FORMATION AND FORECASTING OF LARGE (CATASTROPHIC) NEW SNOW AVALANCHES

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Abstract

The catastrophic avalanche winter 1998/99 in the Alps demonstrated that still larger deficiencies exist within the themes: "formation" and "forecasting" of large, new snow avalanches. It is well known that the two themes are interconnected and that without knowing the proper formation processes of such avalanches a timely and locally accurate forecasting remains an illusion.

In a first part the state of knowledge of the various formation processes is assessed. Based on the indirect evidence of observed catastrophic avalanches and on the existing theories of the mechanics of snow slab release, several variants of release mechanisms are reconnoitered. It will be shown that the load rate, the terrain and the mechanical behavior of new snow are major factors for the initiation of very large avalanches, whereas the instability of previously existing snow surface layers may rather hamper the formation of large avalanches.

In a second part the forecasting procedures and their relevances are discussed. A major point is the fact, that the imminent amounts of new snow are seldom known, because large snowfall events may only be forecasted quantitatively with a success rate of about 60%. Hence, if forecasters apply the usual methods of stability evaluation – in default of more adequate procedures – they face the problem that only a few of the so-called contributing factors are really known. Moreover the ones which are best known from previous field work (stability factors) are – as mentioned above – not the most deciding ones.

Keywords: Snow mechanics,slab avalanche formation, avalanche forecasting, catastrophic avalanches

1. Introduction

Every 5 to 10 years the Alps experience catastrophic avalanche periods, which produce life losses and tremendous damages to property. In the last catastrophic winter 1998/99 in Switzerland 17 people were killed and the economic losses amounted to more than 400 million US $ (Wilhelm et al., 2000). Various preliminary studies revealed the fact that the formation processes of these large avalanches are still not well known. The main question is: "How is it possible that mother Nature piles up 2 to 5m of new snow under certain circumstances on well known avalanche slopes whereas in other *"normal"* conditions only 0.5 to 1.5m of new snow are sufficient for natural avalanches to be released?" Consequently, forecasting procedures must be analyzed in view of some adaptations to such extreme situations.

In this context the question must also be raised, to which degree the weather forecasts – in this case mainly the snowfall predictions – are adequate to foresee these extreme situations.

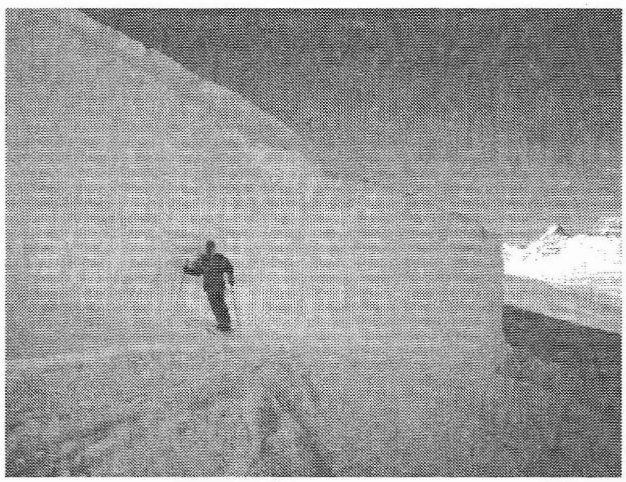

Figure 1: A slab release area end of February 1999 with abnormally high fracture depth.

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2. Formation of large new snow slab avalanches

"Large slab avalanches" may be defined as unusually thick slab avalanches, that is, with large fracture heights and length and therefore with long runout distances, briefly "catastrophic avalanches".

The vast majority of dry slabs release naturally due to loading by new snow fall (McClung and Schaerer et al., 1993). This statement is generally valid, if we also consider the stratigraphy of the slab layers and the stability conditions in the base layers of potential avalanche slopes. Nowadays it seems generally accepted that dry snow slab avalanche release starts with shear failure in a thin weak layer or at a weak interface (McClung and Schaerer, 1998).

