# SCENARIO-BASED AVALANCHE SIMULATIONS INCLUDING SNOW ENTRAINMENT, SNOW TEMPERATURE AND DENSITY

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ABSTRACT: Avalanche engineers use scenario-based simulations to predict avalanche runout and quantify impact pressures. An important input parameter for such simulations is the avalanche return period. In Switzerland, 10-, 30-, 100-, 300- and > 300-year avalanche return periods are taken into account for hazard assessment. Another important input parameter is the fracture depth which is determined with a procedure developed by SLF in 1990. Presently, the procedure provides no methodology to include snow entrainment, snow temperatures or snow density. This limitation hampers the application of advanced models that incorporate snow entrainment.

The fracture depth is based on the determination of measured 3-day snow height increase using extreme value statistical approaches. The statistical values are modified to include the effects of altitude, snow drift accumulations and terrain (slope angle). The procedure provides fracture depths $d_0$ for e.g. 10-, 30-, 100- and 300-year avalanche return periods. In this paper, we modify this well-known SLF procedure to determine snow entrainment depths $d_0^*$ (erodible snow) which are associated with measured 3-day snow height increase. The erodible snow along the track is modified including altitude gradients and the slope angle.

Within the framework of the proposed methodology, we demonstrate how to specify snow temperatures that are suitable for typical winter storms in the Alps, depending also on the altitude of the release area. These recommendations are based on snow profiles recorded during storm periods with heavy snow fall of February 1999 and January 2018, 2019 and 2021. The final component of the procedure is to provide a realistic snow density for the fracture slab.

The procedure is straightforward, easily integrated into existing workflows, and benefits from relying on measurement data, ensuring realistic predictions of entrainment and deposition heights. Crucially, this method enables the examination of avalanche runout in a shifting climate marked by rising temperatures.

KEYWORDS: Avalanche dynamics; snow entrainment, snow temperature, snow density, hazard evaluation, climate change.

## 1. INTRODUCTION

In this paper, we present a scenario-based approach for simulating large powder snow avalanches. Our method builds on established calculation techniques used for dense flow avalanches (Salm et al., 1990), making it straightforward to integrate into existing workflows that are widely recognized and utilized by snow hazard engineering offices. The procedure begins by defining fracture depths $d_0$ for various avalanche return periods, such as 10, 30, 100, and 300 years. These fracture depths are derived from measurements and statistical extrapolation of three-day snow height increase, including wind-blown snow in the release area.

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Simulating the avalanche powder cloud and airblast requires additional elements in the calculation process, particularly snow entrainment. Snow entrainment changes the mass of the avalanche, but, more importantly, the avalanche flow regime. Entrainment of cold snow facilitates of the fluidized, collisional flow regime necessary for the formation of a large and fast-moving powder cloud. Many practical problems encountered in snow engineering practice require finding the strength of the powder cloud not only in the runout zone (the streamwise flow direction) but also for structures located near the lateral edges of the flow. This requires simulating the motion of the avalanche from initiation to runout. Therefore, to accurately model the height of the cloud and intensity of the avalanche air-blast requires considering the terrain in the release, transition and runout areas, the possibility of snow entrainment, as well as the climatic characteristics of the avalanche track, typically represented by elevation and exposure (Stoffel et al., 2016, Interpraevent). Existing procedures for avalanche calculations must therefore be expanded to account for snow entrainment and influence of temperature.

In the following sections, we will use the RAMMS::Extended model (Bartelt et al., 2016; Zhuang et al., 2023) to demonstrate the features of our approach and present numerical results. It is important to note that the proposed procedure is entirely general and can be applied with any model capable of incorporating entrainment, temperature and simulating the formation of the powder cloud. The RAMMS::Extended model assumes the dust-air mixture that forms the cloud is provided initial momentum and direction from the core. Once separated from the core, it is no longer strongly connected to the terrain but flows as an inertial, turbulent suspension.

## 2. OVERVIEW ON THE SCENARIO BASED APPROACH FOR CALCULATING POWDER SNOW AVALANCHES

For the fracture depth $d_0$, the size of the release area, and the friction parameters, we propose a dependency on the avalanche return period, similar to the approach used in RAMMS::Avalanche since many years. The fracture depth $d_0$ (perpendicular to the slope) is calculated based on the increase in snow cover over a three-day period, derived from extreme value statistics of a measurement field. The determination of the release area is largely at the discretion of the model user, allowing for flexibility based on specific conditions. The friction parameters, defined as μ, ξ and cohesion, are dependent on the release volume.

