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SNOW PROFILE INTERPRETATION

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ABSTRACT: Snow profile interpretation is part of the every day work of any avalanche forecasting service. However, profile evaluation is considered rather an art than a technique. There are hardly any procedures known that could be used, and accordingly most forecasters have their own method. The avalanche forecasting service in Switzerland has to analyse twice a month about 110 snow profiles recorded by its observers. This task is presently quite time consuming, and the results are not fully homogeneous. Therefore, part of the decision making process of some experienced forecasters at the Swiss Federal Institute of Snow and Avalanche Research was explored. Based on this broad experience, each parameter observed in a snow profile with a stability test has been described in view of stability evaluation. A tentative snowpack stability-rating scheme is proposed for dry snow conditions. The principal criteria are rutschblock score, hardness, presence and type of weak layers, grain type and size. It should help the forecasters in the future to more consistently interpret snow profiles.

KEYWORDS: Avalanche forecasting, snow stability evaluation, stability tests.

1. INTRODUCTION

Snow stability evaluation is considered as the essential element of avalanche forecasting (McClung and Schaerer, 1993). The best data for stability evaluation are observations on avalanche occurrence and snow profiles, preferably combined with a stability test like the rutschblock test (RB). Snow profile interpretation is therefore part of the everyday work of avalanche forecasters, and supplements the indirect method of assessing avalanche danger based on contributory meteorological factors (Atwater, 1954).

In Switzerland, the avalanche warning service at the Swiss Federal Institute for Snow and Avalanche Research (SLF) operates an extensive observation program. About 80-90 observers provide snowpit data twice a month. About 50 observe a profile in a level study plot and approximately 40 do the same on a slope. Together with about 20 profiles taken by the forecasters themselves a total of about 110 profiles has to be analysed by the warning service every two weeks in order to derive a pattern of snow stability for the whole area of the Swiss Alps. Each profile is assigned to a stability class: very poor, poor, fair, good and very good. For instance, during winter 1999-2000 forecasters analyzed 1119 profiles (734 from flat study plots and 384 from steep slopes, most of them with a rutschblock test, very few with a compression test). This process is quite time consuming and presently the results partly depend on the view of the forecaster in charge.

Snow stability is the ratio of strength to load (skier, new snow etc.) on a weak layer or interface. Stability evaluation means to assess the probability of avalanche release for the snow conditions under consideration. Although the danger scale used in Europe is based on snow stability (Meister, 1995), snow stability is only very generally described. In Canada there exists a stability rating. It attempts to define classes that can be verified by observation, data or experiments (McClung and Schaerer, 1993; CAA, 1995).

Although, a snow profile, even when completed with a stability test such as the rutschblock test, is not sufficient to derive a final stability assessment, it is nevertheless usually the most important information, in particular in times of rather low avalanche activity.

To improve the process of profile analysis we reviewed stability evaluation, explored the decision making process of experienced forecasters and derived some general guidelines on how to interpret dry snow profiles. The aim of the paper is therefore to describe the elements to consider for the profile and stability test interpretation and then give a description of each

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of the five stability classes with the help of these elements.

There have been only a few attempts to systematically and objectively approach profile interpretation. Mostly snow profile interpretation is demonstrated based on examples (McClung and Schaerer, 1993). Ferguson (1984) quantitatively analysed snow profiles from stable and unstable slopes. Numerical avalanche forecasting has rarely included snowpack and stability information. McClung (1995) describes an expert system that was developed for profile interpretation. The forecast by the French Safran-Crocus-Mepra model chain (Durand et al. 1999) is based on the stability interpretation of calculated (modelled) snow profiles. Schweizer and Föhn (1996) have included in their statistically based models for regional avalanche forecasting stability information. They also drafted a first scheme on how to assign a snow profile with a stability test to a certain class of snow stability (Schweizer et al. 1992). Recently, Schweizer and Jamieson (2000) described the snowpack characteristics of skier-triggered avalanches.

2. METHODS

Stability evaluation based on snow profile and stability test interpretation means essentially to seek for signs of instability (McClung; 1999), rather than stability.

