Terrain analysis of skier-triggered avalanche starting zones

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ABSTRACT: Terrain is one of the main factors contributing to avalanche formation and important for the assessment of avalanche risk. Terrain characteristics of small to medium human triggered avalanches have however been the subject of limited attention. This work focused on analyzing the terrain characteristics of human triggered avalanches and their starting zones. Photos and shapes of avalanches in Switzerland between 1999/2000 and 2009/2010 and a high-quality digital elevation models (ADS-DOM) were used for this study. It was possible to digitalize 142 starting zones and to analyse them at high resolution with the ADS-DOM. Geomorphometric methods were used to extract different terrain features (ridges, slope, aspect, roughness, exposure and curvature) from the DEM. Furthermore a method was developed to estimate starting zones from a complete avalanche perimeter und to divide the starting zones automatically in different districts.

The majority of the avalanches were released on planar or concave slopes and the roughness of the terrain corresponded a relatively constant debris covered surface. The slope angle often decreased from the crown to the Stauchwall.

KEYWORDS: avalanche, avalanche starting zone, terrain, GIS

1 INTRODUCTION

In Switzerland on average 25 people are killed in avalanches annually. Most of these avalanches are released by those involved. Despite advances in understanding their release processes, predicting the locations and times of individual avalanches remains beyond the scope of current forecasting. Most factors controlling avalanche release (e.g. snowpack, weather and the behaviour of individual groups) vary in both time and space, however one remains, over time scales relevant to avalanche forecasting, constant - terrain.

Terrain is of central importance in assessing avalanche danger, but nonetheless detailed analyses of small to medium human triggered avalanches remain rather rare. There are a number of reasons for this. Firstly, the resolutions of widely available Digital Elevation Models (DEMs), from which avalanche relevant parameters such as gradient, aspect and curvature can be calculated, are typically of the order of 25-50m. Calculating most terrain derivatives requires use of a focal function, typically using a 3x3 cell window, and thus the effective resolution of such parameters is calculated over areas similar to the size of individual avalanches. Secondly, data describing avalanche locations commonly consist of point sets, where the point roughly positions a starting zone and is suitable for the calculation of descriptive statistics quantifying values such as elevation, gradient or aspect at a national or regional level, but of insufficiently fine granularity to effectively characterise individual avalanche starting zones. Even where avalanche perimeters are available, these typically encompass both starting zones and run-out areas, and not only starting zones.

In this paper, we take advantage of a high resolution terrain model (10m) in Switzerland (ADS-DOM) and a detailed dataset describing small to medium size human triggered accident avalanches and their starting zones gathered between 1999 and 2010 to explore in detail the terrain characteristics of such events. The dataset consisted of photographs and information about individual avalanches, for which in 579 cases avalanche perimeters (encompassing starting zone and runout area) were available, collected by the SLF. For 142 of these avalanches it was possible to clearly identify the avalanche starting zone, and these were digitised separately (Vontobel, 2011).

The studies objectives were thus as follows:

1. Where only avalanche perimeters were available, to develop a simple method of estimating the perimeter of the avalanche starting zone
2. To develop tools for the analysis of the terrain properties of small to medium size human-triggered avalanches using starting zones and perimeters

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3. To make the resulting tools available as a toolbox, allowing other researchers to carry out comparative studies, and to extend the approach to more typical point-based avalanche datasets

2 METHODS

2.1 Estimating avalanche starting zones

Since it is much more common that, if an avalanche perimeter is available, it describes the starting area and run-out zone, we first developed methods to extract avalanche areas from such perimeters.

Two different methods were experimented with, both of which assume that starting zones form continuous areas within the complete avalanche perimeter. The first method simply extracted all connected pixels with a gradient steeper than 30° in the upper part of the avalanche perimeter. The second method extracted a region based on the total length of the avalanche. Avalanche length was defined by fitting a minimum bounding rectangle to the avalanche perimeter, and defining the avalanche length as the side of the rectangle with the greater difference in elevation. A number of threshold values were experimented with, before a value of 40% of the total avalanche length was identified (this was reduced to 30% for avalanches with lengths of more than 1000m).

