Field observations, full-scale tests, laboratory investigations and numerical modelling of snow avalanches in Switzerland

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Abstract: There are still many unresolved questions in snow avalanche dynamics. This was apparent during the catastrophic avalanche Winter of 1999. In this paper we overview on-going avalanche dynamics research at the Swiss Federal Institute for Snow and Avalanche Research. Field observations, full-scale tests and laboratory investigations are used in combination graphical information systems and numerical modelling to improve our understanding of the basic physical processes in both flowing and powder snow avalanches. Present research topics include mass balance and snow cover entrainment, avalanche release frequency, granular flow dynamics, powder avalanche initiation, avalanche interaction with defense structures and numerical modelling of mixed avalanches from initiation to runout.

Keywords: flowing avalanches, powder avalanches, chute experiments, optical velocity sensors, capacitance density probes, velocity profiles, radar, mass balance, snow cover entrainment, numerical modelling.

1. Introduction

A sound knowledge of snow avalanche dynamics is fundamental to develop efficient protection methods against avalanches. Both land planning (hazard maps) and passive defense measures (snow sheds, deflecting dams, breaking mounds) require estimating avalanche runout distances, flow velocities and impact pressures. The increasing demands for information and basic methodologies (models) requires a basic understanding of the flow dynamics of both flowing and powder avalanches.

The evaluation of the avalanche winter 1999 in Switzerland revealed the as yet unanswered questions of avalanche dynamics (Gruber, 2000a and 2000b). In particular:

a) better estimating the size and fracture heights of avalanche release zones.
b) the conditions of powder cloud formation or the vertical density and velocity profiles within the powder avalanche.
c) the interaction of dense and powder avalanches with defence structures and the dependence of the impact forces on the flow velocity and density.
d) the influence of entrainment and deposition processes on avalanche motion. As a consequence of the avalanche winter 1999 the avalanche dynamics team of the Swiss Federal Institute for Snow and Avalanche Research intensified the effort to collect data from real scale avalanches.

At Vallée de la Sionne avalanche test site (Ammann, 1999) a 20 metre high pylon was equipped with new measurement devices to determine the avalanche velocity, density, flow height and pressure. Experiments at a 34 meters long chute were performed to determine avalanche velocity profiles. Photogrammetric, radar and manual techniques allowed the determination of the avalanche mass of numerous avalanches.

On the basis of the collected information a new mixed numerical model with entrainment was developed.

2. Internal flow velocity and density profiles

2.1 Optical Sensors

To measure the vertical velocity profile inside the avalanche we installed optical sensors on the 20 metre high pylon of the Vallée de la Sionne test site. A new generation of optical sensors based on the design originally proposed at Montana State University (Dent 1997) was developed. The optical sensor consists of three photo diode/photo transistor pairs. The photo
diode emits infrared light and the photo transistor detects the reflected infrared light. If a reflecting object moves over the sensor, the photo transistor supplies a voltage signal as a function of the intensity of the reflected light. Using a band pass filter, only the intensity variations are recorded by our data acquisition system. These three photo diode/photo transistor pairs are built in flush to the side of the pylon. When an avalanche flows past the optical sensor, each pair gives a voltage signal as a function of the instantaneous internal structure of the avalanche. Due to the fact that the internal structure of the flow is constant over a certain (small) distance, the output signals of each pair are similar but time shifted by

\[ \Delta t = \frac{s}{v}, \]

where \( v \) is the flow velocity and the \( s \) spatial distance between two pairs. For the analysis a cross correlation function

\[ S(\tau) = \int_{\text{window}} A(t) \cdot B(t + \tau) \, dt \]

is formed from the sensor output \( A(t) \) and \( B(t) \) of two pairs and this function peaks at \( \tau_{\text{max}} \) which is the time shift between \( A(t) \) and \( B(t) \). Hence the flow velocity is

\[ v = \frac{s}{\tau_{\text{max}}}. \]

\[ I \]

Figure 1: Velocity measurement with optical sensors on a small Vallée de la Sionne avalanche on the 2nd of March 2001.

