HUMAN-TRIGGERED SLAB AVALANCHE PROPERTIES FROM THE CATALAN PYRENEES

Montse Bacardit[1*], Ivan Moner[1], Jordi Gavaldà[1], Glòria Martí[2], Carles Garcia[2]

[1]*Centre de Lauegi - Conselh Generau d'Aran, Vielha e Mijaran, Spain*
[2]*Institut Cartogràfic i Geològic de Catalunya, Barcelona, Spain*

ABSTRACT: During the last three decades in the Catalan Pyrenees (Eastern side of the range), data on avalanche and snowpack characteristics from reported human-triggered slabs (including remotely triggered slab avalanches, whumpfs and shooting cracks) have been collected. This study investigates the characteristics of the human-triggered avalanches from the Catalan Pyrenees, and the related snowpack properties for which a snow profile is available. The research was already started by the authors in 2008 with a limited data set of snow profiles next to skier-triggered slabs and skier-tested slopes in order to compare the snowpack conditions of unstable and stable slopes. The avalanche and snow cover properties from the Pyrenean data set are brought into comparison with previous findings of similar studies on human-triggered slab avalanches from Switzerland and Canada. Finally, based on the current larger unstable profiles database, the previous established Pyrenean structural stability indexes in 2008 were revised and thresholds readjusted in order to produce better results in the particular snow climate of the Pyrenees.

KEYWORDS: slab avalanche, avalanche release, human-triggering, snowpack structure, snowpack stability.

1. INTRODUCTION

Human-triggered avalanches are responsible for most of the avalanche accidents and fatalities in most countries in Europe and North America every winter season. Slab avalanches triggered by humans account without doubt for the most frequent avalanche type causing accidents. For instance, in the Catalan Pyrenees slab avalanches are the cause in 82% of all reported avalanche accidents (ICGC statistics).

In the past few years, a number of studies from Switzerland and North America have significantly contributed to a better understanding of the snow cover and human-triggering mechanisms of slab avalanches (Jamieson and Johnston, 1998; Schweizer and Lütschg, 2001), as well as remotely triggered slabs and whumpfs (Herwijnen and Jamieson, 2007). Snow stability is a key component to forecast avalanches. Data on snow cover stability can be obtained from field stability tests which evaluate fracture initiation and/or propagation capacity (Herwijnen and Jamieson, 2004; Simenhois and Birkeland, 2006; Gauthier et al., 2008; Winkler and Schweizer, 2009), and snow stability indexes such as a sum of critical ranges or thresholds derived from snow stratigraphy (McCammon and Schweizer, 2002; Schweizer et al., 2004; Jamieson and Schweizer, 2005). Amongst all the methods, stability tests are the preferred tool to assess slope instability and probability of avalanching, despite the fact that point observations must carefully be interpreted in an inherent highly variable mountain snowpack (Schweizer and Jamieson, 2010). More recently, new snow stability methods have continued to be developed, such as an automatic snowpack classification algorithm (Techel and Pelmeier, 2014) and a stability index derived from snow micro-penetrometer measurements (Schweizer and Reuter, 2015).

In the Catalan Pyrenees, the Cartographical and Geological Service of Catalonia (ICGC) and the Aran Avalanche Centre from Conselh Generau d'Aran (CGA), collect data on avalanche and snowpack characteristics from reported human-triggered slabs since the end of the 80s. In a previous study, a limited data set of snow profiles next to skier-triggered slabs and skier-tested slopes was investigated in order to evaluate the snowpack conditions of unstable and stable slopes in the Pyrenees. Field stability tests were validated, whereas the structural stability indexes were revised and new thresholds particularly adjusted for the Pyrenean snow climate were established (Moner et al., 2008).

