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Field experiments and numerical modelling of mass entrainment and deposition processes in snow avalanches

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Abstract

Natural hazard mitigation strategies underwent a severe test during the winter of 1998/99 when the northern flank of the European Alps was struck by the worst snow avalanche period in over 50 years. Many alpine countries suffered damage and loss of life. In Switzerland, 12 people were killed in Evolène, Canton of Wallis; 38 people were killed in Galtür, Austria. The winter of 1998/99 revealed deficiencies in present hazard mapping procedures.

Hazard maps can be improved by using modern numerical calculation models that predict flow velocities and runout distances of extreme avalanche events. Because the corresponding processes are not well understood, current numerical models contain many simplifications, one of which concerns snow entrainment. Most avalanche dynamics models assume that avalanche mass is constant along the track, hypothesizing that no entrainment takes place. In reality, post-event observations of avalanche paths show that much of the snow cover has been entrained into the avalanche and that deposits are left along the avalanche path.

The aim of this work is to investigate mass entrainment and deposition processes in snow avalanches in order to determine the influence of these phenomena on avalanche motion. The primary goal is to improve hazard mapping procedures.

This work consists of the following parts:

1. *Design of experiments and field measurements.* First, we introduce experimental methods to determine the following: (1) avalanche mass evolution along the path, (2) the mass distribution in the avalanche body and (3) the interaction between the avalanche and the snow cover. The avalanche mass evolution is measured by: in situ measurements, photogrammetric measurements and orthophoto analysis. Avalanche mass distribution is estimated by measuring the avalanche flow depths using flow depth sensors. The avalanche - snow cover interaction, i.e. the entrainment location and the quantity of the entrained snow, is estimated by frequency modulated continuous wave (FMCW) radar. The mass balance of seventeen avalanches was measured.

Experimental data were collected from the Pizzac and Vallèe de la Sionne test sites and at different sites during the catastrophic winter 1998/99. Indices to characterize entrainment and deposition processes in avalanches are defined.

2. *Data analysis and model inference.* A detailed analysis of the seventeen events shows that, on average, these avalanches increased their mass, with respect to the release mass, by more than a factor of four. On average avalanches erode snow down to a depth of two thirds the fracture depth. It is observed that entrainment is primarily controlled by snow characteristics. Snow cover entrainment at the avalanche front appears to dominate over bed erosion at the basal sliding surface. In our modelling approach, the avalanche is considered as a hydrodynamic continuum acting on a solid snow cover. Entrainment processes are formulated in terms of a dynamic stress exerted by the avalanche on the snow cover. It is assumed that the main mechanism responsible for snow entrainment is the impact between avalanche and snow cover, where impacting particles penetrate the snow cover, fracturing snow bonds.

3. *Model implementation and validation.* A one-dimensional, depth-averaged continuum model was modified to consider snow entrainment and different constitutive equations were tested. Flow was described by a Voellmy-fluid flow law and by a modified Criminale-Ericksen-Filbey (NIS) constitutive equation. In addition to the standard input parameters such as release depth, d_0, release area, A_r, and friction parameters, ξ and μ, the introduction of entrainment into the model requires additional parameters such as snow cover depth, d_m, and snow cover strength, p_{lm}. Sensitivity tests of the input parameters on model results (e.g. runout distances, velocities and flow depths) were performed. It is shown that in models with entrainment, the range of friction parameters decreases substantially. Since, the additional parameters d_m and p_{lm} can be measured, the model becomes less empirical. A validation of the model was performed by comparing simulation results with experimental data. Results show that non-entrainment models should only be used for the determination of runout distances and, under certain limits, for frontal speeds. Simulations performed without entrainment strongly underestimate flow and deposition heights. The introduction of entrainment helps to reduce these discrepancies and allows a more accurate simulation of the experimental data. The influence of the entrained mass is important for both large and small avalanches.

4. *Recommendations for practical calculations.* To verify the influence of entrainment

in practical calculations, six extreme avalanches from the winter 1998/99 were back-calculated using the Swiss Guidelines. At present, in practical applications, entrainment is not considered and the mass defined in the calculation is always smaller that in reality. Inclusion of entrainment leads to:

a) A better prediction of runout distances.

b) A more accurate determination of flow and deposition depths.

A simple rule for practical calculations that can help to define the correct avalanche mass is suggested. The avalanche mass can be defined as the sum of the release mass M_{rSG} and the entrained mass M_e. The entrained mass M_e is calculated by considering an entrainment depth over all the potential entrainment area equal to one half of the fracture depth.