

Avalanche impact pressure on a plate-like obstacle

Emmanuel THIBERT^{1*}, Thierry FAUG^{1,2}, Hervé BELLOT¹ and Djebbar BAROUDI³

¹IRSTEA, UR ETGR, 2 rue de la Papeterie, 38402 Saint Martin d'Hères Cedex, France.

² School of Civil Engineering, The University of Sydney, NSW 2006, Australia

³ School of Science and Technology, Aalto University, Department of Civil and Structural Engineering, FIN-00076 Aalto, Finland

ABSTRACT: Snow avalanche impact pressures on the flat surface of an instrumented structure have been quantified by experiments performed at full-scale. An inverse analysis method is used to reconstruct the pressure applied on this obstacle from the deformations recorded during the impact. The velocity of the avalanche is quantified by inner-flow optical sensors. Results are first analyzed on the basis of the drag coefficient to Froude number dependence via a power law. Then, a scaling law for a granular avalanche flowing around this plate-like obstacle is proposed to relate a generalized granular drag coefficient to the Froude number. Finally, the model's applicability to describe impact pressures measured under real and full-scale conditions is discussed.

KEYWORDS: Avalanche Impact Pressure, Flow Obstacle, Snow Deposition, Granular Flow, Drag Coefficient.

1 INTRODUCTION

The understanding of the action of a snow avalanche against an obstacle is a key step in the design of passive avalanche defence structures and in avalanche hazard zoning. Providing a complete pressure spectrum would require a constitutive equation to describe the flowing medium and its interaction with the obstacle. Unfortunately such a constitutive equation is not well established and flow-structure interactions are therefore mainly investigated by small-scale experimental studies (e.g., Faug et al., 2011; Caccamo et al., 2012), and small-scale discrete numerical simulations (e.g., Faug et al., 2009; Chanut et al., 2010). However, similarity criteria remain difficult to determine and the recourse of full-scale experiments is still necessary to validate small-scale approaches and provide phenomenological information.

In this paper, we report impact pressures of a full-scale avalanche flow on a plate-like obstacle (sections 2 and 3). Whether the impact load follows or deviates from the theoretical kinetic pressure is then investigated analysing how the drag coefficient varies with the Froude number (section 4). Then, a scaling law is developed for a granular avalanche flowing around this obstacle. This law is expected to relate the force experienced by the obstacle to the Froude number, to the length of the influence zone relative

to the flow height, and to other parameters (section 5). Finally, our experimental data are compared with impact pressures predicted by this scaling law and the model's applicability to snow avalanches is discussed (section 6).

2 METHOD

2.1 Study site and experimental set-up

The experiments were carried out at the Lautaret full-scale avalanche test site in the southern French Alps. It is located on the south-east slope of Chaillol Mountain near the Lautaret Pass (2058 m a.s.l.). This site has been described in previous papers (Thibert et al. 2008; Baroudi and Thibert, 2009), so only a brief description is provided here.

Avalanche path no.1 was used for the experiment reported here. It is a 500 m long avalanche track with an average slope of 36°, reaching 40° in the starting zone. The instrumented structure is located midway between departure and runout areas, where avalanches reaches their maximum velocities.

The instrumented structure is a one square-meter plate supported by a 3.5 m high steel cantilever, facing the avalanche, and fixed in a strong concrete foundation (Fig. 1). The plate can be moved along the beam to be located exactly at the surface of the initial snow cover prior to avalanche release. With a ratio of obstacle height to flow depth close to 1, it represents a large obstacle in comparison to the flow depth and integrates the effects of flow heterogeneities. The measurement principle of the impact load done by the avalanche is to record the beam deformations in the maximum bending area with precision strain gages. Force and

Corresponding author address: Emmanuel THIBERT, IRSTEA, UR ETGR, Saint Martin d'Hères, France
tel:+33(0)476762813; Fax:+33(0)476513803
email: emmanuel.thibert@irstea.fr

pressure are then reconstructed by an inverse method (Thibert et al. 2008; Baroudi and Thibert, 2009) as exposed in the next section.

2.2 Pressure reconstruction

Strains are measured at the bottom of the beam with 2 precision strain gages. The sampling rate for data acquisition is 3000 Hz to record dynamic effects. Signals are filtered with a cut-off frequency of 1000 Hz to ensure a bandwidth without aliasing.

