates of stability can be improved by integrating three elements: stability test score, fracture character or release type, and a simple index of structural stability (the stratigraphical threshold sum across the fracture interface). Using field data collected from skier-triggered avalanches and skier-tested slopes that did not release, we show that when these three elements fall into their respective critical ranges the accuracy of predicting the probability of a skier triggered avalanche is higher than when any one element is used alone. Further, we show through a qualitative analysis that these three elements fulfill, at least partially, the criteria for fracture initiation and propagation. As with any field stability method that relies on local snowpack data, the approach presented here is not intended to be used in isolation, but in conjunction with other measurements and observations that relate to the probability and consequences of avalanche release.

Keywords: Snow cover stratigraphy; Avalanche formation; Avalanche release; Skier triggering; Stability test; Snow stability evaluation; Avalanche forecasting; Fracture

1. Introduction

Dry snow slab avalanche release is ultimately a fracture process resulting in catastrophic failure of the sloping snow cover. Seen on the slope scale, a snow slab looses its shear support and slides downslope. Direct application of fracture mechanics to the snow avalanche problem is complicated by the fact that the snow cover is a layered material (Colbeck, 1991), the primary fracture is not in tension and that the fracture mechanical behavior of snow is best described as quasi-brittle which implies non-negligible size effects (Bažant et al., 2003). Only recently, fracture mechanical properties of snow have been measured and interpreted in view of the snow avalanche problem (McClung, 2007; Sigrist and Schweizer, 2007).

Shear (or mode II and III) fractures are not typical of homogeneous materials. Pure shear loading is rare, but usually mixed mode loading conditions prevail, so that cracks in brittle, isotropic, homogeneous materials grow

* Corresponding author. Tel.: +41 81 4170164; fax: +41 81 4170110.
E-mail address: schweizer@slf.ch (J. Schweizer).

0165-232X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.coldregions.2007.04.019

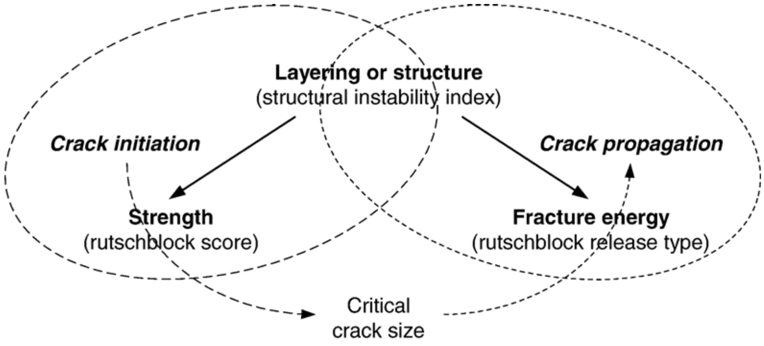

Fig. 1. Schematic display of the elements (structure or layering, strength and energy) believed to be essential for the fracture process and their corresponding proxies (structural instability index, rutschblock (RB) score, rutschblock release type).

in most cases by kinking in a direction such that the advancing tip is in mode I (Hutchinson and Suo, 1992). However, shear fractures under mixed mode loading conditions are common in heterogeneous, composite or layered materials where the interface presents a low-toughness fracture path through joined solids. The competition between crack advance within the interface and kinking out of the interface depends on the relative toughness of the interface to that of the adjoining material (Hutchinson and Suo, 1992).

The snow cover is a layered structure; one layer originating from a deposition process (e.g., precipitation or sublimation) is bonded to the layer below originating from the previous event. The stratified snowpack obviously offers opportunities for preferential interfacial crack growth, i.e. the crack is restricted to grow within a plane. Stiffness changes – as indicated by hardness changes – across layer boundaries act as stress concentrators so that cracks will preferentially grow on, or near, the interface between two layers of dissimilar stiffness.

If there is an avalanche prone structure (distinct differences in layer properties between layers), failure initiation and fracture propagation are required for a dry-snow slab avalanche to release. Failure initiation results from introducing a local failure, for example, when locally the strength of the weak layer or interface is overcome by the additional stress imparted by a skier or snowboarder while moving on the snow surface. Crack initiation, at least for localized dynamic loading due to skiers or explosives, is therefore related to critical stress or strength. If the local failure reaches a critical size, then fast fracture propagation will occur beneath the slab. Fracture mechanics tries to answer the question of how tolerant the snow is to that local flaw. The material property describing this flaw bearing capacity is called fracture toughness. In a material with a high fracture toughness, small cracks will generally not lead to catastrophic failure. We use fracture toughness in the general sense of resistance to propagation so that it also applies to the weak layer collapse model (Heierli, 2005; Heierli and Zaiser, 2006). Slope normal collapse is sometimes evident (van Herwijnen and Jamieson, 2005) but the failure mode at the scale of the snow microstructure is presently unclear. It is however clear that at the scale of the snow slope the slab slides down due to the loss of shear support, i.e. it appears to be a shear failure.

