Avalanche observations related to probabilities

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ABSTRACT
Delineation of avalanche endangered areas or the design of appropriately dimensioned mitigation measures according to the respective regulations while accounting for the possible (economic) consequences is a challenge. Mitigation measures may be very effective for the design event, but may have little or no effect on events that exceed the design event. Even if a mitigation measure reduces the hazard in a certain area, an extension of human activity in this area may increase the social risk. Planning and design of avalanche mitigation measures requires information about avalanche intensity (e.g. impact pressure or velocity) and the corresponding occurrence probability. In this paper, a series of avalanche observations are presented that can help to derive estimates of those probabilities.

1. INTRODUCTION
Oftentimes avalanches are referred to as "Geissel der Alpen", meaning scourge or whip of the Alps. But avalanches are not confined to the Alps. They have endangered and still do endanger the population and their infrastructure in all mountainous areas with at least seasonal snow cover.

Hazard zoning and extensive construction of mitigation measures (such as supporting structures in the starting zones or avalanche dams in the run-out areas) have reduced the number of fatalities in settlements and on roads in areas, where those measures have been implemented. In the Alps, the Winter 2018/2019 has probably shown again that these measures are successful. Despite of two to three meter of snow within seven days in the many precipitation areas, which probably corresponds to a return period of 15 to 30 years, relatively few damages to buildings were reported in the news. Nonetheless, three avalanches, which all hit and slightly damaged hotels, made the news in Switzerland, Austria, and Germany—fortunately without fatalities.

In Norway, for example, hotels belong to safety class S3, which implies that they should only be built in areas where the nominal annual probability for avalanches is less than $2 \cdot 10^{-4}$ (return period > 5000 years) [TEK17 (2017)]. Typical residential buildings belong to safety class S2 for which the annual avalanche probability should not exceed 10^{-3} (return period > 1000 years). There are no explicit specifications concerning impact pressure corresponding to this return period, but it is sometimes taken as 1 kPa. Today's major challenge is to delineate avalanche endangered areas or to design sufficient mitigation measures according to the respective regulations while at the same time accounting for the possible (economic) consequences [Wilhelm (1996), Bründl and Margreth (2015)].

Avalanche hazard is influenced by the combination of various parameters, such as:

- terrain (slope, exposition, roughness, ...);
- vegetation (stand density, tree diameter, undergrowth, ...);
- precipitation (frequency, amount, intensity, rain, snow, ...);

- wind;
- snowpack properties (maritime, continental, ...);
- avalanche type (dry, wet, …), dynamics, run-out distance.

Each of those parameters is related to a probability distribution that needs to be defined and appropriate estimates of the combined probability need to be made. In addition to historical records and longtime observations, numerical models can be useful tools, but keeping in mind that the uncertainties related to model simulations might by higher than the desired accuracy by the regulations. These models include snow cover models such as Crocus [Naaim et al. (2013)] or Alpine3d [Mott et al. (2010)] but also avalanche models like RAMMS [Christen et al. (2010)], SAMOS-AT [Sampl and Granig (2009)], and MN2D [Naaim et al. (2002)]. Models may be especially useful in regions where little historic information is available. As mentioned before, the uncertainties of the models might be higher than the desired accuracy—therefore, their application requires extensive experience from practitioners to assess the model results.

2. AVALANCHE OBSERVATIONS RELATING TO PROBABILITY

In this paper, avalanche observations are presented that can be related in one way or the other to probabilities or help to derive those probabilities.

2.1 Probability to observe a natural avalanche

One of the main challenges with regard to hazard assessment is to estimate avalanche probabilities and avalanche size for a given path. Little data are available to quantify these probabilities as it requires sufficiently long-term observations of all avalanche events. One example of this kind of observations is represented by a data set of approximately 80 surveyed avalanche paths around the Rocky Mountain Biological Laboratory (RMBL), Gothic, Colorado (an area of approx. 60 km^2) during a period 37 years.