The present study investigates for the first time the avalanche characteristics together with the snowpack properties of a data set of 99 unstable

* *Corresponding author address:*
Montse Bacardit, Centre de Lauegi – Conselh Generau d'Aran, Passeg dera Libertad 16, 25530 Vielha e Mijaran, Ileida, Spain
tel: +34-973-64-1801; fax: +34-973-64-1769
email: m.bacardit@aran.org

snow profiles from the Catalan Pyrenees, including data on human-triggered slabs, remotely triggered slabs, whumpfs and shooting cracks. The main objective is to describe the avalanche release patterns and snowpack conditions associated with unstable slopes for the particular snow climate in the Pyrenees. Results are compared with previous investigated slab avalanche releases in Switzerland and Canada. Finally, the previous established Pyrenean thresholds are revised and new adjustments are proposed in order to produce better results in the particular snow climate of the Pyrenees.

2. DATA AND STUDY SITE

From winters 1986-87 to 2015-16, 216 avalanche accidents have been reported in the Catalan Pyrenees, including 178 slab-avalanche-type accidents. From the reported avalanche accidents, only basic measurements, which often are partly estimates like width, fracture depth, slope angle, aspect, etc. are available. This study investigates a selection of avalanche and snowpack data from 99 manual snow profiles next to human-triggered slabs (N=74), remotely triggered slabs (N=15), as well as whumpfs and shooting cracks (N=10).

Observations were recorded by field observers and forecasters from the ICGC and CGA. Accidentally triggered avalanches were investigated within 1 or 2 days after the release and some of them a few minutes after it. If snowpack conditions were evaluated to have changed considerably since the event occurred, the data were not used. Snow pits next to ski-cuts, whumpfs and shooting cracks were observed immediately. The data used for this study are partially the same as the data used by Moner et al. (2008).

These data were collected in the Eastern Pyrenees, Catalonia, Spain (Fig. 1). 69% were collected in the Aran Valley (AR), which is the unique Catalan region located on the Northern (i.e. Atlantic) slope of the Pyrenees. All other data were compiled from different avalanche (i.e. forecast) regions on the Southern (i.e. Mediterranean) slope of the Catalan Pyrenees with the contributions as follows: RI: Ribagorça and Vall Fosca (7%); FN: Franja Nord (5%); PA: Pallars (4%); PP: Pedrafita-Puigpedrós (3%); CM: Cadí-Moixeró (3%); PR: Pre-Pirineu (1%); TF: Ter-Freser (8%).

3. METHODS

At each human-triggered slab avalanche, the size of the avalanche was observed according to the European Avalanche Size Classification Scale (www.avalanches.org), mainly using the destructive potential parameter. Half sizes (e.g. size 1.5) were usually recorded. Avalanche width, length (from the fracture line to the end of the deposit) and fracture depth were measured or estimated on site. Slope angle, aspect and elevation were taken at or near the fracture line. At each snow pit, we observed the variables of snow height, layer thickness, crystal size, crystal type, hardness and liquid water content of snowpack layers according to the standard snowpack observations as described in Fierz et al. (2009).

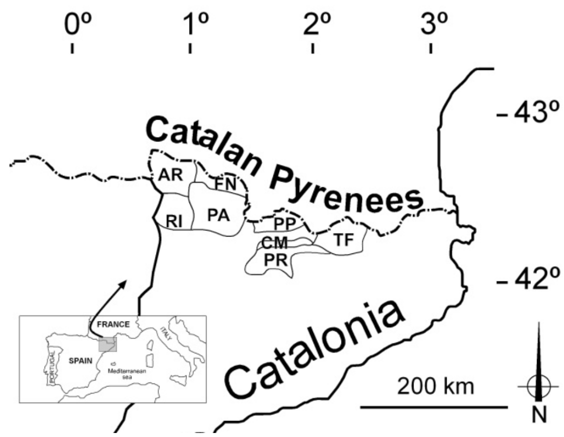

Fig. 1: Location of the Catalan Pyrenees with indication of the avalanche regions.

