Monitoring a Shear Frame Stability Index and Skier-Triggered Slab Avalanches Involving Persistent Snowpack Weaknesses

Bruce Jamieson and Colin Johnston
Dept. of Civil Engineering, University of Calgary

Ski guides routinely decide whether to ski or avoid particular avalanche slopes. Similarly, avalanche forecasters for ski areas and highways decide whether to open or close parts of ski areas and mountain highways. Such important safety decisions are based on many factors that can be grouped into operational procedures, human factors, terrain factors and snow stability factors.

The snow stability factors can be grouped into intuitive inputs based on experience, qualitative factors and quantitative measures.

SNOW STABILITY FACTORS
(after McClung and Schaerer 1993)

III { WEATHER

II { SNOWPACK

I { Stability Tests AVALANCHES

Snow stability factors can also be classified as either direct indicators such as observations of avalanches or snow stability tests (class I), or as less direct indicators such as snowpack factors (class II) or weather factors (class III) (McClung and Schaerer 1993, p. 125).

This paper summarizes recent work in Canada on a snow stability index for skier triggering. Although this index is quantitative and class I, we emphasize that it is only one of the many factors that can be used by forecasters and guides to make decisions concerning access to avalanche areas.

1 Presented at the International Snow Science Workshop at Snowbird, Utah on October 31, 1994.
The project’s field staff make snowpack measurements and avalanche observations at study sites in the Purcell, Cariboo, Monashee, Selkirk and Rocky Mountains. Canadian Mountain Holidays and Mike Wiegele Helicopter Skiing, as well as the Canadian Parks Service and the BC Ministry of Transportation and Highways provide access to study areas and logistical support and—most importantly—provide the skilled staff to do the field tests.

**Field Methods**

At the various study areas during the last two winters, approximately 400 profiles, over 430 sets of 7-12 shear frame tests and 400 rutschblock tests were completed. At Mike Wiegele Helicopter Skiing near Blue River and at Canadian Mountain Holidays in the Bobby Burns, field staff test the shear strength of persistent snowpack weaknesses with shear frames in study plots and slopes every 3-9 days, and—when possible—on skier-tested avalanche slopes. Tests on skier-tested avalanche slopes are used to assess critical values of the stability index and to understand its limitations. Tests on study slopes are used to monitor changes in the stability index for particular weak layers and to compare values of the stability index with avalanche activity reported to have occurred on the same weakness within 10-15 km of the study slope.

Most fatal avalanches in Canada are triggered by people, mostly skiers, and have failure planes involving persistent snowpack weaknesses such as surface hoar, facets or poorly bonded crusts (Jamieson and Johnston 1992). Although many avalanches during storms start in layers of “new snow”, only 4 of the 50 accident reports that specified the failure plane cited “new snow”.

To address stability evaluation for snowpack weaknesses such as surface hoar, facets and poorly bonded crusts, the Persistent Slab Instabilities Project began in the fall of 1992. One of the project’s objectives is to refine shear frame stability indices for persistent snowpack weaknesses, with special attention to skier triggering.

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**GRAIN TYPE OF FAILURE PLANE**

Fatal Slab Avalanche Accidents in Canada 1972-91

**Decision-Maker**

Amateur Professional

Based on accident reports that specified the failure plane (34 accidents with amateur decision makers and 16 with professional decision makers.)
We measure shear strength by placing shear frames (usually 250 cm$^2$) on, or a few mm above, the weak layer or weak interface. A force gauge is attached to the frame and manually pulled to failure within 1 second.

The following graphs and discussion apply shear frame data to a stability index for skier triggering.

**The Swiss Index for Skier Triggering**

Föhn (1987) of the Swiss Federal Institute for Snow and Avalanche Research derived a stability index for skier triggering based on the ratio of shear strength to shear stress. In simplified form, the equation for the index is

$$S_s = \frac{\text{strength of weak layer}}{\text{stress due to slab} + \text{stress due to skier}}$$

(1)

The shear strength of the weak layer or interface is calculated from the pull force on the shear frame at failure divided by the size of the frame, and is corrected for frame area and normal load as described by Föhn (1987). The shear stress due to the slab is

$$\sigma_{xz} = \bar{p}gh \sin \Psi \cos \Psi$$

(2)

where $\bar{p}$ is the average density of the slab, $g$ is the acceleration due to gravity, $H$ is the depth of the weak layer measured vertically and $\Psi$ is the slope angle. The static shear stress due to the skier, as derived by Föhn, is

$$\Delta \sigma_{xz} = 2R \cos \alpha_{\max} \sin^2 \alpha_{\max} \sin(\alpha_{\max} + \Psi) / \pi H \cos \Psi$$

(3)

where $R$ is the line load due to a skier (500 N/m) and $\alpha_{\max}$ is angle between the snow surface and the peak skier stress (Föhn 1987). Equation 3 for shear stress due to skier makes various simplifying assumptions including

- the skier is stationary,
- ski penetration is negligible,
- slab failure begins with shear failure, and
- snowpack is uniform on a planar slope.

