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Snow stability variation on small slopes

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Abstract

The spatial variability of snowpack mechanical properties strongly influences the fracture initiation and fracture propagation properties of the snowpack, thereby largely controlling the avalanche formation process. To investigate variations in stability on the slope scale, we measured stability with stuffblock and rammrutsch tests on eight small potential avalanche slopes above timberline near Davos, Switzerland. On each slope, 17–26 point stability tests arranged in predefined arrays were done. The median, the spread and the spatial structure of the stability was investigated for 16 weak layers. Significant slope scale trends in stability were found in six weak layers. The quartile coefficient of variation for the drop heights was around 40% overall, 20% if the slope scale linear trend was removed. Auto-correlation in drop height was found in eight layers. In none of these layers a range of spatial auto-correlation could be determined. Depth of the fracture layer partly explained variations in stability. A stability rating scheme based on the median, the spread and the spatial structure of stability test results predicted the layers that were most critical for slope stability.

Keywords: Snow stability; Snow stratigraphy; Stability tests; Avalanche formation; Spatial variability

1. Introduction

Spatial variability is an inherent property of the snowpack, in particular above the tree line. The natural release of dry snow slab avalanches starts from imperfections in the snowpack, i.e. from areas of lower than average stability in a weak layer (Schweizer, 1999). Spatial variability of the snowpack is therefore one of the key factors in avalanche formation. The critical size for self-propagating fractures is estimated to be of the order of 0.1–10 m (McClung and Schweizer, 1999). Areas of below critical stability (deficit zones) are transient phenomena. They are supposed to form during the failure process and if the slab is not released, considered to disappear within minutes or hours due to sintering (Schweizer, 1999). With such limited spatial and temporal extent it is hard to verify the existence of such areas in the field. However, since deficit areas likely form in areas of lower than average stability, the study of spatial variability of snowpack stability is nevertheless highly relevant. Some field studies have shown the existence of large variation in stability over short distances (Conway and Abrahamson, 1984, 1988; Landry, 2002). Other studies conclude that the variation in stability is no larger than the variation in other snowpack variables (Föhn, 1989; Jamieson, 1995). These contrasting conclusions could however be due to different measurement methods and interpretation of results.

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From previous studies it is not possible to draw final conclusions regarding the type and size of stability variation or the scale of stability patterns on small slopes. To examine the effect of spatial variability on avalanche formation, conclusive measurements are therefore needed. As multidimensional models of stress and strain rates in a layered snowpack are starting to appear (Stoffel and Bartelt, in press), such measurements can also be used to specify input parameters for the models or to verify the model results.

The aim of the investigations presented here was to describe the spatial variability of snow stability on potential avalanche slopes. For this purpose we used small stability tests (30 × 30 cm) to investigate point stability over an 18 × 18 m area on potential avalanche slopes. From the results we derived consequences for avalanche formation based on a stability evaluation scheme which used the average stability, the spread of the stability, and the scale of spatial patterns of strong and weak areas on the slope to predict the slope stability for rapid near surface loading. The ultimate goal is to find characteristic spatial patterns (e.g. for a certain type of weak layer) that can be predicted based on meteorological conditions and hence included in regional avalanche forecasts.

2. Methods

2.1. Field site

During the winter 2001–2002 measurements were done in a 2 × 2 km study area north–west of Davos, Switzerland. The area was not heavily disturbed by skiers and the access was safe, easy and fast. The area is located on a major ridge with elevations between 2350 and 2650 m a.s.l. Surrounding peaks reach 2700 m a.s.l. The terrain is above the timberline, which in the region is at around 2000 m a.s.l.

2.2. Slope selection

Selection of the slopes was done in the field. The slopes were typical avalanche slopes in terms of aspect and slope angle. However, due to safety considerations the selected slopes were rather short, typically about 30 m high, and might therefore only represent the smaller avalanche slopes in the area. Most sampled slopes had a northern aspect because north-facing slopes generally were more unstable than south-facing slopes in the study area.

2.3. Stability tests

On each slope a series of stability tests was done in a predefined array. In the first three arrays we used the stuffblock test (Birkeland and Johnson, 1996). In the last five arrays we used a modified version of the rammrutsch test (Schweizer et al., 1995). Only rammrutsch tests were intended for the study but before the rammrutsch equipment was finished the first three arrays had been completed. Both tests progressively load an isolated 30 × 30 cm column of snow until fracture. For the stuffblock test we used a 4.5-kg drop weight with drop heights increasing in 10-cm intervals. For the rammrutsch test a 1-kg weight was dropped from heights increasing in 5-cm intervals. For each column we recorded the snow depth, the height of the isolated column and the slope angle.

Most tested columns produced multiple fractures. After a fracture, or when the top of the column was uneven or soft, it was cut off and leveled with a shovel. It was attempted to keep the amount cut from the top of the columns constant within each array. For each fracture the following was recorded:

- Depth of the fracture below snow surface.
- Drop height of the drop weight.
- Average thickness of snow between fracture and top of column at the time of fracture.
- Compressive deformation of the snow below the shovel or plate at the drop leading to fracture—for the rammrutsch test the deformation was hard to judge and thus not always recorded.
- Type of the fracture, adapted from Jamieson (1999).
- Location of fracture layer in the manual profile—this was not always possible as the snow stratigraphy was not always the same at the location of a stability test and at the location of the manual profile.

Measurement errors were introduced mainly through (a) the isolation procedure of the column, (b) imprecise dropping of the weight from large heights in the stuffblock test and (c) leveling off the column to different heights after each fracture. To reduce errors one person supervised or carried out all tests in each array. The magnitude of the error is discussed below.