In the context of a powder snow avalanche scenario, we assume these events typically occur during or shortly after winter storms, where significant amounts of new snow can be eroded along the avalanche track. For snow entrainment, we propose a basic value of erodible (new) snow, denoted as $d_0$*. This value $d_0$* can be calculated as part of a sub-step for estimating the fracture depth $d_0$ (as detailed in Chapter 3). In addition, we give a procedure that takes into account the decrease in erodible snow along the avalanche path as a function of elevation and slope angle.

The snow temperature in the release area can be estimated based on our findings from snow profile studies conducted during storm periods (discussed in Chapters 4 and 5). Unlike other parameters, the snow temperature does not correlate with a specific return period. The colder the snow temperature, particularly within the range of -3°C to -8°C, the longer the calculated runout distance. Typically, a change in snow temperature along the avalanche track should also be considered.

Snow density in the release area (respectively in the upper area) generally depends on the shape and size of the snow crystals, snow temperature, wind speed, relative humidity, the amount of new snow and the duration of the snowfall. Three-day snow densification will be discussed in Chapters 6 and 7. We have also analyzed measured snow densities from snow profiles. The typical new snow density in wind influenced release areas may vary between 150 and 200 kg/m$^3$ at the topmost meter (Swiss Alps). A higher density means more mass which leads to a longer run out.

## 3. FRACTURE DEPTH AND BASIC VALUE OF ERODIBLE SNOW

The fracture depth $d_0$ is calculated as for dry dense flow avalanches according to the SLF procedure (Salm et al., 1990) as follows:

1) Three-day snow height increase: extreme value statistical analysis of data from a representative measurement field (preferably long-term measurement series); based on the return period of the scenario to assess.

2) Altitude correction: difference in altitude between the measurement field and the release area. For avalanche simulations in the Swiss Alps typically an increase of 5 cm / 100 m is used, see Salm et al. [1990].

3) Correction to 28° slope: Conversion of the snow height increase measured on a flat field (value of 1) and 2)) to a 28° inclined slope which is the basic value for the calculation of the fracture depth $d_0$ and the depth of erodible snow $d_0$*. For a slope inclination of 28°, a correction factor of 1 is assumed in accordance with 5).

4) Snow drift accumulation due to wind influence: depending on the return period and the terrain situation we still propose 0 to 50 cm [Salm et al., 1990], which is added to $d_0$*. If there is also a lot of wind-blown snow in the track, the value from step 4 can be used as depth of the erodible snow.

5) Correction with mean slope angle (release area). We assume that more snow can accumulate on a relatively flat slope than on a steep slope before the release of an avalanche. Consideration of the slope angle factor shown in Fig. 1 (e.g. factor 0.71 for a slope angle of 35°) → $d_0$.

This procedure is used to calculate the slope-perpendicular fracture depth $d_0$.

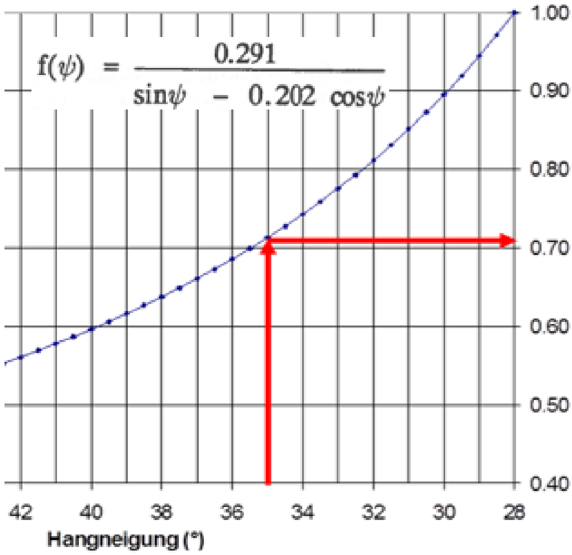


Figure 1: Slope angle correction factor $f(\psi)$ [Salm et al, 1990]

Table 1 contains typical fracture depths $d_0$ for the Swiss Alps for release areas around 2500 m and 35°.

| Return period | T=10y | T=30y | T=100y | T=300y |
|---|---|---|---|---|
| Frac. depth [cm] | 80 – 110 | 100 - 140 | 125 - 170 | 150 - 200 |

Table 1: Typical fracture depths $d_0$ for avalanche simulations in Switzerland (based on SLF procedure 1990), for release areas around 2500 m and a slope angle of 35°.

