Schweizer, J., 2004. Skier-triggered avalanches: observations and concepts. *In:* K. Kristensen (Editor), Proceedings Snoskred og friluftsliv, Stryn, Norway, 24-27 October 2002: pp. 52-55.

Skier-triggered avalanches: observations and concepts

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Abstract: Characteristics of skier-triggered avalanches are described with special focus on release conditions and snowpack properties. The analysis is based on data from skier-triggered avalanches and skier-tested slopes from the Swiss Alps and the Columbia Mountains of Western Canada. Results are compared to the present understanding of dry snow slab release. The effect of snowpack variability on avalanche formation is discussed. Conclusions are drawn in regard to snowpack stability evaluation.

Keywords: Snow avalanche, avalanche formation, avalanche release, snow stability evaluation, skier triggering

1. Introduction

Snow avalanches are the main threat to recreationists in the backcountry in snow covered steep terrain. Roughly about 150 skiers, snowboarders and mountaineers are killed by avalanches each year in Europe and North America where off-piste skiing and ski touring are quite popular. Most of the victims (90%) trigger the fatal avalanche themselves or were caught by an avalanche that was triggered by another member of their party. So, accidents are to a large extent not incidental. Education and training, proper equipment, information on conditions and risk adequate behaviour (situational awareness) are the keys to avalanche prevention, i.e. to reduce the probability to be caught in an avalanche. An avalanche involvement should be avoided by all means, since only about 50% of all completely buried victims survive. However, snow stability evaluation is not an easy task and false predictions are inherent due to the partly unknown and variable nature of the mountain snowpack. Therefore, the modern approach to the problem is largely statistically based and tries to avoid avalanche prone situations by – among other things – proper trip planing thereby heavily relying on public avalanche warning bulletins (Munter, 1997). These statistically based rules aim to transfer experience and to minimise the bias of human factors on decisions. If detailed avalanche forecasts are unavailable, personal efforts to evaluate snow stability become much more important. Accordingly, it is a prerequisite to know the beast – the skier-triggered avalanche – and its habitat – the snowpack.

What follows is a summary of a few studies that focus on skier triggering and more details can be found there (Camponovo and Schweizer, 1997; Jamieson, 1995; Jamieson, 1999; Schweizer and Jamieson, 2001; Schweizer and Jamieson, 2002; Schweizer and Lütschg, 2001). Avalanche characteristics given below are based on observations from the Swiss Alps and Western Canada.

2. Avalanche characteristics

There are two principal types of avalanches: loose snow avalanches and slab avalanches. Human-triggered avalanches are nearly exclusively slab avalanches. Very few fatalities are due to loose snow avalanches; about half of these were wet loose snow avalanches that caused the fall of the skier/climber. Hardly ever, a wet slab avalanche is triggered, reflecting the fact that wet slabs can hardly be triggered by rapid, near-surface loading.

A human-triggered avalanche typically involves dry snow, and is about 50 m wide, and 150 m long,

Figure 1: Typical skier-triggered, dry-snow slab avalanches on a steep, shaded slopes.

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with a fracture depth of 45 cm (Table 1). In 98% of the cases reported the mean fracture depth is less than 100 cm clearly showing that a skier is not a very effective trigger for deep weak layers/interfaces. On average, the slope angle in the starting zone is about 39°. Size and terrain characteristics in the starting zone are independent of the danger level for the danger levels relevant for recreationists (Harvey, 2002). In the Swiss Alps human-triggered avalanches occur most frequently (23%) on slopes of north-eastern aspect; overall about 60% were triggered in shady slopes. For most of the Swiss Alps, on the north-easterly slopes the unfavourable factors shady slope and lee slope are combined. The southern aspects (SE, S and SW) contribute 18%. The rest is triggered in the eastern (15%) and western (8%) aspect. The elevation of the typical starting zone is about 2400 m a.s.l., which is above treeline in most parts of the Swiss Alps. Most avalanches are triggered close to the ridge top (52%), and/or in bowls, gullies and on open slopes. The key parameters are summarised in Table 1.

*Table 1: Characteristics of human triggered avalanches (Swiss Alps, 1987-88 to 1996-97). Median values given. Between the 1st and 3rd quartiles 50 % of the cases are found. *) The aspect given is the one most frequently found (mode).*

Avalanche characteristics	*N*	*1st quartile*	*Median*	*3rd quartile*
Width	611	28.8 m	50 m	100 m
Length of slab	61	50 m	80 m	150 m
Aval. length	619	80 m	150 m	300 m
Fracture depth	522	30 cm	45 cm	60 cm
Slope angle	617	36°	38°	40°
Elevation	629	2190 m	2410 m	2610 m
Aspect*	634	-	NE*	-

Based on the avalanche incident reports from 1987-88 to 1996-97 the vast majority of avalanches were triggered by skiers (80%), 11.5% by snowboarders and 6.8% by climbers Triggering occurs primarily while off-piste skiing (58%) and ski touring (41%); less than 1% was triggered within controlled ski areas.