To obtain a vertical velocity profile of the avalanche optical sensors of the described type are installed at six different heights on the pylon from 1.5 meter to 7.5 meter above ground. With this arrangement of sensors we are able to measure the velocity of both the dense and powder part of the avalanche. A point of interest is also the transition of the velocity between the dense to the powder part (see Fig. 1).

2.2 Density Measurements

To measure the snow density within an avalanche we use capacitance probes mounted, as for the optical sensors flush to the side of the pylon. This technique has been developed by Michel Louge (1995 and 1998) from Cornell University. In Figure 2 there is a schematic diagram of the measurement principle of these capacitance probes.

There is an electric field formed between the sensor plate and the ground plate which are separated by the guard. The guard voltage is always kept on the same value as the sensor voltage to avoid stray capacitances which would reduce the sensitivity of the probe. Also the shielding of the coaxial cable between sensor and amplifier is on the guard voltage so that there are also no stray capacitances in the cable.

\[ I \]

Figure 2: Measurement principles of the capacitance density probes. The ground plate is part of the side of the pylon.

If snow is flowing over the sensor, the capacitance of the of the probe rises because there is a dielectric material between sensor and ground (see Fig. 2). The effective dielectric constant of snow

\[ \epsilon_e \equiv \epsilon' - j \epsilon'' \]

exhibits a real and an imaginary part \( (j^2 = -1) \). The modulus of the effective dielectric constant is obtained by the voltage ratio

\[ \frac{V_0}{V} = \sqrt{\epsilon'^2 + \epsilon''^2}, \]

where \( V_0 \) is the rectified probe output in air and \( V \) the output in the presence of snow. To measure both components of the effective dielectric constant (Louge, 1997) determined the phase lag \( \Phi \) between the guard voltage and the reference oscillator of the processing
electronics. Using amplifiers of the company Capacitec\textsuperscript{1} we have

\[ |\tan \Phi| = \frac{\varepsilon''}{\varepsilon'}. \]

The capacitance probes we use are run with an oscillator frequency of 16 kHz. In this frequency range the function \( \varepsilon_r(p) \) depends also on the microstructure of the snow. Thus, we need to calibrate the capacitance probe to the actual snow conditions using a snow press as described in (Louge, 1997).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{As the optical sensors for measuring the avalanche velocity, the capacitance density probes are integrated flush to the side of the pylon. The electronics of the optical sensors and the capacitance density probes are located behind the aluminium plates.}
\end{figure}

In the Vallée de la Sionne avalanche test site two types of capacitance probes are installed: one probe to measure the density of the flowing part of the avalanche and one for the powder part. The difference between the two types is the geometry of the probes. The one for the powder part has a much bigger measurement volume because the densities of the powder cloud are smaller than the density of the dense part. To achieve a comparable sensitivity of the probe, the measurement volume of the powder probe must be increased (see Fig. 3).

2.3 Relation between pressure density e velocity

On the front side of the pylon in Vallée de la Sionne nine pressure sensors are installed on different heights, from 1.5 meters to 10 meters above ground. Another one is mounted at the top of the pylon at a height of 19 m (Schaer, 2001) (see Fig. 4). The comparison of the pressure data with the speed profiles and density profiles should allow the important correlation between these three parameters. Although pressures have been recorded, to prove the correlation between density, velocity and pressure more data must be collected.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.png}
\caption{On the front of the pylon there are mounted impact pressure sensors on different height with different diameters (from 5 cm up to 25 cm).}
\end{figure}

2.4 Chute experiments

In the following, experiments on the Weissfluhjoch snow chute are briefly outlined. The Weissfluhjoch chute was built in the early 1960ies for impact force measurements (Salm, 1964 and Issler, 1999) and is located 2663 m a.s.l. beside the old SLF building at Weissfluhjoch, Davos.

