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## DENSE AVALANCHE FRICTION COEFFICIENTS

### INFLUENCE OF NIVOLOGICAL PARAMETERS

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**ABSTRACT:** High altitudes, heavy snow, and sharp mountainous relief of Mont Blanc massif make the upper part of the Arve valley (Chamonix, France) one of the most threatened areas by snow avalanches. 115 paths from this area were included in the avalanches national observatory, 26 of them have experienced between 20 and 100 events over a period of almost 100 years, among these avalanches 729 are posterior to 1958. Recently, Météo France reconstructed, for all the French massifs, the daily evolution of the snowpack properties since 1958 producing a consistent data set with available measurements, advanced meteorological models and snow physics. These two data sources were combined to calibrate an avalanche dynamics model including sub models for friction, erosion, entrainment and deposition. First topographic profiles of the 26 well documented paths were built using an accurate laser scan model. Then, the snow conditions were determined from the reconstructed snow packs for each of the 729 avalanches. Finally the full range of friction coefficients was scanned and a numerical simulation was performed for each pair of friction parameters and thus the corresponding run-out altitude determined. Only the pairs of parameters, for which the run out altitude is found close enough to the observed one ( $\pm 5$ m), was retained. Statistical methods such as CPA and stepwise were used to investigate correlations between the obtained friction coefficients and the snow properties. Concerning the static friction coefficient, an increasing tendency with the temperature and the density was evidenced as well as a decreasing tendency with the liquid water content and the snow depth.

#### 1 INTRODUCTION

The propagation of snow avalanches displays highly complex features. Longitudinally, the avalanche is made of a front followed by a core and a tail. The flow may present a strong vertical stratification of velocity and density. In addition, the nivological occurrence conditions and the morphology of avalanche paths vary widely making the avalanche dynamics, and consequently its modeling, a very difficult matter.

#### 2 AVALANCHE MODELING

Despite this complexity several simple models were proposed during the last century to capture the main features of snow avalanches (see Harbitz 1998). The majority has focused on the dense flowing part.

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One of the first models for dense snow avalanche has been proposed by Voellmy in 1955. This one-dimensional model has assimilated the avalanche to a sliding snow block, submitted to the sum of a Coulomb friction and a dynamic drag. This last is proportional to the square of the velocity. Under quasi similar assumptions, several other authors have developed various models that predict velocities along the path and run-outs of the center of mass of the avalanche. To account for the flow depth variations with time and space during an avalanche event, the hydraulic framework has been adopted and a second generation of models, based on depth-averaged hydraulic framework, has emerged. It incorporates the two-parameter friction model of Voellmy and several other terms to deal with erosion and deposition processes and with vertical (active / passive) pressure distribution. In addition to the velocities and run-outs, this second class of models allows predicting the flow depth along the path as well as the depth of the deposit. These models have been developed in one and two dimensional by numerous authors.

The model used in the following concerns the dense avalanche flows and belongs to the

hydraulic models class. Because the ratio of the height  $h$  of an avalanche to its length  $L$ , is small enough ( $\frac{h}{L} \ll 1$ ), the shallow water formalism has been extended to dense avalanches. The shear, (and consequently the resulting dissipation), is mainly located at the interface between the moving snow, and the snow or the soil at rest at the base of the flow, in accordance with the measured velocity profiles, published in the literature (Dent 1998 and many others). In the model used here the friction at the base is represented by the two parameters standard model of Voellmy. The total friction coefficient  $\mu$  ( $\mu(F) = \mu_0 + \frac{g}{\xi} F^2$ ) is a sum of a Coulomb friction  $\mu_0$  and a dynamic drag coefficient proportional to the square of the Froude number, ( $F = U/\sqrt{gh}$ ) ratio of the mean velocity  $U$  to the gravitational wave velocity  $\sqrt{gh}$ , and inversely proportional to the inertial friction coefficient  $\xi$  ( $m \cdot s^{-2}$ ).

In this model the avalanche path is represented by its longitudinal profile  $z(x)$  where  $z$  is the altitude and  $x$  the longitudinal horizontal coordinate. The "wetted" cross-section  $S(x)$  is given as a function of the flowing snow depth  $h$  ( $S(x) = k(x)h^\alpha$ ), where  $k(x)$  and  $\alpha$  are parameters representing the local traverse morphology of the path, parameters to be calibrated from the local crosswise section.

