

HOW SNOW COVER PROPERTIES INFLUENCE AVALANCHE DYNAMICS

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ABSTRACT: The run-out distance depends, among other things, on the release mass and the snow conditions in the avalanche path. So far, our knowledge on the effect of snow conditions on avalanche run-out is limited and qualitative at best. In the Interreg project STRADA we investigate the effects of snow cover conditions on avalanche dynamics, and thus run-out distance. We selected five avalanches from the Vallée de la Sionne test site (Western Swiss Alps), with similar initial mass and flow paths but different flow dynamics. For each of these avalanches, the snow conditions were reconstructed using either field data from local snow pits or the numerical snow cover model SNOWPACK. Our data suggest that even for short vertical distances distinct flow regimes develop depending on the amount of entrained snow and its properties. In contrast, the lack of potentially erodible snow along the track or snow with relatively warm temperature did not only reduce the run-out distance but also strongly affected other flow characteristics such as front velocity and deposition structures. In the future, model calculations may provide real-time information on potential run-out distance provided information on snow conditions in the release zone and the track are available. Snow cover modeling has the potential to fill this gap.

1. INTRODUCTION

While it is already difficult to assess location and time window of release for a snow avalanche threatening, for example, a road, it is often impossible to predict the run-out distance. However, to decide on a road closure, it is essential for local avalanche safety services to know whether the avalanche will reach the road or stop above. Those decisions are often very difficult as they demand the ability to interpret weather forecasts, to establish their implication for the stability and the structure of the snow cover and to evaluate the influence of the snow cover on avalanche run-out distances (Blattenberger and Fowles (1995)). Literature on the direct influence of snow characteristics on avalanche dynamics, and thus the run-out distance, are sparse and mostly describe the link between new snow amounts and run-out for extreme avalanches (Eckert et al. (2010)).

Schweizer et al. (2009) analyzed a dataset of 54 avalanches for an avalanche path close to Davos, Switzerland. They found that the run-out distances of the investigated avalanches are related to the difference in snow depth over the last three days (ΔHS3d). Furthermore, their investigations suggest that weak basal layers in the avalanche track were favorable for strong snow entrainment and might have contributed to the large run-out distances. This is again indicating the importance of snow cover properties on run-out distances. However, the influence of snow properties could not be quantified.

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The importance of snow cover entrainment, i.e. the process of adding snow along the avalanche track by erosion, on the terminal deposition mass was clearly demonstrated by Sovilla et al. (2006). To accurately estimate the mass balance, it is essential to consider snow cover properties, e.g. density. This is even more important for small to mid-sized avalanches since they have smaller initial mass and the entrainment of snow along the track is strongly affected by the snow cover properties.

ΔHS3d is also commonly used in numerical avalanche dynamics calculations of run-out distances (Salm et al. (1990)). Until now most avalanche dynamics models, e.g. RAMMS (Christen et al. (2010)), are calibrated for extreme avalanches and they often produce unsatisfactory results for run-out distances of small- and midsized avalanches, which may still produce problems for infrastructure, however. This fact can mainly be attributed to the insufficient consideration of snow cover property effects on avalanche dynamics. New approaches and model modifications seem to be very promising for the calculation of smaller sized avalanches and in defining different flow regimes (Bartelt et al. (2011), Gauer et al. (2007)). A better understanding of the influence of snow cover properties on avalanche dynamical parameters would be of great interest for further improvements of those models.

We focus on the effects of snow cover properties on avalanche dynamics, and thus run-out distance, with the aim to provide a better understanding of this influence and to ultimately develop tools to support snow safety officers in their decision process. The results can then be

implemented in numerical avalanche dynamics models (e.g. RAMMS (Christen et al. (2010))) and thus increase their performance.

2. DATA

Avalanches with similar release zones and release mass which followed the same topography but showed different flow dynamics were selected for the Vallée de la Sionne (VDLS) field site (figure 1) located in the Western Swiss Alps. Selecting only avalanches that fulfill these criteria allow to neglect topography effects on the flow dynamical behavior of the individual avalanches. In a second step the mass balance (release, entrainment and deposition mass) was determined for all events using airborne laser scans, pictures and field observations.