Snowpack observations for stability evaluation should ideally focus on the above mentioned essential

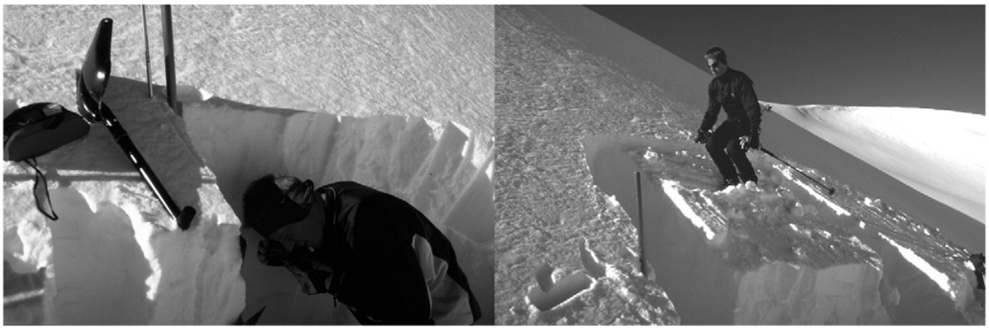

Fig. 2. Snowpack observations on skier-tested avalanche slope: snow profile (left) and adjacent snow stability test: rutschblock (right) that was performed subsequently.

Table 1
Critical ranges of variables to calculate the stratigraphical threshold sum

Variable	Critical range
Difference in grain size (mm)	≥ 0.75
Failure layer grain size (mm)	≥ 1.25
Difference in hardness	≥ 1.7
Failure layer hardness	≤ 1.3
Failure layer grain type	Persistent
Slab thickness or failure layer depth (cm)	18...94

elements (or ingredients): layering, crack initiation (strength) and fracture propagation (toughness) (McCammon and Sharaf, 2005) (Fig. 1). Not surprisingly, this is and has long been the standard procedure. A snow stability test following a snow profile provides evidence of all three elements. The stability test results include the location of potential failure layers, test scores and characteristics of the fracture, which are expressed as fracture character (van Herwijnen and Jamieson, 2002, 2007), release type (Schweizer and Wiesinger, 2001) or shear quality (Johnson and Birkeland, 2002). To evaluate whether the snowpack has the critical layering, structural instability indices based on threshold sums such as the lemons or yellow flags have recently been introduced (Jamieson and Schweizer, 2005; McCammon and Schweizer, 2002; Schweizer and Jamieson, 2007).

In this paper, we will relate three variables (field observations) to skier triggering probability. The variables thought to be predictors of snow slope stability are: 1) stratigraphical threshold sum (corresponding to the release element of layering), 2) the rutschblock (RB) score (corresponding to failure initiation) and 3) the rutschblock release type (corresponding to fracture propagation). The layering is expected to be of crucial importance for failure initiation (weak layer and slab properties) and fracture propagation (fracture path and slab properties). Results will be discussed in terms of snow slope stability evaluation with a particular view on the fracture process. We will analyze a dataset of more than 500 snow profiles with adjacent stability tests from the Swiss Alps and the Columbia Mountains of western Canada.

2. Data

Our data come from snow profiles completed with a stability test, usually a rutschblock test. Profiles were done on skier-tested slopes (no avalanche released) or on slopes where a recent skier-triggered slab avalanche occurred. For the sake of simplicity, we called these two categories "stable" (=skier-tested, i.e. not skier-triggered) and "unstable" (=skier-triggered), although we are aware that a single snowpack observation may not represent slope stability, and that under so-called "stable" conditions similar slopes (in particular those with unsupported slabs) may have had the potential to avalanche as a result of skier triggering. The stable cases did include a few profiles from slopes with poor stability, sometimes even whumpfs and shooting cracks were recorded on the same day as the so-called stable profile was taken. However, as the slope was skier-tested and did not release an avalanche, these cases were classified as stable. There were no relevant differences in site characteristics (such as elevation, aspect and slope angle) between stable and unstable cases (Schweizer and Jamieson, 2003), for example, the median slope angle was 35° for the profiles from skier-tested (not triggered) slopes and 37° for profiles from skier-triggered slopes.

