Skier Triggering of Slab Avalanches: Concepts and Research

Bruce Jamieson

Department of Civil Engineering, University of Calgary

October 1999, slightly revised February 2000

Introduction

Most avalanche fatalities are recreationists, mainly skiers and snowboarders. Yet until recently, research has focussed on natural avalanches. In this article, I'll review some recent research on skier triggering and also illustrate some important concepts.

The stress underneath skiers

Let's start with a conceptual model. As it starts to snow, we place a bathroom scale on the snow surface where it is level. After 30 cm of snowfall, we place another scale above the first (Figure 1). After another 30 cm of snowfall, we place a third scale above the first two. The storm snow does not settle because … well, because it is only a model. A skier weighing 80 kg stands on the top scale and it now reads 80 kg. What is the *increase* in the reading on the middle scale when the skier stands on the top scale? 40 kg seems like a reasonable guess. And 20 kg seems like a reasonable guess for *increase* on the bottom scale. Some people might not agree with my estimated scale readings, but I hope the model makes it intuitively clear that the skier's stress decreases with depth.

The decrease in skier load with depth can also be calculated by assuming the snowpack is uniform (e.g. Salm, 1977; Föhn, 1987). The calculated shear stress in the top metre of a uniform snowpack on a 38° slope caused by a standing 80 kg skier decreases with depth as shown in Figure 2. (I'll get to moving skiers and a layered snowpack shortly.) The stress decreases quickly with depth. Ten centimetres below the skis, the stress is about 1.5 kPa–enough to crush low density snow. (And the feel of skis crushing the surface snow is what draws us to untracked snow.) One metre below the skis, the calculated skier stress is only 0.1 kPa, about 7% of what it was 10 cm below the skis. There is also the shear stress due to gravity pulling the slab down-slope. This static stress *increases* with depth, unlike the skier stress which *decreases* rapidly with depth. Since the calculated skier stress at 1 m is only 10% of the stress due to gravity acting on the slab, skiers are not efficient triggers where the slab is more than a metre thick. Field data support this: in a study of 82 skier-triggered slabs, the average slab thickness in the start zone was 39 cm, 75% of the slabs were less than 56 cm thick and the thickest was 103 cm. (Jamieson and

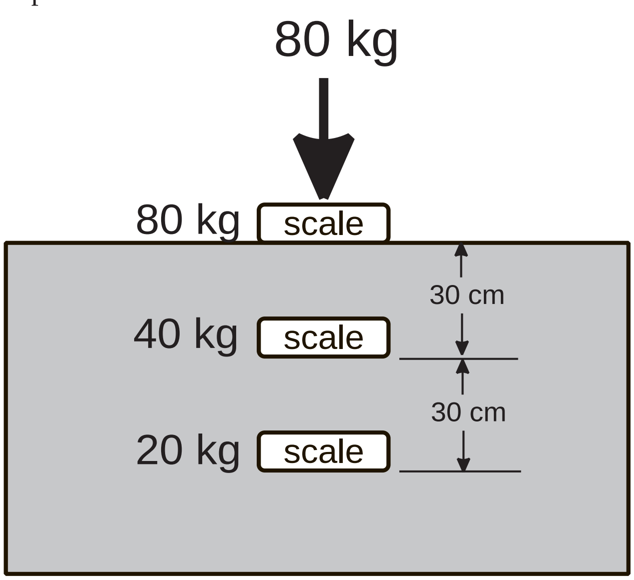

Figure 1. A conceptual model showing decreased skier load with depth. Values are only to qualitatively illustrate the decrease in load with depth.

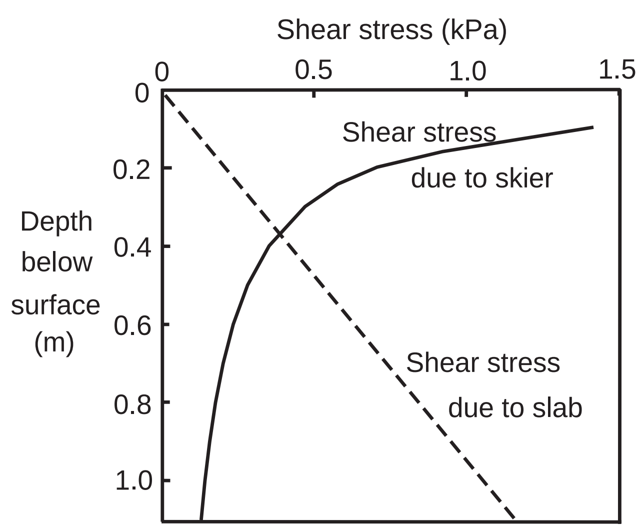

Figure 2. Shear stress due to skier (solid line) and due to slab (220 kg/m³) on a 38° slope (dashed line). The skier stress decreases with depth whereas the slab stress increases with depth. After Föhn (1987).

Johnston, 1998). However, we should not conclude that we cannot trigger a slab just because the weak layer is a metre below the surface—the slab may be thinner or the snowpack may be locally weak where we make our next turn.