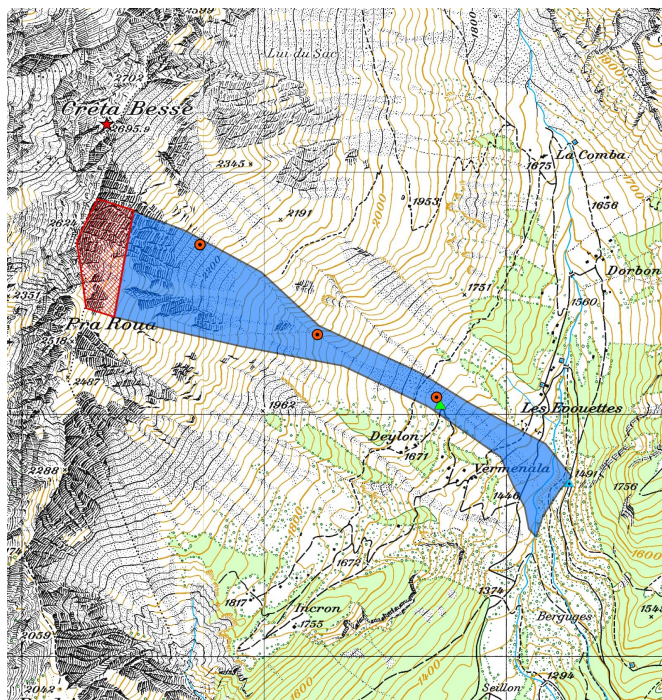


Figure 1: Overview of Vallée de la Sionne (VDLS) field site. The Creta Besse 1 release area (red, hatched area), where all investigated avalanches released, and avalanche track (blue area) are marked. Furthermore the positions of the FMCW radars (red circles), the VDLS 1 automatic weather station (red star) on the ridge, the measurement mast (green triangle) and the bunker (blue triangle) are marked.

2.1 Snow cover data

To investigate the eroded snow layers and their properties in more detail, information on the prevailing snow stratigraphy were extracted from profiles taken

at the fracture crown. In cases where measured profiles were unavailable or incomplete, the available measurements were supplemented with simulations from the one-dimensional numerical snow cover model SNOWPACK (Lehning and Fierz (2008)). To get accurate SNOWPACK results for the avalanche path, the meteorological input data, such as temperature and precipitation, were spatially interpolated with the three-dimensional model Alpine3D (Lehning et al. (2006)). The performance of SNOWPACK was verified with measured profiles and the performance of Alpine3D to model the solid precipitation distribution in the VDLS catchment was compared existing to airborne laser scan data.

2.2 Flow dynamical data

Upward-looking frequency-modulated continuous wave (FMCW) radar buried in the ground along the avalanche path allowed to estimate the amount of eroded snow as well as to identify flow regimes in the avalanche. Furthermore, the combination of measured and modeled snow profiles and FMCW radar information allowed to estimate the properties, e.g. density or temperature, of the eroded snow layers. Additional flow dynamical measurements, such as pressure and flow velocity, are available from the 20 m pylon located directly in the avalanche path (green triangle, figure 1).

3. METHODS

Based on the available data presented in section 2 we conduct our study in the following steps:

1. Compare and identify differences of individual avalanches
2. Reconstruct the prevailing snow cover properties prior and during avalanche events (measured and modeled snow profiles)
3. Describe the potential of individual snow cover properties, such as temperature, to influence flow dynamical processes

4. EFFECTS OF SNOW COVER PROPERTIES ON FLOW DYNAMICS

The properties of the initial and entrained snow along the path and its inherent characteristics, such as density and temperature, can influence flow dynamical properties in multiple ways. To list and discuss the investigated processes individually we divided this section into two parts. Firstly, the effects on the mass balance of an avalanche will be discussed (section 4.1) and secondly we show how the development of flow regimes is directly

influenced by temperature (section 4.2). For both effects a general description is given, followed by an example where it was observed in our data and the most influential snow parameters are summarized. Of course, in nature, all discussed processes can take place at the same time, influence each other and depending on the conditions one process can be more dominant than another.

