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FIELD OBSERVATIONS OF SKIER-TRIGGERED AVALANCHES

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ABSTRACT: Snowpack characteristics for skier-triggered avalanches are described in order to better understand skier triggering, to improve snow profile observation and interpretation, to make suggestions for route selection and to provide a basis for further research. Our analysis is based on field observations of skier-triggered avalanche sites in the Columbia Mountains of Canada and the Swiss Alps. Although these two mountain ranges have different climates the characteristics for skier triggering are similar. The analysis has focussed on slab properties and weak layer properties, and in particular their interaction. The findings support the simple model of skier loading. The slab should preferably be soft to enable the skier to efficiently impart deformations to the weak layer. The slab has to be relatively shallow (50 cm), 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 for testing snow stability.

KEYWORDS: avalanche forecasting, avalanche formation, skier triggering, snow cover stability, snow physical properties.

1. INTRODUCTION

In most studies of avalanche accidents in Europe or North America (Schweizer and Lütschg, 2000; Logan and Atkins, 1996; Jamieson and Geldsetzer, 1996) approximately 85% of fatal avalanches are triggered by people. Earlier field studies of snow cover properties summarized results of avalanches most of which were released naturally or by explosives. Perla (1977) described the dimensions of slab avalanches, as well as some snowpack and terrain properties associated with avalanching. The article provided much needed field data on slab avalanches, and is still widely referenced. Ferguson (1984) used cluster analysis and pattern recognition techniques to distinguish between stabile and unstable snowpacks. Föhn (1993) summarized the properties of about 300 weak layers underlying slabs, 20 % of which were identified by avalanche investigations and the remainder by snowpack tests such as the rutschblock test (Föhn, 1987).

Except for Jamieson and Johnston (1998), these previous studies have not focussed on skier-triggered avalanches. Except for Ferguson (1984) and in a limited way Föhn (1993), the previous studies have analyzed the weak layer in isolation from the properties of the slab and snow cover.

The present study comprehensively summarizes the properties of the snow cover, slab, weak layer or interface for almost 200 skier-triggered avalanches in Switzerland and Canada. These results are supplemented with a larger but less comprehensive data set of reported avalanches in both countries. The analysis of the snow cover and terrain properties is intended to provide insight into skier triggering of slab avalanches, and to assist with site selection for snowpack tests, profiles and explosive control, as well as snow profile interpretation and route selection. Further, the results should provide a basis for further research into skier triggering, and for modelling.

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2. DATA

We explore four data sets of human triggered avalanches, two from Switzerland, and two from Canada. For each country we have a data set of *reported* avalanches with basic measurements (partly estimates) like width, slope angle, aspect, etc. These data sets are large: 635 cases for Switzerland from the winters 1987-88 to 1996-97 and 1136 cases for Canada from the winters 1989-90 to 1999-2000. The other two data sets contain human-triggered avalanches with profiles (usually taken one day after release) which we call *investigated* avalanches (95 for Switzerland, 91 for Canada). These data sets will therefore be used to describe the snowpack conditions. As in any data set on avalanche measurements there is a selection bias.

The Swiss data sets are based on avalanche reports of the Swiss Federal Institute for Snow and Avalanche Research (SLF). Avalanches are consistently reported to the SLF if there is a serious involvement. The Canadian data set is based on the avalanche reports of the two large helicopter skiing companies: Canadian Mountain Holidays (CMH) and Mike Wiegele Helicopter Skiing, both of which operate in the Columbia Mountains of western Canada. These operations report avalanches consistently, and in the very vast majority of the Canadian cases, the avalanches were intentionally triggered (skier controlled) and nobody was caught or injured.