For grain size we used the average value in mm. In the cases where the grain size of a crust was unknown, we assigned a value of 0 mm according to Moner et al. (2008). Grains of a layer were classified as persistent (P, i.e. facets, depth hoar, surface hoar), melt-freeze crust or ice layer (MF), *graupel* (GP) or non-persistent (NP, i.e. other crystal grains). For crystal type analysis, primary grain type was considered. However, the presence of persistent grains in a layer, even if in a minor proportion, automatically classified that layer as persistent. For layer hardness we used the hand hardness index from 1 to 5 for respectively fist (F), four-finger (4F), one finger (1F), pencil (P) and knife (K). Intermediate values were permitted (e.g. 2-3 → 2.5; F+ → 1.3; 4F- → 1.7). For the liquid water content, we applied the wetness index from 1 to 5 for respectively dry (1), moist (2), wet (3), very wet (4) and soaked (5).

Failure layer depth was recorded, too. In some unstable snow pits (N=2), the triggered avalanche stepped down to a second failure interface. In these cases, both failure interfaces were considered as unstable layers and were analyzed separately. Failure layer (i.e. weak layer) was defined as the one with the lowest hardness within the failure interface. When there was no difference in hardness, the one with the highest average grain size was chosen. When none of these values differed, the lowest layer was chosen. Failure layer properties and characteristics of the layer above and the layer below the weak layer (i.e. bed surface) were considered in the analysis. Average weighted properties for the slab (i.e. comprising all layers above the failure layer) were deduced. Differences in average grain size and hardness between the weak layer and adjacent layers were calculated. An index of “bridging” for both the layer above and the whole slab were calculated, by multiplying the thickness of the particular layer or the slab by its corresponding hardness (Schweizer and Jamieson, 2003).

4. RESULTS AND DISCUSSION

4.1 Avalanche triggering

75 of the cases were obtained from slopes where mountaineers had accidentally triggered a slab avalanche, with similar proportions between “accidents”, i.e. people caught, and “incidents”, i.e. no people involved (Tbl. 1). In 14 cases (13 in Aran region), slab avalanches were triggered intentionally as a slope test. Ski-touring accounted for the most frequent activity, whereas out-of-bonds ski/snowboard as the secondary. Heli-skiing, split-board, snowshoes and one case of mountain bike contributed with a reduced number of cases (Tbl. 1).

Tbl. 1: Frequency of investigated-cases classified for triggering type and activity.

Triggering type	Number of cases (Remotely triggered)
Accident (Caught)	37 (4)
Incident (No one involved)	38 (10)
Ski-Cut	14 (1)
Whumpfs and cracks	10
Activity	**Number of cases**
Ski touring	60
Out of bonds	29
Heli-skiing	3
Split-board	2
Snowshoes	2
Mountain-bike	1
Unknown	2

4.2 Avalanche characteristics

Characteristics of investigated human-triggered slab avalanches are summarized in Tbl. 2. A “typical” human-triggered slab in the Catalan Pyrenees is (median values given) a size 1.5 avalanche, 45 m wide and 130 m long, though there is important variability in avalanche dimensions. Small (i.e. size 1 to 1.5) and large (i.e. size 2 to 3.5) avalanches occur in similar proportions, whereas in the investigated data set there are no cases of very large (i.e. size 4 to 5) human-triggered avalanches. All skier-tested slopes that released a slab avalanche were size ≤1.5, fitting the safety recommendations for ski tests. Avalanche width mostly ranges from 20 to 110 m and length mostly ranks between 50 and 243 m. Average crown depth is 45 cm, with a large proportion between 30 and 60 cm. Having in mind that as in any avalanche data set there is a selection bias, dimensions of human-triggered avalanches in all three components from the Pyrenean investigated data set are in between those from the Swiss (larger) and the Canadian (smaller) data sets (Schweizer and Jamieson, 2001).

Tbl. 2: Avalanche characteristics of the investigated cases.

Parameter	N	Q1	Median	Q3
Av. size	89	1.0	1.5	2.0
Av. width (m)	88	20	45	110
Av. length (m)	84	50	130	243
Fracture depth (cm)	84	30	45	60
Slope (º)	72	35	40	42
Elevation (m asl)	99	2200	2300	2450

4.3 Terrain

Terrain characteristics found in the Pyrenean human-triggered slabs are as follows: slope angle is in median 40º, mostly varying between 35 and 42º (Tbl. 2), an inclination slightly steeper with respect to the Swiss and Canadian cases (Schweizer and Jamieson, 2001). This could be partially explained by the finding of relatively harder slabs more difficult to trigger, as described and discussed below. Elevation is in median about 2300 m asl, corresponding above the tree line, as it occurs in the Swiss cases. In Canada, the typical elevation is lower and around the tree line (Schweizer and Jamieson, 2001).