4.1 Effects on mass balance

The mass balance of an avalanche comprises the initial release mass, the entrained (and deposited) snow along the track and the terminal deposition mass. The addition of mass along the path by erosion is defined by the height and area of entrained snow and its density. Typical values for the average density of the release slabs are in the range of 150 - 250 kg m⁻³. Typical densities of eroded snow along the avalanche track are in the same range when averaged over the whole entrainment depth.

All selected avalanches (figure 1) in our dataset released from the Creta Besse 1 (CB1) release zone, followed the main gully and the typical run-out zone of the VDLS field site. Although all avalanches had a similar release mass the deposition mass showed large variations. These results show that initial mass is not the main contribution to the overall mass balance or the deposition mass of an avalanche. In fact the amount of eroded snow and its properties form the major influence on the individual characteristics of an avalanche.

The impact of density and erosion depth on the mass balance of an exemplary avalanche, that is representative for our investigated avalanches, was calculated and is summarized in Table 2. We took an entrainment area A_{ent} and varied the density of the entrained snow ρ_{ent} and the erosion depth d_{ent} for a range of typical values. The impact of these changes on the entrained mass M_{ent} is calculated and the corresponding increasing or decreasing factor F is given. The density of the entrained snow ρ_{ent} was varied between 250 and 150 kg m⁻³ (Table 2). In this case the initial mass was changed by a factor of 1.3 and 0.8, respectively. Performing the same calculations for typical entrainment depths d_{ent} of 0.5 and 1.5 m result in a factor 0.5 and 1.5, respectively. Furthermore, avalanches occurring before the main avalanche can significantly reduce the snow cover available for erosion and thus reduce the entrainment depth. This can lead to a complete erosion previously to the main avalanche event and the reduction of entrained mass close to 0 tons. This is regularly observed at the VDLS field site since many avalanches enter the same main path and a preceding event can remove most of the snow along its way. Therefore density affects the mass balance, yet the

influence of previously occurring avalanches, and thus removal of erodible snow for consecutive events, plays a more significant role than density variations. Yet, both processes can change the mass of an avalanche and thus its kinetic energy.

Table 2: Influences on mass balance by varying density and entrainment depth. The data is based on a typical entrainment area (A_{ent}) size for CB1. The density of the entrained snow ρ_{ent} was varied in case I and II and the erosion depth d_{ent} in case III and IV.

	Real	I	II	III	IV
A_{ent} (m ²)	30000	30000	30000	30000	30000
d_{ent} (m)	1	1	1	0.5	1.5
V_{ent} (m ³)	30000	30000	30000	15000	45000
ρ_{ent} (kgm ⁻³)	200	250	150	191	191
M_{ent} (t)	6000	7500	4500	2865	8595
F ()	1	1.3	0.8	0.5	1.4

Furthermore, previously occurring avalanches can deposit snow along the path or densify and harden the existing snow cover. Depending on the prevailing snow cover properties in the track the avalanche will erode more or less snow and will require a varying amount of energy to entrain and accelerate the eroded snow. Especially for small to mid-sized avalanches this can strongly influence their evolution after they released since they have small initial mass, and thus small potential and kinetic energy, which can be used to erode the snow cover.

Most influential snow parameters:

- Erosion depth (potentially reduced by previous avalanches)
- Density
- Hardness
- Weak basal layers

4.2 Effects on mobility, flow regimes and granulation

The mobility of an avalanche, i.e. its potential to move faster and further, can strongly differ for individual avalanches even though the release conditions were similar. This can be well observed for two avalanches from our dataset (avalanche 816 and 917) which released at the same area and for similar snow height distributions at the VDLS field site. They showed similar maximal front velocities for the upper part of the avalanche track but substantially different velocities in the run-out zone.