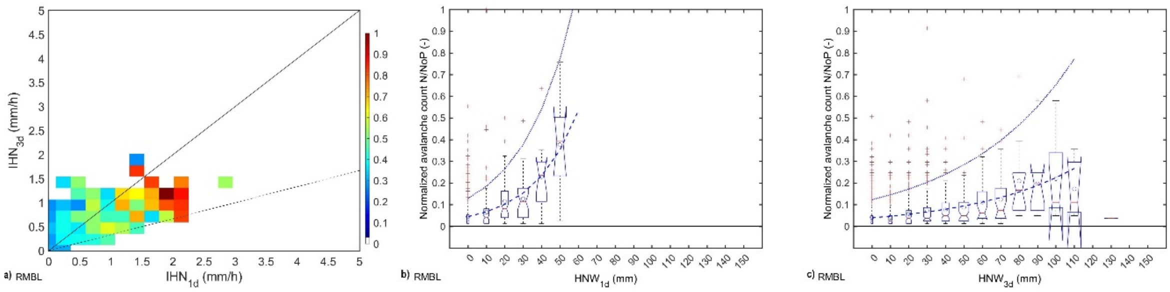

Figure 1 a) Normalized conditional probability (log_{10}-scaled) of observing an avalanche given the mean precipitation intensity of the last day and last 3 days. The continuous line resamples constant intensity during the last 3 days and the dashed line precipitation only during the last day. b) Normalized number of observed avalanches versus one-day new snow water equivalent HNW_{1d} (total number of avalanche paths surveyed NoP = 81). The dashed line shows a fit of the mean value and the dotted line of the 0.95-quantile. c) Normalized number of observed avalanches versus three-day new snow water equivalent HNW_{3d} (number of avalanche paths surveyed NoP = 81).

Figure 1 shows how precipitation or its intensity may relate to the probability of natural avalanches. That recent loading intensity (either as precipitation or snow drift) is a major driver for natural avalanche activity is commonly known, however, little work has been done on the quantification. Figure 1 suggests that especially recent intense loading is important for high avalanche activity. This is, e.g., also reflected in recent experiments by [Birkeland et al. (2018)].

2.2 Fracture depth and avalanche size

Not only how often one has to expect an avalanche in a given path but also what is the expected fracture depth and avalanche size/mass are important parameters in hazard assessment. In modern avalanche models, fracture depth and avalanche size are required as initial parameters.

Based on data from Rogers Pass, [Schaerer and Fitzharris (1984)] proposed an empirical relationship between the mass of avalanches and the most significant determining factors, which can be expressed as

$$M_m = C(S - R)A^n, \quad (1)$$

where M_m, is the total mass of a maximum avalanche for the return period m; S is an index of the amount of snowfall in the avalanche path; R is a factor describing roughness of the ground; A is the surface area of the catchment; C is an avalanche mass coefficient that is a function of the return period, m, as well as of the incline and wind exposure of the starting zone, and n is an empirical exponent.

Nowadays, Geographical Information System (GIS) provide valuable tools to delineate potential releases areas and ease the evaluation of size of catchments [Maggioni (2005), Bühler et al. (2018), Veitinger (2015)].

[Brown et al. (1972), Jamieson and Johnston (1990)] as well as [McClung (2009)] emphasized a relation between the fracture depth D_{REL} and the release size. [McClung (2009)] proposed the relation

$$M = 225 C_0 D_{rel}^{3.2} \quad (2)$$

for the release mass M in tonnes, where C_0 is a constant of the order of 10. The difference between total mass and release mass relates to the mass that the avalanche may erode along the track. For simplicity, the avalanche release depth of major avalanche is often linked to the three-day new snow HNW_{3d} [Salm et al. (1990), McClung and Schaerer (2006)]. This approach may give reasonable fracture depth for major avalanches, but may give a wrong impression of their return periods (see e.g. the discussion by [Schweizer et al. (2008)]). To obtain a better relationship between avalanche release probability and fracture depth/avalanche size, a better understanding of the release mechanism of natural avalanches is required. Recent advances in the understanding of the fracture process of snow [Schweizer et al. (2016)] can help to provide better estimates of return periods and avalanche size.

Based on a simple slab model [Lackinger (1989)], [Gauer (2018a)] used a Monte-Carlo simulation approach, to obtain estimates of avalanche release probabilities and probability distributions of the expected fracture depth (snow water equivalent) depending on climatological conditions. In an extension, he also accounted for forest.

Figure 2 shows some examples of preliminary results of those Monte-Carlo simulations and comparisons with observations.