Avalanches, whumpfs and cracks in the whole investigated data set (Fig. 2, left) take mostly place on shady aspects, particularly NE (25%). Sunny aspects are less frequent, but SE orientations (14%) have a notable contribution. This result is in very good agreement with the Swiss and Canadian data sets showing that skier triggering is more common on shady and/or lee-loaded slopes (Schweizer and Jamieson, 2001). However, when aspect frequencies are represented separately for the Aran and all other regions, results are clearly well segregated on NE and SE aspects, respectively (Fig. 2, right). This result is obviously influenced by the large number of cases from the Aran where most valleys face typically north, whereas the majority of the cases

Tbl. 3: Comparison of snowpack properties related to human-triggered slabs from Pyrenean (this study), Swiss and Canadian avalanche data sets (Schweizer and Jamieson, 2001). FL: failure layer. LA: layer above. LB: layer below.

	Pyrenean				Swiss				Canadian			
Variables	N	Q1	Median	Q3	N	Q1	Median	Q3	N	Q1	Median	Q3
Snow height (m)	96	0.7	1.0	1.4	95	0.9	1.2	1.7	81	2.1	2.8	3.7
Slab thickness (cm)	101	23	35	49	95	36	52	67	91	28	41	60
Slab hardness	100	2	2.4	3	95	1.5	2	2	91	1.3	2	3
Slab bridging	100	53	88	129								
FL depth	101	27	39	53								
FL thickness (cm)	101	2	5	11	47	1	1	2	61	0.5	1	1
FL grain size (mm)	101	0.7	1.0	1.5	47	1.5	2	2.5	61	1.75	3.5	6.5
FL hardness	100	1	1	2	47	1	1	1	54	1	1.7	2
LA grain size (mm)	101	0.3	0.4	0.5	45	0.5	0.75	1.0	46	0.75	1	1.5
LA hardness	100	2	3	3.4	47	2	2.5	3	61	1.7	2.3	3
LB grain size (mm)	58	0.5	0.7	1	47	1	1.5	2	47	0.5	0.75	1.0
LB hardness	96	3	4	5	42	1	2	3.5	60	2	3	3.3
FL – LA grain size difference (mm)	86	0.2	0.5	0.8	45	0.75	1.25	1.75	45	1.0	2.25	5.1
FL – LB grain size difference (mm)	59	0.0	0.2	1.0	47	0.0	0.5	1.0	46	1.0	3.25	5.75
LA – FL hardness difference	100	1	1.3	2.0	47	1	1	2	54	0	1	1.3
LB – FL hardness difference	95	1.3	2.5	3.0	47	0	1	2.5	54	0.7	1	2.3

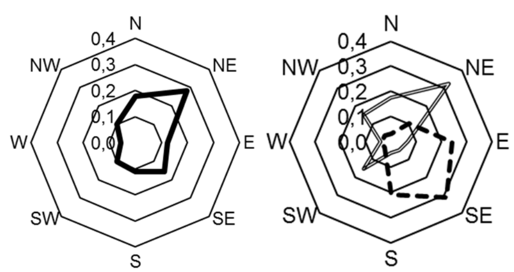

Fig.2: Aspects of investigated cases. Left: portions for all data set. Right: Aran in doubled line; all other cases in dashed line.

from the other regions face south. This fact highly determines the frequency of skiing and hence the probability of triggering.

4.4 <u>Snowpack properties</u>

Characteristics of the snowpack of Pyrenean-investigated cases in comparison to the Swiss and the Canadian data sets are presented in Tbl. 3. Snow height in the Pyrenean data set ranges between 0.7 and 1.4 m, a slightly shallower snowpack than the Swiss but much shallower with respect to the Canadian. This feature is representative of different snow climates between these three mountain ranges. Below these lines we describe the characteristics for human triggering in the Pyrenees, which are not coincident to those from Switzerland and Canada.