McClung (1977) and also Narita (1983) deduced from laboratory experiments that snow strength is rate dependent. This means in practical terms that the loading and the strain rate has to be rather high in order to concentrate the strain energy, which provokes failures. This high level is reached when the strain rate amounts to 1×10^{-4} to $1 \times 10^{-3} s^{-1}$ (McClung, 1977; Gubler, 1987; Fukuzawa and Narita, 1993; Schweizer, 1998). The above strain rate range is according to Schweizer (1998) mainly dependent on the snow type. In the above range the snow seems to be "viscoelastic", which means that microflaws are present (Sentler, 1997). Hence already small deformations might cause damage and by accumulating small damage zones eventually failures may evolve.

A final precondition, which is the base for all snow stability evaluations, is the condition that the stability index $S \leq 1$. This means the stress equals or exceeds – at least locally – the strength of a buried weak layer or an interface.

Summarized, we have the following preconditions in order to get initial failures/fractures, i.e. finally a slab avalanche:

1. A thin weak layer or a weak interface
2. at the base of slab layers, the shear stresses have to surpass the shear strength
3. a rather fast snow deformation in the weak layer or interface is needed to increase the strain rate up to about $10^{-4} s^{-1}$

The first two conditions are periodically met in normal winters, when during cold spells weak layers or interfaces are formed at the old snow surface and then snowed in by a sufficient snow load. An additional subsiding effect for slab release may also arise during warming periods, when the upper snow temperatures get close to 0°C, the slab stiffness decreases significantly and hence the slab stability diminishes (McClung and Schweizer, 1996).

The third condition – a high strain rate – is difficult to be met, except by artificial triggering and by human actions as skiing, snow boarding, etc.

The question is now, how large new snow avalanches release naturally without artificial triggering and human impacts, in particular if their base layers are largely protected against meteorological influences? According to Bader and Salm (1990) even large and thick slab avalanches would need a "super-weak layer" within the snow pack in order to experience sufficient stress and stain rate concentrations.

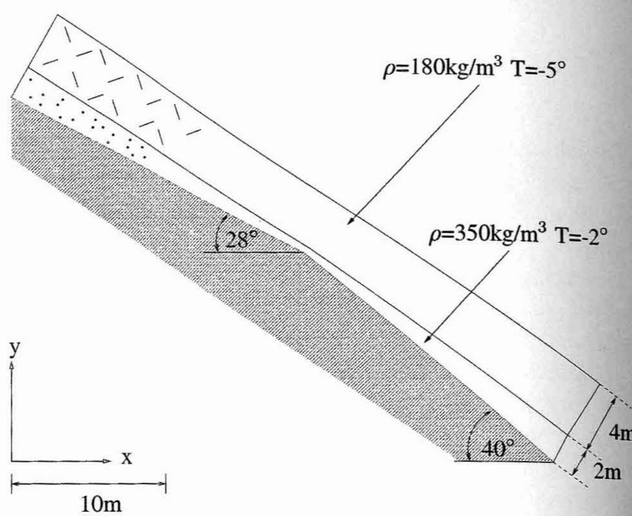

Figure 2: Avalanche slope terrain configuration with a break at 20m of 12° and snow pack layers which were used for the model calculations.

In order to clarify this question we analyzed slab fracture profiles, snow profiles, previous rutschblock scores and the regional physical snow conditions, measured shortly before and during the catastrophic avalanche period 1998/99.

Only in a few cases (3 out of 15) we found obvious weak layers or interfaces in the upper part of the basal snow pack. Weak layers (e. g. surface hoar, graupel) or interfaces survived apparently only in lower altitudes (<2000m a.s.l.) where reduced wind speeds and larger wind and sun shadow-effects are present than in the higher up situated avalanche release zones. Most avalanches ruptured in the fracture zone (>2000m a.s.l.), probably on the old snow surface of end January 1999 (SLF, 2000). During the three increasing snowfall and avalanche cycles maximum fracture heights of 2, 4.5 and 6m, respectively, have been observed (sample size: 530 avalanches).

Therefore we may assume that if the above "thesis", namely that not only weak, but even "super-weak" layers must be present for avalanche formation, we wouldn't have had about 1000 of these large avalanches in the winter 1998/99. On the other side the fracturing of so many large avalanches without "super-weak" layers proves that other features may be necessary, which support the failure and fracturing process. Our first choice is the terrain. Not only "super-weak" layers may cause stress and strain rate concentrations but also abrupt slope-angle variations of extended avalanche slopes. The basic situation is presented in Fig. 2.

