The systematic snow cover diagnosis: A process-based approach for avalanche danger assessment

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ABSTRACT: Recreationists and local avalanche warning services face often the problem of assessing the avalanche danger for a single slope or avalanche path. However, local avalanche danger and release probability for a single slope are both very difficult to predict. Since 1998 the Bavarian Avalanche Warning Service teaches a diagnostic approach for local avalanche authorities and recreationists to provide them a systematic approach for snowpack observations and avalanche danger assessment based on these observations. The key component of this tool is finding the most prominent weak layer, test the weak layer - slab combination with a fast test and interpret the result by considering the processes that lead to the situation observed. Since this approach has never been rigorously validated, we want to present results of a field campaign, which was conducted during the winter seasons 2008—2009 to 2010—2011. In order to corroborate the diagnostic approach, several observers performed snow cover observations that focused on determining the weak layer and testing the weak layer - slab combination with a fast test block. Based on this information the observer had to assess the release probability for the investigated slope. When compared to obvious signs of instability, i.e. avalanches, cracks or whumpfs, the release probability evaluation was in very good agreement. Slopes with a high release probability had mostly a combination of a prominent weak layer, a cohesive slab, sudden fractures and low test scores. In addition to predicting the release probability of the slope tested, the observers had to estimate the danger for neighbouring slopes, which were subsequently evaluated. The transferability of the danger assessment was depended on the danger level and therefore the type of weak layer. Persistent weak layers causing situations with high release probability could be transferred with very good agreement, while situations with lower release probability were more often not found in the neighbouring slopes. With other words at low release probability the variability of the prominent weak layer was higher than for situations with high release probability. The presented approach gives the possibility to include snow cover properties into the evaluation of avalanche danger for a specific slope and provides robust results.

KEYWORDS: slope stability, snow cover test, weak layer

1 INTRODUCTION

The problem of forecasting the timing and extent of a dry slab avalanche on a particular slope is unsolved and no methodology is known, which could deliver such a result. However, since this is a very practical problem, which you need to solve if you want to move safely in avalanche terrain or if you need to decide on road closures or evacuation of houses, many suggestions have been made, how to best approximate a solution. As early as 1989, the Bavarian avalanche warning service has promoted the idea of process-based judgement. Since the 1990ties the Bavarian avalanche warning service has taught a method tailored to expert use, the so-called systematic snow cover analysis (Kronthaler and Zenke, 2006). The key component of this approach is finding the most prominent weak layer, test the weak layer - slab combination with a fast test and interpret the result by considering the processes that lead to the situation observed. Practitioners in the Bavarian Alps have applied this approach since many years, however, until today, a validation or an independent quality check is missing. Therefore, we started in the winter season 2008-2009 to investigate this decision tool for single slopes and expanded the analysis during the two subsequent winter seasons to include a combination of slopes. The main goal was to verify if the systematic snow cover diagnosis was suitable for danger assessment at the single slope scale. In addition, we wanted to check whether the danger assessments could be reliably extrapolated to nearby slopes.

2 DATA AND METHODS

2.1 Systematic snow cover diagnosis

We started with performing snow pits and applying the snow cover diagnosis on one single slope in the Bavarian Alps during the winter

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Table 1: Classes for characterisation of the block test and weak layer detected with the test. Classification is made for the block test, the structure and formation processes of the weak layer.

Variables of block test	Classes			
Applied force	While excavation	Gentle tapping	Moderate tapping	Hard tapping
Fracture plane	sudden	Rough	stepped	

Variables of weak layer	Classes				
Presence of weak layer	Yes		No		
Presence of same weak layer in slope 1 and 2	Yes		No		
Depth of weak layer (cm)	0-50	50-60	60-80	80-100	> 100
Weak layer thickness (cm)	0-2	2-3	3-10	>10	
Grain size difference (mm)	1	1-3	3		
Slab hardness	F – 4F	1F	P - K		

Formation of weak layer	Persistent	Non-persistent
	Buried surface hoar	Fresh/decomposed below wind slab
	Graupel	
	Low density snow on smooth crust	
	Faceted below crust	
	Faceted above crust	

season 2008-2009 (Kronthaler et al., 2009). In the subsequent two winter seasons (2009-2010 and 2010-2011), the evaluation of a first single slope was transferred to a second slope with the same aspect and similar elevation (Fig. 1).

