Avalanche dynamics: On-site studies, modeling and practical applications

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Summary

Im dritten Winter des Projektes wurden ca. 70 Lawinen in der Umgebung von Davos (mehrheitlich im Parsenngebiet) kartiert und neun kleine bis sehr grosse Ereignisse detailliert untersucht. Schon bei kleinen Lawinen konnte oft ein eklatanter Unterschied im Fliessverhalten des fluidisierten Lawinenkopfes und des dichten Körpers festgestellt werden. Anhand der Spuren an Bahnbiegungen konnte in zwei Fällen abgeschätzt werden, dass der Kopf doppelt so schnell floss wie der Körper, in Übereinstimmung mit neueren Radarmessungen aus Norwegen. Die Beobachtung einer gefrorenenen Gleitschicht in manchen Lawinen lässt Rückschlüsse auf die Energiedissipation zu, doch bleiben manche Fragen offen. Die statistische Auswertung der Beobachtungen bestätigte teils bekannte Trends für grössere Lawinen (positive Korrelation zwischen Auslaufwinkel und Sturzbahnneigung), widersprach aber der Erwartung, dass grössere Lawinen kleinere Auslaufwinkel haben. Die theoretischen Arbeiten konnten nur in bescheidenem Umfang weitergeführt werden. Die geomorphologischen Untersuchungen führten auf im Feld anwendbare Charakterisierungsmethoden der lawinenrelevanten Eigenschaften des Geländes, doch konnten bisher keine klaren Zusammenhänge zwischen der kleinräumigen Morphologie (insbesondere der Geländerauigkeit) und der Lawinendynamik ermittelt werden.

During the third project winter approx. 70 avalanches that occurred in the Davos area (mostly in the Parsenn slkiing area) werre mapped and nine events, ranging from small to very large, were investigated in detail. Even in small avalanches, flow behavior was often found to differ strikingly between the fluidized head and the dense core. From scour marks at bends it could be estimated in two cases that the head flowed about twice as fast as the body, in agreement with recent Doppler radar measurements from Norway. Frozen gliding surfaces found in several avalanches allow certain conclusions as to the energy dissipation, but many questions remain open. Statistitcal analysis of our observations in part confirmed known trends in case of relatively large avalanches (such as a positive correlation between the runout angle and the track inclination), but contradicted the expectation that the runout angle decreases with avalanche size. The geomorphological investigations led to methods for characterizing the terrain properties that are relevant to avalanches and that can be applied during field work. However, no clear connections between the small-scale morphology (particularly the terrain roughness) and the dynamical behavior of avalanches has yet emerged from this work.

Abbreviations

A.E.	Alessia Errera (Università degli Studi di Milano – Bicocca)
B.K.	Bernhard Krummenacher (GEOTEST AG)
B.T.	Bernardo Teufen (tur GmbH)
H.G.	Hansueli Gubler (AlpuG GmbH)
D.I.	Dieter Issler (NaDesCoR)
S.P.	Stefano Priano (Università degli Studi di Milano – Bicocca)

Field work (A.E., H.G., D.I., B.K., S.P., B.T.)

The winter 2005/2006 in Davos was characterized by snow quantities above average and unstable snow cover structure throughout most of the winter. This led to a large number of avalanche events in many locations, with several locations releasing more than once, especially where artificial release is used as a security measure. A number of snowfall periods from mid-December through mid-April led to mostly dry-snow avalanches up to March and produced mainly wet-snow avalanches thereafter.

Generally, this winter was much more suitable for the purposes of the project than all previous ones. However, it also posed its own problems: (i) The considerable avalanche hazard that persisted well over the snowfalls made it often unsafe to access the starting zones, so important information on the initial conditions of the observed avalanches had to be crudely estimated. (ii) Large numbers of avalanches released approximately at the same time, often followed by lesser snowfalls and strong winds. Therefore only a limited number of deposits could be investigated in detail, as the traces of other avalanches were lost in a comparatively short time.

A first brief survey of the Parsenn skiing area with an introduction of the students A.E. and S.P. to the field methods was conducted on December 19, following the first substantial snowfall period that produced avalanches. Due to time limitations, no detailed investigations were possible then. A.E. and S.P. began regular surveying in mid-January, other members of the project team joined them in the work on selected avalanche deposits. Many of the investigations required digging deep trenches, sometimes a chain saw was required to cut through the extremely hard and compact deposits. The last field survey was made in mid-April. Due to a leisure-related accident of S.P. in the first half of March and the limited alpine experience of A.E., we had to abandon our plans for preparing a suitable path with different kinds of tracer particles and then releasing an avalanche artificially to study the mixing processes inside the flow.

