IMPROVED FORECASTING OF PERSISTENT DEEP SLAB AVALANCHES WITH A DECISION SUPPORT TOOL

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Abstract: Persistent deep slab snow avalanches are generally difficult to forecast because of the relatively large depth to the failure layer. A decision support tool was developed to help professionals forecast the likelihood of such events. The tool follows a threshold sum approach, where users answer yes/no questions and points for each yes answer are summed and compared to a threshold value. The questions were derived from parameters important in the release of persistent deep slab avalanches. The questions comprise three sections: snowpack conditions, weather conditions, and avalanche conditions. Values within each of the questions were obtained from three independent data sources, including persistent deep slab avalanches that were accessed by field teams, a dataset of historical persistent deep slab avalanches, and an expert opinion survey. A classification tree was used to determine the threshold tool sum that separates days with higher likelihood from days with lower likelihood. For a dataset of 110 days, the tool correctly classified 89 % of days where naturally triggered persistent deep slab avalanches were observed and 74 % of days where avalanches were not observed. The tool also indicates whether persistent deep slab avalanches triggered by skiers or snowmobiles are possible. The output of the tool only indicates the likelihood of such events within a forecast region and cannot predict when or where they will occur. The tool may help streamline the decision making process for some avalanche forecasters in mountainous terrain.

1 INTRODUCTION

Persistent deep slab avalanches are often difficult to forecast. The failed weak layers are generally deeply buried in the snowpack, often deeper than influences from skiers, snowmobiles, or daily temperature changes. When they do release, large and destructive avalanches are generally the result (Jamieson et al., 2001). This is because a thick slab of cohesive snow is often released, generally tens to hundreds of metres wide (Conlan et al., 2014). Under such situations, humans or infrastructure within the avalanche paths are at great risk. The difficulty of predicting deep slab avalanches creates uncertainty in the avalanche forecast.

1.1 The release of naturally triggered persistent deep slab avalanches

Natural avalanches (also called spontaneous avalanches) occur because of the weather (Schweizer, 1999). Common forms of natural releases include applied stresses from snow loading and from increased strain rates in the upper snowpack from air temperature or solar warming. For natural avalanches, fracture initiation is caused by strain softening of the weak layer (Schweizer et al., 2003).

Gradual overburden loading generally occurs from snowfall, rain, or snow transported by wind. Such loading applies stress on buried persistent weak layers. With rapid loading, strain softening may occur within the persistent weak layer, which may lead to brittle fracture (Schweizer, 1999; McClung and Schweizer, 2006). This fracture may then propagate over a much larger area until the fracture toughness is higher than the work of the propagating fracture.

Another natural release mechanism is from snowpack warming. Warming of the snowpack reduces the stiffness of the upper snowpack, which increases strain rates in weak layers. Elevated strain rates can lead to ductile failure and strain softening of a persistent weak layer or interface. This may lead to brittle fracture and the release of a slab avalanche (Schweizer, 1999). Warming can cause the release of persistent deep slab avalanches in locations where the snowpack is shallow, where the persistent weak layer is substantially closer to the snow surface. Fracture initiation occurs in the shallow area, followed by widespread propagation in areas where the persistent weak layer is substantially deeper (e.g. Conlan and Jamieson, 2014b).

With the combination of snowpack and weather conditions required for naturally triggered persistent deep slab avalanches, a decision support tool holds promise for aiding forecasters in assessing the likelihood of their release.

1.2 Decision support tools

For complex decision making processes, decision support tools can greatly improve the value of the decision. One decision support tool method is the threshold-sum approach, where the user compares their findings with rule-based questions. Incremental values are applied for each positive response (e.g. add 1 if the value of a parameter is greater than its threshold) and the total sum is compared to a threshold for the sum.

2 METHODS

The decision support tool for persistent deep slab avalanches was created from a variety of independent data sources.

