Spatial variability of snow stability on small slopes

Kalle Kronholm*, Jürg Schweizer and Martin Schneebeli
Swiss Federal Institute for Snow and Avalanche Research SLF, Davos, Switzerland

Abstract: Spatial snowpack variability is thought to strongly influence 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, stuffblock and rammrutsch stability tests were carried out in an array on eight small avalanche slopes above timberline near Davos, Switzerland over the winter 2001-02. On each slope 17 to 26 stability tests were done. The analysis focuses on failures in two persistent weak layers that were found on all eight slopes. The median and the spread of the stability values are calculated. Slopes with low average stability and low variation in stability are more critical than if either average stability or variation in stability is high. Slope scale trends in stability were found on some slopes. Depth of the failure layer partly explained variations in stability. The quartile coefficient of variation was of the order 50% for the drop heights and 20% if the slope scale linear trend was removed.

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 tree line. The natural release of dry snow slab avalanches is suggested to start from imperfections in the snowpack, i.e. from areas of lower than average stability (Schweizer, 1999). Spatial variability is therefore seen as one of the keys to understand avalanche formation. McClung and Schweizer (1999) have estimated the critical size for self-propagating fractures to be of the order of 0.1 m to 10 m. Kronholm et al. (2001) suggested that slope stability is controlled by the average slope stability, the spread of the stability on a slope and by the scale of spatial patterns of strong and weak areas on the slope. So far, the various studies on slope scale variability have to our knowledge not been fully conclusive in regard to the effect on avalanche formation (Birkeland et al., 1995; Conway and Abrahamson, 1984, 1988; Föhn, 1989; Jamieson, 1995; Jamieson and Johnston, 1993a,b; Kronholm et al., 2001; Landry, 2002; Stewart, 2002). The type of stability variation and in particular the scale of the scale of the spatial pattern are largely unknown.

The aim of the investigations presented here is to explore the spatial variability of snow stability on potential avalanche slopes and to derive consequences for avalanche formation based on the stability evaluation scheme proposed by Kronholm et al. (2001).

* *Corresponding author address:* Kalle Kronholm, Swiss Federal Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland; tel: +41-81-417-0176; fax: +41-81-417-0110; e-mail: kronholm@slf.ch

2. Methods

2.1. Location

Over the winter 2001-02 investigations were carried out in a 2 km x 2 km area north-west of Davos, Switzerland. The study area was chosen due to its considerable number of undisturbed slopes of various aspects and because the access was relatively safe, easy and fast. The elevation of the study area was between 2350 and 2650 m.a.s.l. and therefore considerably above the timberline, which in the region is at around 2000 m.a.s.l.

2.2. Slope selection

Within the study area the slopes selected for investigation 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.

2.3. Measurements

On each slope multiple stability tests were done. On the first three slopes we used the stuffblock test (Birkeland and Johnson, 1996). On the last five slopes we used a modified version of the rammrutsch test (Schweizer et al., 1995). Both tests gradually load an isolated 30 cm x 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, whereas for the rammrutsch test we used a 1 kg weight 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. For each fracture the following was recorded:

- Depth of the fracture below snow surface, *FD.*
- Drop height of the drop weight, *DH.*
- Average thickness of snow between failure and top of column.
- Amount of compression of the snow below the shovel or plate at the drop leading to failure. For the rammrutsch test the amount of compression was hard to judge and thus not always noted.
- Type of the fracture, adapted from Jamieson (1999): clean, partially clean, uneven, stepped between two fracture planes, collapse or with irregularities in the fracture plane.
- Location of failure 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.

The drop height needed to produce a fracture in a weak layer represents a stability index for that layer.

On each slope several other measurements were done: A manual profile including ram hardness and a rutschblock test, penetrometer profiles with the SnowMicroPen (Schneebeli et al., 1999), snow samples, macro photographs of snow crystals and meteorological parameters. Results from these measurements will be presented elsewhere.

2.4. Spatial arrangement of stability tests

On each slope, the stability tests were done in a predefined cross-like array. The array was designed to cover most of the small slopes selected for our measurements, and to reveal variability at various scales. The maximum number of 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. Figure 1 shows the locations of the 24 stability tests on each slope and the local coordinate system. The stability tests were placed in pairs 1 m apart in the same pit to resolve the small scale spatial variability. The distance between each pair was 6 m to resolve the larger scale variability. One exception was around coordinate (6;6) where stability tests were placed on either side of a rutschblock test.

