Avalanche Forecasting for Transportation Corridor and Backcountry in Glacier National Park (BC, Canada)

Jürg Schweizer[1] and J. Bruce Jamieson
Department of Civil Engineering, University of Calgary, 2500 University Drive NW
Calgary AB T2N 1N4, Canada

David Skjonsberg
Avalanche Control, Mt. Revelstoke and Glacier National Parks, PO Box 350
Revelstoke BC V0E 2S0, Canada

ABSTRACT. The Avalanche Control Section at Rogers Pass is responsible for avalanche safety on the Trans Canada Highway and Canadian Pacific Railroad within Glacier National Park and for the daily issue of an avalanche warning bulletin for backcountry users of the park. During the winter of 1995-96 a small research project made shear frame tests of persistent weak layers at a study plot near tree line to study strength changes. The shear frame data were also used to assess the snow stability in the surrounding terrain. Concurrently, at the same location, traditional meteorological and snowpack observations were made to assess snow stability for operational use. The two methods of stability assessment are compared and related to the avalanche activity (natural and artificial) along the highway and in the adjacent backcountry for an active storm and avalanche period. At that time avalanche forecasting strongly depended on a buried surface hoar layer that showed some interesting behaviour. Shear frame measurements proved again to be an important parameter to assess snow stability. Experience in winter 1995-96 suggests that a combination of shear frame measurements in study plots with stability tests on slopes is most efficient since it reveals (1) the temporal development of instabilities, and (2) the spatial distribution of instabilities and the reactivity on artificial triggering, strongly depending on slab properties.

Key words: snow strength, shear frame measurements, snow cover stability, avalanches, avalanche forecasting, avalanche control

INTRODUCTION

The Avalanche Control Section at Rogers Pass is responsible for avalanche safety on the Trans Canada Highway (TCH) and Canadian Pacific Railroad (CPR) within Glacier National Park (British Columbia, Canada) and for the daily issue of an avalanche warning bulletin for backcountry users of the park. Whereas the first task is well known and procedures are established (Schleiss and Schleiss, 1970), increased winter backcountry usage has added a new set of clients.

Backcountry avalanche information has been available in various forms for many years. The main method for disseminating avalanche information is the information center at the summit of Rogers Pass. Since 1992, winter recreationists have been able to access the current avalanche warning bulletin by phone. A recorded message is revised each morning and contains the current weather conditions, a discussion of the snow stability, an assessment of the present avalanche danger and forecasted trends when changes are expected. In 1998, internet access to the current backcountry avalanche warning bulletin was introduced. With the large increase in winter backcountry use, an objective of the

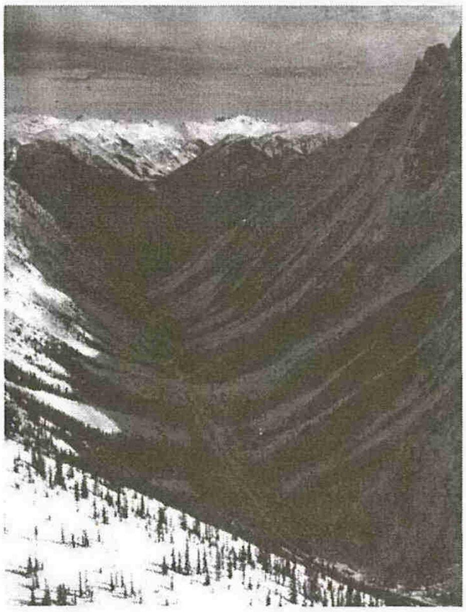

Fig. 1. Rogers Pass looking east into the Connaught Canyon, the part of the Trans Canada Highway most exposed to avalanches.

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[1] Permanent address: Swiss Federal Institute for Snow and Avalanche Research, Flüelastr. 11, CH-7260 Davos Dorf, Switzerland.

program had been to improve the level of service. The present priority is to find better methods to assess backcountry avalanche danger over a large area and communicate the pertinent factors to the backcountry users in terms they can understand and utilize. This should result in better decision making and a reduction in backcountry avalanche incidents.