The chute was partly destroyed by extraordinary large snow loads during the catastrophic winter 1999/2000. In the time from 2000-2002, the chute was reconstructed and equipped with optical velocity sensors (see § 2.1) and a basal friction measurement system. The chute has a total length of 25 m and is 2.5 m wide. Its inclination can be varied between 35° and 45°. Up to 25 m\textsuperscript{3} of snow can be stored in the upper part of the chute and be released by opening the release gate.

\textsuperscript{1} Capacitec, PO Box 819, 87 Fitchburg Road, Ayer, MA 01432, USA
In order to achieve a turbulent, avalanche-like flow of the snow in the chute, the bottom is roughened by rubber bars. The rubber bars cover the lower part of the chute and are collectively linked to piezoelectric force sensors to get an idea of the basal friction forces.

The motivation for the large scale chute experiments is, on one hand, to have the possibility to examine the internal flow structure of reproducible avalanche-like snow flows, and, on the other hand, to clear the question of how far real avalanche flow problems may be scaled down to granular model flows with similar Froude numbers. The validation of scaling laws is important when studying the interaction of snow avalanches with breaking structures. (Hákonardóttir, 2001 and Hákonardóttir, 2002). Another important application of the experimental chute, is to test newly developed measuring techniques (velocity and density sensors, radar) on real snow flows, before they are placed in the field.

Figure 5: Side view of the chute lifted up to an inclination angle of 45°.

The velocity profiles measured by a linear sensor arrangement perpendicular to the flow direction at the side wall of the chute are similar to the ones found in little real snow flow avalanches (Dent, 1997). This is a hint to the chute being an appropriate instrument to generate reproducible avalanche-like snow flows. An example of velocity profiles measured on the chute is provided in Figure 6.

Furthermore, measurements on the effectiveness of different shaped dams and retarding structures were performed on the chute. The effectiveness of the structures was derived from the analysis of snow flow velocities in front of and behind the breaking structures.

Summarizing, the Weissfluhjoch chute is a powerful tool to generate reproducible, avalanche-like snow flows, which are analyzed with respect to the internal snow flow structure to get an idea of possible constitutive laws governing the snow flow behaviour. A better knowledge about the constitutive behaviour of flowing snow will be an important step towards more realistic numerical modelling of snow flow avalanches.

Figure 6. Example for the time evolution of velocity profiles.

3. Avalanche mass balance

3.1 Avalanche mass balance

At present, measurements along the avalanche path are the only possibility to determine mass and volume variations in flowing avalanches. This information is collected by means of field measurements and/or using more sophisticated but not necessarily more precise techniques such as photogrammetry or orthophoto analysis.

Field measurements allow only the avalanche mass to be determined. However, it should be observed that not only the avalanche mass is important but also its distribution inside the avalanche can substantially modify the avalanche dynamics.

Therefore, additional measurements are collected to find the distribution of the avalanche mass. A representative parameter concerning the avalanche mass distribution has been obtained by measuring the avalanche flow depth distribution.

For flowing avalanches, the entrainment process is mainly controlled by the interaction between avalanche and snow cover. The avalanche mass variation is related to the forces exerted by the avalanche on the snow cover. These forces control the erosion rate, the entrainment location and influence the avalanche motion. To achieve information about this process radar techniques and field experiments have been used.
3.2 Avalanche mass

The techniques used for determining the avalanche mass are divided into two main sections: a) Field measurements and b) Photogrammetric measurements.

In general, field observations allow a more detailed and accurate definition of the avalanche mass but they require a large amount of manual work in very difficult conditions. This analysis is suitable for small avalanches where the average volume is of the order of few thousand cubic meters and where safety condition allow the avalanche path to be entered (for detailed information see Sovilla (2001)).

For large avalanches, where the avalanche volume can reach millions of cubic meters, photogrammetric techniques are used. This technology has two main advantages: measurements can be performed without entering the path and very large areas and volumes can be mapped without much effort. On the other hand, all information concerning the snow cover i.e. stratigraphy, densities, etc., can not be collected with sufficient detail, as in the manual method. A second problem is due to the difficulties in applying the photogrammetric method to a snow surface.

