Shear frame stability parameters for large-scale avalanche forecasting

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ABSTRACT. During the winters of 1990, 1991 and 1992, a field study of stability parameters for forecasting slab avalanches was conducted in the Cariboo and Monashee mountains of western Canada. In a level study plot at 1900 m and on nearby slopes, the shear strength of the weak snowpack layer judged most likely to cause slab avalanches was measured with a 0.025 m² shear frame and a force gauge. Based on the ratio of shear strength to stress due to the snow load overlying the weak layer, a simple stability parameter and a more theoretically based stability index which corrects the strength for normal load were calculated. These stability parameters are compared with avalanche activity reported for the same day within approximately 30 km of the study plot. Each stability parameter is assessed on the basis of the number of days that it successfully predicted one or more potentially harmful avalanches and the number of days that it successfully predicted no potentially harmful avalanches. Both parameters predicted correctly on at least 75% of the 70 days they were evaluated. The simpler empirical stability parameter worked as well as the one that corrects strength for normal load. For large-scale forecasting of dry-snow slab avalanches, shear frame stability parameters appear to be a useful addition to meteorological data, snowpack observations and slope tests.

INTRODUCTION

Traditionally, meteorological measurements (including the amount of storm snow) have proven more useful for avalanche forecasting than measurements of the mechanical properties of the snowpack (Perla, 1970). This is surprising since the slab avalanches that constitute most hazardous avalanches begin with shear failure of an identifiable weak layer in the snowpack (McClung, 1987). Accordingly, several researchers have used shear frames (Fig. 1) to test the shear strength of the weak snowpack layers that were judged most likely to cause slab avalanches, and the results of such tests have been used to calculate stability parameters for comparison with avalanche activity on the tested slopes or nearby slopes (Roch, 1966a; Sommerfeld and King, 1979; Stethem and Tweedy, 1981; Conway and Abrahamson, 1984; Föhn, 1987b). In contrast, our study compares stability parameters with avalanche activity reported within 15–30 km of the test site.

Although this study compares stability parameters with avalanche activity, other meteorological factors such as increasing air temperature cannot be ignored in operational avalanche forecasting. It is likely that such warming contributes to dry slab failure by reducing slab stiffness (McClung, 1987) rather than by reducing the shear strength of the active weak layer. Hence, the stability parameters used in this study will not show any effect from warming although slab stability may be reduced by increases in solar radiation or air temperature.

STABILITY PARAMETERS

Various stability parameters can be derived from the ratio of shear strength $\Sigma$ to overburden stress $\sigma_v$. One of the simplest that has been used operationally by two highway avalanche control programs in Canada is the stability factor $SF$, where

$$SF = \Sigma/\sigma_v,$$

in which overburden stress $\sigma_v$ is determined from a vertical series of density $\rho$ samples of known height $h$ as
The transitional value of $S_F$, which distinguishes values associated with stability from values associated with instability, must be determined empirically since there is no critical ratio of horizontal (or slope-parallel) shear strength to vertical stress that can be derived theoretically.

Föh (1987b) has proposed a stability index $S$ which is the ratio of shear strength $\Sigma\omega$ corrected for normal load and the statistical effects of shear frame size to the shear stress $\sigma_{x_0}$ adjusted for slope angle $\psi$

$$S = \Sigma\omega/\sigma_{x_0}.$$  

(The $x$ and $z$ axes are down-slope and slope-perpendicular, respectively.) Since slab failure is believed to begin with slope-parallel shear failure (e.g. McClung, 1987) and $S$ is the ratio of slope-parallel shear strength to slope-parallel shear stress, values of $S$ near 1 are expected for snow slopes that are just at the point of releasing natural slab avalanches.

The shear strength $\Sigma\omega$ of a large area ($> 1 \text{ m}^2$) is less than that obtained using a small shear frame because of the greater probability of a weakness or flaw over the larger area (Sommerfeld and others, 1976). According to Sommerfeld (1980), the size correction for a 0.025 m$^2$ shear frame is given by $\Sigma\omega = 0.65 \Sigma_{0.025}$.  