Snow profile interpretation is largely experience based. So we can not describe a rigorous method how we arrived at our results. We used different elements. First, we tried to quantify the experience of some forecasters with the help of a questionnaire, and then we discussed the problem with experts. Furthermore, we used a previously developed scheme by Schweizer et al. (1992), and the general knowledge as e.g. described in McClung and Schaerer (1993). Finally, we refer to some recent results on the snowpack characteristics of skier-triggered avalanches (Schweizer and Jamieson, 2000).

When interpreting a snow profile, the following measured or estimated parameters are available: snow depth, layering, grain type, grain size and hardness, liquid water content (dry, moist, etc.), snow temperature, ram hardness (not always), density (not frequently), RB score, slab thickness, information on type of RB failure as e.g. whether the whole or only part of the block was released, or whether the failure plane is smooth or undulated.

We used a questionnaire to explore the importance of certain parameters as seen by 10 experienced forecasters and/or researchers from the Swiss Federal Institute for Snow and Avalanche Research. They had to classify 14 mostly dry snow profiles based on a number of questions, particularly on the importance of certain parameters.

Finally, we tested the draft of the derived stability rating scheme by applying it to about a 100 randomly chosen snow profiles. This showed some deficiencies. By repeating this procedure the preliminary scheme was successively improved.

3. RESULTS OF QUESTIONNAIRE

The evaluation of the questionnaires showed that in general the agreement on the stability rating of the profiles is relatively high between the different forecasters, but interestingly, their reasoning is often quite different. We will only present the results of the general questions. Figure 1 shows that most forecasters do consider many parameters when interpreting a snow profile. Seven out of the 10 forecasters do consider 4 or 5 of the 7 proposed parameters. Liquid water content is hardly considered, except in spring situations, similarly the snow temperature. Snow temperature is considered to check whether dry snow conditions prevail, but none of the forecasters does explicitly use the snow temperature in dry snow conditions for stability evaluation. A few take into account the effect of future changes of temperature on snow stability.

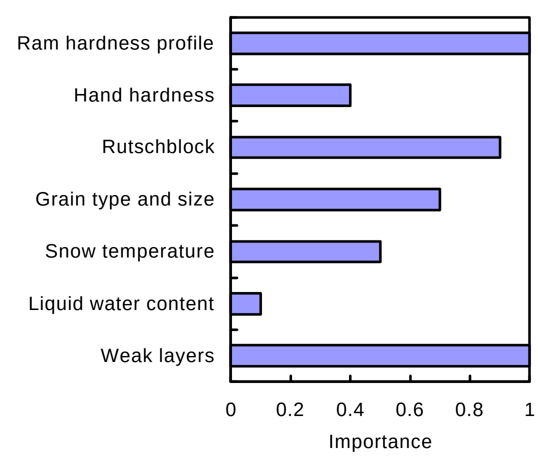

Figure 1: Relative importance of parameters for profile interpretation (very important: 1, not important: 0).

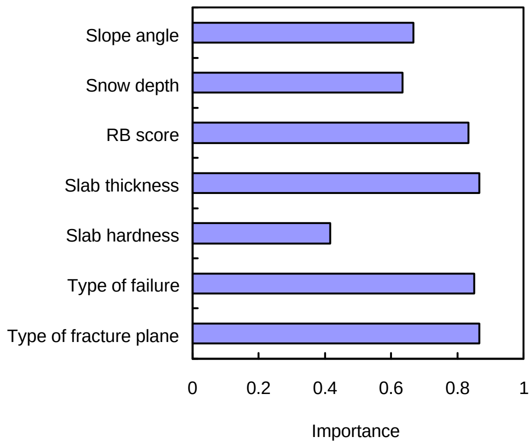

Figure 2: Relative importance of parameters for RB interpretation (1: very important, 0: not important) .

The low importance of the hand hardness is rather surprising but explained by the fact that in Switzerland most profiles include the ram hardness. Since the hand hardness is a more subjective measure the ram hardness is preferred. The three parameters that are considered most are the ram hardness profile, the RB score and the existence and type of weak layers.

A similar result shows Figure 2 for the case of interpreting a rutschblock test. Again each of the forecasters considers many parameters. The ones that were most homogeneously rated as important are the RB score, the slab thickness and the type of fracture plane. High, but some less homogeneous rating has the type of release (whole block, below the skis, only an edge).