2.5. Failure layers

Our measurements produced failures at new snow interfaces, facets above crusts, facets below crusts and depth hoar layers. In the results presented here we have chosen to focus on two persistent weak layers consisting of faceted crystals that we observed on all slopes investigated.

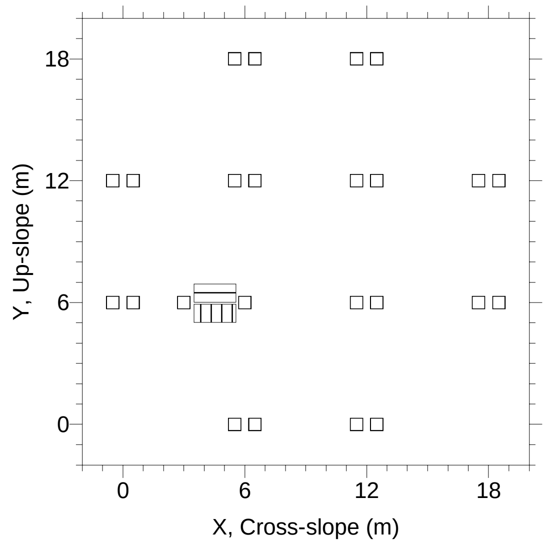

Figure 1: Locations of stability tests on the slopes investigated. Test locations are marked with squares. The left lower corner is the origin of the local coordinate system. The location of the manual profile is shown by a vertically hatched rectangle; the rutschblock test by a horizontally hatched rectangle.

In early December 2001 rain and wet snow moistened the snow surface up to an elevation of about 2800 m.a.s.l. in our 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 for the rest of the winter. 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 had their initial fracture in this layer and it remained critical for most of the winter. We call it PWL-1. Faceting also took place below the lowest crust (Fierz, 1998). However, until the beginning of March 2002 we only produced sporadic failures 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.

Judged from the rutschblock test and the series of stability tests on each slope, PWL-1 was the most critical weak layer on slopes 1 to 5, whereas PWL-2 was the most critical weak layer on slopes 6, 7 and 8.

3. Results

Over the winter 2001-02 eight slopes were investigated. Table 1 shows the stability test results. The elevation of the slopes investigated was between 2415 and 2450 m.a.s.l. Most sampled slopes had a northern aspect because north facing slopes generally were more unstable than south facing slopes in the study area.

All slopes investigated were within 500 m of each other, except slope 2, which was 2 km away from the other slopes. Slopes 4, 5 and 7 (Table 1) were side by side on the same slope about 10 m from each other.

Snow depth at the site of the manual profile varied between 87 cm and 155 cm. The depths were typical for the winter 2001-02. The upper part of all slopes had significantly less snow; the lower part significantly more snow than at the location of the manual profile. The persistent weak layers on slope 6 were exceptionally deep in the snowpack: only 9 cm above the ground. On the remaining slopes the layers studied were between 37 cm and 85 cm above the ground.

The following results only take into consideration layers with ≥ 7 failures. Accordingly ten layers on the eight slopes are analyzed.

A typical example of the variation in drop height over a slope is shown in Figure 2.

Since most of the datasets are skewed and do not follow a Gaussian normal distribution we use robust statistical measures to represent our data. The median is used to represent the center of our data. For the spread of the data the semi-interquartile range Q is used:

$$Q = \tfrac{1}{2} (Q_3 - Q_1) \quad (1)$$

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

$$V_Q = \frac{Q_3 - Q_1}{Q_3 + Q_1} \quad (2)$$

Summary statistics for the stuffblock results on all eight slopes are given in Table 2.

The drop height required to produce a fracture in a weak layer showed variation on two scales. At the slope scale a trend in the drop height often existed. In PWL-1 on slope 4 shown in Figure 2, the drop height increased towards the bottom right. At the short scale between two stuffblock tests a meter from each other, differences in drop height were as large as 40 cm (25 cm in Figure 2), but in most cases no more than 10 cm.

With slope scale trends in variability the semi-interquartile range, Q, of the drop heights on a slope is not a good measure of the real variation of the drop height values since it includes the range of the spatial trend. The same is the case for V_Q, the measure of relative spread. To investigate possible ways to remove the trend in the drop heights, the influence of the fracture depth, snow depth and slope angle on the stability was analyzed with linear least square regressions. Since none of these snow cover properties correlated well with stability of all weak layers, we adopted another approach. In geostatistics a trend in spatial measurements is often removed by fitting an inclined least square plane through the values (Webster and Oliver, 2001). The resulting residuals are then treated as random fluctuations around this plane. The parameters of such a plane are calculated with a multiple linear least square regression on the drop height, DH, and the local coordinates X and Y:

$$DH = \alpha X + \beta Y + c \quad (3)$$

where α and β are the regression coefficients for the X and Y coordinates, respectively, and c is a constant. The slope scale trend in drop height for PWL-1 on slope 4 is shown in Figure 2.