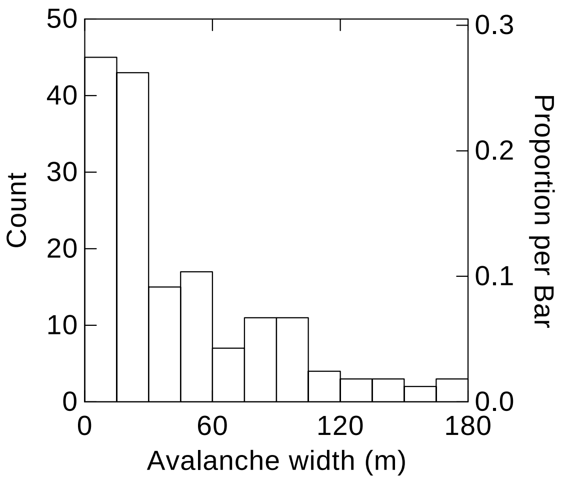

Figure 1: Average width of Swiss-Canadian investigated avalanches (N=186, 15 cases with width >180 m not shown).

3. METHODS

For the analysis of the snow profiles the vertical hardness distribution within the snowpack (hand or ram hardness) was classified according to the profile types given in Schweizer and Lütschg (2000). The slab and the underlying snowpack have been characterized separately. Hand hardness for individual layers are indexed from 1 to 6 for Fist (F), 4-Finger (4F), 1-Finger (1F), Pencil (P), Knife (K) and Ice (I), respectively. Intermediate values are allowed, e.g. 1-2, or 2+.

As many of the parameters are not normally distributed we give median and 1st and 3rd quartiles as key statistics. The middle 50 % of the sample are between the 1st and 3rd quartile. In general, the Swiss and Canadian data sets are analysed separately. To compare different data sets we used two non-parametric tests. The Kruskal-Wallis (H-Test) for independent samples of different size, e.g. for comparing the fracture depth found in the Swiss and the Canadian sample; and the Wilcoxon signed rank test for related samples, e.g. if comparing layer characteristics case by case. For both tests a p-value of significance can be given. If $p<0.05$ the two samples are considered significantly different. Comparing categorical variables such as grain type or profile type, the distributions are compared by cross-tabulating the data and calculating the Pearson chi-squared statistic. Although many of the samples considered in the following are statistically significantly different, the results presented below will be given for the combined Swiss-Canadian data set only, except if mentioned. This procedure is chosen since the samples are often sufficiently similar, and since it is much easier for the reader.

4. RESULTS

We will first describe the results for the avalanche and terrain characteristics, relying mainly on the large data sets of reported avalanches, and then describe the snowpack conditions based on the two smaller data sets of investigated avalanches for which snow profiles are available. The main data are summarized in Table 1.

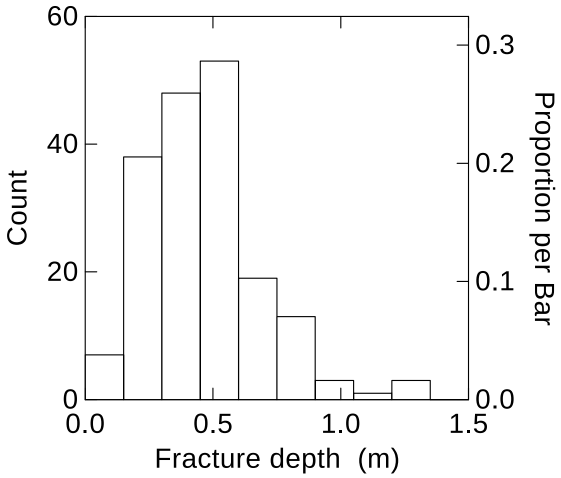

Figure 2: Fracture depth of investigated Swiss-Canadian avalanches (N=186, 1 case with fracture depth >1.5 m not shown).

4.1 Type of avalanche

Only few loose snow avalanches were reported (2-5 %). Moist or wet snow avalanches are not frequent as well, and represent about 1-3 % of all cases. Most of the wet snow avalanches reported are loose snow avalanches. The very vast majority therefore is dry snow slab avalanches.