The main observations concerning dry-snow avalanches can be summarized as follows:

- Vestiges of fluidisation were found in a significant number of events, both small and large. All large dry-snow avalanches developed a fluidised part at the head, but it was not readily apparent why some of the smaller events would fluidise but not others that took place under very similar conditions.
- It could be determined in one very large, one medium-size and one small avalanche that the fluidised head was significantly faster than the dense body of the avalanches. This corroborates measurements from the experimental test sites at Vallée de la Sionne and Ryggfonn.
- Three medium-size avalanches of very similar length and run-out angle exhibited deposits of the fluidised part that ranged from less than 1% to about 25% of the total deposit mass. This suggests that fluidisation depends critically on the flow parameters in the practically interesting range—an important fact for modelling.
- The largest avalanche of the winter (accidentally released by snowboarders!) developed a significant powder-snow part that was experienced first-hand by several persons and even photographed. In two other medium-sized avalanches trees in the run-out zone showed traces of a developing suspension layer. There may have been other cases of incipient suspension layers, but only if the avalanche reached forested areas were we able to detect them.

- As in previous winters, most of the observed avalanches (46 out of 56 events) showed clear signs of snow entrainment along at least parts of their path. In the remaining cases, entrainment was likely but not unequivocally verified. Estimated entrainment depths ranged from 25 to 100 cm. One may conclude that entrainment is not as much linked to the size of the avalanche as it is to the snow conditions.
- In most medium to large avalanches, a hard layer formed the base of the deposits. Its thickness ranged from 1 cm to more than 10 cm and typically grew with avalanche size, and it was found more often in the central parts of the flow than on the sides. Such layers had been found at the gliding surface of wet-snow avalanches in the preceding years, but occurred in dry-snow avalanches in 2006. They are best interpreted as the result of localized snow melting in the most rapidly sheared bottom layer of the flow, followed by refreezing after the avalanche had passed. For smaller avalanches, it could not yet be determined why some would develop a hard layer and others would not under apparently similar conditions. This phenomenon can be used to estimate the energy dissipation rate in the shear layer.

In one medium-to-large avalanche that approached Sertig Dörfli in mid-February, topsoil was entrained in a single, limited area of about $10{\times}5\ \mathrm{m}^2$. The eroded quantity was small, but could be clearly detected in the deposits. The most distal 30–40 m of the deposit tongue were free of soil, and nearly so were the deposits that we observed on the slope below the erosion patch. Most of the material was found within about 30 m from the foot of the slope and a little upslope where deposits had piled up. Its distribution across the depth of the deposit was more or less uniform. Several conclusions can be drawn for this specific avalanche, which are likely to have more general validity for dry-snow avalanches:

Soil erosion did not occur at the very front of the avalanche, presumably because the snow cover had to be eroded first. This observation contradicts the plough-like entrainment mechanism favoured by Sovilla (2004) on the basis of FMCW radar measurements at Vallée de la Sionne. However, interpretation of those data is not unambiguous and the rapid but gradual erosion apparent in the 1999 radar data (Gauer and Issler, 2004) agrees with our observations.

Mixing was strong throughout the avalanche, as an essentially uniform distribution throughout the entire depth of the deposits was achieved after no more than 200 m. The tapering of the soil concentration at the distal and proximal ends of the “dirty” part of the deposit may in part also be attributable to mixing.

The tail of the avalanche did not erode significant quantities of soil, either because the soil strength increased with depth or because the bottom shear stress of the avalanche diminished. We cannot exclude the first possibility because sunshine, water seepage and refreezing may have changed the properties of the exposed soil between the event and our investigation, but the second explanation is favoured by the low velocities in the avalanche tail observed in other events of similar type.

A fortunate coincidence made these observations possible, which tell much about the internal dynamics of dry-snow avalanches. Our inferences corroborate conclusions and conjectures from earlier measurement data, indicating that they might be quite generally valid for this type of avalanche. The usefulness of such data also suggests carrying out experiments where different kinds of suitable tracer particles are placed at different locations and at different depths in the snow cover of an avalanche path before an avalanche is artificially released.

Fig. 1. Powder snow avalanche released by snowboarders on 10 March 2006 , photographed just before reaching the farm at Chaiseren, Dischma Valley, Davos. Photo Annette Laubscher, 4574 Nennigkofen.

Data analysis (A.E., S.P., D.I.)

All collected data were entered in a large spreadsheet for statistical analysis and also introduced as attributes in a geographical information system (GIS) for visualization. Comparison of the data shows immediately that the mean run-out angle of the observed dry-snow avalanches (30°) is about 5° less than that of the wet-snow avalanches in our sample (35°), the spread being somewhat larger in the latter. This corresponds to expectations, but it should be noted that wet-snow avalanches can sometimes have very low run-out angles. Accordingly, further analyses distinguished between these two types of avalanches.