But how close is the calculated stress due to a stationary skier to the real stress caused by a moving skier? Fortunately, Camponovo and Schweizer (1997) have measured the stress below a skier. At a level site, they buried a device like a bathroom scale (but with wires and more expensive) at various depths in the snowpack. A skier moved onto the overlying snow and loaded the snow in stages similar to a skier loading a rutschblock: standing, pushing down without jumping, then jumping. Not surprisingly, the stress on the load cell increased with the increasing dynamic forces on the snow surface (Figure 3). Remarkably, the stress due to the skier pushing down with his or her legs is closest to the calculated stress. Since a skier down-weighting between turns is very similar to a skier pushing down without jumping (rutschblock step 3), the calculated stress for a stationary skier is a good approximation to the dynamic stress caused by a skier.

There is further field evidence that the calculated static stress is close to the real stress. Colin Johnston and I (1998) used a skier stability index based on this calculated stress to assess 115 skier-tested slabs. The index correctly predicted the stability of 77% of the 95 slabs outside the range of transitional stability.

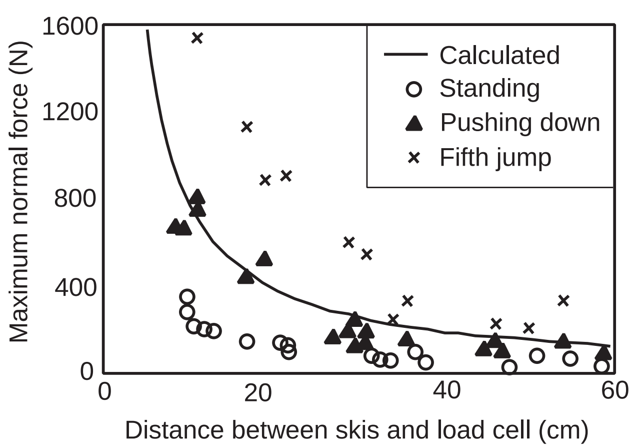

Figure 3. Measured force on buried load cell due to a skier compared to calculated force. After Camponovo and Schweize, (1997).

This sort of predictive success would not be possible if the real stress caused by real skiers was far from the calculated stress for stationary skiers.

This index predicts skier triggering when the calculated shear stress is 1.5 times the shear strength of the weak layer measured *where the snowpack was judged to be typical of the start zone*. The success of the index indicates that no deficit zone (super weak zone) is required for most cases of skier triggering. However, since most of our measurements were at skier-controlled avalanches, it does not follow that areas of the start zone where snowpack properties appear average can be used to reliably predict all skier-triggered avalanches or the skier-triggered avalanches that surprise experienced avalanche workers. The spatial variability of the snowpack undermines the value of point observations of the snowpack, like rutschblock tests, and creates serious challenges for winter recreationists and avalanche workers.

Slab properties

I mentioned that the calculated skier stress was derived for a uniform snowpack, but that the stability index based on the calculated stress works for many real slabs. More realistic models of stress in layered slabs may improve the success of such stability indices. For a handful of layered slabs, Schweizer (1993) showed that stress in the weak layer depended on stiffness and layering of the overlying slab.

Slab hardness

Using their fancy scale buried in the snowpack, Christian Camponovo and Jürg Schweizer (1997) showed that more skier stress penetrated through a 35 cm-thick soft slab than through a hard slab of similar thickness. Although the results were complicated by greater skier penetration into the soft slab, much more stress penetrated the soft slab (180 kg/m^3, F to 4F, +,/,●) compared to the slab with the pencil-hard surface crust (210 kg/m^3).

Conceptual model for the effect of slab stiffness

For this conceptual model, a foam slab is placed across three bathroom scales as shown in Figure 4. Since the slab will only spread the load out slightly, we expect the middle scale to increase more than the outer scales when the 80 kg skier stands over the middle scale. Let's say the reading on the middle scale increases by 60 kg and the reading on each outer scale increases by 10 kg.

If we replace the foam slab by a wooden slab, say 4" thick, the readings on the scales might increase by something like 25 kg, 30 kg (middle scale) and 25 kg when the 80 kg skier stands over the middle scale (Figure 4). So intuitively, the stiffer wooden slab spreads the skier's load out more than the less stiff foam slab.

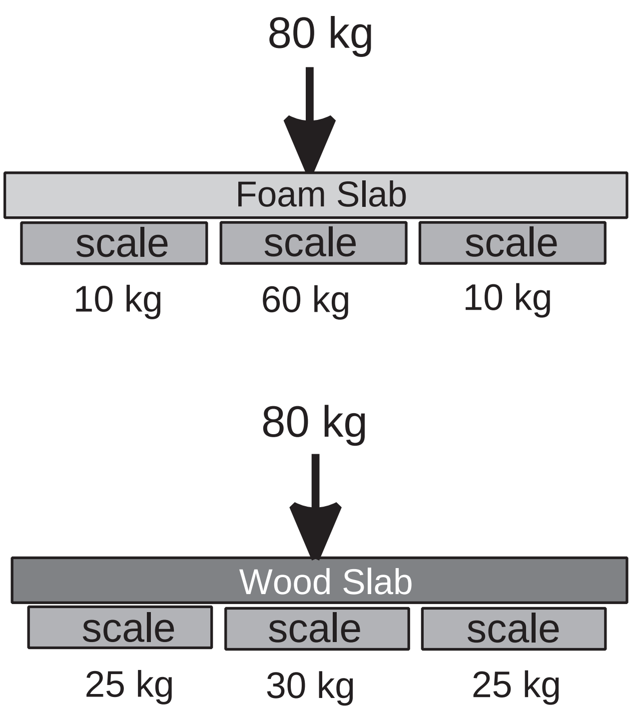

Figure 4. Distribution of a skier's weight under a foam slab (upper diagram) and under a wooden slab (lower diagram). The values in kg are increases in scale readings due to the 80 kg skier. These estimates depend on the properties of the slabs.