Table 1: Summary of stability test results on the eight slopes investigated. RB score is the score of the rutschblock test.

Slope	Date, 2002	RB score	Slope aspect	Slope angle, deg.	Stability test method	Number of stability tests	Number of failures	
							PWL-1	PWL-2
1	Jan. 9	3/5	ESE	28 - 31	Stuffblock	26	16	2
2	Jan. 15	5	N	24 - 32	Stuffblock	24	18	2
3	Jan. 29	3	NE	23 - 30	Stuffblock	17	14	3
4	Feb. 18	4-5	NNW	25 - 32	Rammrutsch	24	22	2
5	Mar. 1	2/5	NNW	25 - 34	Rammrutsch	24	15	10
6	Mar. 5	4	N	23 - 28	Rammrutsch	24	7	14
7	Mar. 8	3	NNW	22 - 37	Rammrutsch	24	3	17
8	Mar. 13	5	WNW	29 - 35	Rammrutsch	24	0	18

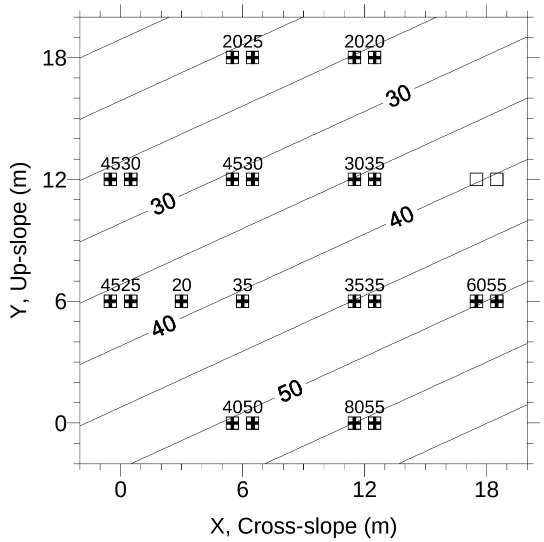

Figure 2: Failures in PWL-1 on slope 4. Stability (rammrutsch) test locations are marked by squares. A cross through a square marks a failure in the weak layer. The drop height (in cm) needed to produce the fracture is shown above the test location. The linear trend in drop height is shown by 5 cm contours.

Although the regressions involving the local coordinates were not significant for all layers, we calculated for all slopes the semi-interquartile range and the quartile coefficient of variation of the drop heights after removal of the spatial trend. The spread and relative spread for each weak layer is shown in Table 2.

No significant correlation existed between the median drop height values and the interquartile range of the drop heights (R=0.22, p=0.54) nor between the median drop height and the interquartile range of the regression residuals (R=0.14, p=0.69) suggesting that the stability variation is not related to mean stability.

For the drop heights Q varied between 7.5 cm and 23.8 cm. After removal of spatial trends Q dropped to between 4.5 cm and 12.0 cm with the lowest value found in PWL-1 on slope 5 which fractured while working on it. This weak layer also had the lowest median drop height (15 cm). The quartile coefficient of variation varied between 23% and 71% for the uncorrected drop heights and dropped to between 13% and 44% after spatial trends were removed.

PWL-1 on slope 6 showed an increase in Q and in V_Q after removal of a spatial trend as the only layer. This is presumably due to the few failures (7) and the insignificant (p=0.31) spatial trend in the drop heights.

4. Discussion

We observed no relationship between the median stability of a layer and the variation in stability in that layer. It is thus reasonable to use median stability and variation in stability as independent variables to judge slope stability as suggested in the stability rating scheme presented by Kronholm et al. (2001). The stability rating scheme suggests that slopes with low average stability and low variability are weaker than if the variability is high and weaker than slopes with high average stability. To verify this suggestion with the variability data presented above we need to know the failure probability for the specific slope. Independently estimating the failure probability is hard, maybe impossible to do. However, in PWL-1 on slope 5 we produced a fracture as we carried out the measurements. We thus assume that this layer had the highest failure probability of all the layers investigated.