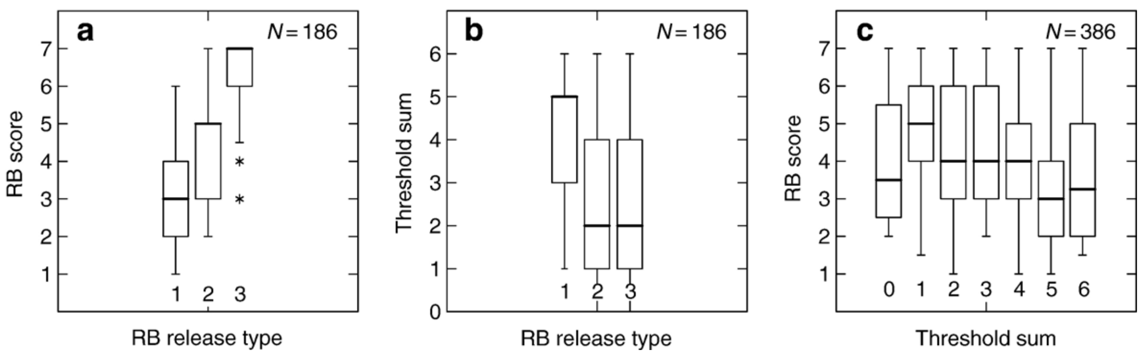

Fig. 3. Distribution of (a) RB score and (b) stratigraphical threshold sum with RB release type (1: whole block, 2: part of the block, 3: edge only), and (c) distribution of RB score with stratigraphical threshold sum. Boxes span the interquartile range from 1st to 3rd quartile with a horizontal line showing the median. 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.

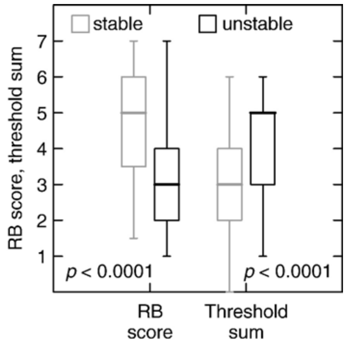

Fig. 4. Distributions of rutschblock (RB) score ($N=459$) and threshold sum ($N=428$) for the skier-tested ("stable") (left) and skier-triggered ("unstable") (right) samples (same figure type as shown in Fig. 3).

Overall, the dataset included 512 cases (228 from Canada, 284 from Switzerland) and was almost balanced in terms of skier-triggered (258 cases) vs. skier-tested cases (254 cases). The data were collected during the last 17 winters (1988–1989 to 2005–2006). As the release type was recorded routinely only in the more recent winters (but occasionally since the early 1990s), there were only 184 cases that included RB score, RB release type and complete structural information for calculating the stratigraphical threshold sum.

Alternatively, instead of using the stable/unstable categories, profiles – regardless whether from skier-tested or skier-triggered slopes – were classified into "poor", "fair" and "good" stability following the scheme proposed by Schweizer and Wiesinger (2001). This type of stability rating was available only for the profiles from Switzerland ($N=168$).

3. Methods

Standard methods were applied for snowpack observations (e.g., CAA, 2002). In most cases, rutschblock tests were performed along with a snow profile (Fig. 2). Not only the rutschblock score but also the release type was recorded: "whole block", "part of the block", "edge only" (Schweizer, 2002). To take into account the structural instability, we calculated the stratigraphical threshold sum using six unweighted variables: difference in grain size, failure layer grain size, difference in hardness, failure layer hardness, failure layer grain type and slab thickness (or failure layer depth). We used the same threshold values (or critical ranges) as described by Schweizer and Jamieson (2007) (Table 1).

To evaluate the performance of predictors, various categorical statistics (skill scores) were used (Wilks, 1995). The scores were described in Schweizer and Jamieson (2007) with the exception of the threat score (also called critical success index) that measures the fraction of observed and/or forecast events that were correctly predicted. In the notation typically used in contingency tables (see, e.g., Schweizer and Jamieson, 2007) it is defined as: TS = hits/(misses + false alarms + hits).

When comparing variables from the stable/unstable cases, the non-parametric Mann–Whitney *U*-Test was used — except for categorical data such as release type, which were cross-tabulated and a Yates' corrected Pearson χ^2 statistic was calculated. A level of significance $p=0.05$ was chosen to decide whether the observed differences were statistically significant. Split values between two categories were determined with the classification tree method (Breiman et al., 1998). To check for correlations between variables Spearman rank-order correlation coefficients were calculated.

4. Results

4.1. Predictor variables

The three predictor variables RB score, RB release type and stratigraphical threshold sum were all highly correlated ($p<0.001$) with each other. For whole block releases, lower RB scores and higher threshold sums were found than for rutschblocks where only an edge was triggered (Fig. 3). The RB score decreased with increasing stratigraphical threshold sum.

The RB score as well as the threshold sum slightly increased with increasing failure layer depth ($p<0.001$ and $p=0.009$, respectively). Slab thickness was lowest for the RB release type "part of the block" (median: 37 cm), and very similar for "whole block" (48 cm) and "edge only" (52 cm).