The avalanche action is assumed to be uniformly distributed over the plate and no avalanche force is assumed to act directly on the beam. If h denotes the avalanche flow height, the impact pressure P is related to the reconstructed force F by $P = F/(h \times 1\text{m})$. We use structural dynamics equations of motion (Gerardin and Rixen, 1993) and an Euler-Bernoulli beam model to simulate the structure. An additional point load (190 kg) on the model is used to simulate the plate. The direct problem consists in evaluating the strain history from the loading, boundary and initial conditions. Using the Euler-Bernoulli beam model, the direct problem is first solved by assuming that the impacting force acts at a specific point. This formulation is equivalent to solving a Fredholm integral equation of the first kind:

$$\varepsilon_i(t) = \sum_j \int_0^t h_{ij}(t-\tau) f_j(\tau) d\tau, \quad (1)$$

where ε_i is the measured at time t at a gage locations i , f_j is the impact load at the center j of the plate) and h_{ij} is the transfer function between excitation and measurement points. The transfer function or its equivalent Frequency Response Function (FRF) in the frequency domain, $\hat{h}(\omega)$, where ω denotes the angular frequency, is known once the mechanical model of the structure including its boundary conditions has been defined. As explained in that paper, we use the analytical Euler-Bernoulli beam model which gives consistent results with other possible determinations of the FRF.

The reconstructed avalanche load is obtained from the solution of the inverse problem given by the regularized deconvolution formula:

$$\hat{f}_\delta(\omega) = \frac{\hat{\varepsilon}^\delta(\omega) \cdot \hat{\phi}(\omega)}{\hat{h}(\omega)}, \quad (2)$$

where the symbol “ $\wedge$ ” denotes Fourier transform functions of the angular frequency variable ω , and ϕ is the regularization low pass filter. Given that the FRF can have very small amplitudes and that the measured signal, $\varepsilon_i(t)$, is polluted by noise, the direct deconvolution of Eq. (2) without

regularization ($\Phi = 1$) can lead to an instability of the inverse problem (Tikhonov and Arsenin, 1977). The answer is therefore to determine the optimal level of regularization, striking a balance between stability and accuracy. This optimal level is achieved using the Morozov discrepancy principle as explained in our previous studies (Baroudi and Thibert., 2009).

2.3 Velocity measurements

From the first studies where avalanche velocities were roughly estimated with video recordings at the free-surface of the avalanche flow (e.g. Baroudi and Thibert, 2009), a significant step forward has been achieved while measuring now the velocity within the vertical structure of the flow help of optical sensors as developed initially by Dent et al. (1998) and applied at Vallée de LaSionne (VDLS) avalanche test site (e.g. Kern et al., 2010). Velocity measurements exploit the correlation of time-lagged optical signals. Optical velocity sensors are placed 0.35 and 0.65 m vertically above the bottom of the plate and flush laterally on its hillside (Fig. 3).

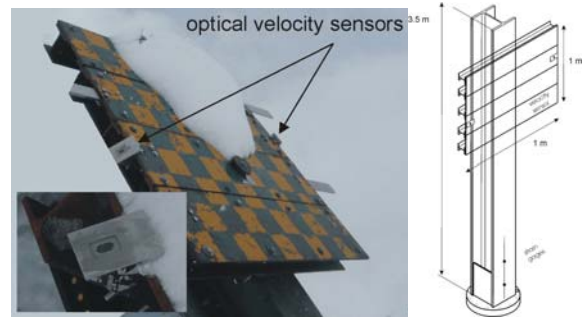


Figure 1. Left: Optical velocity sensors set on the 2 sides of the plate supported by the beam. Right: overall instrumented structure.

Sensors are mounted in steel wedges to ensure proper contact with the flow. The mean flow deflection is about of 15° relative to a normal impact of the plate. The principle of optical velocity measurement requires that grains and snow particles aggregates within the flow does not change significantly in relative position during the travel over a short distance d so that their optical backscattering remains self-correlated with a time lag τ . From this, the velocity u of the passing flow can be estimated as $u = d/\tau$. Our optical velocity sensors have been first improved and adapted to laboratory-scale and snow-chute (Rognon et al., 2008). At Lautaret full-scale avalanche test site, we set $d=0.00762$ m, one fourth of the flow-wise spacing used at VDLS where larger velocities are observed. Practically, in search of the optimal time lag, the correlation integral, $C(t)$, of the backscattered

signal BS captured by the uphill and downhill sensors:

$$CI(t, \tau) = \int_{t-w/2}^{t+w/2} BS_{up}(t) BS_{do.}(t + \tau) dt, \quad (3)$$

where w is the time frame used for integration, and τ the time lag inquired to maximize CI at time t . In order to solve the question of the integration length with respect of the various sources of error in velocity reconstruction (Kern et al 2010), a series of integration is performed with an incremental dichotomic divide of w . This scheme allows investigating from large to reduce integration time frames and cover from long time trends to high frequency variations of the velocity signal. The dichotomic divide is stopped once the boundary of the spectral content of the signal is reached.