Nevertheless, protection of the transportation corridor which is vital to the Canadian economy remains as the main priority. Costs of traffic delays due to short closures are the main factor contributing to the economic impact of avalanches in Canada. Morrall and Abdelwahab (1992) estimate the cost of a two hour closure for avalanche control at \$50'000 to \$90'000 depending on proportion of heavy trucks in traffic volume of 350 vehicles/h in each direction. Since avalanche-related closures in Rogers Pass total about 100 hours in an average winter, the cost approximates a few million dollars per year.

During the winter 1995-96 a small field research program studying the strength changes of persistent weak layers was performed in the study plot of the Mount Fidelity observation site. The data from this study can be used to assess the snow stability in the surrounding terrain. Concurrently at the same location, traditional meteorological and snowpack observations were made to assess stability for operational use.

Based on the description of the snow conditions and avalanche activity during 1-17 January 1996, we will compare the two methods and draw conclusions about their potential for backcountry and highway forecasting.

GEOGRAPHIC AREA, PROCEDURES AND METHODS

Glacier National Park is located in the Selkirk range of the Columbia Mountains in western Canada (Fig. 1 and 2). It is well known for its maritime climate influence with large amounts of precipitation. Average annual snow fall is just about 15 m at 1905 m a.s.l. (Fig. 3). The Park is divided centrally by the TCH/CPR, both running east-west. Control and/or monitoring is carried out on 144 avalanche paths that affect the transportation corridor (Schleiss, 1989). Most of the large paths that affect the highway have start zones between 2200 and 3200 m a.s.l.

Fig. 2. Map of the area

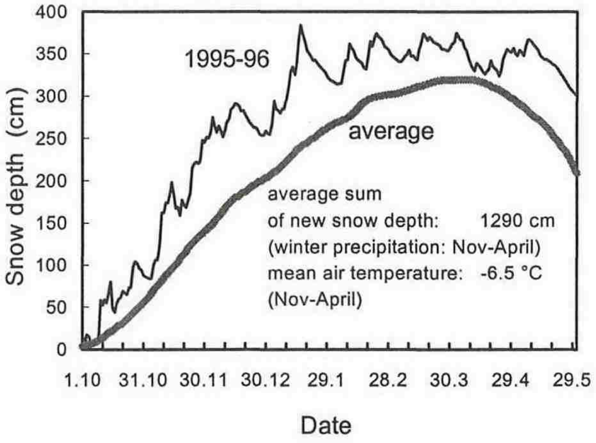

Fig. 3. Snow depth at Mt. Fidelity 1905 m. Long term average and winter 1995-96.

Due to this high exposure and its importance as an economic and transportation link, the avalanche control program was established prior to the construction of the TCH in 1959. The Rogers Pass route has had a long history of avalanche problems dating back to the completion of the railway in 1885. The avalanche defense study by Schaerer (1962) showed that the cost of constructing avalanche defenses that would guarantee a continuously open highway would be unreasonably high. Although it had not been previously attempted on this large a scale, avalanche control by artillery fire was implemented. It has proven to be a relatively cheap and versatile method providing safety from avalanches that could not be controlled economically by other methods.

Based on a network of observational sites, snow stability is evaluated, and when necessary the TCH and CPR are closed and avalanches are artificially released using artillery. Presently, both the 105 mm Howitzer and 106 mm Recoilless Rifle are used, directed from 18 gun positions to over 240 designated targets; probably the largest mobile control program in the world.

The program has evolved to meet changing safety standards, fiscal restraints and about a five fold increase in traffic volumes from 1962 to 1991. Whereas it was once a required standard to maintain an instantaneous emergency response capability to the rapidly changing snow and avalanche conditions, the current standard is to maintain a level of service which is designed to meet average conditions. For example, the park gates and the staff that were once needed to inform and control traffic when necessary (24 hours a day during winter) have been removed. This has placed more emphasis on a system of avalanche hazard analysis which will provide adequate time to put traffic and avalanche control operations into place in advance of these rapidly changing situations.