2.1 Data sources

2.1.1 Dataset of avalanches accessed by field teams

Conlan et al. (2014) summarized measurements from 41 accessed persistent deep slab avalanches from 1993 to 2012 in western Canada. The dataset was expanded with more accessed avalanches between 2012 and 2014, for a total of 63 avalanches. Of these avalanches, 18 were naturally triggered. The dataset included snowpack properties, snowpack test results, and weather data. The weather parameters were further evaluated by Conlan and Jamieson (2013) by grouping the avalanches by primary cause-of-release (i.e. precipitation loading, loading from wind-transported snow, solar warming, air temperature warming).

2.1.2 InfoEx dataset

Weather parameters preceding naturally triggered persistent deep slab avalanches were studied by Conlan (2015). He obtaining data from the Information Exchange (InfoEx) from operations in Canada, organized by the Canadian Avalanche Association. The dataset included 161 naturally triggered avalanches between 2006 and 2013 from the InfoEx along with an additional 16 naturally triggered avalanches from the accessed dataset, for a total of 177 avalanches. Weather data were obtained from weather stations of nearby avalanche operations as well as from the numerical weather prediction model GEM15 (Mailhot et al., 2006). The avalanches were grouped by primary cause-of-release.

2.1.3 Expert opinion survey

An expert opinion survey was conducted by Conlan and Jamieson (2014a) to identify important variables and observational values associated with naturally triggered persistent deep slab avalanches. The experts were avalanche professionals working as ski patrollers, mountain guides, avalanche researchers, and avalanche forecasters. The survey consisted of snowpack conditions, weather conditions, and avalanche conditions. The questions were derived from parameters that were found to be important from previous studies on persistent deep slab avalanches. Thirty-one professionals from western Canada answered the questions that were based on threshold values that favour the release of naturally triggered persistent deep slab avalanches. They indicated their confidence in their values, as Poor, Fair, or Good. The confidences were used to calculate weighted averages for each question. The professionals also indicated if they thought the observation had Low (1), Medium (2), or High (3) importance for the release of persistent deep slab avalanches.

2.2 Development of the decision support tool

Important parameters were identified from preceding studies and from discussions with avalanche professionals. Thresholds for each parameter were obtained from the previously described studies. The relative importance for each parameter in the tool was calculated from the expert opinion survey results in Conlan and Jamieson (2014a); the importance averages for each question were linearly adjusted to range between 1 and 3 and rounded to the nearest integer. The threshold tool sums that increase the likelihood of observing naturally triggered persistent deep slab avalanches in the tool were determined by comparing avalanche days with non-avalanche days.

Eighteen avalanche days were obtained from the accessed dataset of Conlan et al. (2014). Non-avalanche days were obtained from 92 snow profiles conducted at two locations in the Columbia Mountains on days where persistent deep slab avalanches were not observed in the forecasted region. The locations were Mt. Fidelity (1905 m asl) near Rogers Pass, B.C. and Mt. St. Anne (1880 m asl) near Blue River, B.C. Each snow profile included snowpack tests on buried persistent weak layers, if any were present deeper than 80 cm. Precipitation, air temperature, and sky cover data were obtained from nearby weather stations and GEM15. Sky cover was used in conjunction with precipitation data in the solar warming model SWarm (Bakermans and Jamieson, 2009). Solar warming was modelled for south aspects of 40^{o} incline. Avalanche conditions were examined from InfoEx submissions of nearby operations to Mt. Fidelity and Mt. St. Anne.

A univariate classification tree (Breiman et al., 1984) was created to separate days with natural avalanches from days without natural avalanches. This was conducted to determine threshold sum required to discriminate the likelihood levels for observing naturally triggered persistent deep slab avalanches. The primary split was analyzed. The sole input variable was the tool sum.

3 RESULTS

Results from the accessed avalanches, InfoEx dataset, and expert opinion survey are presented in Table 1. Results were generally similar between the different sources. The decision support tool was created based on their findings.