4.2 Avalanche size

The avalanches in the Swiss data sets are substantially larger than in the Canadian data sets due to the reporting and selection biases. The Canadian data sets include many small and shallow slabs of storm snow that have been intentionally triggered. The median width for the reported avalanches is 25 m. The median width of the investigated cases is larger: 35 m (Figure 1).

The median average fracture depth (measured vertically at the crown) is about 40 cm (Figure 2). Only 2-3 % of the average fracture depths are thicker than 1 m. Since the fracture depth

Table 1: Key statistics of combined Swiss-Canadian field data of skier-triggered slab avalanches (WL: weak layer, LA: layer above weak layer, LB: layer below weak layer). Unless specified, results are for investigated avalanches.

Parameter	N	1st quartile	Median	3rd quartile
Width reported (m)	1441	15	25	50
Width investigated (m)	179	16	35	89
Fracture depth reported (m)	1524	0.25	0.39	0.5
Fracture depth investigated (m)	186	0.35	0.46	0.6
Slope angle investigated (°)	186	37	39	42
RB score	106	2-3	3	4
Slab thickness (m)	186	0.3	0.46	0.63
Slab hardness	186	1+	2	2-3
Slab temperature (°C)	166	-7.5	-5.0	-3.2
Slab density (kg m^{-3})	98	110	140	200
WL grain size (mm)	103	1.5	2.5	5
WL hardness	96	1	1	2
WL thickness (cm)	103	0.5	1	1.75
WL temperature (°C)	89	-6.0	-4.0	-3.0
LA grain size (mm)	86	0.5	0.875	1.25
LA hardness	103	2-	2+	3
LB grain size (mm)	89	0.75	1.0	1.5
LB hardness	102	2-	3	3+

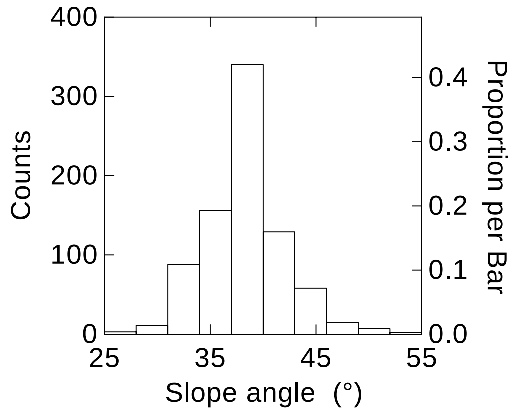

Figure 3: Slope angle in starting zone of human triggered avalanches. Swiss reported and investigated, and Canadian investigated cases are shown jointly (N=809).

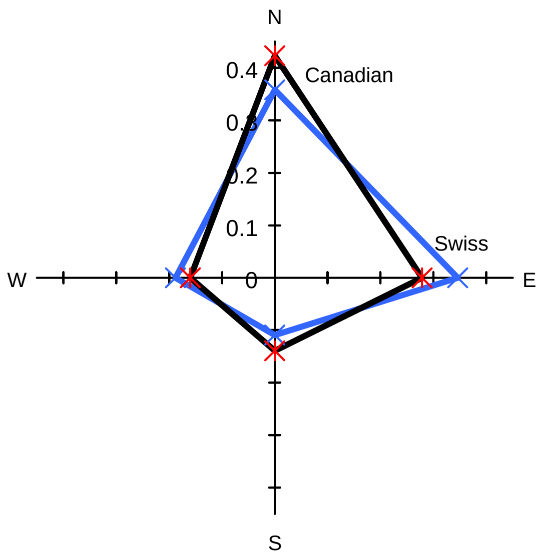

Figure 4: Frequency of aspect of reported skier-triggered avalanches in Switzerland (N=633) and Canada (N=914).

is usually measured or estimated at the fracture line, it is frequently not representative of the triggering location (Jamieson and Johnston, 1998).