A side by side trial of the two types of stability tests showed that the median of the drop height values happen to be of the same order and that the spread of the two tests was comparable. Results from the two tests can therefore be considered together to study stability patterns. The use of the tests to study stability assumes that the drop height associated with a fracture in a weak layer is a measure of stability of that layer.

Within each array several other measurements were done: A manual profile including ram hardness, a rutschblock test, and penetrometer profiles with the SnowMicroPen (Schneebeli et al., 1999). Snow samples and macro photographs of snow crystals were taken and meteorological parameters recorded.

2.4. Spatial arrangement of stability tests

On each slope, the stability tests were placed in a predefined cross-like array (Fig. 1) covering 18 × 18 m. The array was designed to cover most of the small

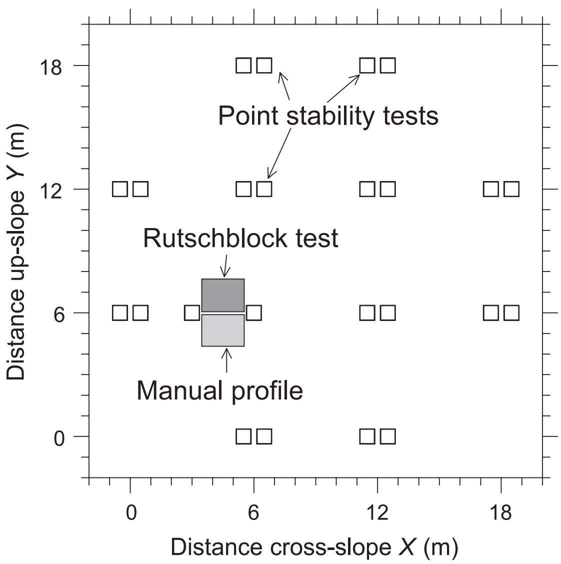

Fig. 1. Locations of the stability tests and the manual profile in the arrays. The distance between pairs of adjacent point stability tests was approximately 1 m.

slopes selected for our measurements, and to reveal variability at various scales. The maximum number of repeated stability tests that could be done in a day also had to be taken into consideration. Due to our other measurements this number was limited to 24. The stability tests were placed in pairs approximately 1 m apart in the same pit to study the small scale spatial variability, here called the “pit-scale”. To resolve the larger scale variability, here called the “slope-scale”, the distance between each pair was 6 m. One exception was around coordinate (6, 6) where stability tests were placed on either side of a rutschblock test, about 2.5 m apart.

2.5. Data analysis

Within each array we selected a number of layers for analysis. The selected layers are called array-layers. Each array-layer repeatedly produced fractures in the point stability tests. For each selected array-layer we analyzed the drop height needed to produce a fracture, DH. Since the drop heights for most of the analyzed array-layers did not follow a Gaussian normal distribution we used non-parametric statistics to analyze the data. The median was used to represent the center of our data. The absolute spread of the drop heights within each array-layer was represented by the semi-interquartile range Q:

$$Q = 1/2(Q_3 - Q_1) \tag{1}$$

where Q_1 is the first quartile and Q_3 is the third quartile. For the relative spread of the drop heights we used the quartile coefficient of variation V_Q (Spiegel and Stephens, 1999) given by

$$V_Q = \frac{Q_3 - Q_1}{Q_3 + Q_1} \tag{2}$$

The measured drop heights DH in each array-layer were split into a linear spatial trend, DH_{trend} and the residuals, DH_{res} such that

$$DH = DH_{trend} + DH_{res} \tag{3}$$

The linear spatial trend in drop heights was described by the best least square plane through the drop heights. The parameters were calculated with a multiple linear least square regression on the measured drop heights, DH, and the local coordinates X and Y:

$$DH_{\mathrm{lin}} = \alpha X + \beta Y + c \tag{4}$$

where α and β are the regression coefficients for the X and Y coordinates, respectively, and c is a constant. The regression residuals DH_{res} were treated as being randomly fluctuating around the fitted plane. Further, the dependence of the measured drop heights DH on the fracture depth FD and the slope angle ψ was determined with a multiple linear regression.

Spatial structure in the drop height values was investigated with experimental semi-variograms for the regression residuals DH_{res} (Webster and Oliver, 2001). If auto-correlation existed between drop height residuals we wanted to determine the largest distance of the auto-correlation, known as the range. Semi-variograms were produced for each of the analyzed array-layers by calculating the semi-variance γ of DH_{res} as a function of the lag distance h between locations i and j:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{(i,j)|h_{ij}=h} [(DH_{\mathrm{res},i} - DH_{\mathrm{res},j})^2] \tag{5}$$

where N is the number of pairs separated by the distance h and $DH_{\mathrm{res},i}$ and $DH_{\mathrm{res},j}$ are the DH_{res} values at the locations i and j, respectively. The lag distances, h, were grouped into an appropriate number of bins and the average semi-variance calculated for each bin.

If the DH_{res} values for a layer were not auto-correlated the semi-variance for all lag distances would approach the total variance of the DH_{res} values. If auto-correlation existed the semi-variance increased with the lag distance. The lag distance at which the semi-variance in some semi-variograms reaches a plateau is the range. The semi-variance at $h=0$ m is the nugget. The size of the nugget is influenced by variations at scales smaller than the shortest distance between the measurements as well as measurement errors. Since we did not use the experimental semi-variogram for modeling but to determine if auto-correlation existed, we did not transform the data to approach a standard normal distribution before calculating the semi-variance.