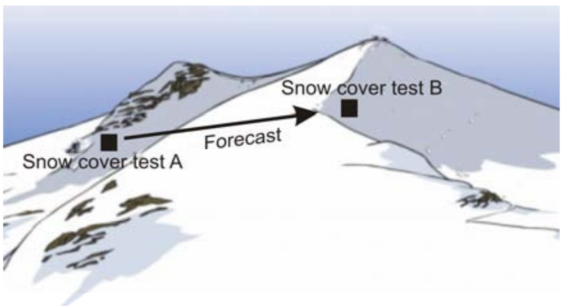

Figure 1: Test set-up during the winter seasons 2009-2010 and 2010-2011.

The snow pits were performed according to the systematic snow cover diagnosis approach (Kronthaler and Zenke, 2006). The focus of the approach is on the weak layer and the overlying slab only. A block of snow approximately 0.4×0.4 meters and to a depth of approximately 1 meter is isolated from the surrounding snow cover. By using the shovel, the block is brought to failure by tapping on its side. It is important that the tapping increases in intensity until failure. In the worst case, the block fails during the excavation. Subsequently, the failure layer is investigated with respect to the type of fracture plane, applied force, presence of a weak layer, depth of the slab, the thickness of the weak layer, the grain size of the weak layer, its difference to the adjacent layer and the process that created the weak layer. In addition, if two slopes were investigated, we wanted to know whether we could find the same weak layer in both slopes (Table 1).

2.2 Field data

Snow pits were performed in the following manner:

Step 1: Determination of the slope stability using the block test (snow cover test A in Fig. 1)

Based on the results of the applied block test, we came up with a danger rating:

- Spontaneous release of dry slab avalanches
- Release under small additional loading (one skier),
- Release with large additional loading (group of skiers)
- Generally stable conditions.

The rating is done based on the knowledge, which weak layer – slab combinations lead to slab avalanche release (Kronthaler and Zenke, 2006).

Step 2: Extrapolation to second slope

If possible, a second slope with similar elevation, aspect and slope angle was then chosen. Based on the knowledge of Step 1, a forecast for the local danger rating in the second slope had to be made.

Step 3: Verification of danger rating

If topographical (accessibility) and safety conditions (small slopes) permitted test skiing, the danger evaluations were validated. Having skied the slope, signs of instability, such as avalanches, whumpfs or cracks, were noted.

Step 4: Danger rating in second slope

Similar to the first slope, Step1 to 3 were again performed.

In total, N=442 slopes were investigated by 11 different observers. The mean distance between the first and second single slope was 254 m, slope angles varied from 10° to 45°.

2.3 Data analysis

In a first approach, we simply compared the properties given in Table 1 from the first slope to the second one. If the same property was observed in both slopes, we assigned a 1, if no accordance was given we assigned a 0. We summed the results in a frequency distribution.

For the slopes with additional information on the actual danger (Step 3) we applied a classification tree analysis (Breiman et al., 1998) to see which of the in Table 1 presented variables were most important for the danger estimates. Since safety conditions did not permit to test-ski all 442 slopes, the data set was reduced to N=200.

3 RESULTS

By comparing the first slope to the second one, we found a very strong agreement for the properties grain size (94%), hardness of the slab (93%), and presence of a weak layer (94%). However, only in 84% of all cases, we found the same weak layer within both slopes.

When compared to the danger estimate, we found that for the more unstable danger estimates the same weak layer was more likely to present in both slopes as for the classes with lower release probability (Table 2).