3 RESULTS

3.1 Avalanche released on the 18 March 2011

An avalanche was artificially released on the instrumented structure on 18 March 2011 at 11h13. Moderate snowfall over several days from the 12 March 0h30 to the 17 March 9h30 added 20 cm of new snow to the initial snow cover. Mean air temperature was -4.14°C during these snow fall events. Sunny conditions were back on the 17 March at 9h30. Clear sky conditions occurred in the following night and until the time of release on 18 March. At the time of the release, air temperature was $+3.19^{\circ}\text{C}$.

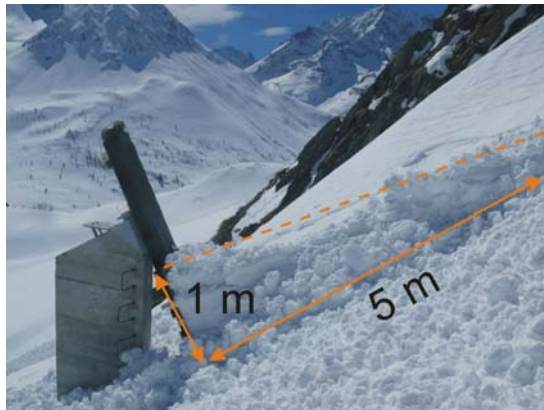


Figure 2. Structure after the 18 March 2011 avalanche impact and the snow deposition on the upstream side of the plate.

A 0.20 m thick layer of small rounded particles (0.3 mm in diameter) and decomposing and fragmented precipitation particles was released in the avalanche path. The density was around 200 kg/m^3 and the mean snow temperature was $\approx 0^{\circ}\text{C}$. At the location of the

measurement structure, the flow was mostly dense (just a limited saltation occurred) and reached with a thickness of 1 m at the time of the impact. Lateral and partly vertical deviations of the flow were observed around the obstacle. As previously observed on this structure (Thibert et al. 2008), an accumulation or stagnant zone settled on the upstream side of the plate. Its shape was an elongated ($\approx 5 \text{ m}$) and symmetric dihedral (Fig. 4).

The height of the flow remained nearly constant and equal to 1 m until the very end of the flow. Snow in the dead zone was composed of compacted, highly cohesive, fine grains, with a temperature of 0°C and a density of 450 kg/m^3 . Numerous spherical balls due to recovered snow cohesion were observed at the surface (Fig. 2), which highlights the granular behavior of the flowing snow.

3.2 Impact pressure signal

In the inversion process, optimal regularization was achieved with a low pass filter, Φ , with a cut-off frequency of 17.5 Hz setting the bandwidth of the pressure signal within 0-17.5 Hz. The reconstructed pressure is plotted in Fig. 3.

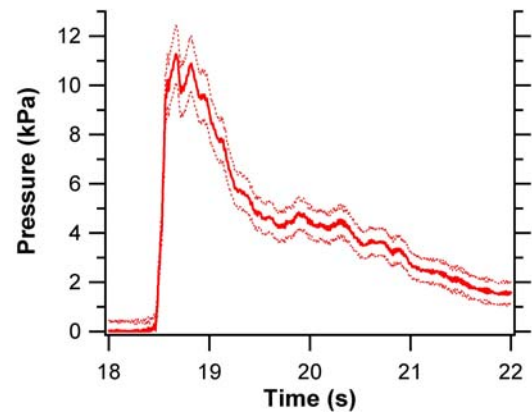


Figure 3. Reconstructed impact pressure from inverse analysis for the avalanche released on 18 March 2011. Dotted curves are pressure signal $\pm$ one standard deviation.

The remaining static pressure at 22 s and later is due to the weight of the deposited snow on the plate. As analyzed by Baroudi and Thibert (2009), the relative error (defined as one standard deviation) associated to the pressure reconstruction from the measurements is typically 10%, which is plotted as dotted curves for the confidence interval ($\pm$ one standard deviation) in Fig. 3.