All statistical calculations were done with the public domain software package "R" version 1.5 (Ihaka and Gentleman, 1996). Spatial statistics were calculated with the "R" package "geoR" version 1.3–3.

3. Results

During the winter 2001–2002 eight arrays were made (Table 1). All arrays were within 500 m of each other, except array 2, which was 2 km away from the other arrays. Arrays 4, 5 and 7 were side by side on the same slope about 10 m from each other. Snow depth at the sites of the manual profiles varied between 87 and 155 cm. The depths were typical for the winter 2001–2002. The upper part of all arrays had less snow; the lower part more snow than at the location of the manual profile. A total of 365 point stability tests were carried out. From these tests 224 fractures in 16 array-layers were analyzed. Eighty-eight percent (196) of the analyzed fractures had a planar (smooth) fracture. Most of the remaining fractures were either planar with a corner broken off or collapses which normally involved a collapse of a layer of faceted crystals with a distinct layer boundary on both sides.

3.1. Fracture layers

The stability tests produced fractures at new snow interfaces, facets above crusts, facets below crusts

Table 1
Slope angle, aspect, rutschblock score and stability test used in the eight arrays investigated

Array	Sampling date, 2002	RB score	Slope aspect	Slope angle ψ	Stability test method
1	Jan. 9	3/5	ESE	28–31	Stuffblock
2	Jan. 15	5	N	24–32	Stuffblock
3	Jan. 29	3	NE	23–30	Stuffblock
4	Feb. 18	4–5	NNW	25–32	Rammrutsch
5	Mar. 1	2/5	NNW	25–34	Rammrutsch
6	Mar. 5	4	N	23–28	Rammrutsch
7	Mar. 8	3	NNW	22–37	Rammrutsch
8	Mar. 13	5	WNW	29–35	Rammrutsch

RB score is the score of the rutschblock test on the slope. The ranges of slope angles are from the point stability test locations. Two numbers such as 3/5 indicates multiple fractures.

and in depth hoar layers. Some of the slopes investigated primarily had fracture layers and interfaces that could be followed over most of the array. On other slopes only a few fractures could be associated with a specific layer or interface that was observed in most of the columns. Only layers and interfaces with more than five fractures within an array were used in the present analysis. Layers and interfaces with fewer fractures did not yield good statistical results and were of little interest for our investigation. An analyzed layer within an array is here called an array-layer. The percentage of fractures in an array-layer, *F*, was calculated for each array-layer (Table 2). All array-layers were grouped into persistent and non-persistent (Jamieson, 1995, p. 11) (Table 2).

Two persistent weak layers consisting of faceted crystals were observed on all slopes investigated. In early December 2001 rain and wet snow moistened the snow surface up to an elevation of about 2800 m a.s.l. in the study area. The result after freezing was two separate crusts above each other. This double crust was found in all profiles from the investigated area throughout the measurement period. Above the upper crust faceted crystals formed (Birkeland, 1998; Colbeck and Jamieson, 2001; Jamieson and van Herwijnen, 2002), producing a 2–5 cm thick weak layer. A number of natural and skier released avalanches failed in this layer, and it remained critical for most of the winter. We call it PWL-1. Faceting also took place below the lower crust (Seligman, 1936; Colbeck, 1991; Fierz, 1998). Until the beginning of March 2002 we only produced sporadic fractures in this weak layer. The persistent weak layer that developed below the crust we call PWL-2. These two persistent weak layers were present on all slopes and everywhere on the slopes investigated, although we could not produce fractures in the layers at all stability test locations. These two persistent weak layers were between 37 and 132 cm above the ground except in array 6 where they were only 13 and 9 cm above the ground.

Table 2
Description of the stability and type of each of the 16 array-layers investigated

Array-layer	Array	Number of tests, *N*	Number of fractures, *n*	Percentage of fractures, *F*	RB score	Persistent layer?	Weak layer description
1	1	26	16	62	3	Y	Facets (PWL-1)
2	2	24	18	75	–	Y	Facets (PWL-1)
3	3	17	14	82	–	Y	Facets (PWL-1)
4	3	17	9	53	3	N	Partially decomposed crystals above crust
5	3	17	7	41	–	N	Interface between two layers with small facets
6	4	24	22	92	4	Y	Facets (PWL-1)
7	4	24	8	33	–	N	Small rounded and small facets above a crust
8	5	24	15	63	5	Y	Facets (PWL-1)
9	5	24	10	42	–	Y	Facets (PWL-2)
10	5	24	20	83	2	N	Large new snow crystals
11	6	24	7	29	–	Y	Facets (PWL-1)
12	6	24	14	58	–	Y	Facets (PWL-2)
13	6	24	19	79	–	N	Partially decomposed crystals above a harder layer with small rounds and partially decomposed crystals
14	6	24	10	42	4	Y	Thin layer of rounded facets
15	7	24	17	71	–	Y	Facets (PWL-2)
16	8	24	18	75	–	Y	Facets (PWL-2)

N is the number of repeated point stability tests on the slope and *n* is the number of fractures in the array-layer. *F* is the percentage of fractures on a slope. For layers that produced a fracture in the rutschblock test, the score is given (RB score). For a description of PWL-1 and PWL-2, see the text.