2.2. Deriving terrain parameters

Having estimated avalanche starting zones, the next stage of our investigation was to describe these starting zones in terms of terrain parameters. We experimented with a range of terrain attributes (e.g. gradient, aspect, roughness, curvature, distance to ridge, exposure, etc.) and quickly established that the gradient, curvature and roughness appeared to offer the most promise.

Gradient was calculated using the standard ArcGIS implementation, based on the finite differences (Horn, 1981). Plan and profile curvature were both calculated using ArcGIS' implementation described in Zevenbergen and Thorne (1987). Roughness was calculated using the approach of Sappington et al. (2007), which effectively defines the Surface Ruggedness as the variation of the orientation of grid cells in a given neighbourhood.

Each of these parameters was calculated for all pixels within the avalanche perimeters and their starting zones. Starting zones were also divided into three zones (upper, middle and lower) (Vontobel, 2011). Using zonal statistics average gradient, curvature and roughness were then calculated for all avalanches.

Curvature values have more semantic meaning if they can be related to landforms, and one useful classification scheme is that presented by Dikau (1989), which classifies each location into one of 9 possible classes (Figure 1). To assign avalanches to curvature classes, we experimented with a number of threshold values of average plan and profile curvature, before selecting values of -0.2/0.2, analogously to Maggioni and Gruber (2003).

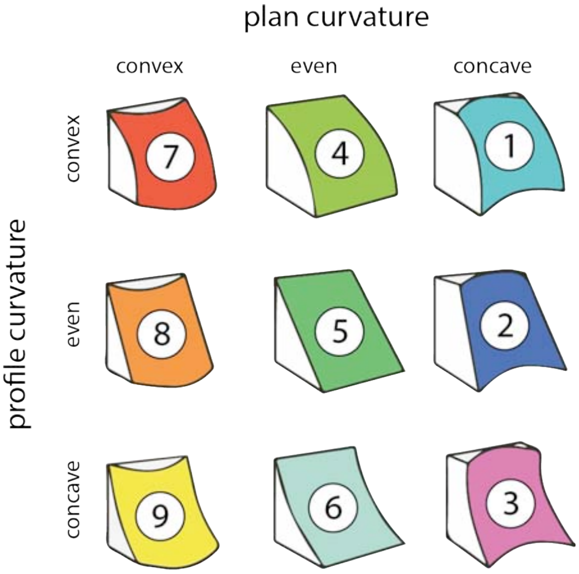

Figure 1: Classification of locations according to their plan and profile curvature. Threshold values -0.2/0.2.

2.3 ArcGIS toolbox

To both extract avalanche starting zones, and calculate and summarise terrain parameters, we developed a set of ArcGIS tools, which have been integrated together in a bespoke toolbox. The toolbox is menu-driven, and will be made freely available to the community to allow the possibility of comparative studies using similar data.

3 RESULTS AND DISCUSSION

3.1 Classification of avalanche starting zones

Having automatically estimated starting zones using two methods, we evaluated this approach by comparing the areas identified using this method with the 142 starting zones which were manually digitised. The Jaccard Index is a metric which gives a value of 1.0 for areas which exactly overlap, and 0.0 for areas with no overlap. In our case, the best results were obtained using avalanche length, with a Jaccard Index of 0.69, indicating statistically significant overlap ($p < 0.001$). Thus, we were confident that using the larger dataset, based on all 567 automatically extracted starting zones, was a sensible next step.

3.2 Slope gradients

The median maximum gradient of avalanche starting zones was 42°. However, when extreme values were truncated by 5% on each side, a median maximum gradient of 40° was obtained. These values are similar to other studies, e.g. 38° (Schweizer and Lütschg, 2000) and to 39° Harvey, 2002) from other data sets.

Unlike these studies, we were also able to calculate descriptive statistics for gradients within the starting zones. Figure 2 and 3 show these values for the original digitised starting zones, and the automatically generated starting zones respectively. In both cases the median and mean values are almost identical and lie around 35°. Figure 4 shows the variation of mean gradient within starting zones, demonstrating a gradual, slight, decline in gradient of starting zones, equivalent to a slope which is concave in profile curvature.