3.3 Velocity data

Figure 4 shows time series of flow velocity obtained by the 2 sensors. Both signals are in reasonable consistency. The upper sensor set

0.3 m above the down sensor tends to record higher velocity (by 30% in average) which is reasonable as the flow is expected to be highly sheared at bottom (Rognon et al., 2008). For comparison, we also performed a manual correlation on peak values which were easily identifiable on the optical sensor signals (white markers in Fig. 4). We obtained a good agreement which gives us confidence in the correlation computations.

From these pressure and velocity measurements, we identify the dense part of the avalanche flow to hit the structure at 18.47 s at about 10-12 m/s (avalanche head). Then, flow velocity decreases to get within the range 1-4 m/s from 19.25 to 21 s (avalanche main body). After, flow velocity gets more difficult to be quantified in the tail of the avalanche. To cut the high variability, we adopted a mean velocity signal obtained by a 0.2 s-wide moving average (black curve; Fig.4).

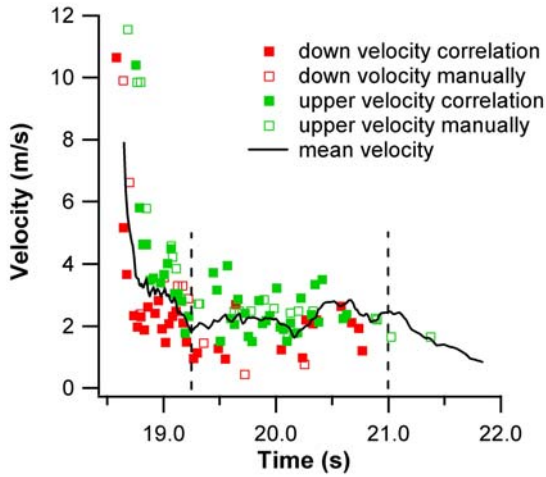


Figure 4. Velocity of the avalanche flow as measured by the 2 sensors set-up on the plate of the instrumented structure (green and red squares, upper and down sensors, respectively). Squares with white color at centre are velocity determined by manual correlation (see text).

4 DRAG COEFFICIENT

4.1 Implication for the drag coefficient

Using velocities, v , derived from optical sensors during the avalanche (Fig. 4) and the pressure P obtained by the inverse analysis, it is possible to calculate the drag coefficient C_d of the obstacle defined as done for conventional simple fluids:

$$C_d = \frac{P}{\frac{1}{2} \rho v^2}, \quad (4)$$

where ρ is the density of the avalanche flow. The denominator in the right-hand side of Equa-

tion (4) being the kinetic pressure of the flow, C_d therefore quantifies how the loading experience by the obstacle deviates from the kinetic pressure.

Variations of the drag coefficient can be analyzed as a function of the Froude number F_r defined by:

$$F_r = \frac{v}{\sqrt{gh}}, \quad (5)$$

where g is the gravitational acceleration. The Froude number defines the ratio of the avalanche flow's inertia to gravitational forces. For the studied avalanche, the Froude number ranges between a little less than 0.3 and 2.5, i.e. from the subcritical ($F_r < 1$) to the supercritical ($F_r > 1$) regimes.

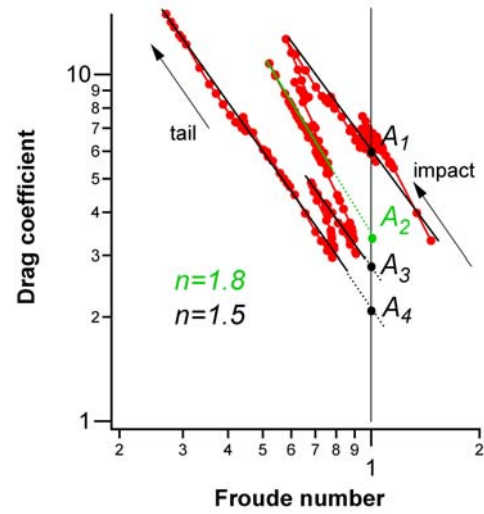


Figure 5. Drag coefficient versus Froude number as obtained from the avalanche released on the 18 March 2011. From the drag coefficient dependence to Froude, four specific steps are analysed during the loading for which data are fitted to Eq. (6) and results shown in Table 1.