### 2.1 Model equations

The equations of the model are the conservation of mass and the conservation of momentum. If  $\theta$  is the local slope angle and  $t$  the time, governing equations are given by the following partial differential equations:

$$\frac{\partial S}{\partial t} + \frac{\partial SU}{\partial x} = \varphi \quad (1)$$

$$\frac{\partial SU}{\partial t} + \frac{\partial}{\partial x} \left[ \beta SU^2 + \frac{g}{\alpha+1} Sh \right] = gS \cos \theta (\tan \theta - \mu) \quad (2)$$

According to the formalism developed in Naaim et al. 2004, a specific distributed erosion and deposition model is used to determine  $\varphi$ .

All of the existing models require the specification of values for the friction parameters. Because the physics of flowing snow is still poorly understood, this cannot be achieved with reference to rheological measurements. An empirical calibration is required. This paper summarizes the methodology and the main results of a simple calibration of a hydraulic type model over 729 historical events and addresses the correlation between the calibrated friction coefficients, and the nivological parameters of the involved snow.

Detailed developments and detailed results could be found in the version submitted to CRST.

## 3 DATA AND PROCEDURE OF CALIBRATION

### 3.1 Avalanche historical release and run-out altitudes

In the national French avalanche observatory, 115 avalanches paths of Chamonix valley are monitored. The number of events per path is ranged from 5 to 100 and the observation period is ranged from 50 to 100 years. Among many various data, the date, the release altitude and the run-out altitude of each event are recorded. The altitudes of the trigger and the run-out are determined from in-situ observation. The snow avalanches are recorded only if it reaches a predefined threshold. The magnitude of the recorded avalanches can then be considered moderate to large.

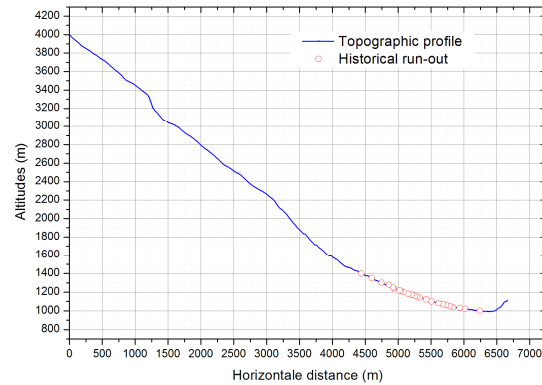


Figure 1: Example of path topographic profile and historical run-out altitudes (Taconnaz path)

We have focused on the 26 paths well documented. This means paths that have (1) a continuous observation, (2) a good data quality (few obviously wrong data), and (3) the number of events exceeding 20. These paths are listed in the following : Le petit Cervin (24/27), La Fillaz (4/23), Les Vorgeats (28/61), Orthaz (51/101), Les Plants (44/75), Brevent (33/63), Pecheux (40/64), Favre (39/65), Entremene (37/68), Rocher (13/25), Vouillours (38/63), Etrangleur (23/51), Lays (23/44), Egoleros (32/50), Epinettes (20/29), Pichet (21/31), Greppon (21/34), Chapeau (28/43), Grand-Chantet (36/63), Nant-Montets (22/34), Lyapet (33/56), Griaz (30/79), Bourgeat (30/82), Arandellys (7/37), Taconnaz (40/88), Nant-Freynt (12/27). In this list, the pair of numbers between brackets attached to the name of each path, corresponds to its number of event posterior to 1958 and its total events number.

The longitudinal and traverse profiles of each avalanche path have been determined from 1 m digital terrain model obtained using a laser scan technology.

### 3.2 Avalanche historical nivological data

The avalanche dynamics model used in this study requires accurate knowledge, at the date of the event, of the distributed snow mantle and its vertical structuring. Whether it's remote (satellite, radar) or classic (polls/surveys), currently no operational network allows the knowledge or the reconstruction of the snow cover and its structure at a spatial scale of an avalanche path and at an hourly time scale, especially in times of imminent release of avalanches, where the snow conditions changes significantly. To overcome this difficulty, the snow center of Meteo-France, developed an integrated tool combining assimilation of meteorology data and snow pack models. The spatial scale of this chain of models is the mountain massif (approximately 500 km<sup>2</sup>) and the time scale is few hours. In this chain each massif is represented by several altitude slices of 300m, in six exposures (North, East, South East, South, Southwest and West) and the avalanche diagnostic is made for two slopes 20° and 40°. This modeling allows taking into account the significant effects of altitude, exposure and sloping which are the effects that contribute significantly in the structural differences of the snowpack.