The principle observation site is a study plot and test slopes located on Mount Fidelity at 1905 m a.s.l. The observatory is located 900 m above the highway near the west entrance to the park. It is accessible on a road by over snow vehicle. When necessary avalanche control staff are housed

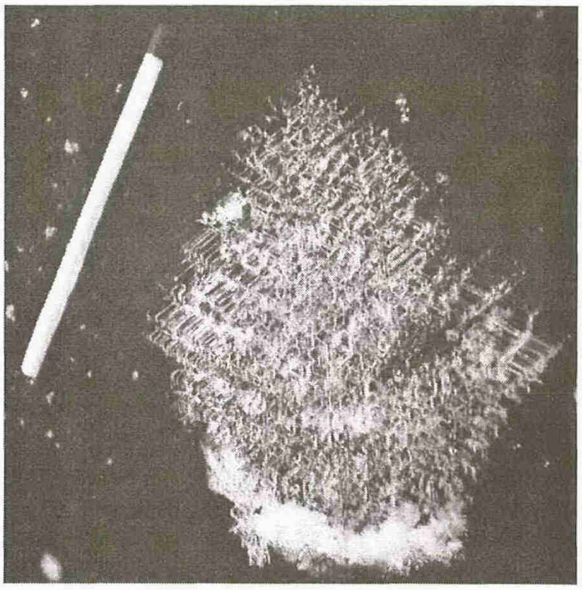

Fig. 4. Large surface hoar crystal found at around 1500 m a.s.l. below Mt. Fidelity, shortly before buried with new snow on Dec 28, 1995.

at the facility and monitor meteorological and snowpack conditions continuously. Snow depth, new snow, storm snow, air temperature, humidity, precipitation, new snow density and barometric trend are measured or recorded manually each morning at 07:00. If an observer is present at the station, the readings are taken also at 16:00. An automatic station continuously measures new snow depth, temperature, humidity at the study plot (1905 m a.s.l.) and wind speed and direction (and temperature and humidity) at Round Hill (2080 m a.s.l.) on the ridge above the main station. Three additional automatic stations are located within the control area and collect similar data which all is transmitted by radio modem to the control center at Rogers Pass (1315 m a.s.l.).

In addition to these standard observations, shear frame tests are performed in the level study plot whenever it is considered important to assess the stability of new (or storm) snow. The shear strength of weak layers near the surface, primarily in the recent storm snow (usually in the uppermost 60 to 80 cm), identified by the tilt board method (CAA, 1995), is tested with a 100 cm^2 shear frame. For each layer found, a minimum of three measurements are done, and the value of the best test is recorded. The weight of the snow column above the weak layer is measured using a standard snow sampling tube. The measured force at failure is divided by the frame area to get the shear strength. To calculate the so-called stability ratio (CAA, 1995) the shear strength is divided by the weight per unit area, i.e. the stability ratio compares the shear strength of the weak layer to the load on the layer. Historically, the stability ratio was called stability factor by Schleiss and Schleiss (1970); they considered snow stability as to be critical when the stability factor was less than 1.5. Periodically snow profiles are taken in the study plot and on adjacent avalanche slopes which usually incorporate rutschblock (Föhn, 1987b) and compression tests (Jamieson and Johnston, 1997). Stability tests using explosives are performed to assess the potential effectivity of artillery control. The non-daily observations depend on operational requirements.

During the winter 1995-96 the shear strength of prominent, persistent weak layers was measured in the study plot following the procedures established by Jamieson (1995). Measurements were done twice a week for shallow layers (< 70 cm) and about once a week for layers buried more than 70 cm. A full snow profile was taken with each set of measurements (at least 12 measurements per layer). Three layers were monitored during the winter 1995-96. All of them were surface hoar layers that where present in most parts of the Columbia Mountains from the Cariboo range to the Bugaboo range. Surface hoar layers were buried on Dec 28, Feb 3 and Feb 17, respectively. The profiles and measurements in the study plot were periodically supplemented with the same measurements and additionally a rutschblock test on adjacent test slopes. The shear frame measurements were used to calculate the indices of natural and skier stability as introduced by Föhn (1987a) and refined by Jamieson (1995). Jamieson's (1995) nomenclature and definitions for the extrapolated indices are used: S_{N38} and S_{K38} for the natural and the skier stability index, respectively. These stability indices are calculated for 38° slopes, include adjustments for frame size, for microstructure-dependent effect of normal load on weak layer, and (in the case of S_{K38}) for ski penetration.