It is now well established that, for snow avalanche flows (Sovilla et al., 2007, 2008, 2010; Gauer et al., 2007, Thibert and Baroudi 2009), granular flow experiments (Chehata et al., 2003; Chanut et al., 2010; Faug et al. 2011), as well as from theoretical considerations on gravity driven free-surface viscous fluids (Naaïm et al., 2008) or granular flows (Faug et al., 2012), the drag coefficient increases when the Froude number decreases. The functional form of this dependence has been generally found consistent with:

$$C_d = A_0 F_r^{-n}, \quad (6)$$

where n (>0) is the rate at which the drag coefficient increases with decreasing Froude number on a double-log scale. The intercept A_0 is the drag coefficient expected for the obstacle around the transition between the supercritical and subcritical regimes (i.e. $F_r = 1$).

Figure 5 plots the drag coefficient as a function of the Froude number for the avalanche released on the 18 March with fixed values of 300 kg/m^3 and $h=1 \text{ m}$. The time evolution from the avalanche head to the tail of the Drag coefficient is structured in parallel lines with a systematic shift. The line slopes in the double-scale diagram correspond to the n exponent of Eq. (6). Different loading steps can be identified, of which we highlight 4 with fit results to Eq. (6) reported in Table 1. For steps 1 and 3-4, the exponent n is almost identical ($n \approx 1.5$) while the intercept A_0 decreases by a factor of three. For these 3 steps, the Froude number almost always decreases in time, following the velocity signal (Fig. 4) as we adopted $h=1 \text{ m}$. On the contrary, step 2 along which Froude number tends to remain stationary or slightly increasing exhibits a significantly higher exponent, the intercept being in the range of those found for steps 1 and 3-4.

Table 1. Results of the fit according to the four steps indentified on Figure 5.

	A_0	n
step 1: 18.63→19.26 s	6.03 ± 0.19	1.46 ± 0.05
step 2: 19.60→20.41 s	2.93 ± 0.14	2.05 ± 0.04
step 3: 20.47→20.90 s	2.73 ± 0.14	1.47 ± 0.04
step 4: 21.09→21.85 s	2.14 ± 0.11	1.47 ± 0.03

4.2 Sensitivity analysis: effect of variations in density and height on A_0

Except for step 2, the exponent n can be considered as a constant and we analysed in this section how variations in the intercept A_0 can be explained by changes in flow height and density of the avalanche.

A change in the flow height h , affects the impact pressure P calculated from the reconstructed force F , and the drag C_d coefficient as:

$$\frac{dC_d}{C_d} = \frac{dP}{P} = -\frac{dh}{h}. \quad (7)$$

The Froude number variation due to a change in the flow height h is

$$dF_r = -\frac{1}{2} F_r \frac{dh}{h}. \quad (8)$$

A change in the density of the flow results in a change in the Drag coefficient which is given by:

$$dC_d = -C_d \frac{d\rho}{\rho}. \quad (9)$$

Admitting that n remains constant during the avalanche flow as fulfilled by our data (excluding step 2) (Fig. 5):

$$-C_d \frac{d\rho}{\rho} - C_d \frac{dh}{h} = F_r^{-n} dA_0 + \frac{1}{2} n A_0 F_r^{-n} \frac{dh}{h}, \quad (10)$$

which can be written:

$$d(\ln A_0) = -d(\ln \rho) - d(\ln h^{1+\frac{n}{2}}). \quad (11)$$

This equation states how variations in density and flow height explains variations in the intercept A_0 obtained by the fit of equation (6) on the data.

If the density is to remain constant, integration of equation (11) gives

$$A = A_0 \left(\frac{h}{h_0} \right)^{-(1+\frac{n}{2})}, \text{ or } h = h_0 \left(\frac{A}{A_0} \right)^{-1/(1+\frac{n}{2})} \quad (12)$$

If the height variations are assumed to be negligible, integration of equation (11) gives the simple functional form of the dependence of the intercept A_0 to the avalanche density:

$$A = A_0 \left(\frac{\rho}{\rho_0} \right)^{-1}, \text{ or } \rho = \rho_0 \left(\frac{A}{A_0} \right)^{-1} \quad (13)$$

Qualitatively, with a decrease in the flow height along the time, last points (tail) of Fig. 5 should be plotted with a shift towards higher Froude number and higher drag according to the signs of Eq. (7) and (8).