This chain (SCM) made of Safran, Crocus and Mepra, was submitted to several validations through comparisons between the snow profiles measured to the simulated ones. Its results in terms of avalanche activity were successfully compared to the observed natural avalanche activity. Recently, runs since 1958 until today were made to build two data sets daily on all the Alps and Pyrenees (Durand et al. 2009). This simulation campaign produced a consistent snowpack data set with available measurements, advanced meteorological models and snow physics. An important aspect to be highlighted here to support the use of these data in our study (scale of path and valley) is that almost the entire surface of the Mont Blanc massif is occupied by the Chamonix Valley and the magnitude of the events analyzed here are medium to large for which the weather can be considered much more homogenous.

Among the SCM chain data, one has the total snow depth ( $h_t$ ), the snow density ( $\rho$ ), the average temperature ( $T$ ), the average liquid water content (Lwc), and the burial depth of the weakest layer

( $h$ ), the cohesion ( $\tau_c$ ). These quantities have been generated for each avalanche date, for the main orientation of each path and for all the three hundred meters from 900 m to 3100 m altitude.

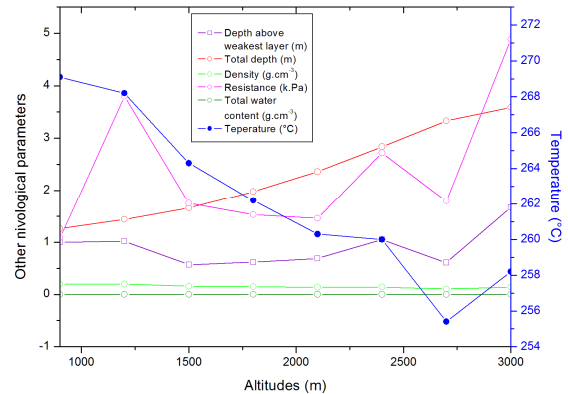


Figure 2 : Example of nivological data profile

## 4 BACK ANALYSIS OF HISTORICAL DATA

The initial conditions let say release altitude and initial snow pack (the snow depth above the weakest layer, the total snow depth and the cohesion  $\tau_c(x)$ ) was defined. The run out altitude, used as calibration criterion, is known. So, one has all the ingredients to perform a calibration as long as one considers constant the friction coefficients for each event.

The calibration procedure has been as simple and free as possible. One was scanned the range of the static friction parameter from 0.1 to 0.7 in steps of 0.01 and the range of the inertial friction coefficient from 500 to 1500 in steps of 50 m.s<sup>-2</sup>. Therefore for each pair ( $\mu_0$ ,  $\xi$ ), a numerical simulation was performed and the corresponding run-out altitude was determined and the gap to the actually observed altitude was calculated. The pairs of parameters that minimize this gap (and for which the gap is lower than 10 m) was retained. 874800 simulations have been performed. The simulation campaign has taken 2890 hours on a twelve processors parallel computer.

### 4.1 Inertial friction coefficient

The set of inertial friction coefficients  $\xi$  obtained has been analyzed. No obvious correlation was detected neither with temperature nor with the density. The only outcome that could be drawn up from this simulation campaign was the statistical distribution of  $\xi$ . As shown in the Figure 3, the statistical distribution of  $\xi$  can be approximated by a Gaussian distribution (mean 940 m.s<sup>-2</sup> and standard deviation 220 m.s<sup>-2</sup>).

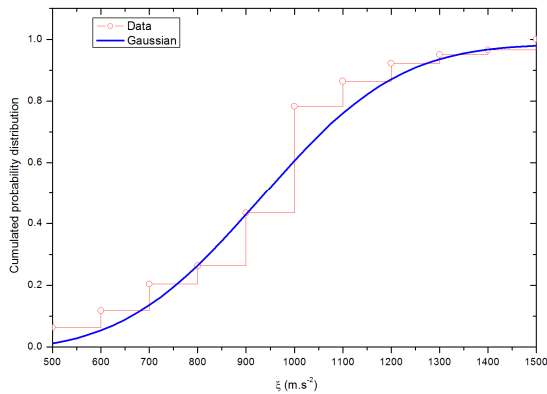


Figure 3 :  $\xi$  statistical distribution

#### 4.2 Static friction coefficients

For each path, one studied the eventual correlations between the obtained static friction coefficients and the corresponding nivological quantities. The stepwise method and the principal component analysis were used to this end. Several trends were observed. For example, the temperature and the total liquid water content have a significant influence on the static friction coefficients for five paths and the initial snow depth have a significant influence for 13 paths. However, no systematic trend was observed due to the number of dependant nivological quantities and the limited number of data per path.