4. DESCRIPTION OF PARAMETERS

Based on the above-mentioned elements of experience we describe each of the parameters observed in a full snow profile in view of stability evaluation.

Grain type

Weak layers of skier triggered avalanches typically consist of surface hoar, faceted grains or depth hoar (e.g. Föhn, 1993). These grain types are generally rather large and have plane faces. The number of bonds is relatively low, making layers of these grain types weaker than others (Jamieson and Johnston, 2000). They are also called persistent (Jamieson, 1995) and tend to gain strength slowly. Persistent weak layers that have been buried for some days or even weeks become rounded and are less critical, but frequently still showing clean shears.

Melt-freeze crusts and ice lenses tend to stabilise the snowpack provided they are thick enough. However, they also can be gliding surfaces as long as the bonding of new snow to the crust is insufficient. In spring wetting of these impermeable layers causes a reduction of friction. In certain situations, the bonding within new or partly settled snow layers is poor during or immediately after a storm, in particular during cold heavy snow storms. In that case failures occur within a layer of new snow, or partly decomposing and fragmented precipitation particles. Rime and graupel are rarely observed to form weak layers. Graupel is formed at relatively high temperatures. Although it survives in the snowpack once it is buried quite long, Graupel has been mainly observed as weak layer shortly after deposition on a smooth crust.

Grain size

The larger the grains the lower the number of bonds per unit volume, in particular in combination with persistent grain types. On the contrary, layers consisting of small grains rather indicate strength. Significant differences in grain size from one layer to the other are usually unfavourable to instability.

Existence of weak layers or interfaces

The lower stability the more prominent weak layers/interfaces are present. In a profile rated as good there are only moderately prominent or inconclusive potential weak layers present. The absence of weak layers/interfaces points toward very good stability. With increasing stability weak layers become more unlikely whereas interfaces become more likely. Interface failures frequently involve a crust. The strength of bonding of the adjacent layers to the crust can not be judged from a snow profile unless it is supplemented with a stability test.

Hand hardness index

Weak layers are usually soft, mostly hand hardness “fist”, sometimes “fist to four fingers”. Although the hand hardness is rather subjectively estimated, it is relevant to look for difference in hardness, since hardness differences are frequently associated with weak layers or interfaces. A hardness difference of two steps of the hardness scale, in particular, hard on soft, has to be interpreted as sign of instability. Critical weak layers are frequently sandwiched between harder layers. Hard layers such as crusts are most frequently found in the case of interface failures. In general, large gradients of hardness between two layers are more critical than small differences, and frequent changes of the sign of the gradient are unfavourable. Thick layers of low strength consisting of faceted crystals or depth hoar in the uppermost part of the snowpack frequently have not sufficient cohesion to represent potential slab layers, even with a prominent weak layer directly below. The same situation can occasionally be found during storms.

Snow temperature

In dry snow conditions the snow temperature does not reveal potential instability, and snow temperature is of limited value. Sometimes it is used to assess the stability trend given a certain temperature distribution, layering and expected trend of air temperature evolution. Snow temperature becomes important when the snowpack tends to get isothermal.

Liquid water content

The amount of liquid water is not measured but estimated. Until the snowpack is not (or not at least partly) isothermal the amount of liquid water is not relevant for instability assessment.

Ram profile

The ram profile shows the vertical distribution of penetration resistance or ram hardness of the snowpack. The resolution is limited, so that thin layers whether hard or soft, are frequently missed. Soft layers of at least 5-10 cm thickness can be detected. However, whether e.g. the basal layer of the snowpack is weak (depth hoar) can be seen. This is important to assess, whether an avalanche due to a failure in the upper snowpack might sweep out deeper layers of the snowpack which could lead to a much larger avalanche. Slab structures can usually be recognised as well.