There is an equation developed by Bousinesq (Salm, 1977; Föhn, 1987) that indicates that the bulb-shaped distribution of stress (Figure 5) is independent of the stiffness of the snowpack. However, this is only true if the snowpack is uniform. As soon as we consider a snowpack with layered slab or a weak layer, the stress bulb below the skier and, of course, the stress in the weak layer, depend on the stiffness of the slab, the thickness of the slab and the stiffness of the weak layer. To calculate the stress in a snowpack with a slab and weak layer, we usually resort to a computer model of the snowpack (Schweizer, 1993; Wilson and others, 1999). While no one has yet systematically studied the effect of slab stiffness on stress in the weak layer, it is clear that the stiffer the slab, the more the skier stress spreads out, other factors being equal (Schweizer, 1993). If we combine the effect of slab thickness with the effect of slab stiffness, we see that:

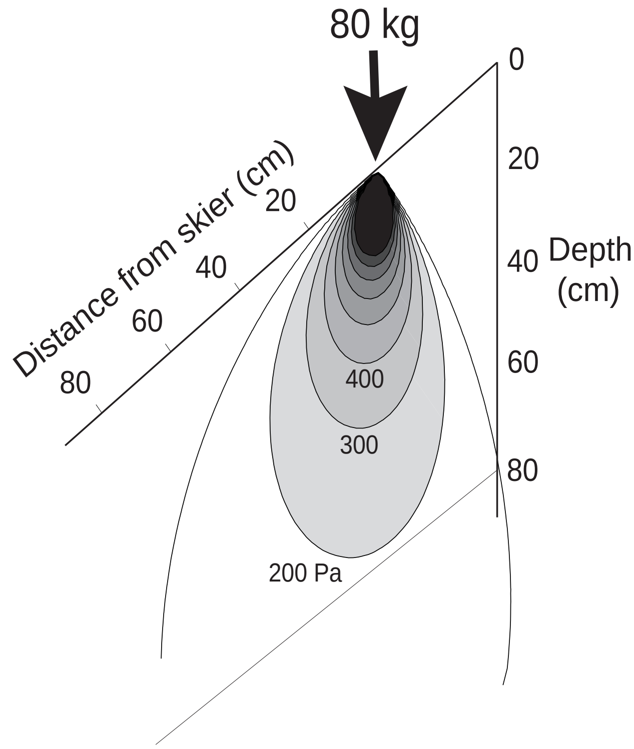

Figure 5. Calculated distribution of shear stress due to a skier in a uniform snowpack. After Föhn (1987). Next time you watch a skier or snowboarder descend a steep snow slope, imagine the stress bulb beneath their feet moving through the snowpack, with its strong and weak areas. If the skier's bulb encounters an area where the weak layer fractures, they will have triggered a slab avalanche. Otherwise, they have one more great run to talk about afterwards.

- skier stress penetrates deeper in less stiff slabs (Schweizer, 1993; Camponovo and Schweizer, 1997), and
- skier stress spreads farther laterally for stiffer slabs, other factors being equal (Schweizer, 1993).

This indicates an important concept: in a snowpack with a slab overlying a weaker layer, a stiffer slab results in a wider, shallower stress bulb beneath the skier than does a softer slab (Figure 6).