Correlation analysis: The degree of correlation between pairs of measured parameters was studied first. The main results were the following:

- For each avalanche type (dry/wet) separately the run-out angle was independent of the drop height, but the combined sample of wet and dry-snow avalanches showed the run-out angle to decrease markedly with increasing drop height, due to the bias in our data towards small wet-snow avalanches. Interestingly, wet-snow avalanches showed the run-out angle to decrease rapidly with increasing run-out distance.
- For dry-snow avalanches only, the release depth decreased with increasing steepness of the release area.
- For either type of avalanche, the run-out angle diminishes markedly with increasing release depth, but there is a large scatter in our data.
- For dry-snow avalanches only, the probability of fluidising or of forming a hard layer increased strongly with increasing release depth. No traces of fluidisation and too few indications of a hard layer were found in wet-snow avalanches for a valid statistical interpretation.

Our data from a single winter in a restricted area are potentially too strongly biased for far-reaching conclusions to be drawn. Nevertheless, the results of this analysis show that a very valuable stock of relationships between readily observable quantities and important dynamical parameters of avalanche flow could be obtained if the study were extended over several years in the same area and repeated in areas with different topographical characteristics and different climate. Such data could also be used for practical problems where a quick estimate of avalanche properties under given conditions is required before detailed numerical simulations can be made.

Analysis of the flow dynamics: In two cases (medium-to-large avalanche in the Rüchitobel/Dischma, 18.01.2006; small avalanche near Kreuzweg/Parsenn, 22.01.2006) the avalanche path had significant bends that showed clear flow marks on the outer side. In both cases, the dense part remained clearly channelled in the bend, with no indication that it had climbed to any significant height on the outside wall. In contrast, the Rüchitobel avalanche showed traces of the fluidized part 10–15 m above the gully floor on the outside but less than 5 m on the inside. The fluidized part of the Kreuzweg avalanche went in an almost straight line over an approximately 6 m high terrain shoulder obstructing the path while the dense part had to go around it. Assuming reasonable values for the effective friction coefficient, a minimum velocity of about 15 m/s is required for going over the shoulder whereas the location and inclination of the dense-flow deposits are compatible with a speed of approximately 7 m/s. From the superelevation of the flow traces, the speed of the dense part of the Rüchitobel avalanche was at most 19 m/s whereas the fluidised part flowed at a speed of at least 30 m/s at the location of the bend.

For the large Dischma avalanche on 09.03.2006 no gully bends could be used for determining the speed, but near its south-eastern margin the dense part stopped on the slope before plunging into the deep incision of the Dischma river whereas the fluidised part went across the river and climbed approximately 20 vertical meters on the steep opposite slope. This indicates a speed of the fluidised head at the river in the range 20–25 m/s.

In a second part of the MSc theses of A.E. and S.P. several of the observed avalanches will be back-calculated with AVAL-2D from SLF and the two advanced avalanche models developed in the SATSIE project, namely MN2L (from CEMAGREF, France) and D2-FRAM (from NGI, Norway).

Theoretical work (D.I.)

Little time could be devoted to model development and theoretical investigations in 2006 because the field work in this avalanche-rich winter used up most of the credit attributed to D.I. and much of the working time he could devote to the project. A draft paper on general aspects of entrainment in depth-averaged gravity mass flow (GMF) models was extended by adding a section on the conceptual differences between entrainment and deposition. The paper will be submitted to *Natural Hazards and Earth System Sciences* (NHESS) in February 2007.

Further work concerned the correct formulation of depth-averaged GMF models in complex topography with significant surface curvature. Most present models neglect these effects and the few remaining ones assume the curvature radius to be large compared to the length and width of the avalanche. This condition is often not met in practical situations. Using the methods of differential geometry, it was shown that the extra terms due to the terrain curvature are source terms containing the dynamical fields and the Christoffel symbols obtained by using curvilinear coordinates following the terrain. Exceptions occur if the constitutive relationships contain derivatives of the fields. In practical implementations, great care must be taken to evaluate a host of curvature and flow-height dependent coefficients in the most efficient way possible. It is planned to submit a paper to *Computers & Geosciences* in early 2007.

Know-how transfer (D.I., B.T.)

The project website (http://www.tur.ch/nfp/index.html) has been enhanced by reports on the avalanches observed during the winter 2005/2006. Furthermore, the lecture notes on powder-snow avalanches and their modelling, presented by D. Issler at the course “Valanghe: dinamica, zonazione di pericolo e sistemi di difesa, Modulo 1" organised by SUPSI (Scuola Universitaria Professionale della Svizzera Italiana) and SLF in Rodi-Fiesso (TI) from June 16 to 18, 2005, was made accessible on the website in early 2006.