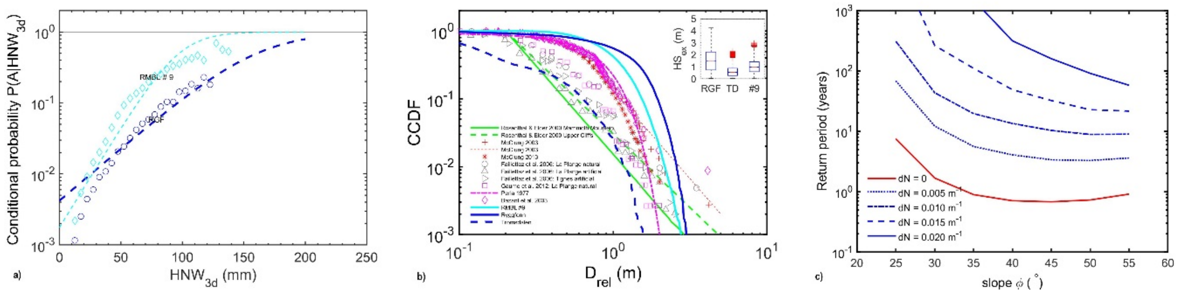

Figure 2 a) Distribution of the conditional probability $P(A|\mathrm{HNW}_{3d})$. Comparison of observations (lines) and simulations (dots) for data from Gothic, Colorado (RMBL #9 and Ryggfonn, Norway (RGF). b) Complementary cumulative distribution function of D_{rel}. Comparison between simulations for Ryggfonn (RGF, Norway), Tromsdalen (TD, Norway), and Gothic (#9, Colorado) and observations or proposed relations in the literature. The boxplot shows the snow height distributions for the three simulations reflecting different climatic conditions. c) Comparison of the nominal return period versus mean slope angle of the release area with the forest stand factor dN as parameter (dN is given by the breast height diameter in m times the number of trees per m^2).

2.3 Scaling behavior of maximum front velocity of major avalanches

Avalanche velocity is an important intensity factor; it is decisive for the dimensioning of mitigation measures, like dams or reinforced buildings [Jóhannesson et al. (2009)], but also for defining warning times.

A scaling analysis using a simple mass block model, supported by observations and measurements of snow avalanches, indicates that the maximum front velocity of major avalanches scales with the total drop height as $U_{max} \sim \sqrt{gH_{sc}/2}$ and that the mean velocity is $\overline{U} \approx 0.64 U_{max}$. Here, H_{sc} is the maximum drop height, i.e., for major avalanches usually the altitude difference from the release area to the valley bottom. The analysis also suggest that the effective friction depends on the mean slope angle.

Furthermore, the observations may also help to estimate run-out probabilities. Figure 3 shows exceedance probabilities (i.e. the probability to observe a value larger than a given one) for a series of observed $U_{max} / \sqrt{gH_{sc}/2}$ [McClung and Gauer (2018)] and expected α values according to the $\alpha{-}\beta$ model [Lied and Bakkehøi (1980)]. The assumption of the empirical $\alpha{-}\beta$ model is that the data on which the model is based reflect rare avalanches; that is events with return periods of the order of 100 years. With that in mind, exceedance probability in Figure 3 b) might be multiplied by a factor of the order of 10^{-2} to obtain annual probabilities. The CCDF of U_{max} can be approximated reasonably well by a Generalized Extreme Value (GEV) distribution.

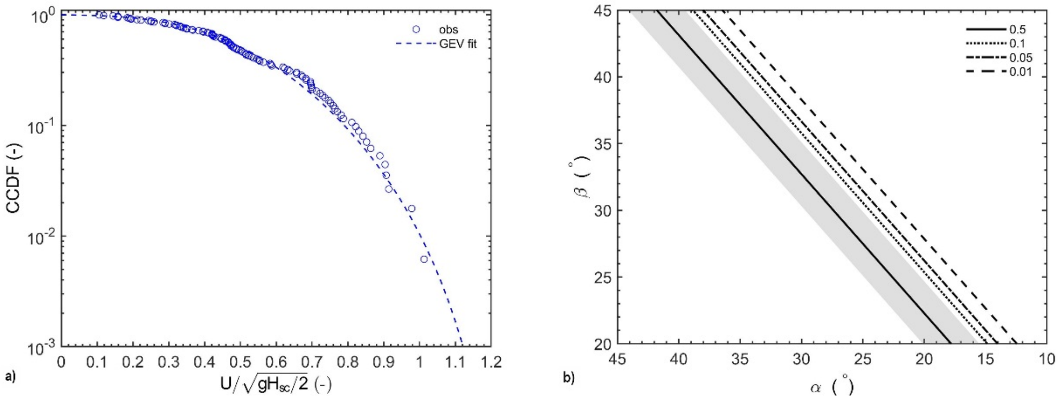

Figure 3 a) Complementary Cumulative Distribution Function (CCDF, survivor function) of observed values of $U_{max} /\sqrt{gH_{sc}/2}$ and b) estimated exceedance probability of α versus β according to the α−β model [Lied and Bakkehøi (1980)] for major avalanche events.