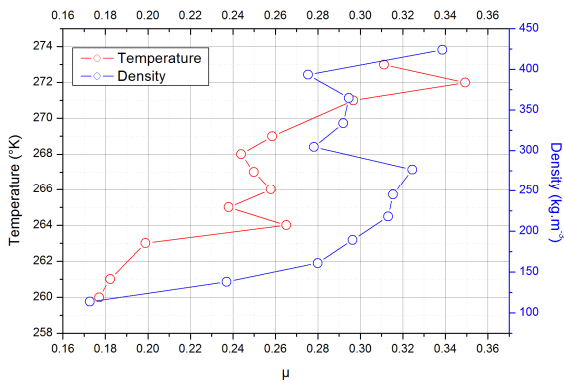


Figure 4: mean static friction coefficient  $\mu$  according to the mean initial snow temperature and mean density

One then grouped all the data in a single file and one analyzed, one by one, the influence of the depth, of the density, of the total liquid water content and of the temperature. For each one, the dataset was sampled into 6 to 14 classes of equal amplitude and for each class, the mean and the standard deviation were calculated for the static

friction coefficient and for the nivological parameter studied. The results are presented and commented here after.

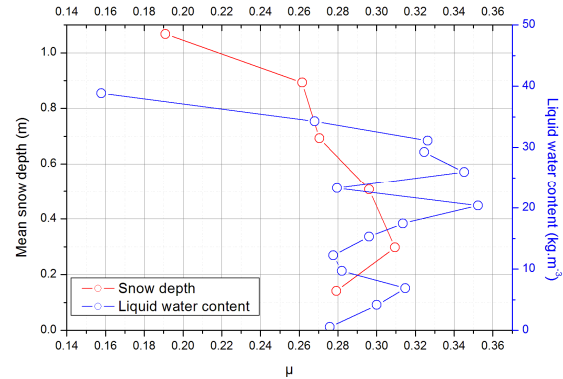


Figure 5 : mean static friction coefficient according to the mean initial snow depth and liquid water content

#### 5 CONCLUSIONS

The calibration of a two parameters hydraulic avalanche dynamics model has been performed on 729 historical avalanches occurred at Chamonix valley during the last 54 years. All the studied avalanches have reached a predefined alert threshold, criteria to be recorded in the national data base. The magnitude of these avalanches can then be considered as moderate to large. The weather in this valley, especially during avalanche times, has been considered homogeneous and the model initial conditions have been extracted from the reconstructed snow mantle by the nivo meteorological chain SCM. The friction parameters ranges were scanned and for each pair  $(\mu_0, \xi)$  the run-out altitude was determined. The run out altitude served as criteria to calibrate the friction parameters.

The correlations of parameters that reproduce historical avalanches with the other available quantities let say snow density, snow depth, snow temperature and snow liquid water content were searched for. The range of each nivological quantity has been split into classes of equal amplitudes. For each class the mean and the standard deviation of the static and inertial friction coefficient have been determined.

Before drawing any conclusions, it is essential to keep in mind the level of uncertainty when manipulating field observations. Another important matter to recall is related to the various approximations and assumptions we have adopted for modeling both the dynamics of dense

avalanches and the reconstruction of the snowpack. An additional important aspect to recall is the statistical character of data obtained. The coefficients are averaged over significant number of data. The conclusions concern average trends.

This study revealed or confirmed several existing knowledge concerning the avalanches friction parameters dependency to nivological quantities. The main result is the linear increase of the static friction coefficient with the temperature and with the density, even if for this last the trend is observed only for density below 200 (kg.m<sup>-3</sup>) (see figures 4) .

Another important result concerns the case of wet snow avalanches (figure 5). The results showed that the liquid water content has no significant effect except for high values, for which the static friction coefficient decreases significantly and may reach the same low value obtained for very low temperature. The last conclusion is related to the snow depth. The results obtained in this work showed a decrease of the static friction coefficient with the snow depth (figure 5). Finally no evident trend or correlation between the inertial friction coefficient and the nivological quantities could be found.

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