4.2. Univariate analysis

Fig. 4 and Table 2 show how well the three predictors RB score, RB release type and stratigraphical threshold

Table 2
Frequency of release type with snowpack stability ($N=188$)

Release type	Snowpack		Total
	Skier-tested: "stable"	Skier-triggered: "unstable"	
Whole block	42	51	93
Part of the block	50	9	59
Edge only	33	3	36
Total	125	63	188

Table 3
Univariate classification results

Variable or classifier	N (stable/unstable)	Critical range or threshold	Accuracy (%)	Probability of detection (%)	False alarm ratio (%)	True skill score (%)	Threat score (%)	False-stable predictions (%)
RB score	459 (255/204)	<4	68	61	35	35	46	30
RB release type	189 (125/63)	Whole block	71	81	45	47	49	13
Threshold sum	416 (204/212)	≥4	66	74	36	33	53	31

sum discriminate between so-called stable (skier-tested) and unstable (skier-triggered) cases. All three classifiers are highly significant variables (non-parametric *U*-test, level of significance $p<0.001$).

Their classification accuracy (not cross-validated) varied between 71% for the RB release type to 66% for the threshold sum (Table 3). For the RB score, values <4 indicated rather unstable, values ≥4 rather stable conditions. For the threshold sum, the critical range (rather unstable) included the values of 4, 5 and 6. However, when the threshold sum was 4, 48% of the cases in the database were rather stable, 52% were rather unstable. Only the release type "whole block" indicated rather unstable conditions, whereas the other two types were clearly more frequently found with rather stable conditions. The RB release type was the best classifier in terms of the true skill score (47%). It had the highest probability of detection (81%) and the lowest portion of false-stable predictions (13%).

4.3. Multivariate analysis

4.3.1. Classification tree

A multivariate analysis using the classification tree method included all three variables with the threshold sum as first node (<5 stable), and the RB score and RB release type as second and third node to improve the classification of the rather unstable cases (Fig. 5). Fig. 5 shows that a RB score <4 was an indicator of rather unstable conditions only, if the block released as a whole. Low RB scores (≤3) with partial release were considered as less critical and assigned to the stable category.

The overall classification accuracy was 83% and the true skill score was 51%, but due to the unbalanced dataset (124 stable cases vs. only 60 unstable cases) the classification accuracy for the unstable cases was fairly poor. The probability of detection was 53%, hence 47% of the unstable cases were not recognized, and 19% of the cases predicted to be rather stable were in fact

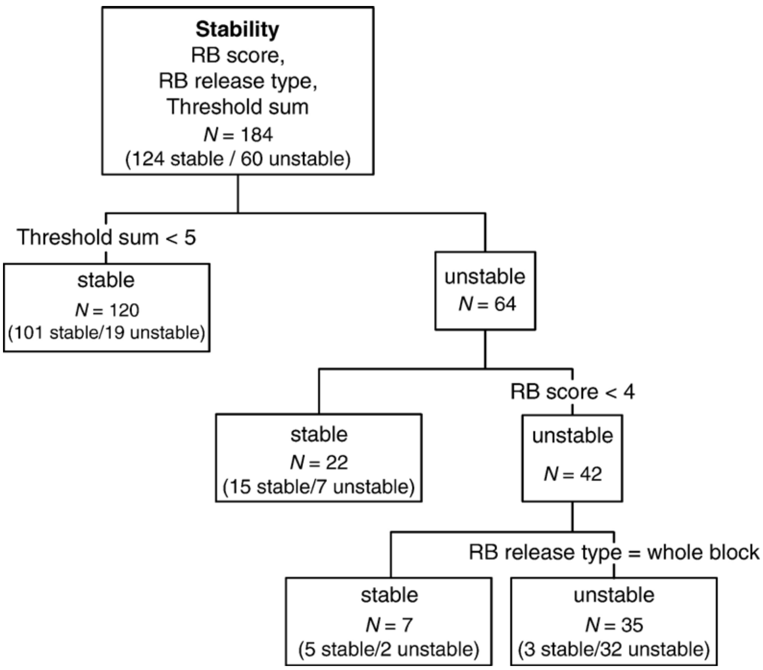

Fig. 5. Classification tree ($N=184$). Snow profiles were classified into rather stable (skier-tested) or rather unstable (skier-triggered) cases based on RB score, RB release type and stratigraphical threshold sum. Classification accuracy was 83%.

Table 4
Frequency of skier-tested ("stable") and skier-triggered ("unstable") cases depending on the value of the three variables RB score, RB release type and threshold sum

Variables (critical range)			Total number of variables in critical range	Observation	
RB score (<4)	RB release type (whole block)	Threshold sum (≥5)		Skier-tested: "stable"	Skier-triggered: "unstable"
No	No	No	0	59 (**97%**)	2 (3%)
No	No	Yes	1	6 (60%)	4 (40%)
No	Yes	No	1	15 (**79%**)	4 (21%)
Yes	No	No	1	12 (**80%**)	3 (20%)
Yes	No	Yes	2	5 (**71%**)	2 (29%)
No	Yes	Yes	2	9 (**75%**)	3 (25%)
Yes	Yes	No	2	15 (60%)	10 (40%)
Yes	Yes	Yes	3	3 (9%)	32 (**91%**)

The values of yes or no indicate whether the variables' values were in the critical range. Bold indicates a clear majority of either stable or unstable cases.

unstable cases. The 10-fold cross-validated accuracy was 82±3%. Due to the fact that the data set was unbalanced, the 10-fold cross-validated unweighted average accuracy was lower: 77±2%.