3.2. Drop height variation

Values of the quartiles, the absolute spread, Q (Eq. (1)) and the relative spread of the drop height values, V_Q (Eq. (2)) for each array-layer are given in Table 3. The median drop height ranged from 5 cm to 50 cm. The highest drop height recorded was 90 cm while the lowest was 0 cm. In the latter case a fracture was produced as the test equipment was placed on the snow surface. This happened with both the rammrutsch and the stuffblock test. The non-persistent array-layers analyzed here had significantly lower median drop height than the persistent array-layers (two-sided Wilcoxon rank sum test, $p = 0.023$). The non-persistent array-layers were closer to the surface than the persistent array-layers, which could have caused the lower median drop height.

The drop height required to produce a fracture in a weak layer or interface showed variation on two scales. On the slope-scale a trend in the drop height often existed. For example, in array-layer 6 the drop height increased towards the bottom right (Fig. 2). Slope-scale trends were investigated with linear least square regressions (Eq. (4)). Regression results (Table 4) showed significant slope scale trends for 6 out of the 16 array-layers. At the pit-scale between two tests 1 m apart, differences in drop height were as large as 40 cm, but in most cases no more than 10 cm. In arrays where large slope-scale trends in stability existed, the semi-interquartile range, Q, of the drop heights reflected to a large degree the range of the slope-scale trend. The same was the case for the measure of relative spread, V_Q. Values of Q and V_Q for the drop heights with the slope-scale trend removed are given in Table 3. The absolute spread of variability, Q, varied between 2.5 and 23.8 cm and V_Q between 18% and 71%. After removal of spatial trends, both Q and V_Q decreased for the majority (11 of 16) of the array-layers: Q varied between 2.8 and 12.0 cm, and V_Q between 13% and 49%. However, array-layers 4, 5, 10, 11 and 14 showed increases in either Q or V_Q or both (Table 3). The increase in spread for these layers after removal of the spatial trend was due to either few fractures in the layer or to insignificant spatial trends in drop height or both. Part of the pit-scale variation was due to measurement errors. The absolute error of the tests was difficult to estimate, but based on Q for DH_{res} (Table 3) we

Table 3
Summary statistics for the point stability tests in the 16 array-layers

Array-layer	Fracture depth *FD* (cm)	Drop height *DH* (cm)					Semi-interquartile range, Q (cm)		Quartile coefficient of variation, V_Q (%)	
	Median	Min	Q_1	Median	Q_3	Max	*DH*	DH_{res}	*DH*	DH_{res}
1	48.5	0	10.0	35.0	52.5	70	21.3	5.3	68	15
2	35.5	20	30.0	40.0	47.5	60	8.8	7.4	23	19
3	58	10	20.0	50.0	67.5	80	23.8	6.1	54	13
4	22	0	10.0	10.0	20.0	20	5.0	4.9	33	37
5	21	10	10.0	10.0	15.0	30	2.5	2.8	20	20
6	52.5	20	26.3	35.0	45.0	80	9.4	5.2	26	14
7	27	20	20.0	35.0	41.3	45	10.6	4.6	35	14
8	**57**	**0**	**5.0**	**15.0**	**30.0**	**40**	**12.5**	**4.5**	**71**	**29**
9	54	5	7.5	22.5	33.8	40	13.1	6.3	64	33
10	14.5	0	5.0	5.0	11.3	20	3.1	3.5	38	49
11	28	0	20.0	30.0	35.0	60	7.5	12.0	27	44
12	64	5	21.3	32.5	53.8	75	16.3	8.5	43	22
13	18	5	10.0	15.0	25.0	45	7.5	5.0	43	30
14	34	10	35.0	45.0	50.0	70	7.5	11.3	18	26
15	62	5	15.0	20.0	55.0	65	20.0	11.2	57	40
16	50	15	25.0	32.5	43.8	90	9.4	7.4	27	20
Median	*42*	*5*	*17.5*	*31.3*	*42.5*	*60*	*9.4*	*5.7*	*36.5*	*24*

The quartiles are given for the measured drop heights (*DH*). Q_1 is the first quartile and Q_3 the third quartile. The semi-interquartile range and the quartile coefficient of variation are given for the measured drop heights (*DH*) and for the drop heights with linear trend removed (DH_{res}). Array-layer 8 which failed while working on the slope is marked in bold. The median value of each column is shown in italic in the last row.

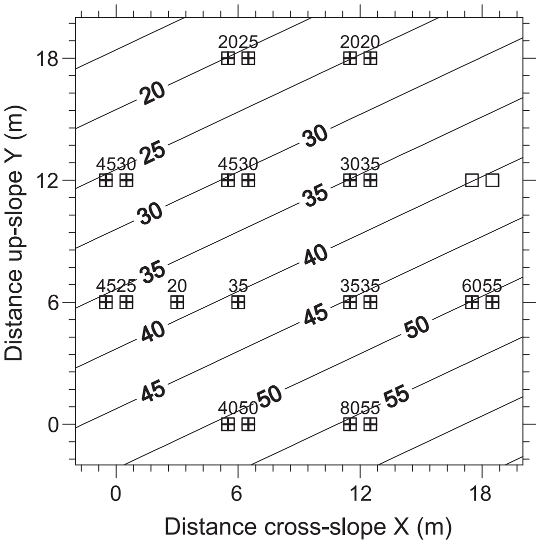

Fig. 2. Drop height required to produce fractures in array-layer 6. Stability (rammrutsch) test locations are marked by squares. A cross through a square marks a fracture in array-layer 6. The drop height (in cm) needed to produce the fracture is shown above the test location. The linear trend in drop height is shown by 5 cm contours.

estimate the measurement error in the measured drop heights to be smaller than ± 10 cm.