3.1 Decision support tool sections

The decision support tool is displayed in Table 2. To facilitate timely responses for busy forecasters, only *yes* or *no* questions are asked based on threshold values. It consists of questions related to snowpack conditions, weather conditions, and avalanche conditions. The questions are to be answered for avalanche start zone locations unless otherwise stated. For any question answered *yes*, an importance value is added to the sum, which starts at zero. For an answer of *no*, the sum is not incremented.

3.1.1 Snowpack conditions

The four questions in the snowpack conditions section consist of buried persistent weak layer sizes, stiffness differences between the weak layer and underlying layer, snowpack test results, and whether a melt-freeze crust exists below the weak layer. The threshold values in the tool (Table 2) were obtained from the survey results (Conlan and Jamieson, 2014a) and from the accessed avalanches (Conlan et al., 2014) (Table 1). Respective importance values for each question of 2, 2, 3, and 2 were obtained from the expert opinion survey results (Table 1).

3.1.2 Weather conditions

The weather section consists of six questions (Table 2). The first two questions are related to precipitation amounts in the form of snowfall and rainfall. The threshold values were obtained from most of the data sources described (Table 1). For positive response, an importance value of 2 is applied for the snowfall question and a value of 3 for the rainfall question.

Table 1 – Comparison of parameter thresholds from different studies on persistent deep slab avalanches. The last column, italicized, is the linearly adjusted importance, which was calculated by adjusting the average importance values to an integer range of 1 (low) to 3 (high). Only one linearly adjusted importance value was calculated for questions that were grouped in the decision support tool.

	Conlan et al. (2014)	Conlan and Jamieson (2013)	Conlan (2015)	Conlan (2015)	Conlan and Jamieson (2014a)	
	Accessed avalanches, natural and artificial	Accessed avalanches, natural	InfoEx weather stations, natural	InfoEx and GEM15, natural	Expert opinion survey on natural avalanches	
Fracture character	Sudden	-	-	-	Sudden	*3*
Crust hand hardness	Knife	-	-	-	Pencil	*2*
Faceted grain size (mm)	2	-	-	-	2	*2*
Surface hoar size (mm)	8	-	-	-	4	*“*
Depth hoar size (mm)	4	-	-	-	4	*“*
Hand hardness difference (steps)	1	-	-	-	2	*2*
24-hour precipitation (cm snow)	6	28	15	15	34	*2*
3-day precipitation (cm snow)	17	55	38	19	59	*“*
7-day precipitation (cm snow)	43	80	68	30	79	*“*
1-day rain (mm)	-	-	-	-	13	*3*
1-day rain amount on dry snow (mm)	-	-	-	-	17	*“*
24-hour temperature increase (°C)	-	3	0.5	0.2	8	*2*
3-day temperature increase (°C)	-	3	-	-	13	*“*
12-hour temperature decrease (°C)	-	-	-	-	14	*1*
SWarm threshold (°C 10 cm into snow)	-	-	5	8	-	*2*
Days of predictive relevance for avalanche observations (d)	-	-	-	-	4	*3*
Notes:	Median values. Avalanches were not grouped by primary cause-of-release	Average values. Avalanches were grouped by primary cause-of-release	Median values. Avalanches were grouped by primary cause-of-release	Median values. Avalanches were grouped by primary cause-of-release	Weighted averages	Linearly extrapolated importance (1 to 3) from expert opinion survey results

Table 2 – Decision support tool for persistent deep slab avalanches. The avalanche professional completes the tool by answering the *yes*/*no* questions. The importance value for each *yes* answer is added to the total sum and compared to the threshold tool sum to determine the likelihood. The tool is completed in the morning with values and estimates for the day.