**Ski Penetration During Skiing**

In the soft snow common in our study areas in the Purcells, Cariboos, Monashees, Selkirks and Rockies, ski penetration is often 10 to 40 cm. By replacing $H$ in Equation 3 by $H-P$ where $P$ is the ski penetration, the graph shows that the stress due to the slab and skier depends strongly on ski penetration for penetrations of 20 and 38 cm and slabs less than 70 cm in thickness.
We decided to estimate ski penetration during skiing based on slab density since it can be calculated from the weight and thickness of the slab and hence does not require any additional measurements.

From our studies of the rutschblock (Jamieson and Johnston 1993c), we have data for ski penetration while standing on two skis and after two jumps with skis on the same spot. We take the average of these two values as an estimate of skiing penetration during down-weighting, \( P_K \). For the slabs in our rutschblock studies in the Columbia Mountains, \( P_K \) averaged 30 cm.

As shown in the graph, the snow density increased by an average of 1.28 kg/m\(^3\) per cm of depth for low and high density slabs. Since the average slab density, \( \bar{\rho} \), typically occurs at half the depth of the slab which may not be representative of the density at the depth of ski penetration, we estimated the density at 30 cm as

\[
\rho_{30} = \bar{\rho} + 1.28(30 - H/2) \quad (4)
\]

This improves the correlation between skiing penetration and density from -0.63 to -0.79. Regressing the skiing penetration \( P_K \) on \( \rho_{30} \) gives

\[
P_K = 57.4 - 0.166 \rho_{30} \quad (5)
\]

Adjusting the Skier Stress for Ski Penetration

Using Equation 5 for \( P_K \), we adapt Fohn’s equation for \( Ss \) by replacing \( H \) in Equation 3 by \( H - P_K \) to obtain \( Sk \). Since \( Sk \) adjusts for ski penetration, it results in values that are lower than \( Ss \) particularly for thin and low density slabs. When skiing penetration exceeds slab thickness (\( P_K > H \)), we define \( Sk \) to be zero.

Evaluation of Stability Index on Skier-Tested Avalanche Slopes

Avalanche slopes can be used to evaluate stability indices by comparing avalanche activity on the slopes with stability indices calculated from measurements on the same slopes (Fohn 1987). It is important that snow conditions do not change between the time of the ski tests and the shear frame measurements. So, while a 2-day-old slab avalanche may provide a suitable site for shear frame tests during consistently cold mid-winter conditions, a 2-hour-old slab avalanche that occurred on a
sunny slope during a warm spring afternoon may not be a suitable site after the sun is no longer on the slope.

Since 1990, we have measured the slab weight, slab depth, slope angle and shear strength of persistent weaknesses on 48 skier-tested avalanche slopes. Dry slab avalanches were triggered by skiers on 26 of these slopes. The other 22 avalanche slopes were skied or skier-tested but did not produce slab avalanches.

In general, since stability indices are ratios of strength to stress, values less than 1 should indicate instability and values greater than 1 should indicate stability. Although critical values of 1 are questionable for $S_s$ and $S_k$ since these indices ignore the effects of dynamic loading, a layered snowpack and the fact that snow is not a linear elastic material, field data presented by Fohn (1987) and following two graphs for $S_s$ and $S_k$ support a critical value near 1. Fohn (1987) chose values of $S_s$ between 1 and 1.5 to indicate marginal stability. Consistent with Fohn, we consider values of $S_s$ to be prediction errors if an avalanche did not occur on a slope with $S_s < 1$, or occurred on a slope with $S_s > 1.5$.

Using the 48 slopes with persistent weaknesses that have been skier tested, the graph for $S_s$ shows the percentage of skier-triggered slopes decreasing from

- 89% when $S_s < 1$ to
- 44% when $1 \leq S_s \leq 1.5$ to
- 29% when $S_s > 1.5$.

There are eight prediction errors on the graph: $S_s < 1$ on two slopes that were not triggered and—more seriously—$S_s > 1.5$ on six slopes that were triggered by skiers.

For five of the six slopes for which $S_s$ failed to predict skier triggering, the slabs were 67 to 100 cm thick. Reports from field staff suggest that the three thickest of these slabs (80, 100 and 100 cm) were probably triggered from small areas where the snowpack was thin and weak—areas that were very different from the sites chosen for fracture line profiles and shear frame tests. [See Jamieson and Johnston (1993a) in Avalanche News 40 for a discussion of one of these]. On the graph, the three points for which triggering from thin spots is likely are marked with a box. At the three avalanches with slab thicknesses of 30, 67 and 70 cm, triggering from areas where slab thickness was much less than average is not suspected.

Boxes mark the points for which the slabs were triggered from thin spots. The standard error for $S_s$ is typically $\pm 11\%$ based on 7 shear frame tests.
In comparison, the graph for Sk shows the percentage of skier-triggered slopes decreasing from
- 83% when Sk < 1 to
- 50% when 1 ≤ Sk ≤ 1.5 to
- 18% when Sk > 1.5.
There are six prediction errors: three in which Sk < 1 but the slabs were not skier triggered, and three skier-triggered slabs in which Sk > 1.5. The only three prediction errors for skier-triggered slabs are the three discussed above (thickness 80, 100 and 100 cm) in which thin spot triggering is likely. For this limited data set, Sk is a better predictor of slab stability than Ss.