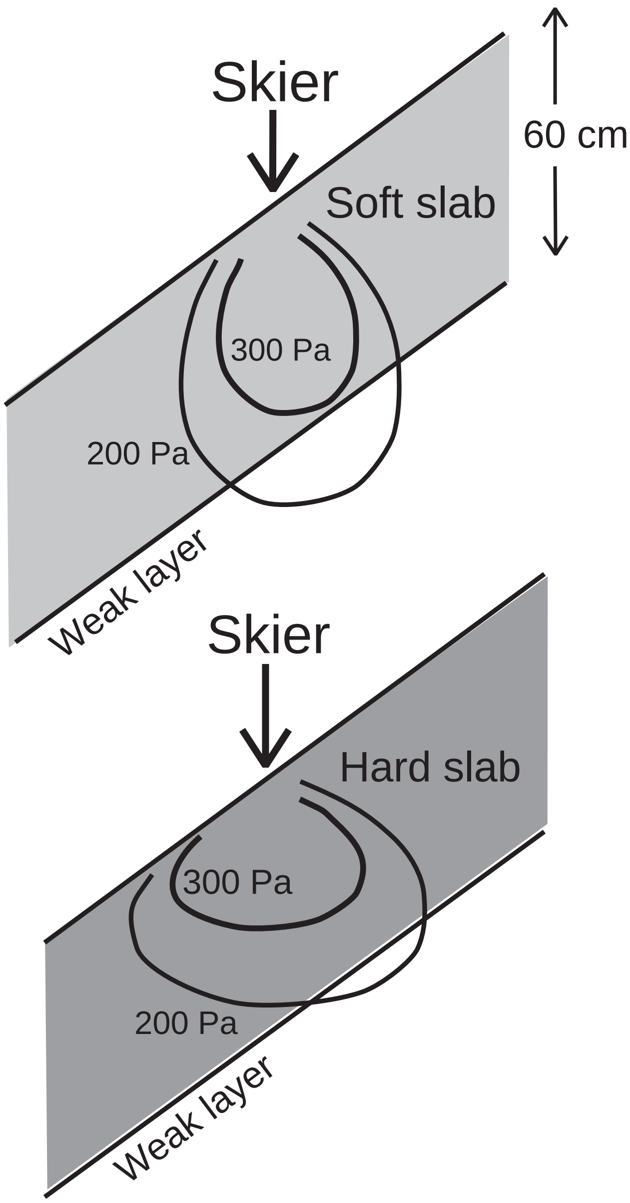

Figure 6. Conceptual model of the skier stress for a hard and soft slab. Shear stress values are approximate and depend on the properties of the slab and weak layer.

Bridging

The stress bulb is a key concept for bridging. Stiff slabs are sometimes difficult to trigger because the skier's stress does not penetrate as deeply as for softer slabs. However, if and when a skier triggers a stiff slab, the fractures will tend to propagate widely, potentially releasing a large slab avalanche with serious consequences for the skier. The variability of stability over a slope and between slopes greatly complicates real decisions in avalanche terrain since the slab may be triggered at a small area where the stability is low and the fractures may propagate long distances because the average slab stiffness is high. Bridging may improve skier stability (decreased likelihood of triggering) but the hazard may remain high.

Stress concentration

Over the last 11 years, the University of Calgary avalanche research team has done over 80 fracture line profiles at the site of skier-triggered dry slab avalanches. We make detailed measurements of the weak layer and adjacent layers. Sometimes, and especially at unexpected slab avalanches, we have noticed a thin stiff layer at the base of the slab. For example, in Figure 7, the fracture spread along a 1F facet layer underneath a hard crust rather than the weaker 4F layer a few cm above.

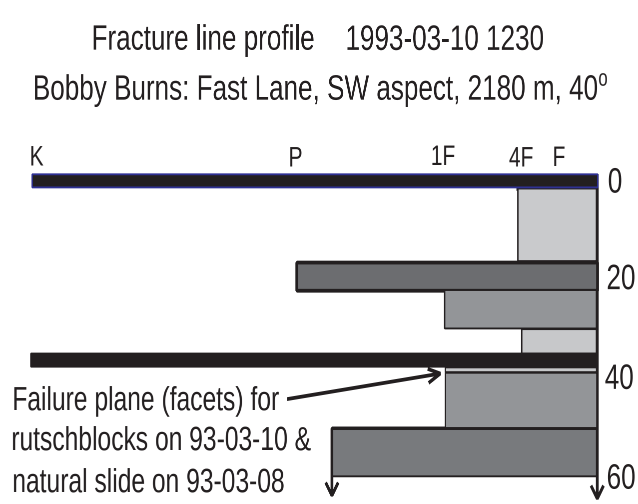

Figure 7. The fracture propagated in a layer of 1F facets under the crust rather than the softer layer of 4F facets above the crust. The thin crust concentrated the stress in the underlying facets.

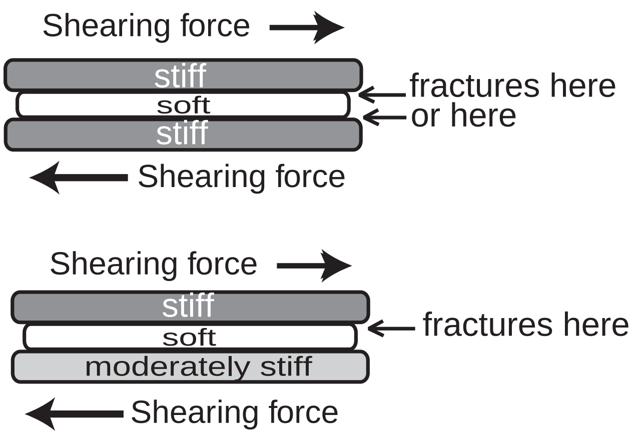

Figure 8. The fractures tend to occur where there is the greatest difference in stiffness. In the lower diagram, the fracture tends to occur at the top of the soft layer where the difference in stiffness is greatest.

To understand this effect, consider a cookie with the cream filling between the biscuits (Figure 8). If we hold the bottom biscuit and push the top biscuit parallel to the bottom biscuit, the cream filling is likely to fracture (in shear) where it meets one of the biscuits (at the interface). If only one of the biscuits gets slightly soggy and loses stiffness, the shear fracture is likely to occur at the interface with the other biscuit. In short, the shear fracture tends to occur at the stress concentration where the difference in stiffness between biscuit and filling is greatest. If the stiff biscuit is on top, the fracture will likely occur where it meets the less stiff filling, and this is analogous to a thin stiff layer at the base of a snow slab. However, if the stiff layer is thick, say the full thickness of the slab, then we are back to the bridging situation where less stress penetrates to the weak layer. So, a soft slab with a thin stiff layer just above the weak layer tends to be sensitive to skier triggering.