To compare the two methods of shear frame tests and the resulting stability parameters, the three weeks from 28 Dec 1996 to 17 Jan 1996, an interesting storm and avalanche period, are described in detail.

THE STORM AND AVALANCHE PERIOD FROM 28 DEC 1995 TO 17 JAN 1996

Snow and weather

Abundant snow fall in November and the first half of December had built up an unusual thick and generally stable early winter snow cover (Fig. 3). Skiing conditions were excellent. During a ten day period of sunny weather during

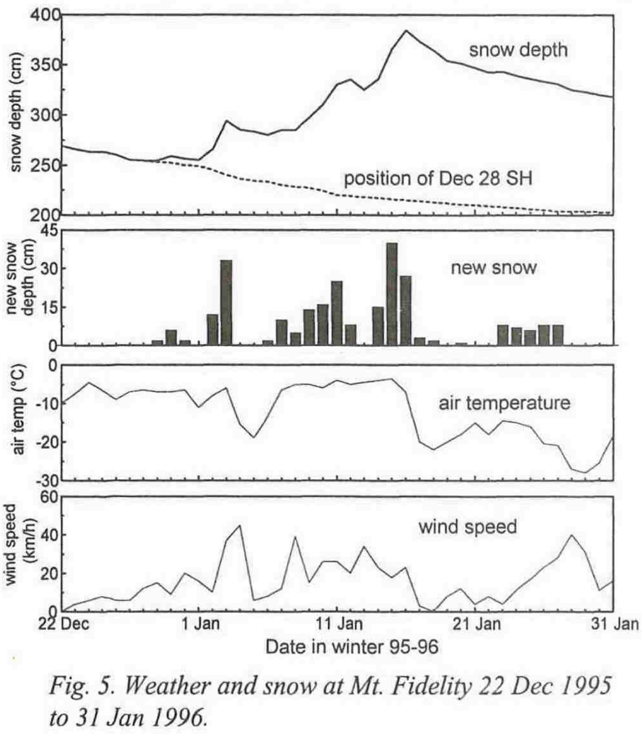

Fig. 5. Weather and snow at Mt. Fidelity 22 Dec 1995 to 31 Jan 1996.

and after Christmas large surface hoar crystals (some up to 8 cm) formed in particular at and below tree line (Fig. 4). To the end of this period it was even possible to trigger small loose snow avalanches consisting of only surface hoar crystals, a rarely seen phenomenon. The layer was most prominent (average layer thickness about 1-1.5 cm, average crystal size 10-20 mm) at elevations between 1500 and 2000 m. (Schweizer et al., 1997).

This fragile surface layer was slightly covered with snow at the end of the month (Dec 28). The weather and snow development is summarized in Fig. 5. Values given below refer to measurements in the study plot at Mt. Fidelity.

On Jan 3, after the first storm in 1996, the surface hoar layer was buried about 40 cm. The new snow was light and nearly cohesionless. Ram penetration (CAA, 1995) was about 60 cm and ski penetration was about 40 cm, i.e. comparable to slab thickness.

While the air temperature increased by about 12 °C in two days, the next moist system moved in on Jan 6 with steady light to moderate intensity lasting almost a week. The highest snow fall intensity was during the night of Jan 11. The total storm snow was 86 cm; the prevailing relatively mild temperatures favored settlement; snow depth increase was 50 cm; ram penetration on Jan 12 was only 40 cm.

Snow fall continued after a very short calm period and within the next three days (Jan 14-16) another 82 cm of snow fell. It cooled down towards the end of the storm and during the next ten days it was mainly cold and cloudy but without major precipitation; the snow pack settled substantially. The surface hoar layer was now deeply buried; on Jan 27 it was 110 cm below the surface in the study plot at Mt. Fidelity.

Stability

Primary parameters for stability evaluation include upper elevation meteorological data (e.g. to assess snow transport by wind), index values from study plots, stability tests from slopes (rutschblock and compression tests, hand charges) and avalanche activity. In the following we concentrate on the shear frame measurements, and in particular on the ones done on the Dec 28 surface hoar layer. This layer was the most prominent weak layer during the period considered. Other new snow instabilities were identified in the tilt board tests, but none of these layers survived more than a few days.