The basic value $d_0^*$ for the snow that can be eroded in the track can be calculated on the basis of the steps 1 to 3. The value of erodible snow $d_0^*$ refers to a slope inclination of 28° and the height of the release area (or immediately below). RAMMS::Extended uses $d_0^*$ to calculate the "snow cover" layer (Fig. 2) by taking into account the altitude and slope inclination for each terrain pixel.

For the scenario-based calculation of powder snow avalanches, we recommend reducing $d_0^*$ in the track by 3-5 cm / 100 m (= gradient $\Delta d_0^*$). A $\Delta d_0^*$ of 3 cm assumes that also a small part of the old snow cover can be eroded.

Erodible snow is thus present in the entire avalanche path with the exception of rocky terrain (steeper than typically 50 - 60°).

When calculating avalanches, the available (new) snow is eroded in the avalanche path according to an erodibility coefficient that depends on terrain steepness. Moreover, the erosion rate is faster on steeper slopes.

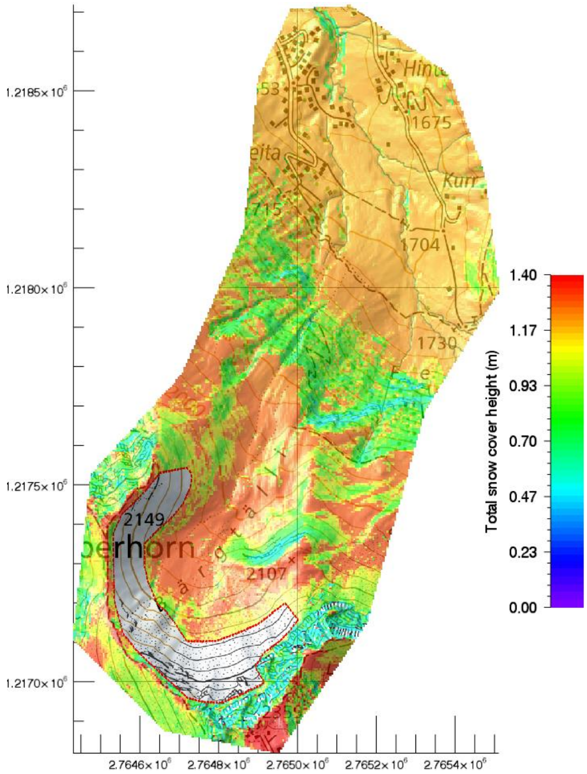


Figure 2: Erodible snow depth in the avalanche track, calculated by RAMMS::Extended (version 2.8.35) based on the basic value $d_0^*$: In the example Bergtälli Malbun it is 130 cm of erodible snow just below the release area (marked with red dotted line), 70 cm in the steeper section and 120 cm at around 1700 m. The erodible snow cover is defined in the slope perpendicular direction.

## 4. SNOW TEMPERATURES FROM SNOW PROFILES

The snow temperature in the release area and the temperature gradient (ΔT) along the avalanche path are crucial input parameters that significantly influence the calculation results, particularly the runout distance.

To analyze snow temperature, we focused on periods characterized by high powder snow avalanche activity. Specifically, we selected snowfall periods from February 1999, January 2018, January 2019, and January 2021, each with approximately 1 meter of new snow accumulation. We identified 33 snow profiles taken during these periods: 4 profiles from February 9/10, 1999, 3 from February 22/23, 1999, 6 from January 22/23, 2018, 11 from January 14/15, 2019, and 9 from January 14/15, 2021. All these profiles were recorded during active snowfall (see Fig. 3). Due to adverse weather conditions, the number of available snow profiles is limited.