The here presented terrain and snow cover conditions are more or less a copy of the ones which occurred during the second and third intense avalanche cycle of the winter 1998/99.

A special purpose finite element program was developed at the SLF by Stoffel and Bartelt (2002 in press). It enables to simulate the basic mechanical properties of snow using a snow creep model describing viscoelastic material behavior, which was experimentally determined over a wide range of densities, strain-rates and temperatures by Scapozza and Bartelt (2002 in press). In a first step the elastic stress state in the snowcover under self-weight is found. Then a viscous solution, depending on density, temperature and the calculated stress state, is determined according to the experimentally based material law. The following multi-dimensional relation between stress and strain rate, introduced by Bader and Salm (1990) was used.

$$-\sigma_{ij,j} = \rho F_i \qquad (1)$$

$$\sigma_{ij} = \eta \left[\dot{\epsilon}_{ij} + \frac{\dot{\epsilon}_{ll}\delta_{ij}}{m-2} \right] \qquad (2)$$

$$\dot{\epsilon}_{ij} = \frac{1}{2}[v_{i,j} + v_{j,i}] \qquad (3)$$

where:

- σ_{ij} components of the stress tensor
- F_i specific body force (gravitation)
- ρ density
- $\dot{\epsilon}_{ij}$ components of the strain rate tensor
- η viscosity
- $v_{i,j}$ partial derivative of the velocity in direction i with respect to x_j
- δ_{ij} Kronecker symbol
- m inverse of the viscous analogue of Poisson's number – set to 5 by Bader and Salm (1990). Based on the experimental tests we set m=∞, which uncouples the stress directions.

With the boundary conditions:

$$v_i|_{\text{ground}} = 0 \qquad (4)$$

$$\sigma_{ij}n_j|_{\text{top}} = 0 \qquad (5)$$

$$(6)$$

i.e. stress free at the surface and zero velocity on the ground. Periodic boundary conditions are employed on the sides, in order to model infinitely long slopes.

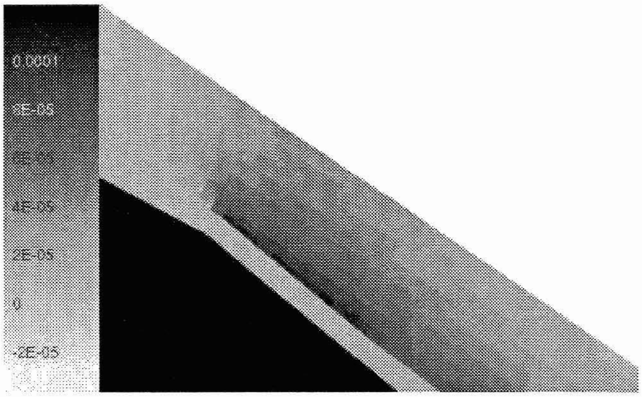

Figure 3: Calculated strain rate in x direction.

The model domain is as shown in Fig. 2. The temperature and density of the two main layers were varied, as well as the height of the top layer. At a critical density of 180kg/m^3 for the top layer and a temperature of -5 °C as well as 350kg/m^3 for the bottom layer and a temperature of -2 °C.

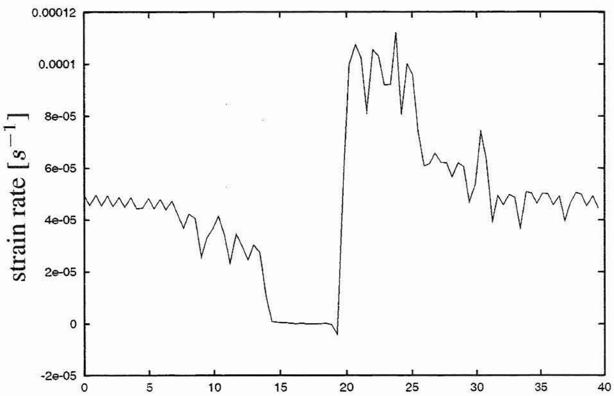

Figure 4: Calculated strain rate at the old/new snow interface in x direction.