It was planned that D.I. would participate in the advanced European Summer University course on snow avalanche modelling in September 2006, to be organized jointly by the SATSIE consortium (http://www.leeds,ac,uk/satsie) and the Pôle Grenoblois d‘Etudes et de Recherches pour la Prévention des Risques Naturels (http://www.risknat.org). However, due to financing problems of the organisers, this course had to be postponed to 2007.

We did not succeed in finishing the vademecum of extraordinary avalanche events because the compilation of the data, the description of the events, their modelling and drawing appropriate conclusions for practitioners is time-consuming and was not possible with our time budgets strained by the intensive field work during the winter. However, the case studies already compiled are made publicly available on the project website.

Contributions by project participants in 2005

Name	**Activity**
Dieter Issler	Field campaigns and corresponding reports Analysis of entrainment process, study of avalanche flow on curved surfaces (in coordination with EU project SATSIE) Project administration Supervision of MSc theses of A. Errera and S. Priano
Hansueli Gubler	Field campaigns and equipment Supervision of A. Errera and S. Priano
Bernardo Teufen	Field campaigns, advising students on safety issues, reports Preparatory negotiations for tests with tracers and articficial release Preparing maps for GIS analysis
Bernhard Krummenacher	Surveying Davos area for released avalanches Geomorphological terrain analysis, including report on results

Alessia Errera	Field campaigns and corresponding reports, analysis of data, GIS representation, MSc. thesis (to be submitted April 2007)
Stefano Priano	Field campaigns and corresponding reports, planning for tracer experiments, MSc. thesis (to be submitted November 2007)

Summary of publications

Given the incomplete status of the data analysis and the time constraints at the official end of the project, no publications were ready yet at the end of September. Work continues, however, beyond the project and by the time of writing of this report, the paper on entrainment in gravity mass flow models is ready for submission to NHESS in a substantially enhanced version that treats the subtle differences between mass entrainment and deposition in detail. A copy of the submitted paper is attached to this report.

Outlines for two research papers on the phenomenology and practical implications of the fluidised layer, and on the observation and possible implications of hard basal layers formed by the flow have emerged from the analysis of data from the winter 2006. The paper on the fluidised layer will relate the present work to unpublished earlier observations of three important avalanches. The properties and circumstances of the formation of hard gliding layers will be described in the second paper. In collaboration with researchers from the University of Oslo and the International Centre for Geohazards in Oslo, our observations will be compared to frictionite formation in rock avalanches and their numerical model adapted and applied to snow avalanches. SNF will receive copies of the papers as soon as they will be ready.

Deviations from original workplan

The modified workplan for 2006 was based on the assumption of an average winter. Throughout this extraordinary winter, however, field work had to be carried out by all project participants with high priority. This fact reduced the time available for analysis and interpretation of the data and exhausted the funding allocated to the project leader. Less work than anticipated could be done by A.E. and S.P. during the spring and summer because of required courses for MSc. degree, which had not yet been scheduled when the workplan was drafted. Furthermore, in the course of 2006 the demand from clients for consulting work on geologic, forestry and hydraulic problems was so large that B.T. and B.K. were forced to radically reduce their ambitions in the project. The two main victims of these constraints were the writing of research papers, which was postponed to 2007, and the extension and completion of the vademecum on peculiar and memorable avalanche events. The parts completed earlier will be made available to the public through the project website, which will continue to be accessible and maintained.

Miscellaneous remarks, personnel

Alessia Errera and **Stefano Priano** contributed in a very significant way to the field work from January to April 2006 for their MSc theses with the Department of Geology of the University of Milano Bicocca (supervisor: Prof. Giovanni Crosta). This winter presented a rare opportunity to investigate a large number of different, interesting avalanches, but working conditions were not always easy and safety concerns often limited what could be done. An accident of S.P. outside their working time prevented him from doing field work from mid-March through the end of the winter, but surveying and several detailed investigations could nevertheless be continued thanks to the other participants' efforts. Both students were given an intensive introduction to the field research methods and a number of lectures/discussions on avalanche dynamics. Their efforts to apply geological techniques to the investigation and interpretation of avalanche deposits were interesting and thought-provoking.

In the spring and summer of 2006, work on their MSc. theses was continued, but had to be reduced in intensity because of course work. Reports on specific avalanches were completed and the statistical analysis of the data carried out. They will carry out the concluding work, including numerical simulation of several observed avalanches and the writing of the theses, under D.I.'s supervision in 2007. Afterwards, we plan to write two research papers based on work in this project, as detailed above.