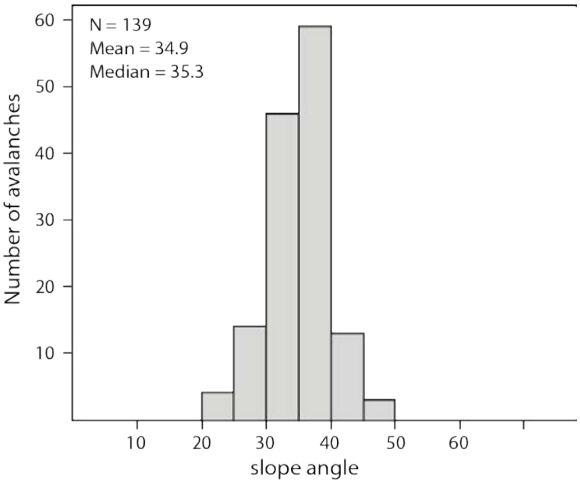

Fig. 2: Distribution of the mean gradient within 139 digitised starting zones.

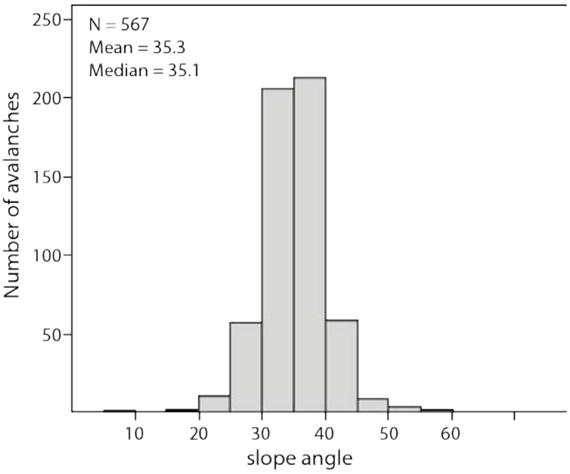

Fig. 3: Distribution of the mean gradient within 567 automatically classified starting zones.

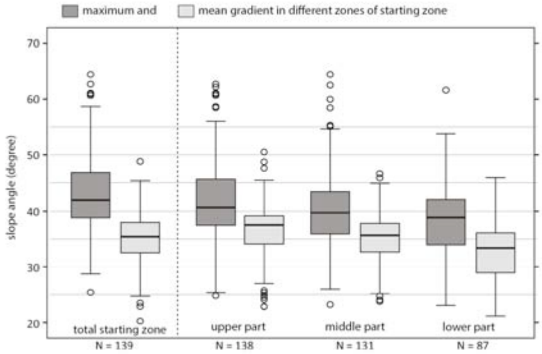

Fig. 4: Maximum and mean gradient within three zones of human triggered avalanche starting zones (upper, middle and lower).

3.3 Curvature and roughness

Figures 5 and 6 show the curvature classes attributed to starting zones for the manually and automatically digitised starting zones. It is immediately apparent that both histograms have very similar features, and that a few classes predominate. In general, convex slopes in both plan and profile curvature are conspicuous by their absence. Four classes, making up all possible combinations of planar and concave slopes dominate both sets of histograms, with some variation in the most prominent class between the digitised and automatically derived starting zones.

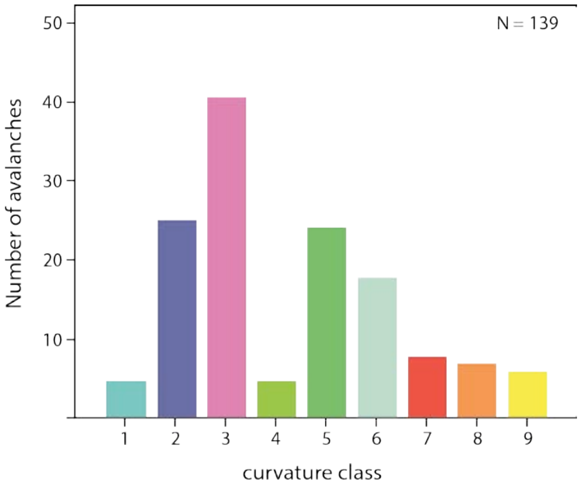

Fig. 5: Curvature class of manually digitised starting zones.