A critical strain rate of more than 1.1 x 10^{-4}s^{-1} could be reached between the old and new snow interface (see Fig. 3 and 4). The stress state is shown in Fig. 5 and reaches values high enough to satisfy the stability condition S$\leq$1. Thus, the finite element simulations indicate that in the specified configuration natural slab avalanches could occur.

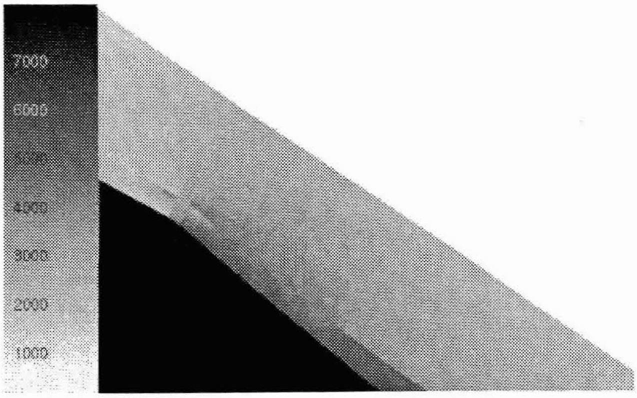

Figure 5: Calculated stress [Pa] in x direction.

3. Forecasting of large new snow slab avalanches

Avalanche forecasting is operational in various countries since about 1950. It is used for regional warning and partly also for the avalanche safety on highways and railroads. In the beginning traditional meteorological measurements and snow pack observations were used to determine the danger level (e.g. Atwater, 1954). In the seventies new methods like "multivariate data analysis" (Bois et al., 1975) and/or combinations of statistical and deterministic methods (Bovis, 1977; Foehn et al., 1977; Foehn and Haechler, 1978; Judson et al., 1980) were attempted, which improved the data analysis and the objectivity. In the eighties "nearest-neighbour" methods were favoured (Buser et al., 1987), finally in the nineties various expert models were implemented (Giraud, 1994; McClung, 1995; Schweizer et al., 1996) and in the same time a new, very adequate technique was developed: a hybrid, neural expert system (Schweizer M. et al., 1994).

All these models have been tried out and were consequently used for some time, but only a few were later used on a daily basis. The reasons are manifold (inadequate technique for a specific problem area, poor results in operational use or solely too demanding data structure, etc.).

It is clear that all purely statistical and also nearest neighbour approaches are not suited to forecast scarce large new snow avalanches. Deterministic methods and partly rule based expert systems are well to be the fore. During the extreme avalanche period 1998/99 in Switzerland after the analysis of weather, snowfall, snow profiles, rutschblocks and avalanche observations mainly a rule based decision making for the degree of danger was used. Also the deterministic-statistical model (DET-STAT) of Foehn and Haechler (1978), revised by Meister (1990), was daily consulted and yielded, as the only forecast – model for large new snow avalanches, useful information. The beginning of the third and most dramatic avalanche cycle on the 18./19. 2 99 was well indicated (see Fig. 6).

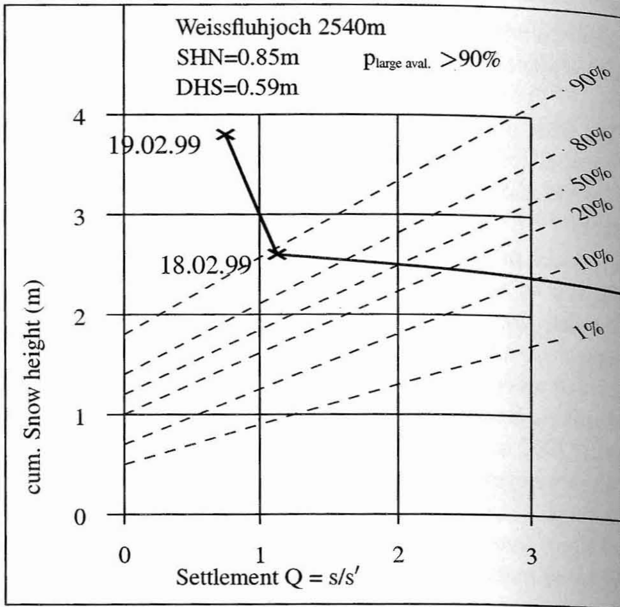

Figure 6: Probability (%) of large new snow avalanches as a function of a cumulated snow height and relative settlement.