Since avalanche starting zones (e.g. avalanche starting zones) to obtain $S_{35}$ as

$$S_{35} = \frac{0.65 \Sigma_{0.025} + \sigma_{e} \cos^2 \theta \sin \phi}{\sigma_{e} \sin \phi \cos \theta}.$$  

which, in terms of $S_F$, is

$$S_{35} = \frac{0.65 S_F}{\sin \phi \cos \theta} + \cot \phi.$$  

Between the low values of a stability parameter that are associated with unstable snow and the high values that are associated with stable snow, there is a critical or transitional value. In practice, the transition consists of a band of values because of differences in snow conditions between avalanche starting zones and measurement sites and because of the variability of shear strength and overburden measurements. Because stability parameters are used in conjunction with other observations, we elected to base the width of the transition band on the 90% confidence band for the stability parameters. The width of this band can be approximated from the shear strength measurements which are much more variable than the density measurements. Typically, values of $S_F$ and $S_{35}$ were based on seven shear frame tests that have an average coefficient of variation of 15%. This corresponds to a 90% confidence band given by $\pm 10\%$ of the transitional value.

**STUDY AREA**

Shear frame tests were performed at a level study plot and on small, nearby, 15-30° slopes near the tree line at 1900 m elevation in the Cariboo Mountains of western Canada. This site is central to the terrain used by Mike Wiegele Helicopter Skiing, a region of more than 5000 km$^2$. Although some of the avalanches used in this study were 30 km from the study plot, most were within 10-15 km, an area that also includes part of the Monashee Mountains. Avalanche starting zones in the area are at elevations of 1500-3000 m.

Most snow storms were accompanied by wind from the south, southwest or west which increases the amount of snow deposited on the north, northeast and east slopes. The small test slopes near the study plot face north, northeast and east as do many of the slide paths on which avalanches were reported.

**TEST METHODS**

The two stability parameters are compared with the avalanche activity reported daily by the helicopter skiing guides. The effectiveness of the parameters for large-scale avalanche forecasting is assessed on the basis of the number of days that the parameters were consistent with the reported avalanche activity.

**Shear strength**

Before the shear frame test is performed, the active weak layer, that is, the weak layer most likely to be associated with slab avalanches, is identified with a tilt board test (NRCC/CAA, 1989), shovel test (NRCC/CAA, 1989), rustyblock test (Föh, 1987a) or profile of snow layers (NRCC/CAA, 1989). Overlying snow is removed, leaving approximately 40-45 mm of undisturbed snow above the active weak layer (Fig. 1). A 0.025 m$^2$ stainless steel shear frame with sharpened lower edges is then gently inserted into the undisturbed snow so that the bottom of the frame is within 5 mm, and preferably within 2 mm, of the active weak layer (Perl and Beck, 1983). A thin blade is passed around the sides of the frame to ensure that surrounding snow is not in contact with, and possibly bonding to, the frame. The force gauge is attached to the cord linking the two sides of the frame and is pulled smoothly and quickly ($< 1 \text{s}$) resulting in a plane failure in the weak layer just below the base of the frame. Shear strength is determined
by dividing the maximum load on the force gauge by the
0.025 m² area of the frame.

We rejected the results of tests for which the fracture
was not approximately planar or deviated beyond the
active weak layer. Average shear strength, based on sets of
at least seven shear frame tests, was determined in the
level study plot on 70 days and on nearby study slopes on
76 days.

Avalanche activity

Avalanche occurrences were compiled by type of release
(slab or loose), size, type of trigger (natural, cornice or
skier-released), moisture, aspect, elevation and location
(NRCC/CAA, 1989) using mainly information obtained
from helicopter skiing guides operating in the study area.
On a given day the portion of the total study area
observed for avalanche occurrences varied from 0-40%
depending on visibility conditions, number of guides
skiing (typically 5-12) and their operating locations. The
research team also compiled occurrence data for slopes
visible from near the study plot, particularly during bad
weather when helicopter skiing operations were
grounded.

An avalanche day was defined as a day on which
measurements for stability parameters were made in the
level study plot or on nearby slopes and on which one or
more naturally released dry slab avalanches potentially
harmful to people (class 1.5 or larger according to
NRCC/CAA, 1989) were reported. (During and imme­
diately following winter storms there are often many small
avalanches of size class 1 or smaller that do not constitute
a serious danger and are too numerous to record in
detail.) Similarly, a non-avalanche day was defined as a
day on which measurements for stability parameters were
made but no large (class 1.5 or larger) naturally released
dry slab avalanches were reported.

Most reported avalanches were within 10-15 km of the
study area, but some were more than 30 km away.
Cornice-triggered avalanches were excluded from the
study since some cornices are powerful triggers which may
release relatively stable slabs. Slab avalanches triggered
by skiers and helicopters were recorded but there were too
few of these avalanches to use in the analysis.