Table 2: Frequency of cases where in both slopes the same weak layer was found according to the danger estimates.

Danger estimate	Frequency (%)
Spontaneous release of dry slab avalanches	100
Release under small additional loading (one skier)	98
Release with large additional loading (group of skiers)	86
Generally stable conditions	71

If no weak layer was present, the observers always decided to ski the slope (N=89) and consequently estimated the conditions as generally stable. In case a weak layer was found within the test block, the observers decided to ski the slope depending their danger estimate (Table 3). Accordingly, if the observers estimated that a release was only expected with large additional loading (group of skiers) or as generally stable, the slope was skied in all cases (N=341). For all these test-skied slope, no signs of instability were recorded. If the slope was rated to release with small additional loading, only in 39% (N=36) of the cases the slope was skied. In 28 out of these 36 slopes (78%) either an avalanche was released or a sign of instability (crack, whumpf) was observed. In 61% (N=58), the observers decided not to ski the slope.

Table 3: Occurrence of alarm signs on test-skied slopes according to the danger estimates.

	Skied		Alarm signs
	%	*N*	
Spontaneous release	0	0	0%
Release under small additional loading (one skier)	39	36	78%
Release with large additional loading (group of skiers)	100	135	0%
Generally stable conditions	100	206	0%

In a second step we applied a classification tree analysis to the slopes, which were test-skied and had identical weak layers. The tree revealed four significant variables in classifying stable from unstable conditions (Table 4). We assumed stable conditions, if a release was possible with a large additional loading or during generally stable conditions. Unstable means that

Table 4: Statistical significant tree nodes and their danger classification using test-skied slopes only.

Tree nodes	Danger estimates
No weak leayer present	stable
Weak layer present+irregular fracture plane+high test scores (i.e. moderate to hard tapping, Table 1)	stable
Weak layer present+smooth fracture plane+low test scores (i.e. while excavation or gentle tapping, Table 1)	unstable

that the release of an avalanche with small additional loading is possible or through spontaneous action.

4 DISCUSSION AND CONCLUSIONS

The results reveal the usefulness of the systematic snow cover diagnosis and illustrate it's applicability in practice.

The possibility to transfer weak layer – slab combinations to other slopes is highly dependent on the danger level. The higher the danger was estimated, the more precise the observer could transfer their findings to a different single slope with similar characteristics. If the conditions during the first test gave a more stable rating, it was hard to transfer the findings of the first slope to the second one (Table 2). This result suggests that if release probability was estimated high, it was likely that the weak layer – slab combination was widespread. For the classes release with large additional loading and under generally stable conditions the variability for a certain weak layer – slab combination was high (Kronholm and Schweizer, 2003; Schweizer and Kronholm, 2007). In practice this means that with the presented approach it is fairly simple to find and transfer weak layer – slab combinations if conditions are critical. During stable conditions, this is not valid any longer. In other words, for instable conditions, only one weak snow cover test might be sufficient to correctly estimate the danger. For stabile condition, however, at least two or more tests are necessary to correctly estimate the danger. These results are in line with previously published findings (Schweizer and Bellaire, 2010).

The quality of the presented systematic approach can be summarized with the findings in Table 3 and 4. If the slope was estimated as generally stable or the release probability was given only with large additional loading, the slopes were skied and no avalanche released. If the slope was estimated as unstable, in 78% of the cases signs of instability were present and confirmed this instability. The remaining 22% are false alarms.

How to forecast an avalanche on a single slope is not solved with this methodology but it is felt that the systematic snow cover analysis may be a practical alternative to include local snow cover properties in an expert danger rating, which is at the same time less labour intensive and more representative than other methods. The method should not replace but complement probabilistic methods in cases where an expert is able to reliably apply the systematic snow cover analysis in a local setting. This procedure has proven to be useful in managing avalanche danger and supporting avalanche forecasting in the Bavarian Alps for many years now.

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