Owing to roughly 50 additional new snow/ weather stations situated since the nineties in the fracture zone of avalanches (Stucki et al., 1998) a fair picture of the snow and weather conditions on the avalanche slopes was possible. Daily used parameters were: New snow, 3-day sum of daily new snow, total sum of new snow since beginning of snowfall, snow height, mean and maximum daily wind speed, mean daily temperatures and temperature changes. The visual correlation of these parameters with the daily number of avalanches and the concurrent danger degrees in two regions is presented in Fig. 7. The new snow amounts are found by a numerical snowpack model which calculates the settelment and temperature distribution within the snowpack (Bartelt and Lehning, 2002).

As the dominant index for the begin of a dry new snow avalanche cycle was once more established a new snow sum(ΣHN3) of 100cm resulting from continuous snowfall within 1 to 3 days (Foehn and Haechler , 1978; Schneebeli et al., 1998). This context is well documented on the uppermost and on the two lowermost diagrams of Fig. 7. The main avalanche activity started when the ΣHN3 reached 100cm in the first cycle and in the next 2 cycles it was close to 100cm probably due to other influences (previous avalanche activity, rising temperature). An additional condition for such an avalanche period is also the fact that new snow is deposited on a sufficiently thick base layer of old snow (HS > 1-1.5m). The lower value corresponds to the snow depth in valley grounds, the higher value to rough Alpine terrain in the starting zones.

The next 2 parameters on Fig. 7: "Air temperature" and "wind speed" describe quite well the typical conditions of a catastrophic new snow avalanche cycle. It is symptomatic that the first two snowfall- and avalanche-periods happened during cold air advection (accumulation of loose, dry snow) whereas during the last and most intensive avalanche cycle the air temperature raised in the fracture zone continuously up to -4°C. This way the stiffness of the upper slab layers decreased and led to the last intensive avalanche cycle. The wind speeds in the fracture zone were during the first 2 avalanche cycles well above the critical limit of about 40km/h for which an appreciable snow drift must be expected.

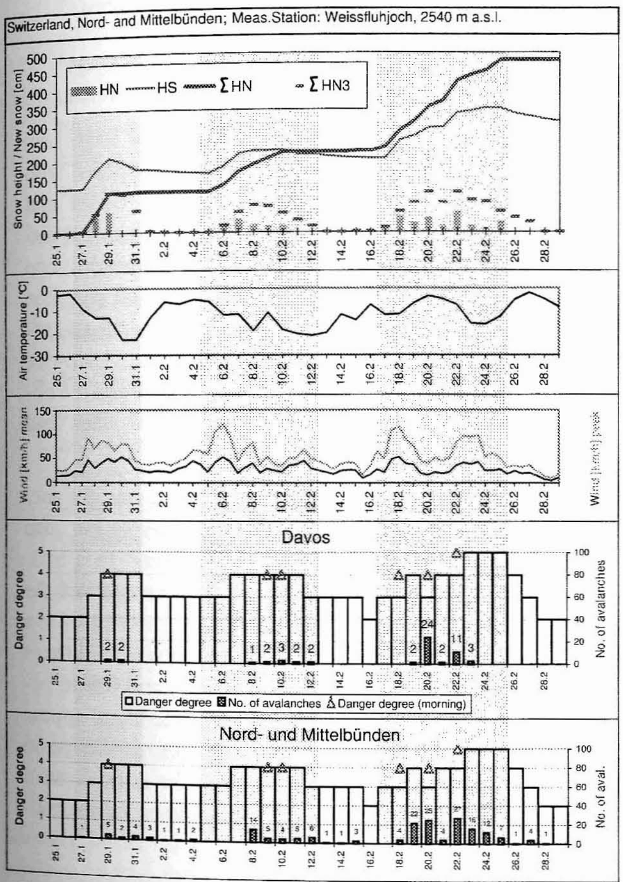

Figure 7: Daily measurements and/or observations of new snow (HN), snow height (HS), total new snow sum, three day sum (ΣHN3), air temperature and wind speed. The two lowest diagrams present the daily number of large avalanches and the daily forecasted avalanche danger degrees in two regions.