Even though both avalanches showed a similar flow regime, i.e. a very turbulent front and a distinct powder cloud, at the beginning, avalanche 917 strongly decelerates at the start of the run-out zone at 1700 m a.s.l.. This strong deceleration of avalanche 917

is also visible when observing video and pictures of the avalanche and its powder cloud (not shown). Yet, the avalanche kept flowing with very small velocity and formed 'flow-fingers' and levees, i.e. elongated walls in the debris that develop due to segregation and shear processes which are usually only observed for 'warm avalanches', before stopping completely. Avalanche 816 on the other hand maintains its velocity far down to the run-out zone and the powder cloud covers the whole valley bottom.

The development of such different flow regimes, e.g. whether a plug flow or a turbulent fluidized flow is formed, strongly depends on the granular structure in the avalanche. Studies on mono- and bidisperse material in granular flow show a strong relation between mobility and the granular distribution (Moro et al. (2010)). Therefore, the mobility of avalanches with seemingly similar initial conditions can strongly change depending on the internal granular distribution.

Granular structures and size distributions in the deposition zone are often interpreted as indirect indicators for the internal flow dynamical characteristics of an avalanche (Issler et al. (2008)). Figure 2 shows pictures that were acquired right after avalanches 816 and 917 stopped. Avalanche 816 shows a fan-shaped, wide deposition field, no strong levee formation and a homogeneous granular size distribution. Contrary, avalanche 917 shows strong levee formation and 'flow-fingers'.

The observed differences in front velocities and deposition structures of avalanche 816 and 917 can be explained by taking the snow cover properties of the entrained snow into account. To investigate the temperature of the entrained snow the snow cover model SNOWPACK was run at 4 different positions along the complete avalanche path. Analyzing the prevailing snow cover conditions for both avalanches reveals that both entrained relatively 'cold snow', i.e. approximately -10°C , until 2000 m a.s.l.. In the lower part of the path avalanche 816 entrained snow with negative temperatures between -10 and -5°C , whereas the simulations for avalanche 917 show warmer temperatures, i.e. between -5 and 0°C . The entrainment of warm snow for avalanche 917 in the lower part explains the rapid decrease in front velocities and the rapidly 'starving' powder cloud. Also the strong levee formation in the run-out zone can only be explained by the erosion of snow with temperatures at or close to 0°C .

Our data suggests that the temperature of the initial and entrained snow have a direct influence on the flow dynamical evolution of an avalanche since it controls the development of granules and flow regimes which define

the mobility of an avalanche.



Figure 2: Pictures taken after avalanche 816 and 917 stopped.

Most influential snow parameters:

- Temperature of initial and entrained snow (e.g. new snow temperature, ground erosion)
- Run-time of avalanche and thus warming due to friction

5. CONCLUSION and DISCUSSION

We listed and discussed relevant snow cover parameters that can have a direct or indirect influence on the flow dynamics. 5 avalanches from the avalanche test site Vallée de la Sionne with similar initial mass, release area and topography were selected. With this data we have shown that different avalanches can form for similar initial conditions and on the same avalanche path. We conclude that the initial mass and release height are not the main driving factors and entrainment can only partly explain differences as observed in our dataset. This illustrates the importance of snow cover properties on flow dynamics which is, up to now, poorly understood and qualitative at best.

Therefore, we list and discuss the most important snow parameters which affect, both directly and indirectly, the flow dynamical evolution of the avalanche. Especially the influence of temperature on granulation and consequently on the mobility of an avalanche seems to play a crucial role and more detailed investigations are needed. This needs to be done by granulometric investigations of avalanche deposits for real scale avalanches as well as a more profound understanding of the granulation in laboratory experiments.

A more comprehensive knowledge on the influence of the individual snow parameters will also allow to better understand the influences among each other and the associated back couplings, e.g. the connection between granulometry, flow regime, mobility and run-out distance.

All of those findings have large potential for implementation in avalanche dynamics models and would greatly increase their performance, especially for non-extreme avalanches.

6. ACKNOWLEDGEMENTS

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