The absolute spread *Q* increased with increasing drop height *DH* (statistically significant: $p = 0.044$), suggesting that array-layers with low median stability were less variable than array-layers with higher stability. There was no significant correlation between the relative spread V_Q and the median dropt height *DH* ($p = 0.625$). When the slope scale trend was removed the increase of the absolute spread with increasing median drop height DH_{res} diminished and was no longer statistically significant ($p = 0.073$). Accordingly, the relative spread decreased with increasing median drop height DH_{res} ($p = 0.010$).

The absolute spread, *Q*, was significantly lower in non-persistent layers than in persistent layers (two-sided Wilcoxon rank sum test, $p = 0.015$ for *DH* and $p = 0.005$ for DH_{res}). No significant difference was found in the relative spread V_Q between persistent and non-persistent layers ($p = 0.496$ for *DH* and $p = 0.461$ for DH_{res}).

3.3. Cause of the drop height variation

The relation between the fracture depth, the slope angle and the drop height was investigated with linear correlation analysis (Table 5). The drop height was significantly positively correlated with the depth of the fracture in 8 of the 16 array-layers. Stewart (2002) found 41% of his arrays to be significantly positively

Table 4
Regression results from linear trend analysis of array-layers (Eq. (4))

Array-layer	α	β	*c*	*p*
1	**4.9**	0.6	− **17.6**	**< 0.001**
2	− 0.7	0.1	**45.1**	0.41
3	0.2	− **4.4**	**83.3**	**< 0.001**
4	− 0.1	− 0.4	**17.0**	0.61
5	− **1.0**	− 0.3	**29.3**	**0.048**
6	0.8	− **1.7**	**46.3**	**0.001**
7	1.0	− **1.1**	**28.2**	0.11
8	− 1.0	**1.4**	15.0	0.11
9	0.9	− 0.5	**20.6**	0.44
10	0.2	0.4	3.5	0.26
11	− 1.4	− 1.4	**61.0**	0.31
12	− 0.2	− **3.9**	**83.5**	**0.002**
13	− 0.3	− 0.5	**25.7**	0.41
14	− 1.1	− 1.3	**59.7**	0.15
15	1.1	− **1.8**	**37.5**	0.10
16	− 0.1	− **3.0**	**71.1**	**< 0.001**

The level of significance, *p*, from the *F*-test statistic is given. Significant coefficients ($p \leq 0.05$) are marked in bold.

Table 5
Correlation coefficients, *r*, from linear correlation analysis between drop height *DH*, fracture depth (*FD*) and snow surface slope angle (ψ)

Array-layer	*FD*	ψ
1	**0.84**	0.08
2	**0.62**	0.29
3	**0.89**	− 0.49
4	0.03	− 0.41
5	**0.94**	− **0.79**
6	**0.60**	− **0.47**
7	0.42	− 0.15
8	− 0.10	0.48
9	**0.71**	− 0.36
10	0.06	0.30
11	0.74	− 0.75
12	0.42	− **0.63**
13	**0.76**	− 0.44
14	0.48	− **0.65**
15	0.31	− 0.43
16	**0.88**	− **0.76**

Variables marked in bold were significantly correlated to drop height ($p \leq 0.05$).

correlated with fracture depth, and considering the arrays means, fracture depth was the only variable that showed a significant correlation. Our data also showed a positive relation between median drop height *DH* and median fracture depth *FD*, although not significant ($p = 0.093$).

Negative correlation between the slope angle and the drop height was significant in five array-layers. However, cross-correlation between the snowpack variables also existed, e.g. a deeper snowpack at lower angles, making the interpretation of the relationships more complex. Stewart (2002) found a significant correlation between drop height energy and slope angle in only 2 out of 39 arrays: In one array the correlation was positive, in the other array negative. Jamieson (1999) found a significant correlation between the number of taps in the compression test with the slope angle in seven out of eleven series. In all seven series the correlation was negative.

To assess the combined effect of fracture depth and slope angle a multiple linear regression on median drop height was calculated. It showed that a significant part of the variation in drop height (Q) could be explained by variations in fracture depth and slope angle. The absolute spread of the drop height with fracture depth and the slope effect removed did no longer depend on drop height ($p = 0.450$). Consequently, array-layers with high median drop height did not show larger variation than array-layers with low median drop height when the combined effect of fracture depth and slope angle was removed. Interestingly, the absolute spread of the drop heights with fracture depth and the slope effect removed increased significantly with increasing fracture depth ($p = 0.015$) possibly due to increasing measurement error of the measurement methods with increasing fracture depth.

3.4. Spatial and temporal structure of the drop height variation

The spatial structure of stability of array-layers was investigated with semi-variograms for DH_{res}, the drop heights after a significant trend had been removed. Typical examples of experimental semi-variograms for DH_{res} are shown in Fig. 3. Array-layers 1, 3, 4, 5, 8, 9, 11, 12 and 14 did not show spatial auto-correlation (Fig. 3a) whereas array-layers 2, 6, 7, 10, 13, 15 and 16 did show spatial auto-correlation (Fig. 3b). For none of the array-layers that showed auto-correlation a range could be determined because the semi-variogram did not reach a plateau within a lag distance of 15 m. Therefore we could not use the range as a measure of the size of spatial patterns in our stability rating scheme.