Some avalanche occurrence data were unavoidably
influenced by weather and operational factors. Typically,
this happened when visibility was limited or there was no
helicopter skiing near the location of the avalanche for
one or more days after an occurrence. Some avalanche
fracture lines and/or deposits were estimated to be several
days old when they were first observed. Consequently, for
most of these avalanches, the date of occurrence was
estimated. In the following analysis, the stability para­
eters are compared to avalanche activity both including
and excluding avalanches with estimated dates.

For the level study plot, stability parameters were
obtained on approximately 25 avalanche days and 45
non-avalanche days (17 avalanche days and 53 non­
avalanche days excluding avalanches with estimated
dates). On nearby study slopes, stability parameters
were obtained on 25 avalanche days and 51 non­
avalanche days (20 avalanche days and 56 non­
avalanche days excluding avalanches with estimated
dates).

An avalanche day is considered to be correctly
predicted when one or more large natural dry slab
avalanches were reported and the value of the stability
parameter was below the transition band. A non­
avalanche day is considered to be correctly predicted
when no large natural dry slab avalanche was reported
and the value of the parameter was above the transition
band. The transition band and the forecasting success of
each stability parameter were determined from the
percentage of avalanche days correctly predicted (PA)
and the percentage of non-avalanche days correctly
predicted (PN). Avalanche days and non-avalanche days
corresponding to values of the stability parameter within
the transition band were not used to calculate PA or PN.

To avalanche forecasters, a high PA and a high PN are
both important. However, non-avalanche days include
days when dry slab avalanches occurred but were not
large (size < class 1.5) and days when poor visibility
restricted the helicopter skiing operation and hence the
reporting of avalanches. Because of the uncertainty
associated with non-avalanche days, the parameters are
assessed, based on P which weights PA three times as
much as PN

\[ P = \frac{3PA + PN}{4}. \] (6)

We acknowledge, however, that other weighting factors
(>1) would also be appropriate.

P was maximized by trial and error to obtain the
transitional value for SF and SfG. These values are given
in Table 1 for four cases determined by two factors:
treatment of avalanches with estimated dates (included
versus excluded) and measurement location (level study
plot versus slope).

RESULTS

Avalanche activity is plotted against concurrent values of
SF and SfG for those days in which measurements were
made in the study plot in Figures 2 and 4, respectively,
and for those days in which measurements were made on
study slopes in Figures 3 and 5. Avalanche activity in
Figures 2-5 includes avalanches with estimated dates.
The transition band between unstable and stable ranges
of the stability parameters is also shown in these figures.

The percentages of avalanche days and non-avalanche
days that were successfully forecast are tabulated in Table
1 along with the weighted percentage of correctly forecast
days P which ranged from 75-87%. These percentages
do not include days with values of the stability parameter
within the transition band.

We did not visit the sites of the large dry slab
avalanches that occurred naturally when the stability
parameters were above their transitional values, but
expect that some such avalanches resulted from loading of
lee slopes by local winds or by intense snow showers.

Including or excluding avalanches with estimated
dates has little or no effect on the transitional values of the
stability parameters and the effect on P is not systematic
and is limited to 5 percentage points.

The transitional values for stability parameters
measured on slopes are lower than for the stability index measured in the study plot. This is likely due to additional snowfall (overburden) on the lee slopes used for shear frame tests compared to the level study plot. The percentage of correctly forecast days is higher, by an average of 7 percentage points, for SF or S35 determined in the level study plot compared to the same parameter determined on study slopes. We suspect this apparent advantage of the level plot over study slopes is due to the more consistent thickness of snowpack layers in the level plot.

For the stability parameter SF, the percentages of correctly forecast days PA, PB, and P, averaged over the four cases presented in Table 1, are within one point of the percentages for S35. This is not surprising since the correction term in Equation (5), cot 35 tan θ, only ranged from 0.58 to 0.87 (based on the shear strengths Σ0.025 that ranged from 0.07 to 4.03 kPa). Hence, S35 is an almost linear function of SF (Equation (5)) and the correction for normal load does not improve PA, PB, or P. Apparently SF, which is simple enough to be calculated by mental arithmetic, is as good a forecasting parameter as S35.

Transitional values for SF ranged from 1.56 to 1.78, slightly greater than the critical value of 1.5 used by Rogers Pass (Schleiss and Schleiss, 1970). This greater transitional value may be due to the increased variability in snowpack conditions encountered within the large forest area of the present study.