Quantitatively from Eq. (12), the change in the intercept from the head to the tail of the avalanche (i.e. from steps 1 to 4 where A_0 is divided by 2.82), can be explained by a decrease from $h=1 \text{ m}$ to $h=0.55 \text{ m}$. If we consider that the density were to have varied to explain this shift in A_0 , one should invoke a important decrease down to nearly 70 kg/m^3 from the initial value of 300 kg/m^3 adopted to plot Fig. 5. Even expecting the density to decrease as reported for small-scale granular avalanches (Bugnion et al., 2013), this would be only by -15 to -50% from the head to the tail. We therefore conclude from this sensitivity analysis, that density variation cannot alone explain the time evolution of the drag coefficient to Froude number dependence. The systematic shift in Fig. 5 can be reasonably explained by a decrease of the flow height.

5 GRANULAR FORCE MODEL

5.1 General formulation

In the previous section, the data were fitted by using a power function in the form $C_d = A_0 F_r^{-n}$. Here we propose to compare the C_d -data to another function in the form:

$$C_{eq} = C^* + \frac{K^*}{F_r^2}, \quad (14)$$

which was derived from a physics-based model, as is described in detail in (Faug, 2013). This model has been successfully calibrated and tested on numerous data stemming from well-controlled and well-documented small-scale tests on granular flows past obstacles (discrete numerical simulations and small-scale labora-

tory tests), in various geometries (flows down an inclined plane, rotating flows, vertical chute-flows) and over a great range of flow regimes from the dense quasi-static regime to the inertial dilute regime, as it is explained in detail by Faug (submitted) and references therein. It is worth mentioning that a similar form for the generalized drag C_{eq} has been also derived when granular flows jump over a wall-like obstacle spanning the whole width of the incident flow (Faug et al., 2012). The coefficients C^* (pure drag coefficient) and K^* (pure earth pressure coefficient) are derived from the force model and have the following expressions:

$$C^* = 2\beta \frac{W}{D} \varepsilon, \quad (15)$$

$$K^* = k \cos \theta \frac{W}{D} \left(1 - \frac{1}{(1-\varepsilon)^2} \right) + 2 \frac{L^*}{h} \frac{\rho}{\rho_0} (\sin \theta - \mu_e \cos \theta) f, \quad (16)$$

C^* depends on the incident width W of the avalanche-flow relative to the width of the obstacle (here 1 m for the plate-like obstacle at Lautaret), on the coefficient β related to the velocity-profile and on the coefficient ε that quantifies the velocity reduction caused by the obstacle. It should be noticed that C^* , which is a pure drag coefficient, should be strictly in the range $[1, C_0]$, where C_0 is the drag coefficient in very dilute granular regimes which can be theoretically predicted from the particles' coefficient of restitution e by $C_0 \approx \frac{4}{3}(1+e)$, as detailed by Wassgren et al. (2003). For hard, rounded granules resulting from compression of initial wet snow ($e \approx 0.8$ typically), we would have $C_0 \approx 2.4$ while for brittle granules of dry cold snow ($e \approx 0.1$), we would have $C_0 \approx 1.5$. The lower limit $C_0 = 1$ is more relevant when the snow granules are closer and can endure longtime contacts when they meet the obstacle, forming a dead zone in front of the obstacle. This behavior is well predicted by the value of the Knudsen number (in the vicinity of the obstacle) measuring the mean free path of particles relative to the width of the obstacle, as detailed by Boudet and Kellay (2010) for dilute granular flows.

K^* is a pure earth coefficient and is the sum of two terms. In the first term k is the earth pressure coefficient in the undisturbed incident flow (assumed to be equal to 1). In the second term, h is the thickness of the undisturbed incident flow and ρ its average density. f is a coefficient depending on ε and D/W according to $f = \frac{1}{2} [1 + 1/((1-\varepsilon)(1-D/W))]$ in the case of free-surface flows down a slope θ , which is relevant

for the Lautaret experiments. An important parameter is the length scale L^* of the mobilized volume of snow, i.e. the volume of snow disturbed upstream from the obstacle (influence zone of the obstacle). This parameter is discussed more in detail in the subsection below. μ_e is the effective basal friction relevant for the mobilized volume, which will be assumed to be equal to $\tan(\theta_{min})$, where θ_{min} is the friction angle associated with quasi-static granular deformations. A typical average value for θ_{min} is 21° , as recently derived from measurements of the thickness of full-scale snow avalanche deposits (Sovilla et al., 2010) cross-compared to the h_{stop} function measured in small-scale granular tests and describing the thickness of deposits left by granular flows (Pouliquen, 1999). ρ_0 is the density of the mobilized volume which can be higher than ρ , because of some initial compaction when the flow impacts the obstacle. However, for the sake of simplicity we will assume $\rho_0 = \rho$ in the following.