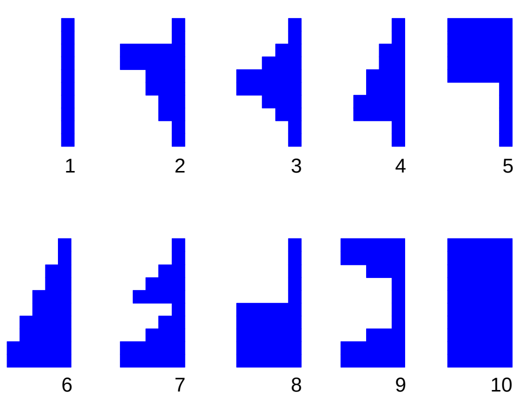

Figure 3: Classification of ram hardness profile

The hardness profile is characterised as one out of 10 types of profiles as proposed by Schweizer and Lütschg (2000) (Figure 3). The general shape is considered. When classifying a hand hardness profile, thin crusts e.g. are usually neglected. The profile types 1-5 all have a weak base, whereas the profile types 6-10 are well consolidated at the bottom. The profile type 1, 5, 7 and 9 indicate potential instability. Profile types 6 and 10 represent in general stable conditions, whereas the types 2, 3, 4, and 8 can not be assigned definitely, but all show some potential, but depending on the conditions, usually less critical weakness.

The presence of a weak base of depth hoar is not conclusive on its own. Most profiles have a weak base due to our intermediate to continental type of climate. If the profile is well consolidated in its middle part (belly shaped profile in combination with a weak base) this points to good or very good stability.

Density

Critical layers are less dense than the surrounding layers. However density measurements of distinct thin layers are usually not available. Density does not directly show instability. Density is used to calculate the load on a weak layer, but unless there is no strength measurement this is again of limited value. In general, dense (warm) snow on loose (cold) snow is unfavourable, but this is usually recognised by the hardness or grain size difference.

RB score

RB scores of 1-3 are clear signs of instability (Föhn, 1987; Jamieson, 1995). Scores 4 and 5 indicate transitional stability. Scores 6 and 7 are generally associated with stable snowpacks. This rating is valid for test results where the whole block was released and the fracture surface indicates a clean shear. Partial release and/or not clean shears indicate correspondingly higher stability.

On a steeper slope a lower score is expected. However, the dependence on slope is rather low (Jamieson and Johnston, 1993). So there is no correction needed for RB tests done on slopes between about 30° to 40°. RB scores from slopes steeper or less steep than these limits might be adjusted by 1 step of RB score.

As a rutschblock is isolated from the surrounding snowpack, there is no peripheral strength. Therefore a rutschblock can fail in a deep weak layer covered by a thick strong slab layer, but triggering a slab on a slope is still rather unlikely, except maybe on a shallow spot.

Layers close to the surface can not be tested (shallower than about ski penetration) but need to be considered as well. Sometimes, during or very shortly after a snowfall the slab might not yet be cohesive enough so that the RB score tends to underestimate the situation in the near future.

In general, slab properties influence the RB test result, but it is not clear e.g. how to assess the fracture propagation potential.

Layer thickness

A snowpack with many thin layers is in general rather more unstable than a snowpack that only consists of a few, relatively thick layers.

Weak layers can be very thin (millimetres), but are usually less than a few centimetres. In extreme cases the entire snowpack can be weak, and could therefore be designated as weak layer, but in general, if we talk about weak layers we have a layer of a few centimetres (about ≤ 3 cm) in mind. The closer the weak layer is to the surface the more critical it has to be considered in view of skier triggering. However, if the layer is within about the first 15 cm, it is less critical. The most favourable range in view of instability is about between 15 cm and 75 cm. If a layer of depth hoar on the ground is thinner than the terrain roughness, it is in general hardly critical, and likewise if a thick strong layer overlies the depth hoar layer.

Slab thickness can vary from centimetres to meters. The thicker and harder the overlying slab the weak layer the more unlikely is skier triggering. On the other hand, a hard and solid slab on a weak layer may produce a spontaneous avalanche as the slab increases due to loading (snowfall, snowdrift).

Crusts are commonly found in our snowpack. Thin crusts are mainly found in profiles rated as poor to fair, whereas thick crusts, providing strength, are more common in stable snowpacks.

5. INTERPRETATION SCHEME

Based on the above description of instability the following tentative and simplified scheme is proposed for stability evaluation based on snow profile and stability test data (Table 1).

There are always exceptions that can not be covered by the system in Table 1. The scheme will be applied in the following winter and needs to be reassessed. It is presently only applicable for dry snow slab avalanches with the skier as trigger in mind. In the spring other parameters have to be considered, as well as for the case of naturally released avalanches.