4.3 Terrain

The median slope angle is 39°. The middle 50 % of cases are between 37° and 41° (Figure 3). North, north-east, and east are the aspects most frequently found (Figure 4). All four data sets indicate that skier triggering is more common on shady and/or lee slopes. The elevation of human-triggered avalanches (starting zone) is typically at or above tree line, at about 2150 m a.s.l.

4.4 Snowpack

In the following we analyse the two data sets each with over 90 profiles from investigated avalanches. Our main interest is to explore the properties of the failure layer or interface in combination with the adjacent layers. First we describe some of the snowpack and failure characteristics in general.

Due to the distinct differences in climate the median snow depth in the investigated cases in Switzerland was 1.2 m and in Canada more than twice as much: 2.8 m.

The percentage of avalanches in which the slab included old snow ranged from 63 % (Swiss) to 48 % (Canadian). In all other cases the slab consisted of storm snow, i.e. the failure was within the storm snow or between the storm snow and the old snowpack. For 45 out of the 91 Canadian cases the age of the weak layer, i.e. the time since it was buried, was recorded. The median age is 11 days, the middle 50 % ranged from 6 to 14 days, and the oldest weak layer was 56 days old when it was triggered by a skier. For the cases when the slab consisted of storm snow, the median age was 5 days, compared to 12.5 days for the 32 cases when the failure occurred in the old snow.

The failure was characterized as interface failure in 56 % of the investigated Swiss cases, and 33 % of Canadian cases. In all other cases a distinct thin weak layer was found. Föhn (1993) reported about 60 % of interface failures in his analysis of 300 snow profiles.

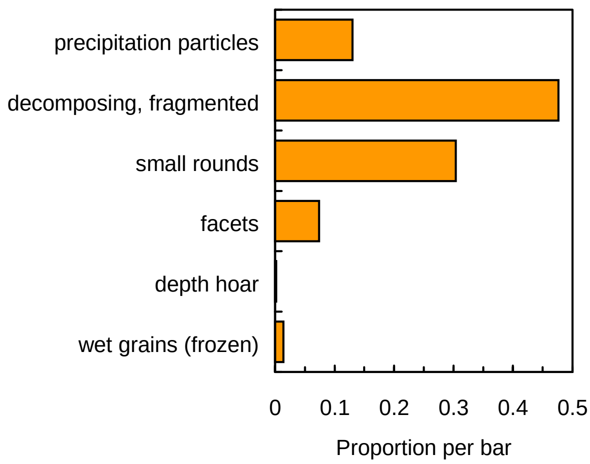

Figure 5: Grain size in slabs of Swiss and Canadian investigated avalanches.

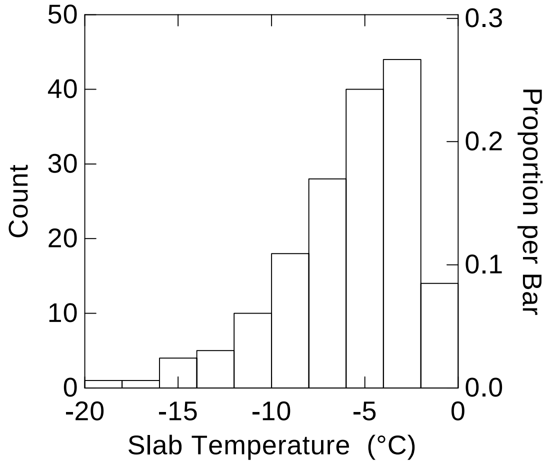

Figure 6: Slab temperature of Swiss-Canadian investigated avalanches (N=166).

In most cases a rutschblock test was performed. The median rutschblock score in both data sets is 3 (weighting). The middle 50% of rutschblock scores near skier-triggered slab avalanches range from 2.5 to 4.

4.5 Slab properties

The median slab thickness is 46 cm. There is a significant difference in slab thickness for storm and old snow avalanches. The median thickness is 40 cm for the cases when the slab consisted of storm snow only, and 50 cm for the cases when the failure surface was within the old snow layers.