The 2 lowermost diagrams on Fig. 7 yield the daily forecasted"danger degrees" in two areas: "Davos" and in the larger area of "Nord- and Mittelbünden".

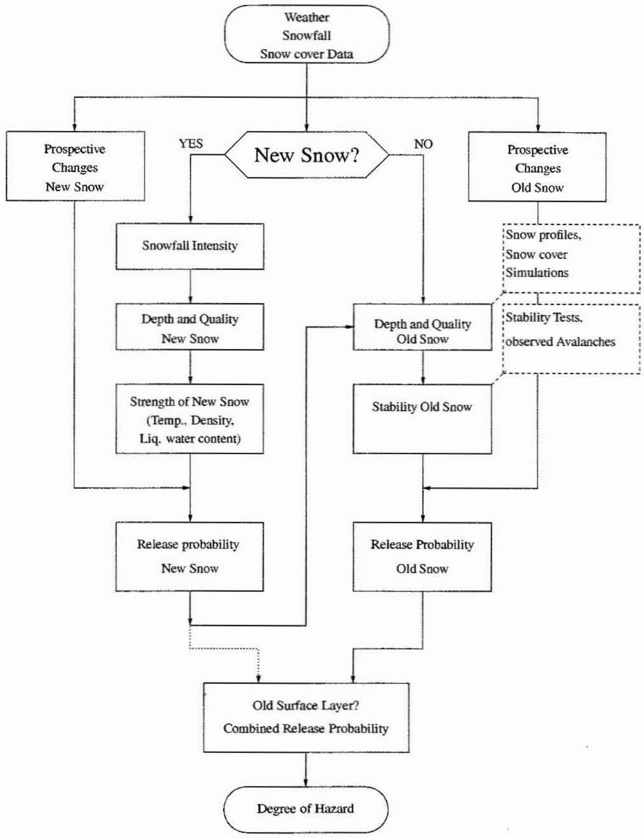

Figure 8: A flow diagram for forecasting New Snow avalanches.

During the first two avalanche cycles the indicated danger degrees may be rated "adequate" compared with the number of medium to large avalanches observed for the same day. (The triangles mark "early morning warnings", issued as a correction or a confirmation of the "yesterday's"-evening warning).

The third avalanche cycle was the most dramatic one and posed much more problems than the two before, because the intense snowfalls were superposed by a strong warm air advection.

As we see from Fig. 7 and 9 during extreme avalanche periods mainly meteorological factors (Class III) and some snowpack factors (Class II) are under compulsion decisive. This means according to McClung and Schaerer (1993)" a more uncertain interpretation and less direct evidence". However, also the snow profile analysis and the rutschblock interpretation (Class I factors) are very important before an intensive and intermittent snowfall period starts, because by this means the release probability of the old snowpack and the combined release probability (i.e. fragile surface layers) can be clarified. The stepwise stability analysis is presented in Fig. 8.