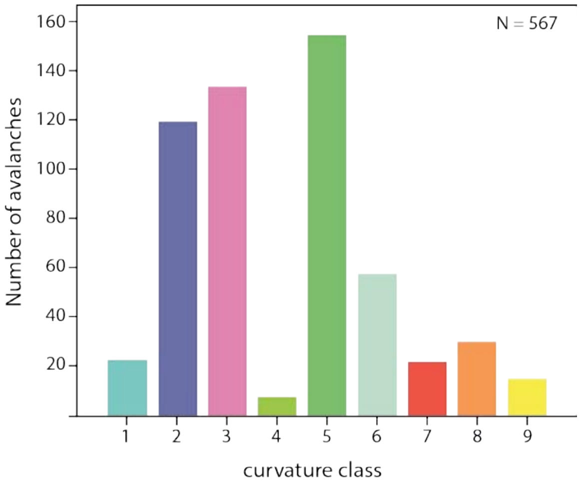

Fig. 6: Curvature class of automatically classified starting zones.

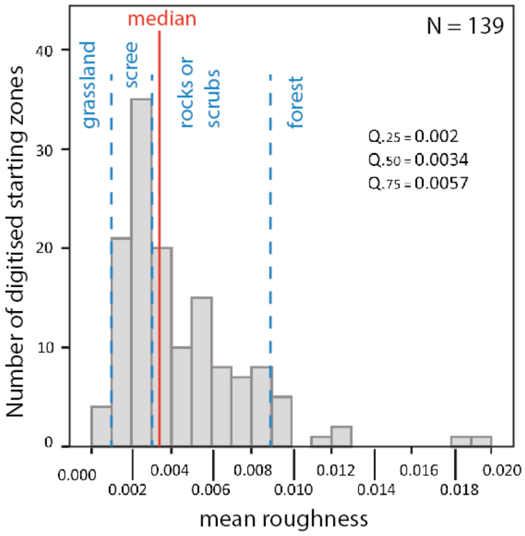

Fig. 7: Mean roughness of manually digitised avalanche starting zones.

Figure 7 shows the relationship between mean roughness and avalanche starting zones. It is clear that most events occur with relatively low values of roughness, equivalent to debris covered surfaces in our DEM.

4 DISCUSSION

In this paper we have presented a set of methods designed to allow us to explore the properties of small to medium-sized accident avalanche starting zones, based on regions rather than points. Since it is often difficult to define starting zones, even where photographs of avalanche starting zones are available, we also developed a simple method to identify such starting zones based on the perimeter of avalanche events, and validated this method using some 142 known avalanche starting zones. The method, although simple, appears to work well for small to medium-sized avalanches, though it is important to realise that the threshold parameters used for defining avalanche starting zones may vary according to avalanche type and size.

We then calculated a range of basic parameters describing the properties of these starting zones. The methods developed return very similar values for starting zone gradient to previous work (Schweizer and Lütschg, 2000; Harvey, 2002), but also allow us to explore the variation of gradient within starting zones.

Our methods also allowed us to explore variation in curvature within starting zones, which resulted in some, perhaps surprising results. Calculations of curvature for individual starting zones are clustered towards planar and concave slopes in both plan and profile curvature. This result requires further investigation, but perhaps suggests differences between locations where avalanches are physically likely to occur, and locations where accidents take place (this analysis is of avalanche accidents). Of particular note is the large number of starting zones in planar terrain. One reason for that might be less spatial variability on such homogeneous slopes.

Finally, roughness, unsurprisingly, tends towards relatively smooth slopes, though with few avalanches on the smoothest slopes and most occurring on those likely to be debris covered slopes. This may again suggest a relationship between where ski-tourers seek the best conditions (higher elevations, with less vegetation) and accident avalanches.

5 CONCLUSIONS AND OUTLOOK

In the near future we will make the toolbox developed available to those wishing to classify starting zones from avalanche perimeters (encompassing starting zone and runout area) or even point data. We also plan to apply the toolbox to describing a Scottish avalanche data set, allowing us to make a first comparative study at this detailed scale.

Further we plan to investigate the relationship between weather and snowpack conditions and terrain features for avalanche starting zones.

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