As the dataset was unbalanced, we ran a series of ten classification tree analyses where we randomly chose about half of the stable cases for each analysis. This resulted in fairly different classification trees. On one hand, the number of splits varied (3 trees with one split, 6 trees with two splits and 1 tree with three splits). On the other hand, the variable at the first split varied and was in seven cases the RB score, in two cases the threshold sum, and in one case the RB release type. Overall, the threshold sum appeared 8 times, the RB score 6 times and the release type 3 times as a split variable. The split values consistently were <4 for the RB score, ≥5 for the threshold sum, and "whole block" for the release type. The mean classification accuracy of the ten trees was 78±1%. Still the stable cases were better classified (87%) than the unstable cases (68%).

4.3.2. Simple point score

Instead of a classification tree analysis, a simple point score (checklist) approach was applied for the three predictors RB score, RB release type and stratigraphical threshold sum. The critical ranges used were those obtained with the classification tree analysis: RB score<4, threshold sum≥5, RB release type=whole block. The results of the point score classification are shown in Table 4. Only if all three variables are in the critical range (bottom row of Table 4) were most of the unstable cases recognized. At the other end, zero or one variable in the critical range (top four rows in Table 4), the majority of the cases were clearly rather stable (88%). However, when only the stratigraphical threshold sum was in the critical range, there was a substantial portion of unstable cases. With two out of the three variables in the critical range, the majority of the cases (66%) were still rather stable.

In the classification tree above (Fig. 5) only the bottom row in Table 4 was selected for the unstable category. For a classification model with the bottom two rows indicating rather unstable conditions, the overall classification accuracy slightly decreased to 80%, but the true skill score increased to 56%, whereas the proportion of false-stable predictions decreased by about a quarter to 15% compared to the classification tree model (Fig. 5, Table 5).

Alternatively, as the RB release type seems to be the best single classifier (Table 3), the bottom three rows in Table 4 can be chosen to describe rather unstable conditions. This corresponds to the situation when the RB release type and at least one of the other two predictors were in their critical range. The accuracy was 77% and the true skill score was about 53% (Table 5).

With an even more conservative approach that included all cases with either two or three variables in their critical range, the number of false-stable prediction slightly decreased (12%), but all other classification scores become worse except the hit rate (or POD) (Table 5).

4.3.3. Alternative stability classification

As there was important uncertainty in regard to the classification into stable and unstable cases, we also

Table 5
Multivariate classification scores for various models

Model	Accuracy (%)	Probability of detection (%)	False alarm ratio (%)	True skill score (%)	Threat score (%)	False-stable predictions (%)
Classification tree (Fig. 5)	83	53	9	51	51	19
Bottom two rows (Table 4)	80	70	30	56	54	15
Bottom three rows (Table 4)	77	75	38	53	52	13
0 or 1 vs. 2 or 3	76	78	41	53	51	12

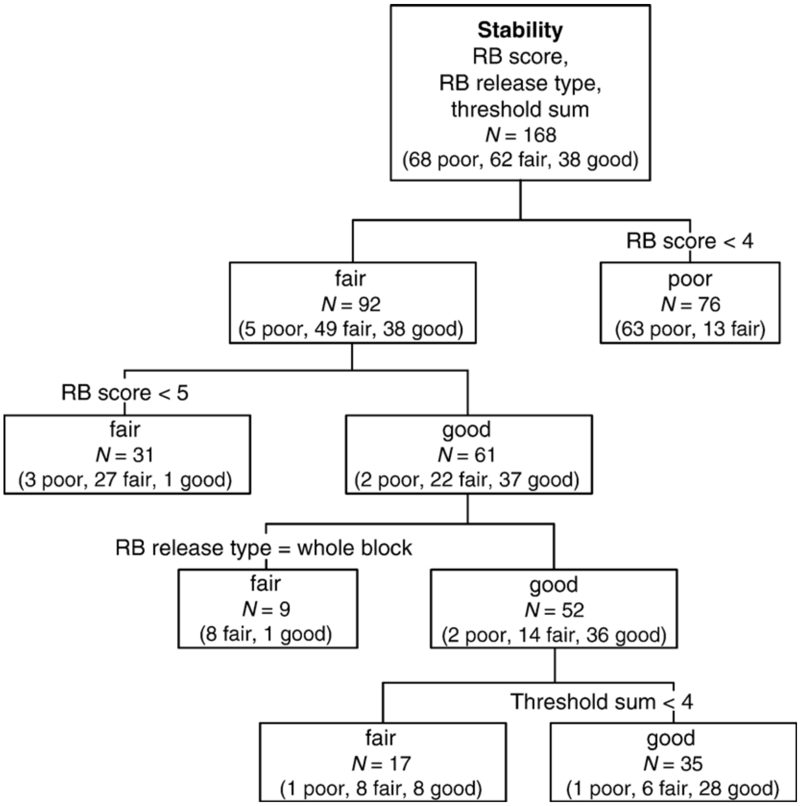

Fig. 6. Classification tree (N=168). Snow profiles were classified into poor, fair, and good stability based on RB score, RB release type and stratigraphical threshold sum. Classification accuracy was 80%.