Combining the effect of slab thickness with stress concentration

Consider the three profiles in Figure 9. In each profile, the weak layer is at the base of a 50 cm slab. In profile A, the slab is uniform and soft (1F). In profile B the slab is uniform and hard (P), and in Profile C the soft slab (1F) has a stiff layer at the base of the slab. Which of these hypothetical profiles is least stable for skiers? I vote for Profile C; the soft slab allows the skier stress to penetrate deeply and the thin stiff layer concentrates the stress in the weak layer. The profile least likely to be skier-triggered is B; the skier's stress will not penetrate the uniformly stiff slab as deeply as the other profiles. Of course, if Profile B is skier triggered, the propagation will tend to be extensive and we don't want to be in or below nearby avalanche terrain.

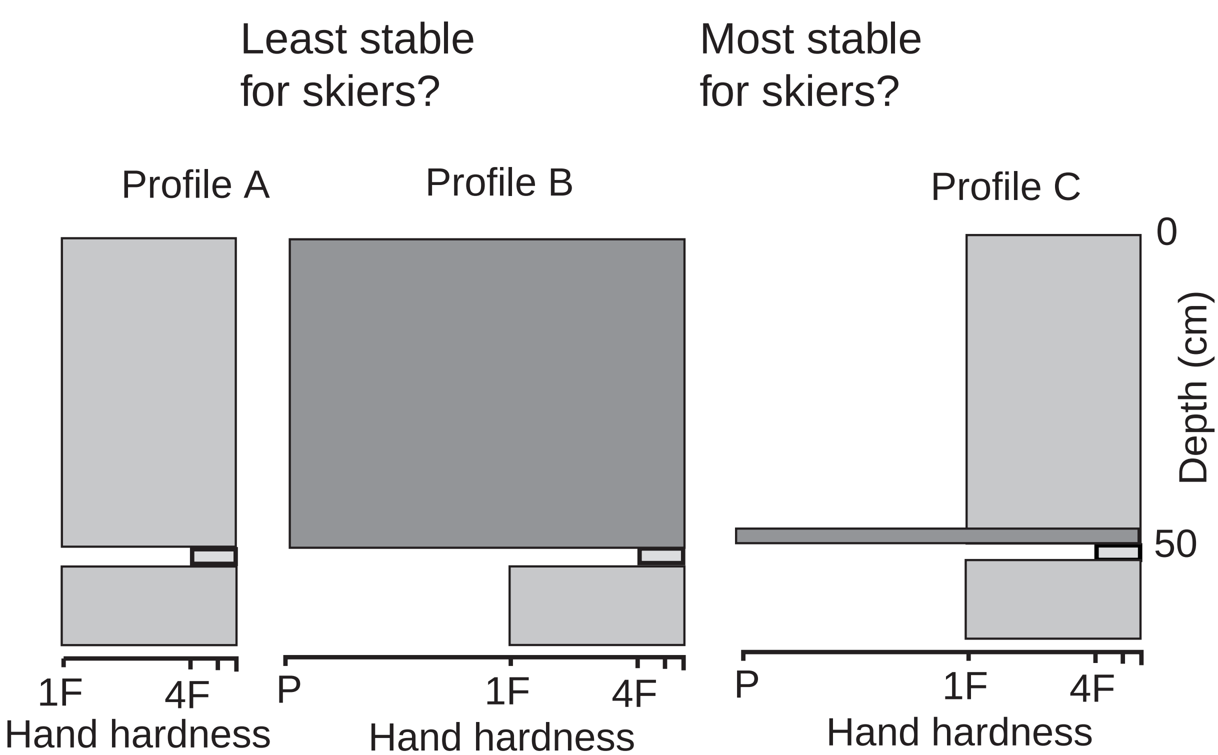

Figure 9. Which of these three profiles is least stable for skiers? Which is most stable for skiers?

Stress due to groups of skiers

When we group up on gentle terrain at the bottom of a slope, many of us have heard a whumpf (and sometimes observed a nearby avalanche). Sure, the whumpf indicates that we triggered a fracture in a buried weak layer (DenHartog, 1982; Jamieson, 1995, p. 184-195), but why did it happen at the base of the slope rather than on the steeper terrain above? Actually, there are several possible reasons:

1. Perhaps we caused whumpfs while skiing the slope–and did not hear them because we were skiing. This is possible, but whumpfs on slopes steep enough to slide usually result in avalanches, which we would have noticed.
2. Could the gentle terrain be less stable than the steeper slope above? It is an important and unanswered research question whether certain types of weak layers such as surface hoar, faceted crystals and depth hoar might be more sensitive to skier loading on gentle terrain (high compressive stress) than on steeper slopes (high shear stress). Perhaps faster creep on the steep slopes forms more bonds between the grains in the weak layer than does slower creep on the gentle slopes.
3. Perhaps we triggered the fracture in the weak layer by grouping together!