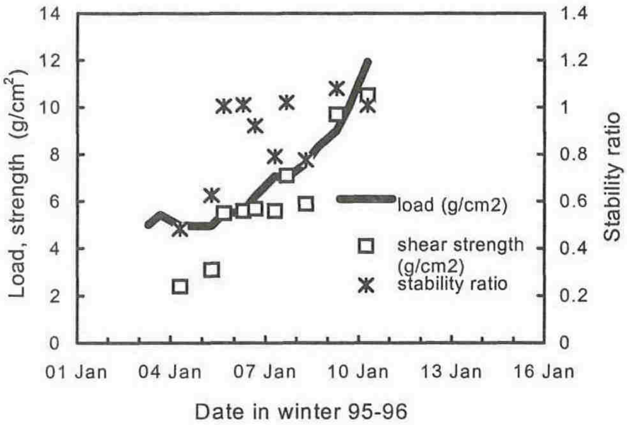

Fig. 6. Results of shear frame tests on Dec 28 surface hoar at Mt. Fidelity 1905 m. Shear strength and normal load (measured), and thereof calculated shear ratio are given.

Fig. 6 shows the results of the shear frame tests performed operationally between 4-10 Jan 1996 with the 100 cm^2 shear frame. The normal load is steadily increasing. The shear strength values generally increase from about 2 g/cm^2 to 10 g/cm^2 in 6 days (these values given in the traditionally used units would correspond to shear strength values of about 100 to 500 Pa, including frame size adjustment). There is substantial scatter, probably since the values shown are not averages and were determined by four different operators. Accordingly the same is true for the stability ratio. Starting at about 0.5 (on Jan 4 and 5), the stability ratio is fluctuating approximately around 1.0 between Jan 6 and 10. This is considered as a low value for the stability ratio, clearly indicating instability. A linear regression shows an increasing trend for the stability ratio (about 0.07 per day), however the correlation between time and stability ratio is just not quite significant ($N = 10$, $r = 0.63$, $p = 0.053$), taking a level of significance (p) of 5 %.

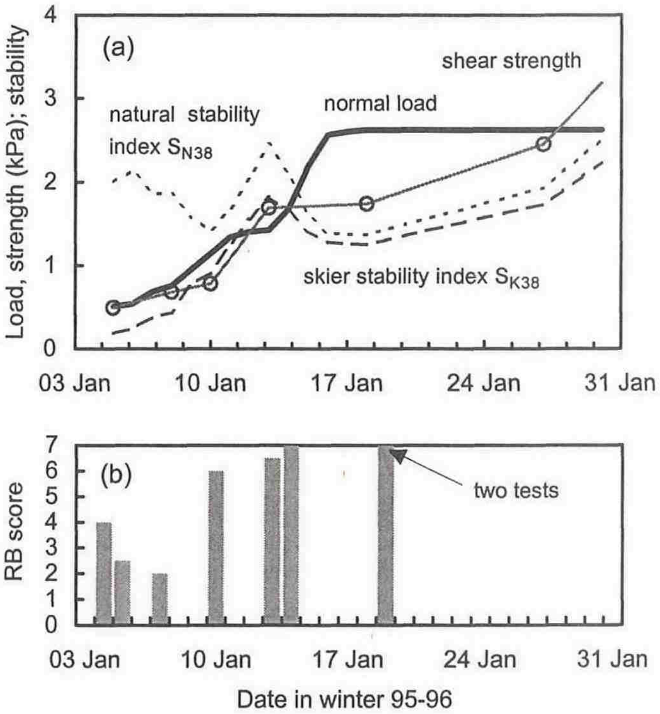

Fig. 7. (a) Changes in Dec 28 surface hoar layer at Mt. Fidelity 1905 m a.s.l.: shear strength (circles indicate measurements), normal load and thereof calculated stability indices S_{N38} and S_{K38}; and (b) results of rutschblock tests from the adjacent backcountry.