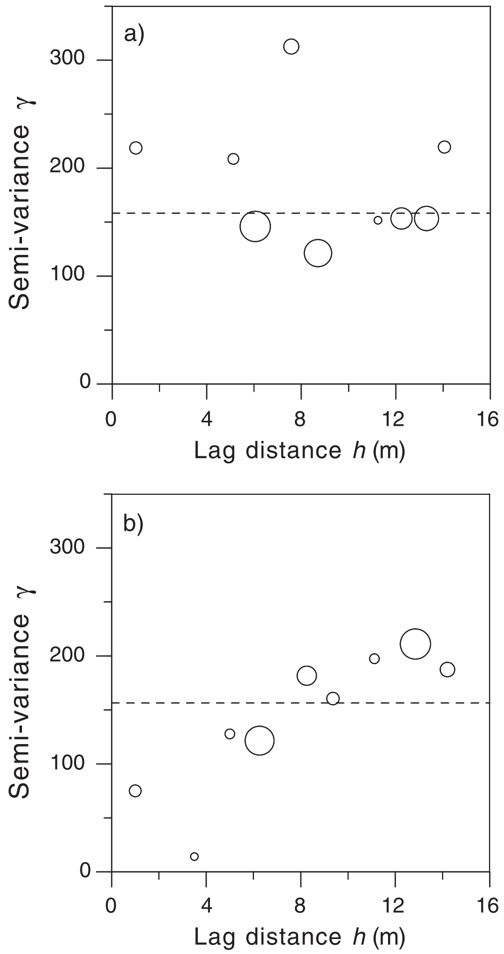

Fig. 3. Typical experimental semi-variograms for the drop heights after removal of the slope scale trend, DH_{res}. The dotted line represents the total variance of DH_{res}. The size of the dots is scaled with the number of point pairs. (a) Some array-layers such as number 12 showed little or no spatial structure in drop height values after removal of a linear slope-scale trend. (b) Other array-layers such as number 16 showed spatial structure but the range could not be determined since the semi-variance did not reach a plateau.

Four out of the eleven array-layers which were classified as persistent (36%) showed spatial auto-correlation. For the non-persistent array-layers three out of five (60%) showed spatial auto-correlation. Because of the limited sample-size it was not possible to conclude if this pattern was due to chance or due to actual differences in spatial structure between persistent and non-persistent weak layers.

The temporal evolution of the spatial structure of point stability was followed for the persistent weak layers PWL-1 and PWL-2 although the measurements were not made on the same slope. PWL-1 was investigated in arrays 1–6 (Table 2) as array-layers 1, 2, 3, 6, 8 and 11. In the first five arrays PWL-1 alternated between showing spatial auto-correlation and not showing any. PWL-2 was investigated in arrays 5, 6, 7 and 8 as array-layers 9, 12, 15 and 16 (Table 2). In arrays 5 and 6 PWL-2 showed spatial auto-correlation, in arrays 7 and 8 no auto-correlation was observed. These rapid changes for a single weak layer between showing spatial auto-correlation and showing no spatial auto-correlation suggested that the spatial structure of stability for the two studied weak layers were not an inherent property of the weak layer but to a larger degree a function of the location in space, probably due to variations in slab properties and variations in metamorphic processes such as kinetic growth. The latter process has been shown to lead to large differences in snow cover properties over short distances if rocky outcrops are present (Arons et al., 1998).

4. Discussion

The slope-scale trend in stability is of interest for the practical estimation of snow slope stability, i.e. whether the slope as a whole is unstable and has a high release probability. If a slope does not have a trend in stability the location of a single stability test is not important since stability is random. If however, a slope-scale stability trend exists, choosing the right location for a stability test is crucial. In 8 of the 16 layers investigated the slab thickness (*FD*) seemed important for the slope-scale stability trend.

For the release of a slope as a dry snow slab avalanche the following criteria must be fulfilled (Schweizer, 1999):

(a) An initial fracture in the snowpack typically within a weak layer or at a weak interface.
(b) A critical size of the fracture in order to meet conditions for brittle fracture propagation.
(c) Peripheral strength must be overcome to release the slab completely.

Fulfillment of these criteria depends not only on the properties of the critical weak layer and the slab at a single point on a slope, but on their properties over a larger part of the slope. The slope-stability evaluation scheme proposed by Kronholm et al. (2003) includes such spatial information to evaluate slope stability by incorporating (1) the average point stability, (2) the spread of point stability and (3) the spatial scale of the point stability variation. To illustrate the reasoning behind the stability scheme six conceptual diagrams are presented in Fig. 4. In each diagram a hypothetical sinusoidal distribution of stability is drawn for a transect of a snow cover. Also drawn on each diagram is a constant critical stability level along the transect. At locations where the stability is lower than the critical stability we expect an increased probability of local fracture.

We hypothesize that the probability of slope release will rise with the sum of the local fracture probability along the transect; slabs with low median point stability (Fig. 4a) will have a higher probability of slope release than slabs with higher median point stability (Fig. 4b). For a constant median point stability above 1, the spread of stability will likely influence the probability of slope release; along a transect on a slope with lower spread the areas with stability below critical stability (Fig. 4c) will be smaller than along a transect with higher spread (Fig. 4d). Thus the release probability for slopes with higher spread should be larger than for slopes with lower spread. This is only the case for median stability above the critical level. If median stability is below the critical level, the opposite would be the case. We expect that slopes with median stability below the critical level are rare or do not exist, since they would probably release spontaneously. The spread is also of interest for fracture propagation because areas of high point stability are likely to inhibit fracture propagation. If the spread of point stability is such that propagating fractures are stopped where the point stability is high, the size (scale) of the areas with high release probability is important. If a fracture cannot spread to an area larger than the size