Pyrenean slabs consist mostly (74% of the investigated cases) of storm snow i.e. the failure was within the storm snow or between the storm snow and the old snowpack (Fig. 3). Thus, slabs failing within the old snow occur in a much lower frequency, still accounting for the 27% in Aran buy only for the 4% in the Southern regions. In any case, the portion of storm snow slabs in the Pyrenees is much higher with respect to the Canadian (52%) and the Swiss (37%). In addition, in 14% of the cases, the slab comprises moist/wet snow layers (not showed in Tbl. 2), a higher value in contrast to the Swiss (1%) and Canadian (4%) data, in which moist/wet snow human-triggered avalanches are not frequent and the majority are loose snow avalanches. Considering both avalanche types, in 80% of the cases, the slab is thus composed of dry storm snow.

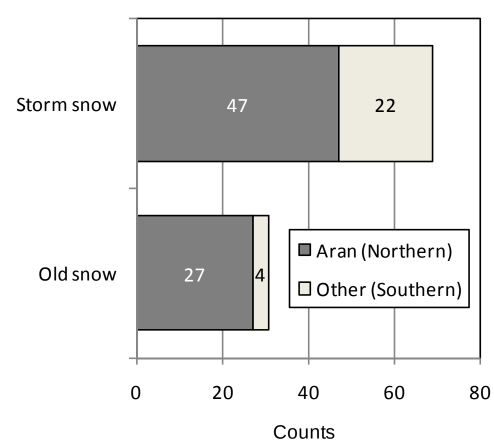

Fig. 3: Slab type for Aran and other regions

The most frequent slab in the Pyrenees is (average weighted values) 35 cm thick, 4F+

hard and mainly consists of 0.3 mm rounded grains (Fig. 4). Pyrenean slabs are thus shallower, harder and composed of smaller rounded crystals in comparison to the Swiss and Canadian slabs. Slab bridging (median value) is 88, varying mostly between 53 and 129, and decreases sharply with higher values of bridging. A similar pattern of bridging was also found in a large Canadian data set (van Herwijnen and Jamieson, 2007).

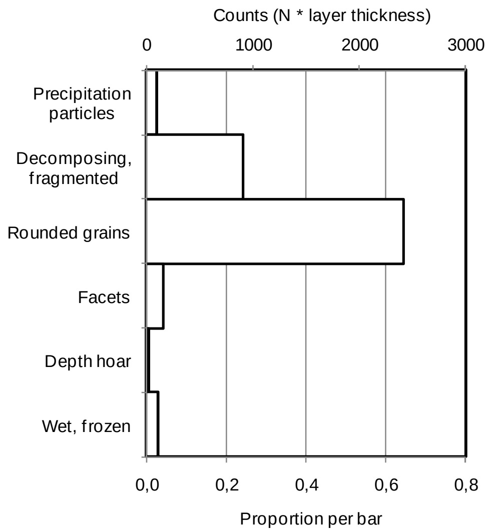

Fig 4: Main grain type in slab layers. Both weighted counts and portions shown.

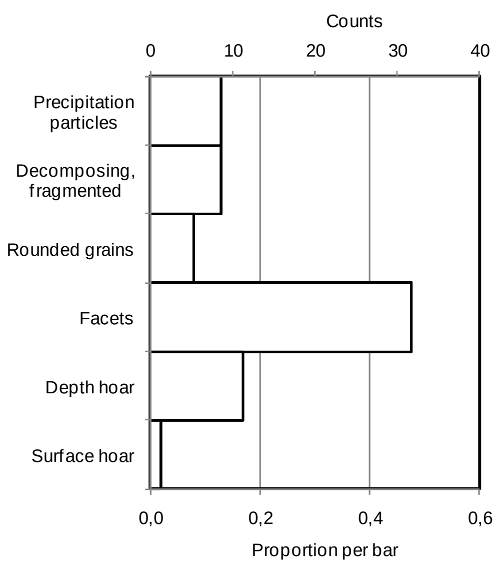

Fig. 5: Main grain type in failure layer. Both counts and portions shown.