Figure 4 shows the calculated (dimensionless) velocity of a mass block moving with a constant retarding acceleration along a cycloidal track. The retarding acceleration is chosen in such a way that the mass block stops at, respectively, the β-point (which is close to the $\alpha_m+1\sigma$ -point), the α_m-point, or at the $\alpha_m-1\sigma$ -point. In these cases, the corresponding dimensionless maximum velocity $U_{max} /\sqrt{gH_{sc}/2}$ is approximately 0.76, 0.86, and 0.96, respectively.

According to Figure 3, such maximum velocities are attained or exceeded by, respectively, 12%, 6% and less than 2% of all avalanches occurring in the path. Comparing these results with the observations in Figure 3 suggests that the simulated run-outs as well as the velocities agree with the assumption that the velocity curves in Figure 4 reflect major dry-snow avalanches that are relevant for dimensioning of mitigation measures.

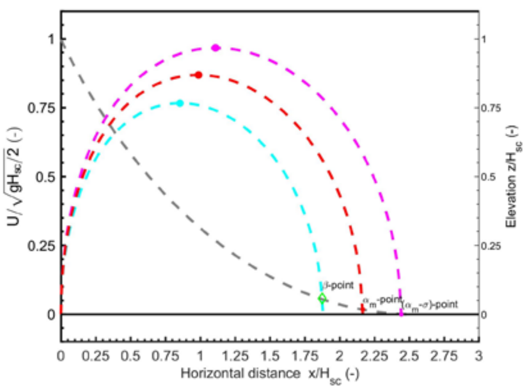

Figure 4 Velocity of a mass block moving with a constant retarding acceleration along a cycloidal track (gray dashed line; steepness in release area is ϕ_0 = 40°) and reaching 1) the β-point (cyan dashed line), 2) the α_m-point (red dashed line), and 3) the α_m−1σ-point (magenta dashed line). The corresponding maximum velocities are marked with a dot •.

Simple dimension criteria for avalanche catching dams relate the required height of the free board H_{fb} to the avalanche velocity (see for example Chapter 8.4 in [Rudolf-Miklau et al. (2014)])

$$H_{fb} = \frac{U^2}{2g\lambda} + h_f \tag{3}$$

where λ is empirical constant with a value typically between 1 and 3 depending on the avalanche type (dry or wet) and h_f is the flow height. In the case of the example in Figure 4, an avalanche stopping at the α_m-point has still a velocity of approximately $0.55\sqrt{gH_{SC}/2}$ at the β-point. Now planning a catching dam at β-point, one could directly relate the required free board to the drop height H_{SC}

$$H_{fb} = \frac{H_{SC}}{12\lambda} + h_f \tag{4}$$

That is, the required free board in this case would be of the order of 5% of the drop height for dry-snow avalanches, which leads to technically impractical dam heights for drop heights in excess of ca. 500 m.

2.4 Estimates of the reach of the powder part of avalanches

Most of the present-day avalanche models only account for the run-out of the dense or fluidized part of the avalanche. However, a destructive effect of the suspension cloud or air blast of the avalanche can often be observed a considerable distance beyond the more obvious deposits of the dense part.

Avalanche observations from Norway, Austria and Switzerland, which distinguish between the dense (fluidized) flow and powder part, are analyzed to obtain probability information about the reach of the powder part [Gauer (2018b)]. Figure 5 show estimates on the survival probability of α_{PSA} versus β. The data provide useful hints for avalanche practitioners about the reach and the corresponding probabilities of the powder part of avalanches.

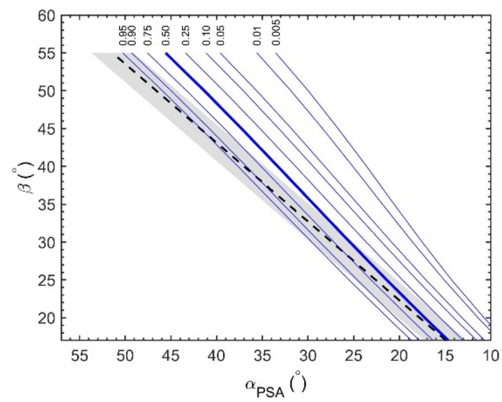

Figure 5 Estimated survival probability of α_{PSA} versus β. For comparison, the dashed line shows the relation angle $\alpha_m = 0.96\beta - 1.4^\circ$ of the dense part and the gray-shaded area marks the corresponding $\pm\sigma$-range.

3. CONCLUSIONS

A quantified avalanche risk management and planning of mitigation measures requires extensive knowledge of all individual processes involved as well as their interactions. Especially regarding a consistent quantification of the interactions of individual processes, be it with regard to the recurrence periods or the vulnerability of objects, there is still a need for research.

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