Complete snow profiles together with sets of shear frame measurements on the Dec 28 surface hoar layer were taken on Jan 5, 8, 10, 13, 18 and 27 as part of the research program. These data were used to calculate the extrapolated stability indices S_{N38} and S_{K38} for natural and skier stability, respectively (see above) (Jamieson, 1995). The results are given in Fig. 7a.

The shear strengths values are low (around 500 Pa) at the beginning and increase up to 3 kPa in the period considered. The increase is continuous, but not uniform. Shear strength values given are averages of at least 12 measurements (average S.E. 16 %). The different amount of increase might be due to the loading conditions (Jamieson and Johnston, 1995). Using the daily observations from Mt. Fidelity, daily values can be established for the load. Simply assuming a linear increase of the shear strength between consecutive measurements, daily values of the stability indices can be calculated, as also proposed by Jamieson (1995). The variation of the natural stability index is substantial and quite surprising. Lowest values were observed around Jan 10 and between Jan 15 and 20. There is a relative maximum around Jan 13. These features are significant and coincide with (or better: are caused by) the loading pattern: Decreasing stability during periods of heavy precipitation, increasing stability in periods without precipitation. The data show clearly that the snow stability is in general decreasing (statistically significant: $N = 60$, $r = 0.30$, $p = 0.022$) as long as the loading continues (till about Jan 16) and then increasing slowly for about a week and improving significantly towards the end of the month.

The two series of data (Fig. 6 and 7a) can only be compared for the short period between Jan 5 and 10. However, due to the substantial differences between the two procedures (e.g. type and number of measurements and operators) the comparison might not be conclusive. Additionally, when frame size adjustments (Föhn, 1987a) are applied to the shear strength data with the 100 cm^2 and the 500 cm^2 frame, values from the 500 cm^2 frame are generally larger. Nevertheless for the 5 day period for which the data can at all be compared, both series of measurements indicate consistently low, slowly increasing shear strength values. Stability parameters (ratio, index) derived from the different shear frame measurements indicate slightly increasing (100 cm^2) and clearly decreasing natural stability (500 cm^2), respectively. The avalanche activity (see below) clearly supports the decreasing trend for the stability determined by the 500 cm^2 shear frame measurements.

Skier stability is increasing with increasing depth of the weak layer (Dec 28 surface hoar) (Figure 7a). The data suggests that skier triggering is likely before about Jan 9, and unlikely after about Jan 27 (Jamieson, 1995). After about Jan 16, at the end of the storm period, there is no longer any significant difference between the two indices of stability, since the weak layer is deeply buried and the additional skier stress accordingly becomes insignificant.

Rutschblock tests on Jan 4, 5, 7, 10, 13, 14 and 19 (two) near Mt. Fidelity or from the adjacent backcountry area revealed scores of 4, 2.5, 2, 6, 6.5, 7, 7 and 7, respectively (Figure 7b). This small sample is in good agreement with the skier index S_{K38}. The high values after Jan 10 are well explained by the strength data and the slab thickness.

Forecasting

Fig. 8 shows the forecasted avalanche danger for the backcountry as a line and the highway forecast as a bar graph. The avalanche forecast for the transportation corridor considers three levels: green/no bar (open), yellow (warning, restrictions, preparations for closure) and red (closure). The closures represented are due to avalanche control and highway clearing operations for avalanches which deposited mass on the highway, e.g. on Jan 11 the highway was closed for more than 20 hours.

Of particular note regarding the backcountry forecast is the number of days in which the low elevation areas were forecasted with a higher danger than the higher elevation areas.

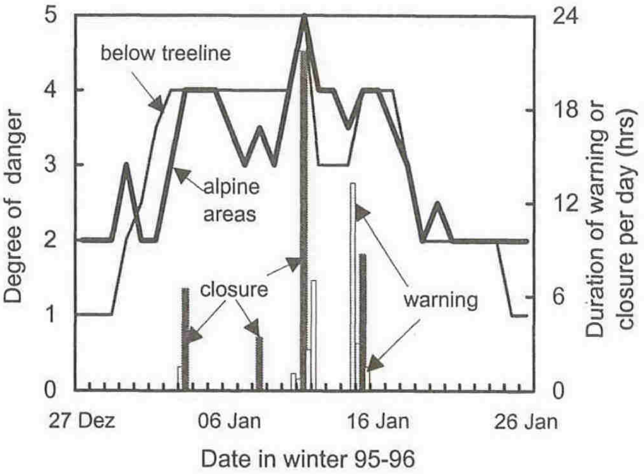

Fig. 8. Avalanche forecast for backcountry (bold line: in alpine areas, thin line: below tree line) and transportation corridor (bars indicate duration of warning levels or closures).