Examination of critical layers in the Pyrenean snowpack depicted the following features. Failure layer depth is 39 cm in median, and ranges mostly differ from 27 to 53 cm, very similarly to the recorded fracture depth values, as shown in Tbl. 2. Failure layer contains persistent grain types in 77% of the cases, with a 48% of facets, 17% of depth hoar, and only 2% of surface hoar (Fig. 5). Amongst the non-persistent grain cases, a small but remarkable 8% consists of *graupel*, a singular grain type not reported in any of the compared studies. Failure layer crystals are typically 1 mm large and F hard.

The high frequency of persistent grain cases could appear to be surprising considering the higher percentage of slabs only comprising the storm snow. However, from this result, it can be deduced that in the Pyrenean snowpack, failure layers of small size and persistent crystals develop often and fast at the base of the storm snow, being an important but transitory cause for an unstable snowpack. Failure layer properties are much different in the Swiss and Canadian data: in Switzerland, large facets are dominant, whereas in Canada, very large surface hoar is typically found. These failure layers, in contrast to the Pyrenees, are slow to metamorphose (Schweizer and Jamieson, 2001).

Layer above the failure layer in the Pyrenean-investigated cases consist mainly of rounded grains, whereas melting-refreezing crusts comprise the majority of the layers below the failure. Notably, in 5% of the cases the weak layer failed above the ground, thus triggering a full-depth slab avalanche (Fig. 6).

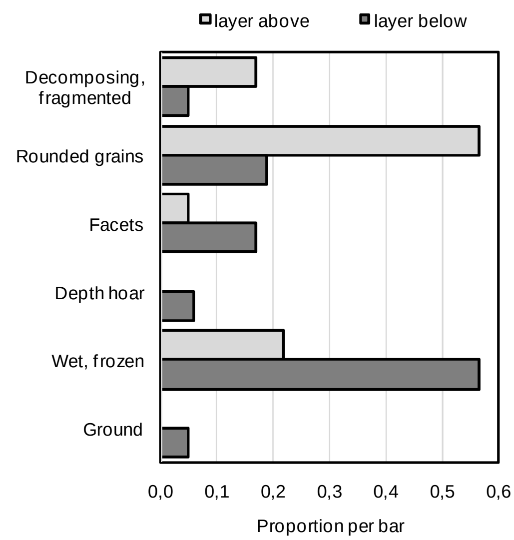

Fig. 6: Main grain type in adjacent layers. Portions shown.

Grain size and hardness in adjacent layers from the Pyrenean data set are lower and higher values respectively compared to the Swiss and Canadian data sets. Concerning grain size and hardness differences, as a result of the smaller absolute grain sizes observed in the investigated layers, grain size differences are relatively smaller than differences found in the Swiss and Canadian data sets. However, hardness differences between the failure layer and adjacent layers are much wider in the Pyrenean cases. Overall, these results are agree with the presence of a higher frequency of very small, hard rounded grains comprising the layer above the failure layer, and/or a very hard melt-freezing crust or ice layer both above and below the failure layer.

In fact, in 22 of the cases, a melt-freezing crust or ice layer was located above the failure layer and fell in the release. Following the work done in the previous study, and as a measure of layer toughness, the bridging index (i.e. layer thickness multiplied by hand hardness) of the crusts was calculated for the 9 "new" cases. Average bridging index of the crusts that collapsed was 5, 12 being the highest, depicting very similar results to those obtained from the previous data. However, in order to establish a boundary of bridging for a crust layering on top of a collapsible failure layer, a study taking into account both unstable and stable profiles should be further performed.