used the three-class stability rating (poor, fair and good) as alternative response variable.

Using again the RB score, the RB release type and the stratigraphical threshold sum as independent predictor variables, the classification tree and its split values (Fig. 6) was very similar to the previous one shown in Fig. 5. The not cross-validated accuracy was about 80%. In about 14% of the cases the stability was underestimated (observed stability>predicted stability), and in the remaining about 6% of the cases overestimated.

Again, also the simple point score, i.e. the number of predictors in the critical range was considered. Based on Table 6 a simple classification can be proposed relating the number of predictors in the critical range to snowpack stability. For example, with 2 or 3 predictors in the critical range rather poor stability is expected, whereas with none of the predictors in the critical range, rather good stability can be expected.

5. Discussion

We analyzed three snowpack observation variables: the RB score, the RB release type and the stratigraphical threshold sum in regard to their classification power to distinguish between cases where a slope had been skier triggered and cases where it had not.

The RB release type proved to be the best single predictor of snow slope stability — it is also the simplest observation and does not require special experience. This result is in agreement with, for example, findings of Schweizer et al. (2003b) and an analysis by van Herwijnen and Jamieson (2007) who showed that the

Table 6
Frequency of the three level stability rating (poor, fair, good) in regard to the simple point score, i.e. the number of predictors (RB score, RB release type, stratigraphical threshold sum) in the critical range

Predictors in critical range	Observed stability			Total
	Good	Fair	Poor	
0	**34**	20	1	55
1	4	**30**	7	41
2	0	11	**29**	40
3	0	1	**31**	32
Total	38	62	68	168

Values given in bold indicate a clear majority and suggest a possible simplified classification.

fracture character in a compression test, which can be considered as analogous to the RB release type, related well to the probability of skier triggering. The release of the whole block seems to be a clear indication of instability. It has previously been proposed that the RB release type might be indicative of the fracture propagation propensity (Schweizer, 2002). The argument is based on theoretical and experimental results on the size of the local failure that is critical for rapid fracture propagation. Best estimates indicate that the critical size is on the order of about 0.1 m–1 m, i.e. on the order of the slab thickness (Bažant et al., 2003; Schweizer et al., 2003a, 2004). Therefore, fracture propagation has to occur in order for the whole area (3 m^2) of the weak layer under a rutschblock to fracture. In cases where the rutschblock released only below the skis, i.e. the fracture did not propagate uphill, the slab thickness was below average (37 cm) indicating that this release type is more frequently found with new snow instabilities (low RB score but a shallow and not yet well-consolidated slab). The failure often seems to occur by merely pushing the snow below the skis downslope rather than initiating a propagating fracture in the weak layer.

The character (roughness) of the fracture surface (clean vs. rough/irregular) (Schweizer and Wiesinger, 2001) that is considered as a measure of energy dissipation during fracture propagation, was not correlated to snow slope stability. It did not discriminate between rather stable/unstable cases ($N=219$, $p=0.08$; true skill score: 10%). Although rough or irregular interfaces are more common with rather stable conditions, most fractures were clean for both stable and unstable cases.

The RB score and the threshold sum were only slightly weaker predictors than the RB release type. The RB score had a relatively low probability of detection (or hit rate), i.e. a substantial number of blocks with low score were observed on slopes where no slab was released. This result might be due to targeted sampling (i.e. experienced observers seeking instability) (McClung, 2002). In fact, the stability of almost 20% of these so-called stable profiles was rated as poor (Schweizer and Wiesinger, 2001) and occasionally even whumpfs and shooting cracks were observed nearby on the day of observation. Accordingly, there is some important uncertainty in their classification as so-called stable cases (i.e. not skier-triggered).

The RB score as well as the threshold sum had an intermediate range (RB score: 4, stratigraphical threshold sum: 4) where neither stable nor unstable cases were clearly dominating. This ambiguity can be accommodated in practice by introducing an intermediate range of extra caution in exposure to avalanche terrain at these values.