Avalanche activity - transportation corridor

During the first two weeks of January four major avalanche cycles occurred (3, 8, 11 and 15 January 1996). Each started as a new (or storm) snow event and resulted in a control operation.

The first two storms produced many small avalanches. Both of these cycles involved high elevation targets with little slab propagation. Natural avalanche activity was confined to very steep high elevation areas (above about 2200 m a.s.l.) not necessarily involving the Dec 28 surface hoar layer. During the following short period of sunny and cold weather very little avalanche activity occurred. It seems that the new snow was not cohesive enough to form slabs.

The cycle of 10-11 January 1996 was much larger in terms of numbers of avalanches and especially of extent. Significant loading had resulted from wind gusts in excess of 70 km/h and storm snow amounts just under one meter. Avalanches that were artificially released in previously shot targets were large enough to initiate the weak layer found at the lower elevations. Consequently large snow masses were released. The speed and run outs were notable and 15 controlled avalanches terminated on the TCH and one onto the CPR mainline. This control program, combined with the one of Jan 15, which picked up some of the surviving lower elevation weak layers, effectively eliminated the danger from that particular instability (Dec 28 surface hoar) for the highway control area.

Fig. 9 describes the avalanche activity observed along the transportation corridor by a single value per day. The avalanche activity index represents the mass of avalanche snow released. It is the sum of all avalanches observed considering a weight according to the size of the avalanche (Canadian avalanche classification) (McClung and Schaerer, 1993). The weights are 0.01, 0.1, 1 and 10 for the sizes 1 to 4, respectively, assuming that the mass, and correspondingly the power of an avalanche, increases 10 times each from one

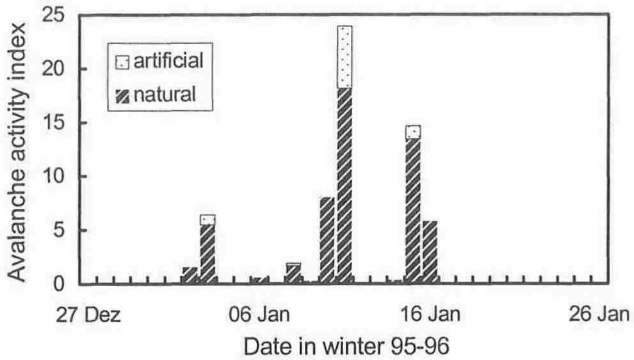

Fig. 9. Avalanche activity index along the transportation corridor. All recorded (natural and artificial) avalanches, sliding on all layers, are given in combination, using weighting factors to consider size and type of triggering.

size to another. The avalanche activity index is primarily given for natural avalanches. Artificial avalanches can be included by considering a weighting factor according to the power of the trigger (Föhn and Schweizer, 1995). In the case of explosives the weighting factor is about 0.2. Accordingly the avalanches resulting from the control operations are included in Fig. 9. On Jan 11, e.g., the avalanche activity index includes 37 natural avalanches and 54 triggered by artillery fire, all of size 2 or 3.

Avalanche activity - backcountry

From the backcountry four avalanche involvements (skier triggered) were reported: three on Jan 8, one on Jan 9. On Jan 14 a slab was remotely triggered. For all these avalanches in the lower elevation backcountry the Dec 28 surface hoar layer was reported as the failure plane. Skier triggering is in contrast to the negative shooting results on Jan 8, but likely due to the spatial distribution of the surface hoar layer. Skier triggering seems to be clustered around January 8. This feature might be explained by the slab properties: medium thickness (about 50 cm) and no longer very light but slightly consolidated snow (due to the warming). It also coincides well with the results from the rutschblock tests (Fig. 7b).