There are a couple of reasons why groups of skiers might be more effective triggers than single skiers. First, more skiers are more triggers testing more of the slope. However, this does not explain why whumpf seem to be heard more often at the base of slopes than on the steeper slopes above. Second, what happens to our stress bulbs when we group together? Since the strain (deformation) caused by each skier is small and roughly proportional to the stress, the stresses can be added. In Figure 10, the left skier causes a shear stress of 300 Pa in the weak layer under the 50 cm thick slab. When the right skier arrives and stops close to the left skier, the stresses add and suddenly the stress in the weak layer has increased substantially. Further, the stiffer

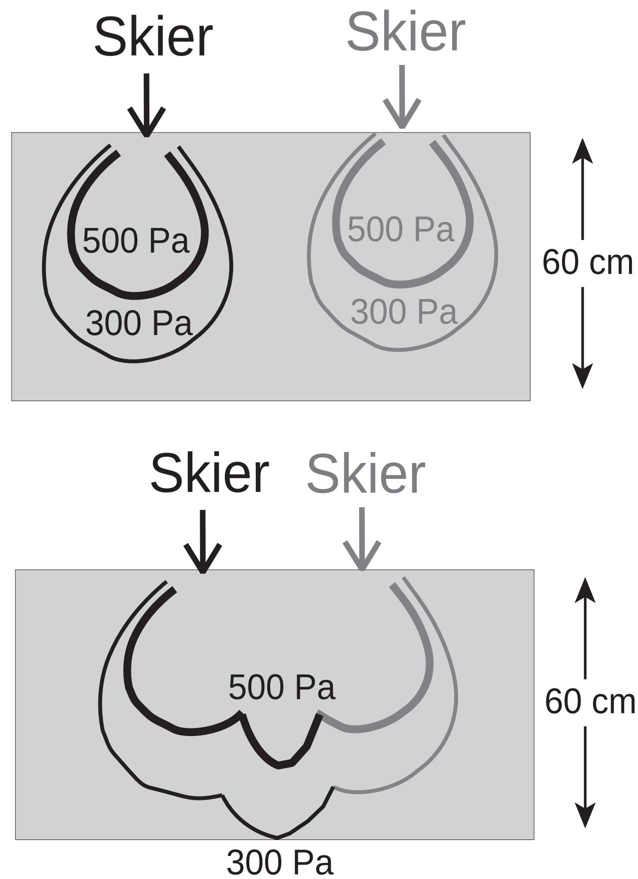

Figure 10. If the skiers are close enough, their combined stress at any particular depth will be greater than the stress due to separate skiers.

the slab, the farther the skiers can be apart and still have their stresses add. But how close do we need to be for this effect? Well, group triggering has not been studied quantitatively but we probably need to be within a metre or two for this effect to be substantial.

There is evidence of this group triggering from other sources. Groups of skiers are considered strong triggers in the European Avalanche Danger Scale (Dennis and Moore, 1997) and the Canadian snow stability ratings (CAA, 1995, p. 94). Also, thirty-eight percent of *unexpected* skier-triggered dry slab avalanches were reportedly triggered by a group of skiers rather than a single skier (Jamieson and Geldsetzer, 1999).

Effect of temperature change on skier stability

Before considering the effect of temperature change on the snowpack and stability, let's review the effect of temperature on snow specimens in the cold lab. McClung (1996) found that temperature had limited effect on strength. And Jürg Schweizer (1997, 1998) showed a strong effect of temperature on stiffness (resistance to deformation.) Specifically, similar specimens were twice as stiff at –15°C than at –5°C.

At the 1996 ISSW in Banff, McClung and Schweizer (1997) proposed a qualitative model for the effect of warming on skier triggering. They pointed out that when the snow surface is warmed its stiffness is reduced. Consequently, the deformation associated with a skier would penetrate more deeply, increasing the deformation on a buried weak layer and possibly triggering a slab avalanche. Stability is reduced without warming reaching the weak layer. When warming first reaches the weak layer, a loss of strength of the weak layer and a loss of toughness of the combined slab and weak layer might also reduce stability. However, if warming reached the weak layer and persisted, then the weak layer would likely gain strength through bonding.

Wilson and others (1998, 1999) used a computer model of a layered snowpack to show how skier stress in buried weak layers would increase when the surface of the slab warmed and lost stiffness. Specifically, when the top 20 cm of a hypothetical mid-winter snowpack lost stiffness, the stress in weak layers 30 and 50 cm below the surface increased by 8% and 6% respectively. When the top 20 cm of a pencil-hard slab warmed and lost stiffness, the skier stress in the weak layers 30 cm and 50 cm below the surface increased by 51% and 37% respectively.

On a cold day in January 1993, Jill Hughes, Aaron Cooperman and I tried repeatedly to trigger a hollow-sounding slab in the Cariboo Mountains … without success. As shown in Figure 11, the top

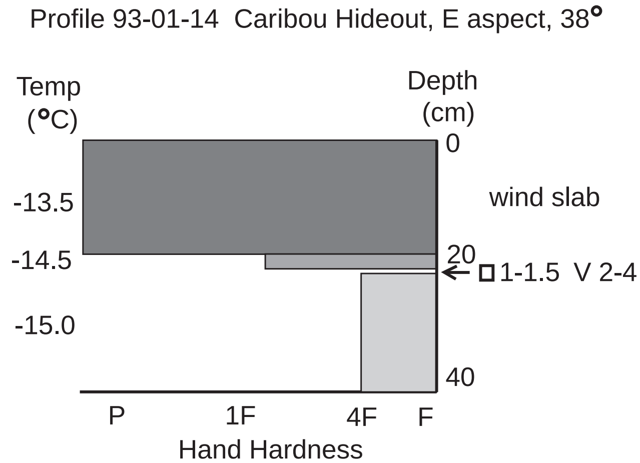

Figure 11. Although hollow sounding, this stiff and cold windslab could not be triggered. If the slab were warmer and therefore softer, more stress would have penetrated to the weak layer and the slab might have been triggered.