The 33 snow profiles analyzed have total snow depths ranging from 1.3 to 4 meters. Thirteen profiles show snow depths between 1.3 and 1.5 meters, while the remaining 20 profiles have depths exceeding 1.5 meters. Of these profiles, 21 were taken at altitudes between 1380 and 2100 m, and the other 12 at higher elevations between 2100 and 2680 m.

In the following analysis, we focus on the average snow temperature of the topmost meter of these snow profiles, which roughly corresponds to the fracture depth of large avalanches. In some profiles, the uppermost 20 cm is excluded due to atmospheric influences, such as colder temperatures near the snow surface.

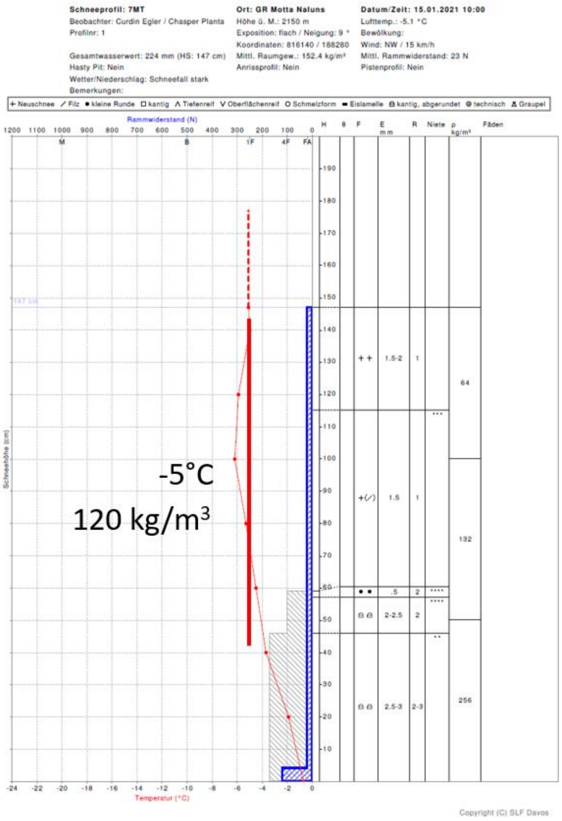


Figure 3: Snow profile taken near Scuol (Engadin) at 2150 m, 15 January 2021: there is an average snow temperature of -5°C in the topmost meter with an average snow density of 120 kg/m³.

The mean snow temperatures in the topmost meter, as measured in the 33 profiles, are displayed in Figure 4, along with the trend line. Snow temperature variation between 1380 and 2100 m is significant, ranging from -1.5°C to -8°C. Colder temperatures, ranging from -3.5°C to -9°C, were recorded at elevations between 2100 and 2680 m. The trend line suggests temperatures between -5° and -7°C for altitudes from 2100 to 2800 m. The large variation is due to the different weather conditions during the avalanche periods investigated.

A gradient ΔT of 0.28° / 100 m can be calculated for the snow temperature based on the trend line.

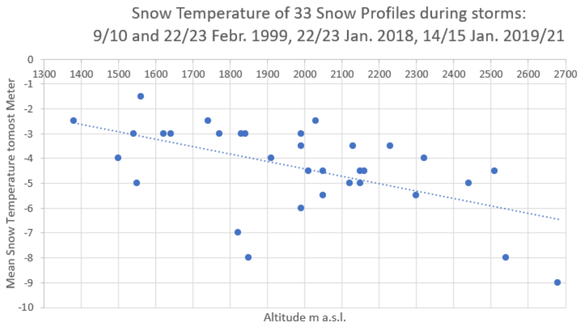


Figure 4: Mean snow temperature of the topmost meter of 33 snow profiles, taken during heavy snow fall in February 1999 and January 2018, 2019, 2021

## 5. SNOW AND AIR TEMPERATURE FOR SIMULATIONS

The goal of scenario-based powder snow avalanche simulations is to model "extreme" events that can occur under typical powder snow avalanche conditions. We recommend the following approach:

- For release areas at "lower" altitudes around 2000 m, which in Switzerland is still above the tree line, we suggest a mean snow temperature of -5°C.
- For medium altitudes we propose a mean snow temperature of -6°C.
- For release areas at "higher" altitudes (e.g., above 2600 m in the Swiss Alps) or to consider extreme powder snow avalanche scenarios, we recommend a mean snow temperature of -7°C.
- To calculate the snow temperature in the avalanche track a temperature gradient ΔT of 0.3°C per 100 m can generally be applied in scenario-based powder snow avalanche simulations (respectively 0.2 – 0.4°C / 100 m).