Although SF has no theoretically based transitional value, transitional values for S35 near 1 are expected when shear frame tests are performed in critical areas of avalanche starting zones (Fohn, 1987b). In the present study, since shear frame tests were not performed in such critical areas, higher transitional values for S35 (Table 1) are expected. However, Fohn’s values of S, calculated for specific avalanche slopes, averaged 2.3 for the slopes which avalanched naturally, implying a transitional value greater than 2.3. While such a difference between theoretical expectation and field observations could be due to shear frame tests being done at locations other than the weak zones (Fohn, 1987b) from which shear failures are believed to spread (Conway and Abrahamson, 1984), it could also indicate that the normal load correction is inappropriate.
Table 1. Comparison of stability parameters

<table>
<thead>
<tr>
<th>Stability parameter</th>
<th>Location</th>
<th>Avalanches with estimated dates</th>
<th>Transition value</th>
<th>Percentage correct</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Avalanche days $P_A$</td>
</tr>
<tr>
<td>SF</td>
<td>plot</td>
<td>included</td>
<td>1.76</td>
<td>87</td>
</tr>
<tr>
<td>SF</td>
<td>plot</td>
<td>excluded</td>
<td>1.68</td>
<td>93</td>
</tr>
<tr>
<td>SF</td>
<td>slope</td>
<td>included</td>
<td>1.56</td>
<td>78</td>
</tr>
<tr>
<td>SF</td>
<td>slope</td>
<td>excluded</td>
<td>1.56</td>
<td>78</td>
</tr>
<tr>
<td>$S_{35}$</td>
<td>plot</td>
<td>included</td>
<td>3.00</td>
<td>85</td>
</tr>
<tr>
<td>$S_{35}$</td>
<td>plot</td>
<td>excluded</td>
<td>3.00</td>
<td>93</td>
</tr>
<tr>
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<td>slope</td>
<td>included</td>
<td>2.89</td>
<td>83</td>
</tr>
<tr>
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<td>excluded</td>
<td>2.71</td>
<td>75</td>
</tr>
<tr>
<td><strong>Average</strong></td>
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<td></td>
<td>84</td>
</tr>
</tbody>
</table>

CASE HISTORY

Between 31 January 1991 and 7 February 1991, a storm accompanied by generally south winds deposited snowfall equivalent to 130 mm of water in the study plot and substantially more in the lee-slope starting zones. In most areas, this snow was deposited on top of a weak layer of surface hoar and resulted in numerous large dry slab avalanches. During this period, instrumentation near the study plot recorded air temperature continuously and wind speed (when the anemometer was not rimed) as shown in Figure 6. The accumulating snow load over the surface hoar layer and the stability parameters were monitored daily. The following case history shows how shear frame stability parameters can complement meteorological measurements for avalanche forecasting.

On 31 January, when the stability parameters were well below their respective transition bands, there were hundreds of small (class 1 or smaller) natural dry slab avalanches. On 1 February, the first large (class 1.5 or larger) natural dry slab avalanche was reported. From 2 to 5 February, snowfall and large natural dry slab avalanches continued. No large natural dry slab avalanches were reported for 6, 7 or 8 February although snowfall continued on 6 and 7 February. The reduction in air temperature from -1°C to -6°C which occurred on 5 February may have contributed to the absence of large avalanches on 6 February; however, the marked increase in the stability parameters to values above the transition band indicates an increase in strength of the weak surface hoar layer. (It is unlikely that the absence of large dry slab avalanches on 6 February is due to surface hoar that was removed from starting zones by previous avalanches since hundreds of starting zones within the study area had not released.) On 7 February, the load increased more rapidly than the shear strength of the surface hoar layer, and as a result the stability parameters dropped into their transition bands. In situations such as occurred on 6 and 7 February, shear frame stability parameters can help the forecaster understand the interaction between loading and the shear strength of active weak layers.

CONCLUSIONS

On 75–87% of days, $SF$ and $S_{35}$ were effective predictors of whether one or more natural dry slab avalanches large...
enough to injure, bury or kill a person were likely to occur, or whether the snow stability was marginal. \( SF \) and \( S_{35} \) are comparable in performance but \( SF \) is easier to calculate. Either of these two stability parameters appears to be effective for large-scale avalanche forecasting when used in conjunction with established techniques including avalanche observations, meteorological measurements, observations of snowpack stratigraphy and slope tests.

The stability parameters \( SF \) and \( S_{35} \) performed better when based on measurements from a level study plot characterized by uniform snowpack layers than when based on measurements from relatively small, safe lee slopes.

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The accuracy of references in the text and in this list is the responsibility of the authors, to whom queries should be addressed.