![Diagram of avalanche track and deposition profile](image)

Figure 7: Catastrophic winter 1999. Jungstafel avalanche. Release area, perimeter and deposition of the avalanche of the 22nd of February 1999 are shown. Deposition depth and snow depth in the avalanche track along five profiles are determined by photogrammetry.

When the snow cover contrast is not well defined (i.e. the avalanche boundaries have a white over white definition) the error can invalidate the measurements. For this reason, only fragmentary information is obtained (for detailed information see Vallet (2001)).

A third technique is the ortophoto analysis. Using this technique the mass of an avalanche can not be determined. However, additional information about release boundary conditions, avalanche width along the path, deposition contour etc. can be defined on the geo-referenced picture, providing an useful tool for the determination of additional avalanche characteristics.

During the winter 1999 photogrammetry data of catastrophic avalanche were collected. Fig. 7 shows a data example. The analysis of the measurements showed that there were avalanches able to erode a snow cover depth, over all the potential erosion area, larger than the release fracture depth. This is likely to happen when the dry low density snow condition favours the erosion process.

On the other hand, there were avalanches for which erosion had a small influence. In this case the high snow water content strongly limited the process. However, it is observed that higher values of the entrainment can be expected, i.e. even longer runout distances, for dry snow conditions along the whole path.

3.3 Distribution of the mass in the avalanche

A representative parameter concerning the avalanche mass distribution is obtained measuring the avalanche flow depth distribution. In the last years measurements have been performed using flow the depth sensors and FMCW radars (Gubler, 1984 and Dawes, 1999).

Figure 8 shows two examples of FMCW radar output. In the figures, the amplitude of the signal reflected from different heights in the avalanche is plotted as a function of time on a three-dimensional intensity plot. A graph relating flow heights and intensities is obtained.

3.4 Avalanche/ snowcover interaction

The avalanche mass and its distribution is strongly related to the interaction between avalanche and snow cover. The location where the snow cover is entrained into the avalanche, the quantity of mass that the avalanche erodes, the force that the avalanche exerts on the snow cover and the resistance the snow cover offers to this force are all factors that modify the avalanche dynamics.

Part of this information, i.e. the entrainment location and the quantity of entrained snow, is determined by analysis of the FMCW radar plots whereas, attempts to measure shear and normal forces exerted by the avalanche on the ground, i.e. snow cover, have been performed without any valuable results. Information about the mechanical properties of the snow cover helps to overcome the problem.

Investigation of the entrainment location can be performed with FMCW radars. Fig. 8 at the bottom-left shows the interaction between avalanche and snow cover. These events were measured at the Vallée de la Sionne test site on the 21st of February 2000 and on the 29th of December 2001. Analysis of different FMCW
measurements shows that front entrainment processes appear to dominate over basal erosion. Our observations are that avalanches tend to dive into the snow cover and slide over a more resistant and older layer or on the ground. A frontal impact between the avalanche front and the snow cover takes place and the avalanche collects all the snow immediately at the front. This process is often referred to as "ploughing". However, it has also been observed that, avalanches flow on a hard resistant layer within the snowcover. It has been conjectured that avalanche scrapes mass from the surface in a process termed "basal erosion".

Figure 8: FMCW radar plots. Measurements collected at the Vallée de la Sionne test site. The avalanches of the 21st of February 2000 (top) and of the 29th of December 2001 are shown.

The radar data can be correlated to the snow characteristics by field measurements. Field measurements are performed after each event in order to collect as much information as possible on the snow cover characteristics and mechanical properties. In particular layering, grain size, shape and density of the snow cover are collected. Ram profile are performed too.