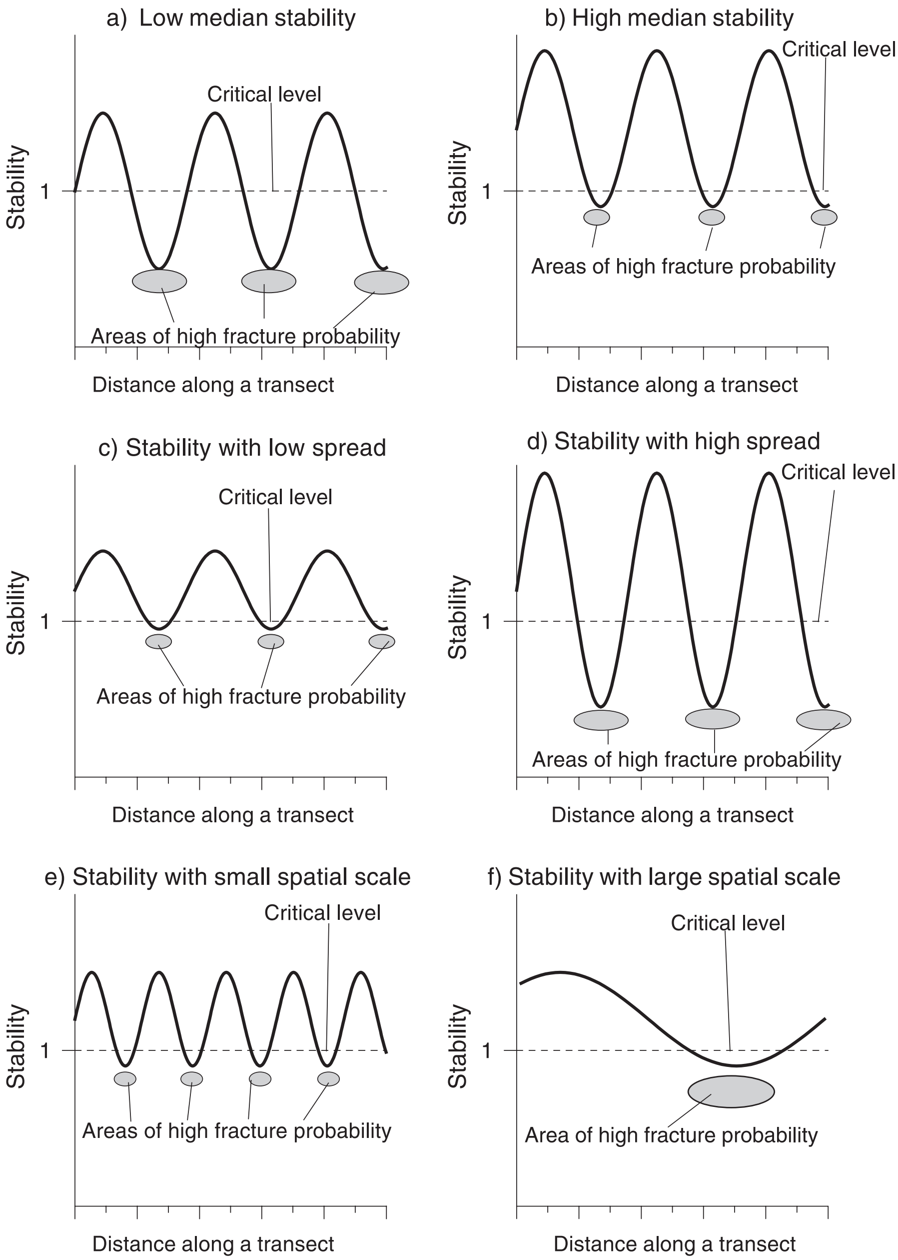

Fig. 4. Six hypothetical transects across (or down) a slope with sinusoidal variation in point stability. Field data do not show such sinusoidal variations in point stability. Point stability below 1 is assumed to be critical. The sinusoidal stability variation with low median point stability in (a) has larger areas of fracture probability than the sinusoidal variation with higher median stability shown in (b). For slopes with median point stability greater than 1 and low spread as in (c) the areas with point stability below the critical level will be smaller than for slopes with high spread as in (d). Variability at a small spatial scale as in (e) will lead to more but smaller areas with stability below the critical level than on a slope with larger scale variability as in (f).

needed for slab avalanche release (Fig. 4e) an avalanche will not be released. However, if the size of the fracture is larger than the critical size needed (Fig. 4f) an avalanche will release.

The median and the spread of stability as measured by the stability test drop heights were calculated for all array-layers (Table 3). We were not able to determine the spatial scale of the stability patterns with the semi-variogram analysis. Instead we used the percentage of fractures, *F*, (Table 2) as an indication of the spatial continuity of a layer. To evaluate how critical each of the 16 array-layers was for slope stability we summed the rank order of the median drop height, the absolute spread and *F* for all layers (Table 6). Using the relative spread V_Q instead of the absolute spread *Q* did not change the interpretation of the results. The lower the ranking sum the more critical the array-layer should be for slope stability. According to this ranking scheme, array-layer 10 is the most critical for slope stability, followed by array-layers 13, 8, 5 and 4 (Table 6). It must be acknowledged that the spread of drop height partly depends on the mean drop height because the distribution of stability is truncated at zero. However, this limitation will not cause significant problems with the proposed scheme.