The most frequently found grain type in the slab are the decomposing and fragmented precipitation particles (Figure 5). The Swiss data set contains more small rounded grains, whereas the Canadian data set contains more precipitation particles. Consistent with the higher proportion of old snow avalanches in the Swiss data and with the shallow snowpack, faceted crystals were found in some slab layers of the Swiss avalanches.

The median average hand hardness index of the slab was 2 (4 fingers). The median of the average slab temperature is -5.0 °C (Figure 6). In both the Swiss and Canadian data set the profile types 1 (36 %) and 6 (38 %) are most frequently found. The median slab density is 205 kgm^{-3} in the Swiss and 125 kgm^{-3} in the Canadian data set. The reason for the difference is probably related to the high portion of old snow slabs in the Swiss data set.

4.6 Weak layer

In 82 % of the weak layers grains with plane faces (persistent grain types) were found, i.e. surface hoar, facets and depth hoar (Figure 7). The size of the grains found in weak layers is a few millimetres (median: 2.5 mm). The median hand hardness index is 1 (fist). The median snow temperature in the weak layer is about -4 °C. The middle 50% of weak layer thickness ranges from 0.5 cm to 1.75 cm; however, many of the layers were only measured to the nearest centimetre and our definition of weak layers excludes most layers thicker than 3 cm.

4.7 Layers above and below the weak layer

The characteristics of the layers above and below of the weak layer are given below thereby focussing on differences of grain type, grain size and hardness between these layers. In the layer above the weak layer, grain types associated with equilibrium metamorphism (precipitation particles, decomposed and fragmented particles and rounded grains) are most frequently found (74 %). There is a significant difference ($p<0.001$) in grain type between the layer above and the weak layer. The grain size in the layer above the weak layer is significantly smaller ($p<0.001$) than in the weak layer, about 0.7-1 mm. The hardness of the layer above the weak layer is significantly greater than in the weak layer ($p<0.001$): hand hardness index: about 2-3. The median difference is one degree of hand hardness. In the layer below the weak layer again significantly different grain types are found compared to the weak layer ($p<0.001$): about 70 % facets, depth hoar and rounded facets in the Swiss, and only about 25 % facets, but 73 % fragmented and decomposing precipitation particles and small rounds in the Canadian data. The statistically

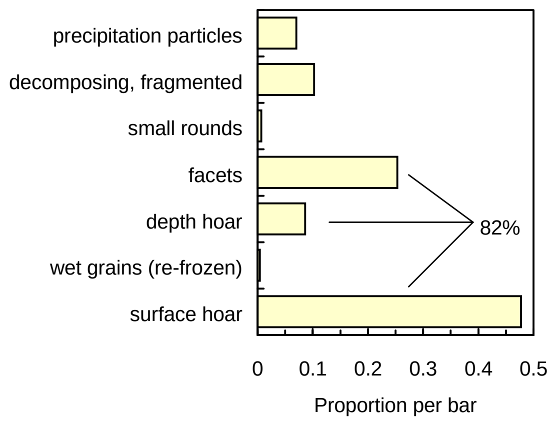

Figure 7: Grain type in weak layers of Swiss-Canadian investigated avalanches (N=103).

significant difference ($p<0.001$) between the Swiss and the Canadian data is a consequence of the different prevailing snow metamorphism in the Swiss and Canadian snowpack due to the different snow depth (1.2 m vs. 2.8 m). The grain size in the layer below of the weak layer is significantly different ($p<0.001$) from the weak layer, i.e. smaller: median grain size: 1 mm. The layer below of the weak layer is significantly harder than the weak layer ($p<0.001$). The median difference is one degree of hand hardness index.

5. DISCUSSION

The typical skier-triggered slab avalanche is 20-50 m wide and close to 100 m long (Canadian size class 2), and consists of dry snow. Loose snow avalanches and wet slab avalanches are rarely reported.