It's important to note that snow temperature is among many other factors related to snow density, as discussed in Chapters 6 and 7.

For air temperature, we recommend to use the same value as for the snow temperature.

## 6. SNOW DENSITIES FROM SNOW PROFILES AND SETTLEMENT MODELS

Snow density is intimately related to initial snowfall amounts, the rate of settlement, new snow characteristics, and temperature.

Of the 33 snow profiles analyzed, only 7 include data on snow density. In the topmost meter of the snow cover, the mean density ranges between 120 and 170 kg/m³ (at elevations between 1700 and 2100 m a.s.l.), with an average of 150 kg/m³.

These profiles were likely recorded in locations sheltered from the wind. We consider snow densities of 150 to 200 kg/m$^3$ to be realistic for typical conditions with wind effects in the release areas, for the topmost meter of the snow cover. The snow density in the avalanche track might be lower than 200 kg/m$^3$ (in the topmost meter), which aligns with the values observed in the snow profiles.

SNOWPACK simulations (Bartelt and Lehning, 2002) further support that a density of 175 to 200 kg/m$^3$ is realistic under storm conditions. We analyzed SNOWPACK data from January 22/23, 2018, and January 14/15, 2019, from the Davos Flüelastrasse and Davos Weissfluhjoch stations.

To further support our density assumptions, we applied both analytical and numerical models. In our analytical we follow the work of Kojima (1967, 1974) who performed measurements of new snow settlement. He found that

$$\frac{1}{\rho(t)}\frac{d\rho(t)}{dt} = \frac{\sigma}{\eta_c(\rho,T)} \qquad (1)$$

where $\rho$ is the snow density, $\sigma$ the overburden stress (three-day new snowfall) and $\eta_c$ the temperature dependent compactive viscosity. New snow settlement measurements revealed the following nonlinear relationship for the compactive viscosity,

$$\eta_c(\rho,T) = \eta_{c1}e^{k\rho} \qquad (2)$$

with $\eta_{c1}$ being the compactive viscosity coefficient which is dependent on the temperature T,

$$\eta_{c1} = \eta_{c0}\left[10^{\left(\frac{1}{T}-\frac{1}{271}\right)*0.4550}\right] \qquad (3)$$

We follow Kojima and take for $\eta_{c0}$ a value of 0.6 g d / cm$^2$. The exponent $k$ has a value of 21 cm$^3$/g.

Table 2 shows the result of our calculations indicating typical snow densities of 150 to 200 kg/m$^3$ after a 3-day snowfall, including densification by settlement. A typical value we employed in our density analysis is a three-day snow water equivalent of 150 mm to 240 mm. For a snow temperature of e.g. -6°C, a 40° steep release area and a fracture depth $d_0$ of 120 cm, the calculated snow density is 170 kg/m$^3$ (see Table 2).

| Input | | | Output | |
|---|---|---|---|---|
| Precipitation (mm) | Temperature (C°) | Slope Angle (°) | Calculated 3-day $d_0$ (cm) | Calculated Density 3-days (kg/m$^3$) |
| 152 | -7 | 30 | 98 | 155 |
| 152 | -6 | 30 | 94 | 162 |
| 152 | -5 | 30 | 90 | 170 |
| 152 | -5 | 0 | 85 | 177 |
| 200 | -7 | 30 | 119 | 169 |
| 200 | -6 | 30 | 113 | 176 |
| 200 | -6 | 40 | 118 | 170 |
| 200 | -5 | 30 | 109 | 184 |
| 200 | -5 | 40 | 113 | 177 |
| 240 | -7 | 30 | 135 | 178 |
| 240 | -6 | 30 | 129 | 186 |
| 240 | -5 | 30 | 124 | 194 |
| 240 | -5 | 20 | 121 | 199 |
| 240 | -5 | 10 | 119 | 201 |
| 240 | -5 | 0 | 119 | 202 |
| 240 | -7 | 40 | 140 | 172 |
| 240 | -6 | 40 | 134 | 179 |
| 240 | -5 | 40 | 128 | 187 |

Table 2: Calculated 3-day snow density based on settlement equations (model Kojima) for snow temperatures between -5° and -7°C, slope angle in the release areas of 30° and 40° and 85 cm to 140 cm as fracture depths $d_0$.