19 cm of the 22 cm thick slab was pencil hard and the weak layer consisted of facets! Wilson and others applied their warming model to the profile of this slab and weak layer. When they reduced the stiffness of the top 19 cm by 50%, which corresponds to warming from –15°C to –5°C (Schweizer, 1998), the skier stress in the weak layer increased by 32%. Perhaps, we might have been able to trigger this slab had it been warmer!

Although applying stiffness changes associated with warming uniformly to the top 20 cm of the snowpack is simplistic, it does show how warming a layered snowpack can increase the skier stress in buried weak layers, without warming penetrating to the weak layer. Further, cooling will have the opposite effect, stiffening surface layers, decreasing the skier stress in weak layers and contributing to skier stability.

While these ideas on warming are very plausible, they have yet not been verified by field studies. However, I have personally observed increases in stability associated with cooling over a few hours, too short a time for the cooling to penetrate to the weak layer.

Remote triggering

Depending on which definition you prefer, a remotely triggered avalanche is either triggered from more than 5 m from where the snow slides (CAA, 1995), or from outside the start zone (Jamieson and Johnston, 1998). Such events are not new to avalanche studies. Seligman (1936, p. 334-335) describes three cases and Bader and others (1939, p. 158) refer to the "well-known release of avalanches from a distance". Jamieson (1995, p. 184-195) also describes several cases. In a study of about 150 *unexpected* dry slab avalanches triggered by skiers or snowboarders (Jamieson and Geldsetzer, 1999), 41% were remotely triggered!

In some cases, the fractures have propagated through areas that were too stable to be triggered (Jamieson, 1995, p. 184-195). Consequently, stability tests are useful (but not definitive) indicators of whether the slab can be triggered but are **not** indicators of whether a fracture can propagate through the area. Stability is the probability of the slab not avalanching, whereas propagation potential is the ability of the snowpack to allow fractures to spread through weak layers. These are distinct properties of the snowpack that we should not confuse. While we lack good tests for propagation potential, almost all cases of remote triggering involve persistent weak layers of faceted crystals, depth hoar or surface hoar (Jamieson and Johnston, 1998). We should be aware of the potential for remote triggering when such persistent weak layers are present in the snowpack. However, because of spatial variability, assessing the likelihood of remote triggering with current field methods ranges from difficult to impractical.

Whumpfs

Whumpfs are similar to remotely triggered avalanches. Both involve a fracture propagating through a weak layer (Figure 12 and 13). If the fracture triggered by the skier reaches an avalanche slope, it usually releases an avalanche and we call it a remotely triggered avalanche, rather than a whumpf.

Figure 12. This fracture was triggered about 8 m to the left of the surface crack by a few skiers who heard a whumpf.

Figure 13. This is a close up of the displacement due to the fractures shown in Figure 12.

Summary

The stress in the snow underneath skiers decreases with depth. Consequently, most skier triggering occurs where the slab is less than a metre thick.

Skiers cause stress bulbs in the snow underneath their skis. Where two or more skiers are close together, the combined stress from their bulbs may be sufficient to trigger the slab even if the separate skiers could not. Where the slab is thick and stiff, the stress bulb underneath a skier tends to be wider and shallower than if the slab was softer. This bridging effect can make hard slabs less sensitive to skier loading.

Thin stiff layers just above weak layers concentrate the stress in weak layers and potentially make the slab more sensitive to skier triggering.

Stability and propagation potential are distinct properties of the snowpack. The stability of a particular slab (and its weak layer) may increase over time while the propagation potential of that slab may decrease or increase. When fractures underneath hard slabs are triggered, they can propagate long distances. Remotely triggered avalanches are particularly difficult to predict.

Skier stability indices based on shear frame measurements where snowpack properties appear average do have predictive merit. This is partly because the calculated stress due to a stationary skier is similar to the measured stress due to skiers pushing down with their skis, which is much like the down-weighting between a skier's turns.

Warming the surface of the slab will reduce its average stiffness and stability. And cooling the surface of the slab will tend to increase its average stiffness and stability.

Point observations of the snowpack such as profiles and snowpack tests are useful information for stability evaluation. However, the spatial variability of the snowpack limits the usefulness of point observations and makes stability evaluation difficult, especially when the variability is high.

Acknowledgements

My thanks to Jürg Schweizer for many stimulating discussions on skier triggering and for insightful comments on a draft of this article, to Steve Rosso and the Alta Ski Patrol for catching a error in an earlier version of this paper, and to Julie Lockhart for proofreading this article

This article is part of an ongoing University-Industry Project funded by the Natural Sciences and Engineering Research Council of Canada, Canada West Ski Areas Association, the Canadian Avalanche Association and the BC Helicopter and Snowcat Skiing Operators Association (BCHSSOA). The supporting members of the BCHSSOA include Canadian Mountain Holidays, Cat Powder Skiing, Crescent Spur Helicopter Holidays, Great Canadian Helicopter Skiing, Great Northern Snow Cat Skiing, Island Lake Lodge, Klondike Heli-Skiing, Last Frontier Heliskiing Ltd., Mike Wiegele Helicopter Skiing, Monashee Powder Adventures, Peace Reach Adventures Ltd., Purcell Helicopter Skiing, R.K. Heli-Skiing, Retallack Alpine Adventures, Robson Heli-Magic, Selkirk Tangiers Heli-Skiing, Selkirk Wilderness Skiing, Sno Much Fun Cat Skiing, TLH Heliskiing, Whistler Heli-Skiing Ltd. and White Grizzly Adventures Ltd. The supporting members of Canada West Ski Areas Association include Apex Mountain Resort, Banff Mt. Norquay, Big White Ski Resort, Hemlock Ski Resort, Intrawest Corporation, Mt. Washington Alpine Resort, Silver Star Mountain Resorts, Ski Marmot Basin, Sun Peaks Resort, Sunshine Village, Whistler Blackcomb, Whitewater Ski Resort, and Resorts of the Canadian Rockies including Skiing Louise, Nakiska, Kimberley Alpine Resort, Fortress Mountain and Fernie Alpine Resort.