Persistent deep slab avalanche forecasting tool

	Response (yes/no)
Snowpack conditions. For the preceding week within start zone locations, buried at least 80 cm in snowpack, in a regional setting.	
I have observed:	
• a persistent weak layer of faceted grains (≥ 2 mm), surface hoar (≥ 4mm), or depth hoar (≥ 4 mm).	yes
• a persistent weak layer that is at least 1 step softer than the underlying layer.	no
• sudden fracture character OR high propagation potential on a persistent weak layer from snowpack tests.	yes
• a melt-freeze crust that is at least P in hand hardness directly under a persistent weak layer.	no
Weather conditions. For start zone locations.	
I expect/have observed:	
• an additional load of at least 34/15/15[a] cm of snow over a 24-hour period, 59/38/19 cm of snow over a 3-day period, OR 79/68/30 cm of snow over a 7-day period.	yes
• at least 13 mm of rain in a 24-hour period.	no
• a maximum air temperature increase of at least 8 °C in a 24-hour period OR 13 °C in a 3-day period AND the maximum air temperature will reach at least -2 °C.	no
• an air temperature drop of at least 14 °C in a 12-hour period.	no
• no overnight freeze for the first time since a freeze.	no
• direct shortwave radiation hit start zones for the first time after a snow storm, OR SWarm estimated warming of at least 5 °C, 10 cm into the snowpack.	no
Avalanche conditions. Regional observations for start zone locations.	
I have observed:	
• deep slab avalanches in the past 4 days at similar elevations to the area being forecasted.	yes

Naturally triggered persistent deep slab avalanches are likely 10

Human triggering of a persistent deep slab avalanche is possible

Notes:

[a] x/x/x cm of snow are for expert opinion/weather station at or below treeline/GEM15.

The tool indicates the likelihood of observing persistent deep slab avalanches for the day it is used. It does not indicate if, when, or where they will occur.

The tool must be applied to certain terrain features of concern when applying the tool. Spatial variability must also be assessed.

The following three questions are related to air temperature variations. The questions comprise conditions of rapid warming and rapid cooling as well as sustained warm temperatures. The values used in the tool (Table 2) were obtained from the survey results (Conlan and Jamieson, 2014a) (Table 1). Importance values of 2, 1, and 1, respectively, were assigned to the questions (Table 1).

The last weather question is associated with solar warming. A threshold SWarm value of 5 ^{o}C was obtained from Conlan (2015) (Table 2). An importance value of 2 was assigned to this question from the expert opinion survey results (Table 1).

3.1.3 Avalanche conditions

One question is in this section, based on the predictive relevance of recent persistent deep slab avalanche observations (Table 2). A threshold number of preceding days of 4 was used in the tool, obtained from the expert opinion survey results (Table 1). The observations should be representative of the start zones being forecasted and may come from the operation or nearby operations with similar snowpack conditions. For a positive response with this question, an importance value of 3 is applied (Table 1).

3.2 Tool sums for naturally triggered accessed avalanches and non-avalanche days

The decision support tool was applied to the natural avalanche days and the non-avalanche days (Figure 1). The natural avalanches had a higher median sum for the snowpack conditions section of the tool (7) than the non-avalanche days (4). Both groups had a median sum of 2 for the weather conditions section. The natural avalanches had a medium sum of 3 for the avalanche conditions section whereas the non-avalanche days had a median of 0. Combining the sections together, the natural avalanches had a median tool sum of 10.5 and the non-avalanche days had a median tool sum of 6.