This procedure has now been implemented in RAMMS::Extended. For every pixel in the calculation domain we solve the governing differential equation given a three-day accumulation, which defines the overburden pressure $\sigma$. The overburden pressure is defined in the slope perpendicular direction and therefore accounts for slope angle. RAMMS input parameters for the snow density along the track are the snow temperature (which varies with elevation), fracture depth and the snow density of the release area.

## 7. PROPOSAL FOR SNOW TEMPERATURE AND SNOW DENSITY FOR SIMULATIONS

Based on our findings in Chapters 4 to 6, we propose the snow temperatures (for release area) and snow densities (function of slope angle of upper area) outlined in Table 3 for use in powder snow avalanche simulations. These values pertain specifically to the topmost meter of the snow cover and were particularly applied in the calculation of 10-, 30-, 100- and 300-year avalanches (RAMMS::Extended 2.8.35).

It is important to note that these values are provisional and will be tested further in additional case studies. Snow temperature and snow density have a significant impact on the calculation results; for example, depending on the topography, a temperature difference of just +1°C can result in a runout distance shortening by approximately 100 meters. These parameters are challenging to determine accurately, as their effects vary with terrain conditions.

We have identified case studies where extreme powder snow avalanches occurred under very low temperature conditions. Therefore, in certain cases, it is crucial to consider not only the altitude of the release area but also the snow and weather conditions during the avalanche cycle. For instance, the approximately 100-year Frauentobel avalanche of January 1968 occurred during extremely cold conditions, which would correspond to a snow temperature of around -7°C for such simulations.

| Snow temperature, release area | | | **Release / snow density** (** very steep: upper track > ca. 30°) Swiss Alps [kg/m³] | Snow Temp. Gradient in track (ΔTS) Swiss Alps [°C/100 m] |
|---|---|---|---|---|
| General | Swiss Alps [m a.s.l.] | **Snow temperature** (topmost meter) Swiss Alps [°C] | | |
| Lower altitudes | < ca. 2100 | -5 (-4) | 200 (175**) | 0.3 (0.2-0.4) |
| Medium altitudes | approx. 2100 - 2600 | -6 | 175 - 200 (150**) | |
| Higher altitudes | > ca. 2600 | -7 (-8) | 175 (rarely 200) (150**) | |

Table 3: Proposal for snow temperature and snow density in release areas for powder snow avalanche simulations.

## 8. RELEASE AREAS FOR SIMULATIONS

At the beginning of this section, it is important to acknowledge that even with a scenario-based method for calculating release and entrainment depths, we still face the challenge of determining the size and location of release zones.

In the first step, all unforested areas with slopes between 28° and 55° should be identified as potential zones where natural avalanches can release. Within this zone, the specific release area for the simulation(s) should be determined in the second step, depending on the return period. The choice of the position and size of an avalanche release area depends on various factors, including the shape and structure of the terrain, slope variations, snow distribution, and many other considerations. The location and size of the selected release area have a significant impact on the calculation results.

We strongly recommend initially conducting dense flow avalanche calculations using RAMMS::Avalanche to verify the release area. Back-calculating a specific runout, as documented in the avalanche cadastre (e.g., a 30-year avalanche), is a commonly used procedure that aids in determining the location and size of potential release areas. With the calculated fracture depth ($d_0$), the corresponding release volume, and associated friction values, the observed runout should align with the simulation.

The identified release area can then be utilized for powder snow avalanche simulations, such as those conducted in RAMMS::Extended.