For in-kind support, I am grateful to the avalanche control staff at Glacier National Park and the Snow Avalanche Programs of BC Ministry of Transportation and Highways.

References

Bader, H., R. Haefeli, E. Bucher, J. Neher, O. Eckel and C. Thams. 1939. Snow and its Metamorphism. Snow Ice and Permafrost Research Establishment Translation 14, 1954. Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 313 pp.

CAA. 1995. Observation Guidelines and Recording Standards for Weather, Snowpack and Avalanches. Canadian Avalanche Association. P.O. Box 2759, Revelstoke, BC, Canada, 98 pp.

Camponovo, C. and J. Schweizer. 1997. Measurements on skier triggering. Proceedings of the International Snow Science Workshop, Banff, Alberta, Canada, 6-10 October 1996. Canadian Avalanche Association, Revelstoke, BC, Canada, 100-103.

DenHartog, S.L. 1982. Firn quake. Cold Regions Science and Technology 6, 173-74.

Föhn, P.M.B, 1987a. The stability index and various triggering mechanisms. In: Avalanche Formation, Movement and Effects, Edited by B. Salm and H. Gubler, International Association of Hydrological Sciences, Publication No. 162, 195-211.

Jamieson, J.B. 1995. Avalanche prediction for persistent snow slabs. PhD Thesis, Dept. of Civil Engineering, University of Calgary, 275 pp.

Jamieson, J.B. and C.D. Johnston. 1992a. Snowpack characteristics associated with avalanche accidents. Canadian Geotechnical Journal 29, 862-866.

Jamieson, B. and T. Geldsetzer. 1996. Avalanche Accidents in Canada, Vol. 4: 1984-96. Canadian Avalanche Association, PO Box 2759, Revelstoke, BC, V0E 2S0, 202 pp.

Jamieson, J.B. and C.D. Johnston. 1998. Refinements to the stability index for skier-triggered slab avalanches. Annals of Glaciology 26, 296-302.

Jamieson, B. and C.D. Johnston. 1998. Snowpack characteristics for skier triggering. Avalanche News 55, 31-39.

Jamieson, B. and T. Geldsetzer. 1999. Patterns in unexpected skier-triggered avalanches. Avalanche News 58, 7-17

Logan, N. 1993. Snow temperature patterns and artificial avalanche release. Proceedings of the International Snow Science Workshop in Breckenridge, Colorado, October 4-8, 1992. ISSW '92 Committee, c/o Colorado Avalanche Information Centre, 10230 Smith Road, Denver, Colorado, 80239 USA, p. 37-46.

McClung, D.M. 1996. Effect of temperature on fracture in dry slab avalanche release. Journal of Geophysical Research, 110(B10), 21,907-21,920.

McClung, D.M. and P.A. Schaerer. 1993. The Avalanche Handbook. The Mountaineers, Seattle, p. 271.

McClung, D.M. and J. Schweizer. 1996. Effect of snow temperatures on skier triggering of dry slab avalanches. Proceedings of the 1996 International Snow Science Workshop in Banff, Alberta. Canadian Avalanche Association, Revelstoke, BC, 113-117.

Dennis, A. and M. Moore. 1997. Evolution of public avalanche information: The North American experience with avalanche danger ratings. Proceedings of the International Snow Science Workshop, Banff, Alberta, Canada, 6-10 October 1996. Canadian Avalanche Association, Revelstoke, BC, Canada, 60-66.

Schweizer, J. 1993. The influence of the layered character of snow cover on the triggering of slab avalanches. Annals of Glaciology 18, 193-198.

Schweizer, J. 1998. On the role of deficit zones or imperfections in dry snow slab avalanche release. Proceedings of the 1998 International Snow Science Workshop in Sunriver, Oregon, 489-501.

Schweizer, J. 1999. Review on the role of deficit zones on dry snow slab avalanche release. Cold Regions Science and Technology.

Schweizer, J., M. Schneebeli, C. Fierz and P.M.B. Föhn. 1995. Snow mechanics and avalanche formation: Field experiments onto the dynamic response of the snow cover. Surveys in Geophysics, 309-315.

Schweizer, J., C. Camponovo, C. Fierz and P.M.B. Föhn. 1995. Skier-triggered slab avalanche release - some practical implications. Proceedings of the International Symposium at Chamonix, 30 May - 3 June 1995: The Contribution of Scientific Research to Snow, Ice and Avalanche Safety. Association Nationale pour l'Etude de la Neige et des Avalanches. Grenoble.

Seligman, G.,1936. Snow Structure and Ski Fields. International Glaciological Society, Cambridge, 555 pp.