5.2 Mobilized domain of snow upstream of the obstacle

The model used in this paper and described in detail in (Faug, submitted) is based on the evidence of a length scale when a granular stream interacts with the obstacle. Granular materials are characterized by complex contact network (intermittent breaking and birth of force chains). Those contact networks are enhanced by boundary conditions such as the presence of an obstacle inside the flow. To derive the above-mentioned equations, it is necessary to take into account the effect of this contact network (mobilized domain) which affects the resulting force on the obstacle. Mass and momentum conservation applied to the mobilized domain shows that, in addition to the inertial force (pure drag term C^*) and the contribution caused by pressure gradients (first term in K^*), it is necessary to consider a third contribution to the force which is the apparent weight of this mobilized domain of typical length L^* , and which leads to second term in the K^* -expression. The cross-comparison of small-scale granular data to the force model clearly evidenced this contribution (Faug, submitted). Predicting in detail the length of the mobilized domain remains a challenging issue even if some crucial information has been already obtained for small-scale granular flows. In particular, this length is driven by (i) the flow-obstacle geometry, (ii) the frictional properties and (iii) the incident granular flow regime at stake (see details in Faug, submitted). In subsection 6.2 is discussed the magnitude of this length scale found for the Lautaret data discussed in the present paper.

6 GRANULAR MODEL VERSUS DATA

6.1 Lautaret data versus force model and small-scale granular data

Figure 6 depicts the data from the Lautaret in terms of C_{eq} (generalized drag) as a function of Fr , together with many data from the granular literature in order to highlight the relevance of the scaling over a very great of Froude numbers, as detailed by Faug (submitted). As a first step, we simply use C^* (pure drag coefficient) and K^* (pure earth pressure coefficient) as direct fitting parameters. Choosing $(C^*, K^*) = (1, 1)$ provides a prediction of the model for which all the data (including granular data) are above this prediction. Choosing $(C^*, K^*) = (1, 100)$ gives a prediction of the model for which all the data are below this prediction. This allows us to stress the great variability of K^* , which is driven by the value of the typical scale length L^* . It is worth mentioning that the Lautaret data are fully consistent with the great number of data from literature about granular flows.

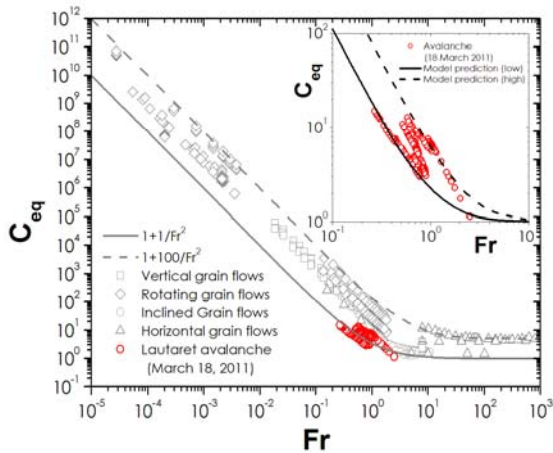


Fig. 6. Measured drag at Lautaret (18 March 2011) versus the Froude number compared to other numerous data from the granular literature on small-scale laboratory and numerical tests (see detail in Faug, submitted). The prediction from the force model is also reported with value of C_{eq} with $(C^*, K^*) = (1, 1)$ and $(C^*, K^*) = (1, 100)$. In inset is a zoom on the avalanche data from Lautaret with the force model prediction $(C^*, K^*) = (1, 1.1)$ and $(C^*, K^*) = (1, 5)$.

In inset of Fig. 6 is shown a zoom on the data from the avalanche released on March 18, 2011 which are systematically closer to the low prediction of the model. Without going into the details of each of the four steps stemming from the analysis proposed in section 4, we simply seek here the two couples (C^*, K^*) for which the prediction exactly surrounds the Lautaret data: we find $(C^*, K^*) = (1, 1.1)$ for the low prediction (step

4) and $(C^*, K^*) = (1, 5)$ for the high prediction (step 1), as shown in inset of Fig. 6. In the following section, we discuss more in detail the model's applicability to the Lautaret data by trying to derive the typical length scale L^* under reasonable assumptions for the other model parameters.