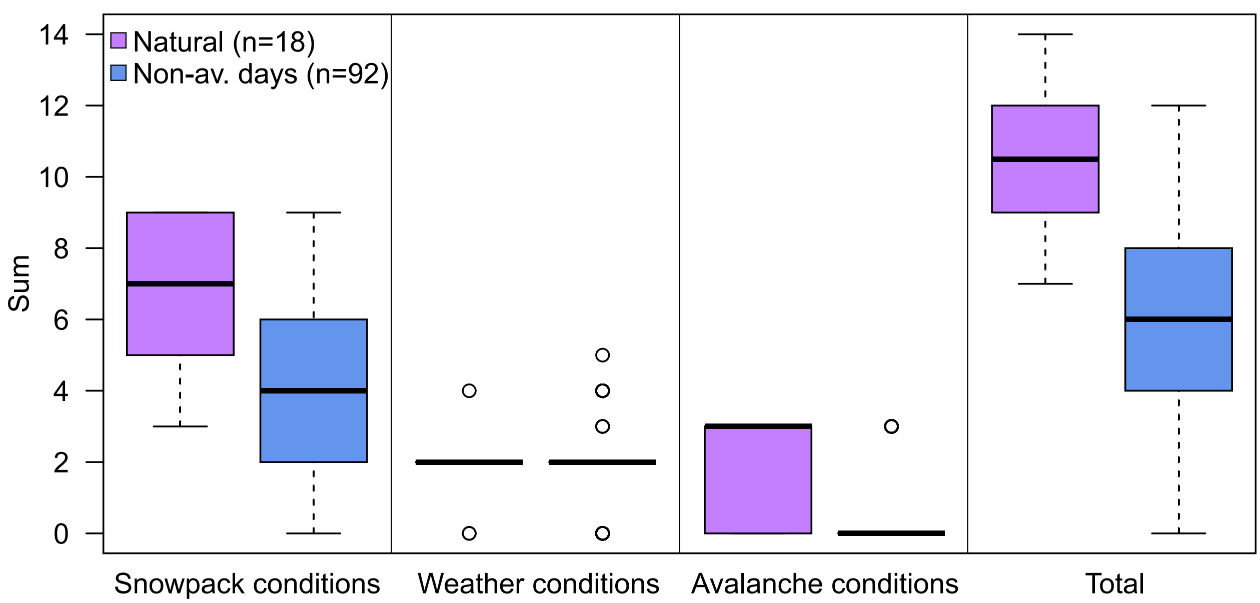

Figure 1 – Decision support tool sums for naturally triggered persistent deep slab avalanche days and non-avalanche days. The sums are grouped by the sections of the tool (snowpack, weather, avalanche conditions), followed by the total sum of the three sections. Black line indicates the median, boxes span the first and third quartiles, and whiskers span the lowest datum and the highest datum within 1.5 times the lower and upper quartiles, respectively. Outliers are displayed as open circles.

3.3 Threshold tool sum

The classification tree used to separate the natural avalanches from the non-avalanche days calculated a primary split of 8 (Figure 2). This was implemented into the decision support tool as the threshold value that increases the likelihood of naturally triggered persistent deep slab avalanches. That is, if the sum of the three sections in the tool is 8 or more, it indicates that naturally triggered persistent deep slab avalanches are likely within the forecast region. This threshold tool sum correctly classified 16 of the 18 natural avalanches (89 %) and 68 of the 92 non-avalanche days (74 %), for a combined total of 76 % correct. The two natural avalanches that were not correctly classified had tool sums of 7. To encompass all naturally triggered avalanches, a moderate likelihood (avalanches are possible) was assigned with a tool sum of 6 or 7. For tool sums below 6, a low likelihood is indicated (avalanches are unlikely).

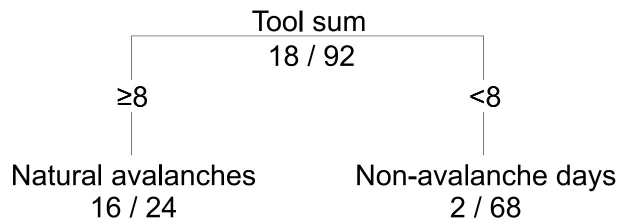

Figure 2 – Classification tree for naturally triggered persistent deep slab avalanches and non-avalanche days. The tool sum was the only input parameter. The numbers below the labels indicate how many days are in the natural avalanche group (n = 18) and non-avalanche group (n = 92), respectively, for each level.

4 DISCUSSION

4.1 Application of the decision support tool

The decision support tool for persistent deep slab avalanches is primarily developed for naturally triggered avalanches. The tool can be used by avalanche professionals that forecast the likelihood of such events. To do so, representative data or expert estimates must be available to answer all the questions. If not all data are available, threshold tool sums may not be reached, even if field conditions actually favour their release. For estimated data, it is the forecaster's responsibility to accurately scale any data to start zones of varying elevation and aspect. For many operations in western Canada, representative data obtained from nearby operations may be useful in completing the decision support tool.