Table 6
Scheme for evaluation of slope stability

Array-layer	Rank			Rank sum	RB score
	Median drop height	Absolute spread, *Q*	Percentage of fractures, *F*		
10	1	2	2	5	2
13	4	6	4	14	–
8	4	3	8	15	5
5	2	1	14	17	–
4	2	5	11	18	3
6	11	7	1	19	4
16	9	11	5	25	–
15	6	14	7	27	–
1	11	8	9	28	3
3	16	9	3	28	–
9	7	10	12	29	–
2	14	11	5	30	–
7	11	4	15	30	–
12	9	13	10	32	–
11	8	16	16	40	–
14	15	15	12	42	4

Partial ranks and their sum for the 16 array-layers investigated. A low rank number indicates a low median drop height, a low absolute spread and a high percentage of fractures, respectively. The array-layers are ordered by the sum of the ranks. According to the suggested scheme, a low rank sum in an array-layer would suggest low slope stability due to that layer. RB score is the score of the rutschblock test.

Evaluation of slope stability in the field is a difficult task, especially if the slope in question does not fail. Verification of the ranking scheme suggested was therefore difficult. During our measurements in array 5 we produced a failure in array-layer 8 (Table 2). The initial fracture was followed by a loud "whumpf" sound and a displacement of the slab of about a centimeter as judged from a crack opening at the top of the slope. Array-layer 8 could therefore be verified as being critical for the stability of array 5. Array-layers 10, 13, 5 and 4 were non-persistent weak layers or interfaces that were near the snow surface (Table 3). Further, the slabs above these four array-layers were relatively soft with hand-hardness typically = 4F (four fingers, Colbeck et al., 1990). While such weak layers often show up in stability test such as the stuffblock and rammrutsch test, they might not be critical for skier triggering because the layers are often penetrated and not loaded by a skier. In the field we penetrated these layers. A stability test such as the rutschblock involving the load of a skier might therefore be more appropriate in combination with the scheme suggested for investigating skier triggered slab stability.

Six of the sixteen array-layers failed in the rutschblock test (Table 6). For array-layers 10 and 4 the rutschblock score and the stability rating scheme conveyed the same information: these two layers were critical for slope stability. However, for array-layer 8 which failed as we were working on the slope and ranked as the third-most critical layer in the ranking scheme, the rutschblock test score of 5 did not seem appropriate. The reason for this inconsistency might be small scale variability in the snowpack, also indicated by the low number of fractures ($F = 63\%$, ranked 8), such as a more stable area at the location of the rutschblock test. A method integrating information from a larger part of the slope like the ranking scheme used here yields a more complete estimate of slope stability than a single point stability test.

The method presented here is not meant as a practical tool for slope stability evaluation in the field, but as a method for assessing the influence of spatial variability of stability on the probability of avalanche release. For practical purposes targeted sampling, i.e. a few stability tests (1–3) located at suitable sites together with other observations of instability yields a good estimate on (regional) snowpack stability (Schweizer et al., in press).

5. Conclusions

To summarize, fractures in 16 weak layers on eight slopes were analyzed with regards to average stability, absolute and relative spread of stability on potential avalanche slopes. Geostatistical methods were used to assess the spatial variability of stability. Finally, a stability ranking scheme using this information was used to evaluate the influence of each weak layer on slope stability. Results from the ranking scheme were compared with stability observations in the field.

Two crusts were present in all eight arrays investigated and everywhere within each array. The meteorological conditions responsible for these layers (rain and wet snow) were of large scale and spatially continuous. Persistent weak layers associated with these crusts were also present within all arrays, but showed considerable variations in point stability. Knowledge of the spatial extent of meteorological conditions responsible for the formation of these weak layers could therefore give much information about the spatial extent of the weak layers, but not necessarily on the stability of the weak layers because the stability depends also on conditions after formation that may vary more locally. Thus, based on the presented results, variability is not an inherent property of a weak layer and might not be predictable.

Shallow weak layers were more easily triggered than deeper weak layers since the stress due to rapid near-surface loading decreases strongly within the snow cover with increasing depth (Schweizer and Camponovo, 2001). This result agrees with what has long been known by avalanche professionals; snow observations and stability tests at sites with a smaller than average snow depth will more likely reveal instabilities (Schweizer et al., in press). Such areas will have a larger potential for kinetic growth of the crystals in the snow cover due to generally larger temperature gradients.

Slope scale trends in stability existed, and could partly be explained by variations in the depth of the weak layer, i.e. by slab properties. If a slope does not have a trend in point stability the location of a single stability test is not important since point stability is random. If, however a slope-scale stability trend exists, choosing the right location for a stability test is crucial. In six layers the slab thickness seemed important for the trend in point stability.

The range of spatial auto-correlation of stability could not be determined by the semi-variogram. More stability tests on a slope would be needed.

The relative variation of point stability expressed as the quartile coefficient of variation of drop height was of the order of 40% and dropped to around 20% after removal of a linear slope scale trend in the drop heights. The absolute spread in point stability, Q, was significantly lower in non-persistent layers than in persistent layers. However, no significant difference was found in the relative spread of stability, V_Q, between persistent and non-persistent layers. It should be pointed out that any measure of variation such as the semi-interquartile range or the quartile coefficient of variation used here does not include any information on spatial variation. Furthermore, measures of variation from different studies can not be compared if the size of the area investigated (extent) and the measurement unit area (support) are not the same.

The proposed stability rating scheme was preliminary assessed. The results support the idea that layers with low median stability, low variability and high continuity are the most critical to slope stability. The micropenetrometer measurements within each array will provide more results on the spatial variability of the penetration resistance of some of the weak layers investigated here (Kronholm et al., 2004).

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