## 9. CASE STUDY

We have tested the scenario-based approach on many avalanches. Fig. 5 shows the core velocity of the 300-year Bergtälli avalanche near Malbun, Liechtenstein. The powder pressure ($\rho \cdot v^2 / 2$) calculated at the location of the first buildings is 5 kPa (Fig. 6). For the release area at 2180 m we used a fracture depth of 135 cm (based on extreme value statistics of flat field in Malbun), 162’000 m³ as release volume, a basic value of 135 cm for the erodible snow (Fig. 2), -6°C as snow temperature and a density of 175 kg/m³. The calculated avalanche run out corresponds very well with the current hazard map (300 years).

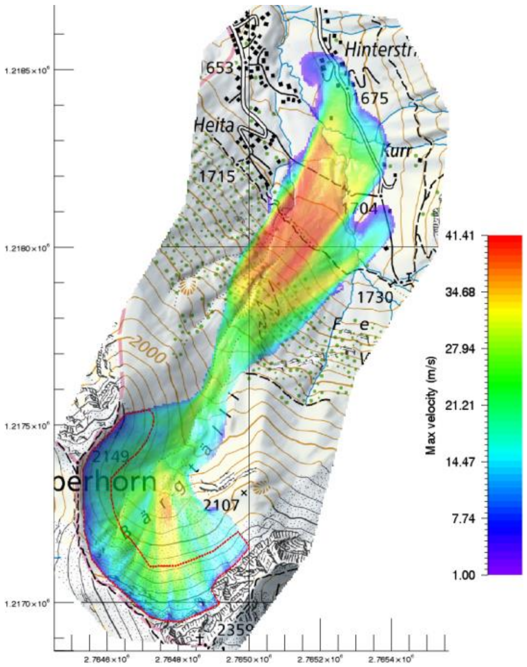


Fig. 5: Core of the 300-year Bergtälli avalanche in Malbun with a maximum velocity of 41 m/s.

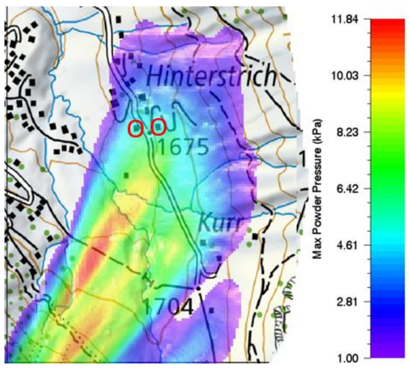


Fig. 6: Maximum powder pressure: 5 kPa at first houses (red circles).

Additionally, a well documented case study is shown in the paper "Large powder snow avalanches in South Tyrol in January 2019: Comparison with scenario-based avalanche simulations" (Oberschmied et. al, 2024) in these proceedings.

## 10. CONCLUSIONS

For engineering purposes, it is often necessary to analyze powder snow avalanches with a specific return period. These studies are frequently conducted in areas where large powder snow avalanches have previously occurred, causing damage to forests, infrastructure, buildings, or power lines. It is crucial that the model results align with the observed damage. However, key information such as fracture depths, release volumes, eroded snow in the avalanche track, snow temperature, snow density and friction is often missing for such large events.

To address this, we have developed a scenario-based approach. The approach is based on the existing SLF procedure for dense flow avalanche calculations (steps 1-4):

1) Choice of avalanche return period; 2) Choice of release area; 3) Determination of fracture depth $d_0$; 4) Choice of friction category.

This procedure is well-established and practical for engineering offices engaged in snow hazard mitigation. Then, we presented our proposal to continue with the steps 5-8 to simulate powder snow avalanches:

5) $d_0^*$ as basic value for erodible snow (28° slope); 6) Determination of snow temperature (release area); 7) Determination of snow density (upper area); 8) Elevation gradients for snow temperature ($\Delta T$) and erodible snow ($\Delta d_0^*$) along the avalanche path. The proposed values are based on measured data, but it is important to note that these are provisional values, subject to further testing in additional case studies.

We also explored methods for determining the location and size of the avalanche release area. As with all simulation models, the choice of the release area significantly influences the simulation results. Other important input parameters include friction values, defined as $\mu_0$, $\xi_0$, and cohesion, all of which depend on the release volume and return period.

Finally, it is essential to emphasize the uncertainties inherent in avalanche calculations, particularly regarding boundary conditions such as snow amounts and temperature. Our approach integrates both numerical and analytical solutions to account for these uncertainties, providing a robust framework for snow hazard analysis.

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