Sixty per cent of human-triggered avalanches are triggered by a single person who is either a party member or travelling individually. During off-piste skiing single triggering is even more common (73%) and obviously nearly exclusively occurs during the descent (99%). During ski touring triggering by a whole group is more frequent (54%), and these incidents are evenly distributed between ascent and descent. Whereas the vast majority of avalanches were triggered by the first person entering the slope or by several persons (group triggering), in a few cases (about 10%) an avalanche was triggered on a very recently skied slope. The avalanche was triggered by e.g. the second or third skier entering the slope, when skiing one by one. However, these statistics include a large amount of cases for which triggering details are not known, but assumed. In steep gullies, skiing tracks on one side do not imply that the other side is safe, since due to the different aspect and other factors the snowpack might be quite different.

3. Snowpack properties

As shown above there is a slab of usually less than 50 cm thickness, slightly consolidated, but still quite soft (hand hardness: 4F [Four Fingers]) lying on top of a snowpack weakness. Slab hardness usually increases with depth, i.e. soft conditions prevail at the top. However, occasionally wind slabs with a relatively hard, near-surface layer were also skier-triggered.

The snowpack weakness is either a thin weak layer or a weak interface where two layers are poorly bonded due to at least one of two layers having weak layer properties. Only about 45% of the fractures occur at the interface between storm snow and old snow surface. The majority of cases involves old snowpack layers. These old snow instabilities can only be found by snowpack stability tests. In over 80% of the snowpack weaknesses of skier triggered avalanches persistent grain types are found, i.e. large grains of surface hoar, faceted crystals or depth hoar. These grain types with plane faces form by kinetic crystal growth and are weak in shear but relatively strong in compression. They can persist for weeks within the snowpack and may represent a lingering instability.

Across the fracture interface there is typically a distinct hardness difference of 1½ to 2 levels of the hand hardness index (e.g. One Finger vs. Fist) and a grain size difference of about ¾-1 mm. The grain size difference is responsible for the poor bonding between the two layers; the hardness difference favours stress/strain concentrations at the interface and promotes fracture propagation. These differences between the layers adjacent to the fracture interface are not only typical of human-triggered avalanches they are even suited to discriminate between stable and unstable snowpack stratification. Stability tests performed beside skier-triggered avalanches showed a median rutschblock score of 3 (weighting), whereas the median RB score was 5 (2nd or 3rd jump with skis from above) for slopes that had been skied but not released. Instability was clearly more distinct when the whole block released and the sliding surface was smooth. Critical ranges for instability when analysing snowpack information are summarised in Table 2 (Schweizer and Jamieson, 2002; McCammon and Schweizer, 2002).

Table *2: Parameters of instability and proposed "unstable" ranges for snow profile classification.*

Parameter	Critical range
Rutschblock score	< 4
Grain size difference	≥ 0.75 mm
Failure layer grain size	≥ 1.25 mm
Hardness difference	≥ 1.7
Failure layer hardness	≤ F+
Failure layer grain type	persistent
Failure depth	< 1 m

4. Snow slab avalanche release

The recipe for a dry snow slab avalanche is - in simplified form (Fredston and Fesler, 1988): steep terrain, a slab sitting on top of a weak layer or interface, a critical balance between the stress acting on and the strength of the weak layer or interface and finally a trigger to tip the balance.

It is widely accepted that dry-snow slab avalanche release typically starts with shear failure then fracture at the weak interface followed by tensile fracture at the crown just before the slab is fully detached. The shear failure starts from a natural imperfection or a somewhat weaker area within the weak layer/interface or is induced by a skier. Rapid, near-surface loading by skiers, snowboarders or mountaineers may frequently cause a local fracture, which might spread out over the entire slope leading to slab release. Frequently this fracture initiation by a skier is accompanied by a characteristic "whumpf"-sound. The fracture initiation is also possible in flat terrain with the propagating shear fracture travelling to a steeper slope to release the slab: this case is known as so-called remotely triggering. Fracture initiation by skiers through near-surface rapid loading is only efficient for relatively shallow slabs of about 30-60 cm thickness, since the skier's induced stress and strain strongly decreases with increasing depth within the snowpack. For weak layers/interfaces buried deeper than about 1 m below the snow surface triggering becomes rather unlikely. The slab properties (hardness, thickness, penetration depth) significantly affect the skier's impact within the snow cover. Harder layers decrease the skier's load for a given depth, but distribute it on a larger area, and vice versa for softer layers.

Easy triggering locations are areas in the snowpack with reduced skier stability due to lower strength (e.g. near rocks or bushes) or different slab properties (e.g. shallow snowpack, wind effects). However, at low stability, triggering is in most cases possible at any spot on the slope, and there is no need to hit a so-called deficit zone where the strength is so low that the load of the overlying slab is not supported. These deficit zones are hypothetical and if they exist they do so only for short periods of time, since such areas will sinter or heal within minutes to hours. Most critical for incidental triggering may be situations of intermediate or fair stability with substantial variability in snowpack properties.