Furthermore, it has to be pointed out that for avalanche danger forecasting any stability rating should be completed with the depth of the potential instability. Only with this additional information the avalanche danger can be assessed.

6. CONCLUSIONS AND OUTLOOK

Snow profile and stability data is one of the essential keys to assess snowpack stability for avalanche forecasting. In order to improve snow profile interpretation we explored by using a questionnaire the decision making process of experienced forecasters when interpreting snow profiles. Based on that and state-of-the-art knowledge a list of criteria has been developed to assign a profile to a certain class of snowpack stability. The principal criteria are: rutschblock score, hardness, presence and type of weak layers, grain type and size. We described a structured approach for snow profile interpretation but experience and judgement are still necessary. Any derived scheme will be tentative and incomplete. It needs to be tested and improved during operational use. Despite its incompleteness, the developed stability rating system will help the forecasters to more homogeneously interpret the large number of profiles which they receive.

An expert system would be ideally suited for the complex, intuitive decision making process of snow profile interpretation. This study might accordingly pave the way for the development of an expert system that will give a first guess on the stability based on a snow profile (modelled or observed), and that will finally be incorporated into the GIS system presently used for drafting the avalanche danger bulletin. This will provide a map of snow stability as an additional supporting tool for the forecaster. Superimposed onto the stability map, other snow and weather parameters might be shown to assess the temporal evolution of stability.

In the future, new methods of measuring snowpack structure (Schneebeli et al., 1999) may improve stability evaluation based on snowpack information and give useful information on the spatial variability of the parameters.

Table 1: Snowpack stability rating scheme for dry snow profiles with stability tests

Class of stability	Description
5: very good	No critical weak layers present. In general well consolidated (ram resistance R larger than about 100 N), some soft layers (new snow or faceted crystals) near the top possible. Faceted crystals in the lower snowpack may be present, but with R>100 N ("4 fingers" or harder). The bottom is usually well consolidated as well, but occasionally a potentially weak base of large faceted crystals or depth hoar may exist, but is covered with a thick cohesive layer (at least 70 cm with R>200 N). Profile type: 4, 6 or 10 Rutschblock score: 6 or 7
4: good	Weak layers may be present, but not very prominent, e.g. showing no clean shear. In general well consolidated middle part with R > 100 N, or prominent hard crust of a few centimetres thickness in the upper third of the snowpack. At the bottom a potentially weak base with large faceted crystals or depth hoar may exist, but is covered with cohesive snow (at least 50 cm with R>100 N) The snowpack might fail if applying high stresses to interfaces or less well pronounced weak layers, or on top of the depth hoar base. Profile type: 2, 3, 4 or 6 Rutschblock score: 5 or 6
3: fair	Weak layers are present, showing clean shears, but transitional scores (4,5). Weak layers often consist of rounded persistent forms. Some soft layers with R ≈ 40 N present (except new snow on top), but most of the snowpack is fairly well consolidated. Profile type: 2, 3, 4, 8 or 9 Rutschblock score: 4 or 5; occasionally 3, e.g. when overlain by thick strong slab.
2: poor	Prominent weak layers and/or interfaces are present, showing clean shears. Weak layers of surface hoar or faceted crystals, larger than 1 mm, or interfaces within the new or partly settled snow or new snow on crust. Hardness of slab is R<40 N ("fist" to "4 fingers"). Some well consolidated parts may exist (R=100...300 N), but the thickness of these layers is less than 30 cm. Profile type: 1, 2, 5, 7, 8 or 9 Rutschblock score: 2 or 3
1: very poor	Prominent weak layers and/or interfaces are present. Thin weak layers of surface hoar or faceted grains, larger than 1-2 mm sandwiched between harder layers, or facets on crusts. The bottom is frequently weak, occasionally covered with only one cohesive slab layer. The ram resistance may be low from top to bottom (R≈20 N). In general, ram resistance above the weak layer is R<50 N, often "fist". There are no hard layers with R>150 N present, crusts are usually thin and do not show up in the ram profile. Profile type: 1, 5, 7 or 9 Rutschblock score: 1 or 2

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