The median slope angle for skier triggering is 39°, very close to the mean slope angles from other studies (e.g. Perla, 1977) that have not focussed on human-triggered avalanches. Most skier-triggered avalanches in our Swiss and Canadian data are on north or east aspects, perhaps because these are most often shaded and/or lee slopes. Most skier-triggered avalanches occur at or above tree-line perhaps because of skier preferences for this terrain and/or the effect of wind on slab formation.

The slab is rather shallow (median thickness: 46 cm). The fact that 82 % of skier-triggered slabs were less than 70 cm, supports the idea that in most, but not necessarily all cases of skier-triggering, the skier is effective in initiating a failure in the weak layer/interface, without the pre-existence of a deficit zone (Schweizer, 1999; Schweizer and Camponovo, 2000). Where a weak layer and slab are present, skier triggering will be more likely where the slab is thinner and softer. Logan (1993) and Jamieson (1995) give examples of skier triggering where the slab is locally thin and/or weak.

As expected for slabs, which are by definition cohesive, most consist of layers of precipitation particles, decomposed and fragmented particles and/or rounded grains. However, in the thin snowpack area of the Swiss Alps, faceted crystals are also commonly found in slabs.

The middle 50 % of slab temperatures (roughly in the middle of the slabs) range from -7.5 °C to -3.2 °C. Within this range moderate changes in temperature can affect the stiffness of the slab (Schweizer, 1998) and consequently the stability for skiers (McClung and Schweizer, 1999).

In the most common profile of the slabs, hardness increased with depth. Soft conditions at the top prevailed. However, occasionally other profiles such as wind slabs with a relatively hard near surface layer, were also skier-triggered.

The majority of the slabs included old snow indicating the importance of observing and/or monitoring weak layers even after they are buried by a recent storm. This is further emphasised by considering the age of weak layers in the Canadian investigated avalanches (median age: 11 days).

The vast majority of weak layers were persistent. That is, they consist of faceted crystals, depth hoar or surface hoar. Such layers are also common in fatal avalanches (Jamieson and Johnston, 1992).

The weak layers typically range from Fist to 4-Finger hardness. The layers above and below the weak layer are typically harder by one degree. For example, if the weak layer hardness is 2 (4F), the layers above and below are typically 3 (1F). Since the force for hand hardness tests is kept approximately constant and the area is varied by a factor of roughly four (Geldsetzer and Jamieson, 2000), the layers above and below are often several times harder, stronger and stiffer than the weak layer. This is an important clue to finding many weak layers in manual snow profiles. However, such hardness differences are common in the snowpack and the presence of such a hardness difference does not, by itself, indicate instability. Also, the stress and strain concentrations associated with the stiffness difference between weak and adjacent layers are relevant to slab release models.

A variety of grain types was found above and below weak layers and interfaces. However, persistent weak grain types such as facets and depth hoar are found more often in weak layers than in adjacent layers. Also, crusts are found more often in layers below than in layers above weak layers. In Swiss and Canadian investigated avalanches, 12% and 9% respectively involve a weak layer of facets overlying a crust. The grains in the weak layer were significantly larger than in the adjacent layers (2½-3 times).

For the first time, snowpack conditions found in skier-triggered avalanches have been comprehensively characterized. Many of these results are not surprising, but are consistent with the experience of many forecasters. However, conditions favourable for skier triggering, have never been documented and quantified, so that the data could be used e.g. for slab release modelling or avalanche education. While we have identified snow cover properties associated with many skier-triggered avalanches, these properties are not necessarily distinct from conditions in which skier-triggering is rather unlikely. The present analysis should be completed with a set of stable snowpack profiles. However, the present results will assist with snow profile interpretation, site selection for stability tests, route selection, as well as models for skier triggering and snowpack evolution for avalanche forecasting.

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