Given the above mentioned uncertainty, we have considered the three-class stability rating (poor, fair, good). This stability classification is, however, not completely independent from the predictor variables. In particular, the RB score is an important element in the qualitative classification scheme by Schweizer and Wiesinger (2001). The very similar results obtained with the three-class stability classification (Fig. 6, Table 6) compared to the stable/unstable classification indicates that the findings on the latter classification (for which predictor and response variables are truly independent) are fairly robust despite the uncertainty mentioned above. Furthermore, the results obtained with the three-class stability rating suggest a simple way of assessing snowpack stability based on the value of the three predictor variables.

It has been previously shown that both the RB score (e.g., Jamieson, 1995) and the threshold sum (Schweizer and Jamieson, 2007) are related to the probability of skier triggering. The rutschblock most closely integrates the fracture process; it combines all essential elements (layering, crack initiation and fracture propagation) and can be considered as class I data (McClung and Schaerer, 2006, pp. 167–168). In contrast, the threshold sum is secondary to the fracture process, and is more accurately considered class II data. However, the rutschblock test score is more affected by spatial variability than the other two predictors (Schweizer et al., 2008-this issue). Also, site selection is crucial and requires considerable expertise (targeted sampling). Table 7 compiles relevant properties of the three predictors.

The univariate classification results (Table 3) suggest that the classification power of the three variables was fairly similar, that they were correlated (and hence included redundant information) (see Fig. 3) and that a

Table 7
Properties of predictor variables in regard to fracture process and spatial variability

Predictor	Relevance to essential elements in the fracture process			Susceptibility to spatial variability
	Layering	Strength (crack initiation)	Toughness (fracture propagation)	
RB score	High	High	Low	High
RB release type	High	Low	High	Low
Threshold sum	High	Moderate	Moderate	Low

combination of the three variables might therefore only slightly increase the classification accuracy.

However, combining the predictors improved the overall accuracy by 10–15% and the true skill score (which describes how well a predictor can differentiate between the categories) relatively increased by about 30–40% to values above 50%. Combining any two of the three variables resulted in only marginally lower scores. This means that the method is fairly robust and if one of the predictors is missing, e.g. if not observed, the probability of a correct interpretation is lessened but still possible.

6. Conclusions

In conclusion, the three predictors rutschblock (RB) score, release type and stratigraphical threshold sum at sites selected by experts on or adjacent to avalanche slopes proved to be all highly significant variables in classifying cases as skier-triggered or skier-tested (i.e. not triggered) and hence are suggested to be indicative of snow slope stability. This result follows from the fact that these variables appear closely related to the three elements that are thought to influence the fracture process: layering, strength and weak layer toughness.

The most robust predictor of skier triggering is the rutschblock release type: a whole block release is a fairly unambiguous indication of instability. We expect that similar results would be obtained with fracture character or shear quality. Nevertheless, combining the predictors of threshold sum and RB score with RB release type appears to provide a more robust estimate of stability, even in the presence of spatial variability.

Practical application of these results would proceed as follows:

- Rather stable conditions can be expected when none of the predictors is in its critical range (RB score: ≥ 4, RB release type: not whole block, stratigraphical threshold sum <5). These conditions might roughly correspond to generally good stability.
- Intermediate conditions can be expected when one of the predictors is in its critical range. These conditions might roughly correspond to generally fair stability.
- Unstable conditions can be expected when at least two of the three predictors are in their critical range (RB score:<4, RB release type = whole block, stratigraphical threshold sum ≥ 5). These conditions might roughly correspond to generally poor stability.

As always snow slope stability evaluation should never rely on a single snowpack observation. We recognize that snowpack observations are only one way to seek snowpack instability, represent just one element (among many others) in the stability evaluation process and include substantial uncertainty (mostly due to the variable nature of the snowpack). The above rating scheme is preliminary, and is intended as an aid towards more objective snow profile interpretation. Future work will be essential in characterizing the uncertainties inherent in such schemes.

As the three predictors variables RB score, RB release type and stratigraphical threshold sum correlated with avalanching, they are related to the fracture process and can be considered as proxies for failure initiation, fracture propagation and fracture path. The rutschblock release type was not only the single best predictor it is also the one that is most closely related to the fracture process — independent of the type of propagation.

Acknowledgements

We thank numerous colleagues and staff members for contributing snowpack data. For support, Bruce Jamieson is grateful to the Natural Sciences and Engineering Research Council of Canada, Helicat Canada, Canadian Avalanche Association, Mike Wiegele Helicopter Skiing, Canada West Ski Area Association and Parks Canada.

We are grateful for the comments by two anonymous reviewers and by the Editor Garry Timco.

References

Bažant, Z.P., Zi, G., McClung, D., 2003. Size effect law and fracture mechanics of the triggering of dry snow slab avalanches. J. Geophys. Res. 108 (B2), 2119. doi:10.1029/2002JB001884.

Breiman, L., Friedman, J.H., Olshen, R.A., Stone, C.J., 1998. Classification and Regression Trees. CRC Press, Boca Raton, U.S.A 368 pp.