The decision support tool also indicates if human triggered persistent deep slab avalanches (e.g. skier or snowmobile) are possible. This is solely based on the snowpack conditions, as weather conditions may not be as important in their release (Conlan and Jamieson, 2013). The tool indicates if human triggering is possible if the avalanche conditions section has a sum of 3 or more. With this sum, the snowpack likely has a deeply buried persistent weak layer that may be triggered.

Terrain features are not included in the tool. The avalanche professional must apply the decision support tool to particular start zones of concern. This may require the tool be used multiple times each day, if different terrain features in the forecasted region have different snowpacks or experience different weather.

After using the tool over an extended period of time, some avalanche professionals may determine better threshold question values or threshold tool sums for their forecasted region. Much of the data used to create this tool were obtained from locations in the Columbia Mountains that experience a transitional snow climate. Different values may be required in locations that experience different snow climates, such as in the Coast Mountains and Rocky Mountains of western Canada. If values are altered, the threshold tool sum may need to be further evaluated to limit the amount of false stable and excessive false unstable predictions.

4.2 Limitations of the decision support tool

The data used to develop the decision support tool was obtained during winter months when below freezing temperatures and snowfall were dominant. Accordingly, the snowpack observations were all for dry snow. This tool may therefore not work properly during spring conditions when the upper snowpack becomes wet, incoming shortwave radiation and air temperatures are substantially higher, and free water exists in the pore spaces.

The decision support tool is only a guideline for avalanche professionals. It cannot indicate when and where persistent deep slab avalanches will release. Forecasters must use their experience and knowledge of their local snowpack, weather, and terrain to decide as to whether certain terrain areas should be artificially controlled or avoided.

5 SUMMARY

We created a decision support tool to forecast the likelihood of persistent deep slab avalanches. The tool consists of three prominent sections: snowpack conditions, weather conditions, and avalanche conditions. The snowpack conditions section comprises four questions related to deeply buried persistent weak layers. The weather conditions section includes six questions about snowfall amounts, rainfall amounts, rapid air temperature warming, rapid air temperature cooling, sustained warm air temperatures, and solar warming. The avalanche conditions section consists of one question, related to preceding avalanche observations.

Threshold values within the tool and their relative importance were obtained from multiple independent data sources. Days with natural avalanches and non-avalanche days were used to determine the threshold tool sum required to increase the likelihood of naturally triggered persistent deep slab avalanches. A classification tree was used for this, which indicated a threshold value of 8. This threshold tool sum correctly classified 89 % of days with natural avalanches and 74 % of non-avalanche days, for a combined total of 76 % correct.

The tool is applicable to avalanche professionals with enough representative data or expert estimates to complete all questions. Professionals must use the tool for certain terrain features of concern. The tool only indicates the likelihood of persistent deep slab avalanches and it does not indicate when or where they will occur. This tool should aid in the decision making process of avalanche professionals that forecast for persistent deep slab avalanches.

ACKNOWLEDGEMENTS

We thank many folks for healthy discussion on this topic that helped shape the tool. This included but was not limited to Paul Berntsen, Mike Boissonneault, John Forrest, Giacum Frei, Shane Haladuick, Simon Horton, Clair Israelson, Kevin Maloney, Bruce McMahon, Michael Schirmer, Scott Savage, Larry Stanier, Scott Thumlert, Dave Tracz, and John Tweedy. For financial support, we thank the Natural Sciences and Engineering Research Council of Canada, Parks Canada, HeliCat Canada, the Canadian Avalanche Association, Mike Wiegele Helicopter Skiing, Canada West Ski Areas Association, Backcountry Lodges of British Columbia Association, the Association of Canadian Mountain Guides, Teck Mining Company, Avalanche Canada, the Canadian Ski Guide Association, Backcountry Access, the B.C. Ministry of Transportation and Infrastructure Avalanche and Weather Programs, the Canadian Avalanche Foundation, and TECTERRA.

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