4. Avalanche release frequency

In paragraph 3.2 different methods to measure the avalanche mass were explained. Concerning the release mass of an avalanche, two parameters are important: the release area and the fracture depth. The ortophoto analysis is a valid technique to determine the release area, but not always it's possible to get these pictures. A try to overcome this lack is to perform an accurate analysis of the topography to find general rules for the definition of potential avalanche release areas. The idea is to work out an automatic procedure to define potential release areas and link them to topographic features. This procedure is applied in the region of Davos, where an almost complete database of avalanche events during the last 50 years is available. Using Geographic Information System (GIS) technologies in combination with Digital Elevation Models (DEM), all avalanche release areas have been analysed with respect to topographic characteristics. Topographic parameters like “distance to the next ridge”, “slope”, “confinement” and “aspect in relation to the main wind direction” are derived from the DEM and from meteorological observations.

The statistical analysis results in general rules and probability distributions for release extents as a function of the frequency and the topographic parameters. The general rules are a valuable aid for the avalanche experts in cases where information about historic avalanche is lacking for a particular track. Furthermore, the probability distributions can be directly used as input for uncertainty modelling of avalanche run-out distances by Monte Carlo methods. In the avalanche winter of 1999 (in the European Alps), the latter topic has been shown to be very important for the further improvement of avalanche hazard maps and for the risk assessment of avalanche hazard in general.

5. Avalanche modeling

5.1 AVAL-1D: A model for avalanche practitioners

The Voellmy-Salm model has been traditionally used in Switzerland to prepare hazard maps. This model is now being replaced by a numerical model that tracks avalanche motion from initiation to runout. The model is called AVAL-1D and is now widely used in Switzerland, Austria and Italy (Christen, in press.). Similar to the Voellmy-Salm model, AVAL-1D combines a dry Coulomb-like friction with a Chezy velocity-squared dependent drag (Bartelt, 1999). The numerical model has been extensively validated by back-calculating many historical avalanches, including many large events from the Winter of 1999. However, the model does not include important effects such as snowcover entrainment.

5.2 A mixed flowing/powder snow avalanche model
A new generation of avalanche model is being developed which includes four main interacting components: the snow cover; the dense flowing avalanche; the powder cloud and a turbulent wake, which together comprise a "mixed" avalanche. In order to understand the dynamics of the constituent parts, it is important to first understand the mass transfers between them. Each of these processes is modelled separately and each model requires careful calibration and validation. This can only be achieved with experiments and investigations on real and laboratory scales.

The significant mass fluxes can be summarised as follows:

a) Snow cover entrainment into both the dense and powder parts (see §3.2).

b) Suspension of mass from the dense core creating a powder cloud. The precise mechanism by which this occurs is not well understood. A combination of factors including shear, turbulent fluctuations over the dense flow surface and aerodynamic lift could all play a role.

c) Entrainment of ambient air into the powder cloud. The powder cloud can be described as a particle-driven gravity current, other examples of which include pyroclastic flows and sediment-laden turbidity currents (Simpson, 1997). The entrainment of ambient fluid into such flows has been a subject of investigation for some years, though the adaptation of these results to powder snow avalanches poses problems. Both the high density ratio between the suspension and the ambient air and the significance of slope angle should be incorporated into the model.

d) Transfer of mass from the powder cloud to the mixed, diffuse turbulent wake. This process is described in terms of a "critical density": if the density of a region of powder cloud drops below a critical value it is assumed that this region no longer plays an significant role in the dynamics of the avalanche and is transferred to the turbulent wake. The wake is the low density, highly mixed region of a powder avalanche with no translational velocity.

e) Deposition of mass from the dense flow and from the turbulent wake.

Once the mass of the component parts is understood, momentum equations describing the dynamics can be written for each.

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6. Conclusion

As a consequence of the avalanche winter 1999 the avalanche dynamics team of the Swiss Federal Institute for Snow and Avalanche Research intensified the effort to collect data from real scale avalanches. In addition, laboratory and snow chute experiments have been performed. The collected data allowed a better understanding of avalanche physical processes and the develop of new numerical models taking into account many of the processes presented in this paper.

7. References


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