CAA, 2002. Observation guidelines and recording standards for weather, snowpack and avalanches. Canadian Avalanche Association (CAA), Revelstoke BC, Canada 78 pp.

Colbeck, S.C., 1991. The layered character of snow covers. Rev. Geophys. 29 (1), 81–96.

Heierli, J., 2005. Solitary fracture waves in metastable snow stratifications. J. Geophys. Res. 110 (F2), F02008. doi:10.1029/2004JF000178.

Heierli, J., Zaiser, M., 2006. An analytical model for fracture nucleation in collapsible stratifications. Geophys. Res. Lett. 33, L06501. doi:10.1029/2005GL025311.

Hutchinson, J.W., Suo, Z., 1992. Mixed-mode cracking in layered materials. In: Hutchinson, J.W., Wu, T.Y. (Eds.), Advances in Applied Mechanics. Advances in Applied Mechanics, vol. 29. Academic Press, London, pp. 63–191.

Jamieson, J.B., 1995. Avalanche prediction for persistent snow slabs. PhD Thesis, University of Calgary, Calgary AB, Canada, 258 pp.

Jamieson, J.B., Schweizer, J., 2005. Using a checklist to assess manual snow profiles. Avalanche News 72, 57–61.
Johnson, R.F., Birkeland, K.W., 2002. Integrating shear quality into stability test results. In: Stevens, J.R. (Ed.), Proceedings ISSW 2002, International Snow Science Workshop, Penticton BC, Canada, 29 September–4 October 2002. International Snow Science Workshop Canada Inc., BC Ministry of Transportation, Snow Avalanche Programs, Victoria BC, Canada, pp. 508–513.
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. International Snow Science Workshop Canada Inc., BC Ministry of Transportation, Snow Avalanche Programs, Victoria BC, Canada, pp. 477–481.
McCammon, I., Sharaf, D., 2005. Integrating strength, energy and structure into stability decisions: so you dig a pit and then what? Avalanche Rev. 23 (3), 18–19.
McClung, D.M., 2002. The elements of applied forecasting — part I: the human issues. Nat. Hazards 26 (2), 111–129.
McClung, D.M., 2007. Fracture energy applicable to dry snow slab avalanche release. Geophys. Res. Lett. 34, L02503. doi:10.1029/2006GL028238.
McClung, D.M., Schaerer, P., 2006. The Avalanche Handbook, 3rd ed. The Mountaineers, Seattle, Washington, U.S.A. 342 pp.
Schweizer, J., 2002. The Rutschblock test — procedure and application in Switzerland. Avalanche Rev. 20 (5), 14–15 (1).
Schweizer, J., Jamieson, J.B., 2003. Snowpack properties for snow profile analysis. Cold Reg. Sci. Technol. 37 (3), 233–241.
Schweizer, J., Jamieson, J.B., 2007. A threshold sum approach to stability evaluation of manual snow profiles. Cold Reg. Sci. Technol. 47 (1–2), 50–59.
Schweizer, J., Wiesinger, T., 2001. Snow profile interpretation for stability evaluation. Cold Reg. Sci. Technol. 33 (2–3), 179–188.
Schweizer, J., Jamieson, J.B., Schneebeli, M., 2003a. Snow avalanche formation. Rev. Geophys. 41 (4), 1016. doi:10.1029/2002RG000123.
Schweizer, J., Kronholm, K., Wiesinger, T., 2003b. Verification of regional snowpack stability and avalanche danger. Cold Reg. Sci. Technol. 37 (3), 277–288.
Schweizer, J., Michot, G., Kirchner, H.O.K., 2004. On the fracture toughness of snow. Ann. Glaciol. 38, 1–8.
Schweizer, J., Kronholm, K., Jamieson, J.B., Birkeland, K.W., 2008. Review of spatial variability of snowpack properties and its importance for avalanche formation. Cold Reg. Sci. Technol. 51, 253–272 (this issue). doi:10.1016/j.coldregions.2007.04.009.
Sigrist, C., Schweizer, J., 2007. Critical energy release rates of weak snowpack layers determined in field experiments. Geophys. Res. Lett. 34 (3), L03502. doi:10.1029/2006GL028576.
van Herwijnen, A., Jamieson, J.B., 2002. Interpreting fracture character in stability tests. Proceedings ISSW 2002. International Snow Science Workshop, Penticton BC, Canada, pp. 514–522. 29 September–4 October.
van Herwijnen, A., Jamieson, J.B., 2005. High-speed photography of fractures in weak snowpack layers. Cold Reg. Sci. Technol. 43 (1–2), 71–82.
van Herwijnen, A., Jamieson, J.B., 2007. Fracture character in compression tests. Cold Reg. Sci. Technol. 47 (1–2), 60–68.
Wilks, D.S., 1995. Statistical methods in the atmospheric sciences: an introduction. International Geophysics, vol. 59. Academic Press, San Diego CA, U.S.A 467 pp.