DISCUSSION

The Dec 28 surface hoar layer was decisive for the stability evaluation during the first weeks of January 1996. Its behavior was interesting in many respects. It was not at all as reactive as originally suspected, or at least not then when assumed. Four points were of particular interest:

(1) The layer was only prominent in a certain range of elevations, roughly between 1500 and 2000 m.

(2) The layer was not very reactive at the beginning. The propagation was insufficient due to the low consolidation of the slab above. Clean-out shootings were unsuccessful in the first attempts, probably due to the specific distribution of the weak layer.

(3) The layer became reactive, when the main concern was directed towards a more recent new snow instability. The new snow instability finally triggered the surface hoar leading to the release of large masses of snow; again the unusual distribution in elevation favored this.

(4) Skier triggering was infrequent and in particular became surprisingly infrequent soon, i.e. no involvements were reported in the second half of January, after the storms.

Despite the rather unusual nature of the instability, other aspects were well recognized. Avalanche safety was fully warranted.

The uneven distribution of the Dec 28 surface hoar layer was clearly recognized due to field observations. Accordingly the forecasted degree of danger for the backcountry was often higher below tree line than in the alpine areas (Fig. 8).

The low reactivity in the very first days of January was clearly recognized and explained by the insufficient consolidation of the snow above the weak layer. Obviously it was not possible to impart the critical deformation over a sufficient area to start slab failure. It reinforced the concept that triggering depends not only on the strength (or lack of it) of the weak layer (that was very low, in fact), but also on the properties of the slab above (Schweizer et al., 1995, Camponovo and Schweizer, 1997). This also explains why there was no skier triggering despite the very low values for the skier stability index.

The eventual widespread release of dangerous layers such as the Dec 28 surface hoar layer during the cycle of Jan 11 is clearly possible as long as the weakness survives which is, however, rather unusual within a control program. Avalanche activity was minor during the first two cycles, suggesting that the surface hoar layer survived. In retrospect, the stability indices derived from the 500 cm^2-shear frame measurements clearly show decreasing natural stability before January 11. The layer still needed more loading. This trend was not indicated by the stability ratios derived from the 100 cm^2 frame, although the generally low values indicated instability.

The fact that skier triggering became uncommon soon after the avalanche cycle of Jan 11, 1996, is supported by the stability indices derived from the 500 cm^2 shear frame measurements and by the slope tests. The quickness of this layer to seemingly strengthen was in contrast to the long term experience where surface hoar layers of this magnitude were observed lingering for many weeks. This time the layer was buried too deeply and the layer had gained strength substantially soon after the major loading period. So, no large skier triggered avalanches were reported. Stabilization coincided with the prominent cooling between Jan 15 and 17.

CONCLUSIONS

For local and regional avalanche forecasting data on snowpack stability (class I factors) (McClung and Schaerer, 1993) still proves to be essential, even nowadays in times of automatic weather stations and numerical models. Avalanche control programs with a dual responsibility of providing avalanche safety for transportation routes and also for backcountry users may want to consider the following points:

- The shear frame test is still an excellent measure to assess new (or storm) snow instabilities. It is of course also helpful for the backcountry avalanche danger evaluation. Essential is to aim for continuous and consistent measurements, e.g. record an average of several measurements, rather than a favorite or plausible value.

- New snow monitoring can be completed by shear frame measurements of persistent weak layers (old snow instabilities) in a representative study plot. Derived stability indices provide important information for stability evaluation. Jamieson (1995) has clearly shown that S_{K38} is a better predictor for skier-triggered avalanches in surrounding terrain than common meteorological observations.
- Procedures for the two measurements mentioned above should be consistent.
- Since the shear frame measurements will primarily provide information on the strength and strength changes of weak layers, the effective reactivity (propagation potential) depending on the slab characteristics should be assessed by supplementary tests. Periodic rutschblock tests on study slopes near the study plot represent a good tool.
- These consistent data can be completed with slope tests at different elevations and aspects, using a standardized stability test, such as the rutschblock or compression test, to assess the spatial distribution of snow stability.

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