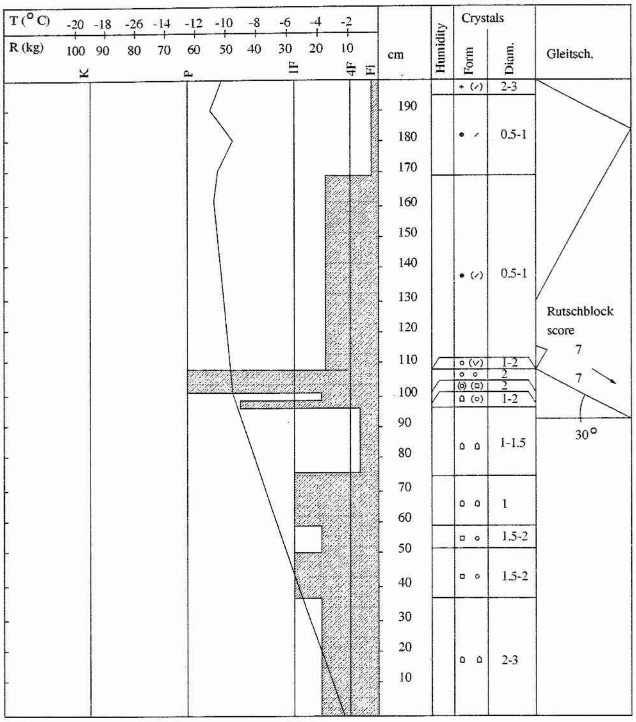

Figure 9: Snow profile from Weissfluhjoch, 2540m a.s.l. meausured on the 29. 1. 1999, 13:00. The rutschblock test shows a potential shear horizon at the base of the deposited new snow layers (snowfall: 27. - 29. 1. 1990) The rutschblock score 7 indicates a low release probability.

4. Importance of weather forecast

During large new snow avalanche cycles the weather and precipitation forecast play a very important role, because these avalanche are mostly "direct-action" avalanches, as we have illustrated also in the chapter "Avalanche formation". Unfortunately – according to the informations from Swiss meteorologists (Meteo Swiss, 2001) – intensive precipitation (and snowfall) periods may regionally not be forecasted better than with a success rate of about 60%. Hence because the Swiss avalanche forecasters in normal winter conditions claim – according to public inquiries – a success rate for their hazard rating between 60 and 70%, the combined success rate, i.e. the forecasting of cycles of large new snow avalanches, amounts to about 60%.

Figure 10: Release Area of large new snow avalanches during the last avalanche cycle (19.-25. 2. 1999).

5. Conclusions

Analysing the possible release mechanics of large new snow slabs, we searched for alternative solutions with regard to the "super-weak" layer solution of Bader and Salm (1990). We used basically a similar mechanical disposition, but we do not use an extended "super-weak" zone as a stress concentrator. Instead, we introduced a common terrain feature, a "knee bend" (see Fig. 2) slope for this effect. The numerical calculations for stress and strain-rate distributions for (potential) large slab avalanches and the observation of a real period of large dry new snow slabs lead to the following conclusions:

- Natural release of large dry snow slabs seems not only possible with a priori "super-weak" layers but also with the above mentioned terrain effect. In a two-layered slab the "knee bend" slope concentrates the strain rate at the base of the thick new snow layer to a rate of 10^{-4} s^{-1}, a value in the range which belongs to the transition zone between ductile and brittle behaviour, meaning that material imperfections appear (Narita, 1980). Salm (1971), St.Lawrence (1977) and McClung (1987) all mentioned that the critical strain rate in tension and in shear is equivalent to a strain-rate on the order of $10^{-4}s^{-1}$.
- The simulated strain at the base of the thick new snow layer amounts to 6 x 10^{-4}. At this strain range low density snow delates, shows strain softening and forms slip surfaces and damage zones. It is assumed, as also mentioned by McClung (1987), that for failure this deformation should change from creep to failure and then to fracture.
- Stability condition: Considering the stress zone at the base of the new snow layer (see Fig. 5) the stress attains the same order of magnitude as the usual strength values.

The fracture propagation of the shear instabilities and changing temperature effects are not analysed here, because these additionally important aspects go beyond the purpose of this paper.

The analysis of the short-term forecasting aspects of large new snow avalanches reveals the following facts:

- As we know, avalanche forecasting in general is often called "a mixture of art and science". This is especially true for the forecasting of large, new snow avalanches. Whereas the usual avalanche activity in a winter is intensively analysed in many mountainous countries around the world, the large new snow avalanches received in the past only a sufficient importance in avalanche-prone and densely populated areas/or in countries where they endangered important highways, mines, etc. There are only very few forecasting models, which explicitly deal this avalanche type. Add to this that all forecasting models, which have a purely statistical basis, are not suited for this special type of avalanches.
- The weather forecasts, indicating the precipitation/snowfall forecasts have a much higher status for large new snow avalanche cycles than for usually small avalanches (eg. Davis et al., 1999).
- We know much less about the formation aspects of these large avalanches than about the usual, small and often "skier"-triggered slabs. This category of avalanches is somehow also inscrutable due to high danger levels, which may pertain for weeks as the catastrophic avalanche period of 1998/99 documents.
- Because this type of avalanches has often a large recurrence interval research projects are difficult to establish, so the state of knowledge improves only slowly.

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