Table 2: Summary statistics for the stability test drop heights. All units are cm unless otherwise stated. Slope 5 which failed (but did not slide) in PWL-1 while working is marked in ***bold****.*

Slope	Fracture layer	Drop height					Semi-interquartile range, Q		Quartile coefficient of variation, V_Q (%)	
		Min	First quartile, Q_1	Median	Third quartile, Q_3	Max	Drop height	Drop height, trend removed	Drop height	Drop height, trend removed
1	PWL-1	0	10.0	35.0	52.5	70	21.5	5.3	68	15
2	PWL-1	20	30.0	40.0	47.5	60	8.8	7.4	23	19
3	PWL-1	10	20.0	50.0	67.5	80	23.8	6.6	54	13
4	PWL-1	20	26.3	35.0	45.0	80	9.4	5.2	26	14
5	**PWL-1**	**0**	**5.0**	**15.0**	**30.0**	**40**	**12.5**	**4.5**	**71**	**29**
6	PWL-1	0	20.0	30.0	35.0	60	7.5	12.0	27	44
5	PWL-2	5	7.5	22.5	33.75	40	13.1	6.3	64	33
6	PWL-2	5	21.3	32.5	53.8	75	16.3	8.5	43	22
7	PWL-2	5	15.0	20.0	55.0	65	20.2	11.2	57	40
8	PWL-2	15	25.0	32.5	43.8	90	9.4	7.4	27	20

Stability tests done after the fracture of the weak layer showed no sign of being more or less stable than the tests done before the fracture. This layer had the lowest middle stability as well as the lowest corrected variability of all layers investigated (Table 2). Variability in other layers was also rather low (PWL-1 on slopes 1 and 4), but these did not fail under our weight, presumably due to higher average stability. PWL-2 on slope 7 had a low median stability, but a rather high variability (Table 2) which probably kept this layer from failing during our measurements. Low average stability combined with low variability in a weak layer thus seems to make a slope unstable as predicted by the stability rating scheme.

In six of the ten layers investigated there existed a significant relationship between stability of the failure layer and the depth of the layer below the snow surface. The thinner part of the slab – which was normally on the upper part of the slope – was easier triggered than the thicker part. In these six layers (on six different slopes) it would have been possible to point out areas of high and low stability if the depth of the critical weak layer would have been known. This suggests that not only the weak layer strength but also slab properties are important for stability as pointed out by Schweizer (1993).

Significant spatial trends in stability were found for five layers. Four of these five layers were layers where also a relationship between fracture depth and stability existed. Slope scale stability trends thus seem to be partly controlled by the depth of the critical failure layer but this was not always the case. Variations in the depth of the weak layer likely follow from wind effects during snow deposition. The measurements presented here do not allow conclusions on which other snowpack properties influence stability variations but results from the additionally made SnowMicroPen measurements might provide more insight.

In two stability tests a meter from each other we found that drop height could vary with up to 40 cm. Such differences are partly due to errors caused by the test method. We find it hard to judge the actual precision of the stability tests used in the study, but two points seem critical: The preparation of the isolated column is not trivial when very weak layers are present in the snowpack. Also the dropping of the weight can lead to errors, especially with the stuffblock test. Despite the source of errors present, the stability of layers on some slopes (PWL-1 on slope 1) appears to vary much more smoothly than is the case with other layers (PWL-2 on slope 6). As the stability tests seem to be able to reflect not only chaotic variations over a slope, but also smooth ones, we can interpret the drop heights from the stability tests with confidence.

The results presented here are based on a limited number of measurements on each slope. The tests used to measure stability seem to provide reliable results but the spatial resolution of the measurements on the slopes was probably minimal to provide a reliable picture of the true variation of stability. Further studies should aim to provide a higher resolution of the stability measurements. A constant spacing of 1 meter or less might be necessary to provide enough information for true spatial analysis. We expect to close this gap with our SnowMicroPen measurements.

5. Conclusions

Based on stability measurements of ten weak layers on avalanche eight slopes above timberline, we conclude that:

- The persistent weak layers followed in this study were present on all slopes, and everywhere on each slope. Accordingly, the variation in stability is the result of either the variation in strength of the weak layer or the variation in slab properties or a combination of both.
- Shallow weak layers were more easily triggered than deeper weak layers.
- Weak layers were often harder to trigger at the bottom of a small slope than at the top.
- Slope scale trends in stability existed, and could be caused by variations in the depth of the weak layer, i.e. by slab properties.
- Relative stability variation expressed as the quartile coefficient of variation of drop height was of the order of 50% and dropped to around 20% after removal of a linear slope scale trend in the drop heights.
- No correlation between median stability and stability variation was found.

The results support the idea that slopes with a weak layer with low average stability and low variability are more critical than if either average stability or stability variation is high.

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