Accordingly, the findings on snowpack characteristics of skier-triggered avalanches support the above outlined model of skier loading in which skiers directly initiate fractures in buried weak layers or interfaces. The slab should preferably be soft at the top to enable the skier to efficiently impart deformations to the depth of the weak layer/interface. The slab has to be relatively shallow, since the skier's impact strongly decreases with increasing depth. A distinct difference in hardness between the slab and the weak layer causes stress concentrations and favours fracture initiation. Accordingly, when travelling in the backcountry, areas of thinner-than-average snowpack may be potential trigger points, especially when a persistent weak layer exists in the snowpack. Therefore areas of thinner-than-average snowpack are as well the preferred sites for snow profiles and to test snow stability.

5. Snowpack variability

As outlined above, snowpack stability variation influences avalanche formation. Snowpack variability is inherent to alpine snowpacks, but its extent, scale and detailed effect on avalanche formation are largely unknown so far. Several studies are presently under way (e.g. Kronholm et al., 2002). Previous studies were not conclusive, since different methods were applied at different scales and results were differently interpreted.

Disorder exists at several scales within the snowpack. In particular meteorological conditions during snowfall events contribute to variability. There are several possibilities for variability in view of avalanche formation. There can be variability of the slab, e.g. varying thickness, or variability of the weak layer. The weak layer might not exist at certain places, or where it exists, the strength of the weak layer varies spatially. For any case the scale of the variability is still unknown. One scale that is important for avalanche release is 0.1 to 10 m. This is the scale of the size of a critical initial fracture that is necessary to drive fracture propagation prior to slab release. It is assumed that the shorter length is critical during rapid loading by a skier. In-situ measurements of the deformation induced by a skier, observation on skier triggering and laboratory measurements on the fracture toughness of snow indicate that for skier triggering the critical size for self-propagating fracture is of the order of 1 m^2. The amount of variability likely depends on the type of weak layer since certain layers are relatively continuous (e.g. facets above crusts), whereas others (surface hoar) are more prone to erosion by wind while on the surface. This means that the conditions of weak layer formation affect the scale of variability. Near-surface or near-crust faceting might exist more widely, at a larger scale whereas surface hoar might be limited to certain terrain features or elevations bands. Finally, when the scales are clear, the effect of variability on avalanche formation is complex. High spatial variability might offer points of fracture initiation, but might also limit fracture propagation since at areas of higher strength fractures may come to arrest. On the other hand low variability seems favourable for fracture propagation, but in this case failure initiation obviously will depend on the level of stability. Intermediate stability with a certain degree of variability seems to be most critical in view of skier triggering, i.e. the probability of triggering is difficult to assess which might suggest special caution when travelling in avalanche terrain.

Snowpack variability hinders extrapolation from single point measurements. Therefore, when assessing snow stability with stability tests, not too much confidence should be placed on any single point observation of the snowpack. Several observations such as hasty pits with stability tests are usually needed. Experienced observers seeking for signs of instability (targeted sampling) (McClung, 2002) will likely find appropriate locations for stability tests and will therefore only need a few tests to estimate regional snowpack stability. In any case snow pit observations always need to be combined with other observations on instability, weather factors and most important terrain for stability evaluation. Knowledge on snow instability, in particular on the existence of weak layers/interfaces and its spatial patterns, will contribute to better decision making when travelling in avalanche terrain when no other information on the snowpack from e.g. public avalanche bulletins is available.

6. Conclusions

Skier-triggered avalanches are responsible for most avalanche victims in Europe and North America. Triggering is not incidental but due to characteristic snowpack properties and due to the fact that skiers or snowboarders represent a rapid near-surface load, which promotes instability. Skier-triggered avalanches are nearly exclusively dry snow slab avalanches, in most cases of considerable size (50 m wide), but relatively thin (45 cm fracture depth). Typical terrain features exist that are particularly critical: very steep, shaded, rather concave slopes that are near to a crest. Together with a detailed avalanche bulletin, these form the basis for risk reduction methods. The observations on avalanche and snowpack characteristics support the simple model of skier triggering that assumes that skiers or snowboarders directly impart a local shear fracture.

The snowpack consists of a typically soft slab overlaying a weak layer or interface. The weak layer or one of the two layers adjacent to the failure interface is soft and consists of large persistent grains. There are distinct grain size and hardness differences across the failure interface. The failure occurs more frequently within the old snowpack than at a new snow/old snow interface. Therefore and despite snowpack variability, snow stability tests are particularly useful for seeking potential instabilities, especially when there is no detailed public avalanche bulletin available.

Besides carefully choosing the terrain, keeping distances and skiing one by one can further reduce the risk of avalanche death which will never be zero but should be targeted, i.e. optimally balanced between profit (steep powder) and loss (avalanche death).

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