4.5 Application of thresholds

We applied the Pyrenean thresholds established by Moner et al. (2008) from a learning data set of 86 profiles (43 of them were unstable). In this study we used the 54 unstable snow pits collected from the winters 2008-09 to 2015-16 as a test data set. Here we examine the probability of detection (POD = hits / hits + false stables) of unstable cases for each variable and for the 5 and 6 variable threshold sums (Tbl. 4). Most POD scores for the variables showed roughly similar values as those already obtained from the learning data set. Failure layer grain type, grain size difference and hardness difference showed the greatest POD scores. Failure interface depth and failure layer grain size had intermediate but slightly lower scores than those from the learning data set, and failure layer hardness showed the poorest POD score, which was much lower than that from the learning data set. Finally, POD scores for the threshold sum of the 5 and 6 variables were lower than the scores obtained from the learning data set.

In order to improve POD scores from the hardness-related variables and the final model accuracy, we propose to readjust the values of failure layer hardness and hardness difference. In fact, as it can be seen from the learning data set (Moner et al., 2008), failure layer hardness and hardness difference presented the highest significant differences between the unstable and stable samples. Moreover, these two variables showed the lowest false alarm rate percentages (i.e. proportion of false alarms to the sum of false alarms and hits). From these results, it can be assumed that values of failure layer hardness and hardness difference can then be extended to wider values without reducing the accuracy of the model. Both readjusted hardness thresholds and threshold sum presented improved POD scores (Tbl. 4). However, they also need to be tested with a new sample of stable cases before they can be applied operationally.

Tbl. 4: Pyrenean variable thresholds and model accuracy from the test data set

Variable	Critical range	POD (%)
Failure layer hardness	≤ 1.5	48.1
Failure layer grain size (mm)	≥ 0.7	68.5
Hardness difference	> 1	83.3
Grain size difference (mm)	≥ 0.5	90.7
Failure layer grain type	P + DF	94.4
Failure interface depth (cm)	23...97	77.8
5 var. without FI depth	≥ 4	70.4
6 variables	≥ 5	55.6
Adjusted failure layer hardness*	≤ 1.7	55.6
Adjusted hardness difference*	≥ 1	94.4
5 var. without FI depth*	≥ 4	79.6
6 variables depth*	≥ 5	94.6

5. CONCLUSIONS AND FURTHER REMARKS

In order to investigate the characteristics of human-triggered slab avalanches in the particular snow climate and terrain of the Pyrenees, a set of 99 unstable snow profiles, including data on human-triggered slabs, remotely triggered slabs, whumpfs and shooting cracks, were analyzed for the first time. The majority (86%) of the cases were triggered during recreational activities, mainly ski-touring or out-of-bonds ski/snowboard, whereas the rest of the investigated cases (14%) were the consequence of an intentional ski-cut during an avalanche operation by professional forecasters or field observers.

From the investigated data set, a human-triggered slab in the Pyrenees is typically a size 1.5 avalanche, 45 m wide, 130 m long, and a fracture depth of 45 cm. Slabs occur mostly on slopes with 40º angle, NE and SE aspects and at 2300 m asl.

In a relatively shallow snowpack compared to the Swiss and Canadian, Pyrenean slabs frequently consist of dry storm snow (80%) which constitute layers about 35 cm thick, 4F+ hard and are composed of 0.3 mm rounded grains. Slabs usually fail above weak layers of persistent grains, particularly facets (48% of the cases) of 1 mm large and F hard. Layers adjacent to the failure layer are remarkably hard and tough, consisting of rounded grains and/or melt freeze crusts or ice layers. This layering constitutes a particular snow cover structure for human-triggered slab avalanches in the Pyrenees, in comparison to Switzerland and Canada, where the snowpack is in general much deeper, slabs are thicker and softer, and failure layers comprise larger and more persistent crystals.

With the characteristics of the slab avalanches and associated snowpack properties well described, the previous established Pyrenean thresholds for snow stability assessment were revised. In order to produce better results of the model, new adjustments of the variable thresholds were proposed. However, before they can be used operationally, they need to be further tested with both unstable and stable profiles.

This study evidences the need of further recording measurements of avalanche and snowpack data in order to continue to inquire the patterns and the variability of the slab avalanche releases within the Catalan Pyrenees but also from other Pyrenean regions. Such investigations would undoubtedly help forecasters in a currently increasing number of regional and local avalanche operations, as well as an increasing number of recreational winter activities in the Pyrenean backcountry.

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