**Extrapolating Stability Indices from Study Slopes to Surrounding Terrain**
Like many stability indices, Sk is intended as an index of stability for a specific avalanche slope. However, it is impractical for many avalanche safety programs to test their avalanche slopes regularly, or unsafe to access them during periods of instability. As a result, avalanche workers for some mountain highway and ski areas make shear frame and slab weight measurements in representative study plots or slopes and use the resulting indices to help assess the stability of surrounding avalanche terrain (Schleiss and Schleiss 1970, Stethem and Tweedy 1981).

Since Sk is calculated for a specific slope angle, it must be generalized before being applied to surrounding terrain (Jamieson and Johnston 1993b). By calculating Sk for an arbitrary 35°, we obtain Sk35. While Sk appears to be critical below approximately 1.5, we expect a slightly higher critical level, perhaps 1.7 for Sk35, since it is being applied to slopes of various aspects, elevations and terrain.

During the winter of 1994, a layer of surface hoar was buried on February 5 or 6 in many mountainous areas of BC. The strength of this layer was measured every 3-9 days from mid-February to mid-March on the Rocky, Pygmy and Bogus study slopes at CMH Bobby Burns, and on the Mt. St. Anne and Sam's study sites at Mike Wiegele Helicopter Skiing near Blue River. Between test days, the stability index Sk35 is calculated by adjusting slab weight and slab height for daily recorded snowfall, and by linear interpolation of shear strength. Since strength changes of thin persistent snowpack weaknesses cannot be predicted at present, daily values of Sk35 cannot be estimated for the days following shear frame tests from basic weather and snowpack data.
The graphs on this page show $Sk35$ during this period as well as the number of skier-triggered dry slab avalanches (wide outlined bar) and the number of dry slab avalanches reported to have failed on the February 5/6 surface hoar layer (narrow black bar). At both operations, skier-triggered avalanche activity dropped off around February 18 when the $Sk35$ exceeded 1.7.

After February 18, four artificially triggered slabs were reported to have started on the February 5/6 surface hoar layer. Of the three at CMH Bobby Burns, the February 20 avalanche was triggered by our staff while ski testing a short unsupported 44° slope, and the remaining two avalanches were triggered remotely from thin spots. We believe the avalanche on March 5 in the Cariboos near Blue River was triggered by a snowmobile traversing 15° terrain 30-50 m above the crown where the slab thickness ranged from 34 to 160 cm.

Clearly, the slab overlying the February 5/6 surface hoar layer could be released in some areas after February 18 by fractures started at localized weak spots or where the slab was thin. Not surprisingly, an extrapolated stability index such as $Sk35$, which is based on tests done where snowpack properties are average, is not indicative of the snow stability where the terrain and/or weather create snowpack anomalies.

However, $Sk35$ extrapolated from study sites at CMH Bobby Burns and in the Cariboos and Monashees near Blue River does effectively show the general stability trend in most areas within 10-15 km of the study sites.
Summary
Ski penetration in our study areas often ranges from 10-40 cm. For slabs less than approximately 70 cm thick, the shear stress due to a skier is strongly affected by ski penetration. We adjusted a previously defined stability index $S_s$ for ski penetration to obtain $S_k$ which is more indicative of slab stability on skier-tested avalanche slopes. By calculating $S_k$ for a 35° slope angle, we obtained $S_k35$ which agreed well with avalanche activity on a prominent surface hoar layer within 10-15 km of our study sites. Most prediction errors for $S_k$ and $S_k35$ involve slabs triggered by skiers where the slab is thin or the snowpack is weak. In several cases, the fractures propagated from such isolated trigger points and released avalanches on adjacent slopes.

Acknowledgements
A research project like this one requires financial support, a commitment from management at the co-operating private and public sector operations and skilled field workers. For financial support, we are grateful to Canada’s Natural Sciences and Engineering Research Council (NSERC), Mike Wiegele Helicopter Skiing (MWHS), Canadian Mountain Holidays (CMH), and members of the BC Helicopter and Snowcat Skiing Operators Association. For their commitment to the research project and willingness to sort out the inevitable difficulties, we thank CMH managers Mark Kingsbury, Walter Bruns, Colani Bezzola and Rob Rohn, MWHS managers Mike Wiegele and Bob Sayer, managers at Banff, Jasper, Glacier, and Yoho National Parks and at the BC Ministry of Transportation and Highways. Of course, there would not be any results without the careful field work of Jill Hughes, James Blench, Leanne Allison, Rodden McGowan, wardens from Yoho, Glacier, Jasper and Banff National Parks and BC Ministry of Transportation and Highways technicians at Kootenay Pass. Peter Schaerer provides a scientific liaison to NSERC and advice regarding study sites and field methods. Many thanks.

References