6.2 Length of the mobilized domain from Lautaret data

This section aims at deriving a typical length L^* of the mobilized domain of snow upstream of the obstacle. In order to match the force model to the data by using L^* as a tuning parameter, we need to assume reasonable values for the other parameters. As already discussed, we use $k=1$, $\mu_e = \tan(\theta_{min}) = 0.38$ (for $\theta_{min} = 21^\circ$), and $\rho = 300 \text{ kg/m}^3$. We assume $\varepsilon = D/(2\beta W)$ in order to simply satisfy $C^* = 1$, which is relevant regarding the previous subsection and the granular experiments in a similar configuration (Caccamo, 2012; Favier et al., 2013). For a typical avalanche width in the avalanche track, $W = 6 \text{ m}$, ($W/D = 6$), and with $\beta = 1$ (compatible with a low sheared layer above a thin high sheared layer or with a plug-like velocity profile), we can obtain $\varepsilon \approx 0.08$, which gives $1 - \frac{1}{(1 - \varepsilon)^2} \approx -0.19$ and ≈ 1.15 . How the ratio L^*/h (equal to L^* for $h = 1 \text{ m}$) evolves over time is displayed in Fig. 7.

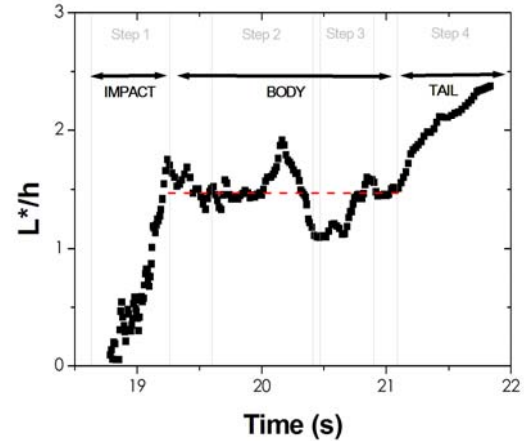


Fig. 7. Length scale, over time, of the mobilized domain calculated from the cross-comparison of the model to the Lautaret data (18 March 2013).

From this curve we can distinguish three phases: (i) sharp increase of L^*/h with time, which is consistent with the transient phase just after avalanche impact (step 1 from section 4), (ii) relatively steady length around the value 1.5 in spite of a sharp variation (step 2 to step 3), and (iii) increase of L^*/h before the flow comes to a standstill (step 4). In this latter phase, the

ratio L^*/h reaches the value 2.5 which is consistently less than the final length of the deposit (around 5 m), as already reported in Fig. 2. However, the assumptions $h=1$ m and $\rho=300$ kg m⁻³ are questionable, as discussed in section 4.

As a conclusion, the granular model proposed in section 5 gives physical insight on the drag dependence on the Froude number. It is mainly driven by the length scale L^* . Predicting accurately this length scale would give the magnitude of the force on the obstacle. However, it is still a challenging issue not only for full-scale snow avalanches investigated in this paper but also for small-scale well-controlled granular flows (Faug, submitted).

7 REFERENCES

- Bouquet, J.F., Kellay, H., 2010. Drag coefficient for a circular obstacle in a quasi-two-dimensional dilute supersonic granular flow, *Phys. Rev. Lett.*, 105, 104501.
- Baroudi D., and Thibert, E., 2009. An instrumented structure to measure avalanche impact pressure: error analysis from Monte Carlo Simulations. *Cold Reg. Sci. Tech.*, 59(2-3), 242-250.
- Bugnion, L., M. Schaefer and P. Bartelt, 2013. Density variations in dry granular avalanches. *Granular Matter*, doi:10.1007/s10035-013-0434-8.
- Caccamo, P., 2012. Experimental study of the influence of protection structures on avalanches and impact pressures, PhD thesis, University of Grenoble.
- Caccamo, P., B. Chanut, T. Faug, H. Bellot, and F. Naaim-Bouvet, 2012. Small-scale tests to investigate the dynamics of finite-sized dry granular avalanches and forces on a wall-like obstacle, *Granular Matter*, 14, 577-587.
- Chanut, B., T. Faug, and M. Naaim (2010), Time-varying force from dense granular avalanches on a wall, *Phys. Rev. E*, 82, 041302.
- Chehata, D., Zenit, R., Wassgren, C.R., 2003. Dense granular flow around an immersed cylinder. *Physics of Fluids* 15 (6): 1622-1631.
- Dent, J.D., K.J. Burrell, D.S. Schmidt, M.Y. Louge, E.E. Adams and T.G. Jazbutis. 1998. Density, velocity and friction measurements in a dry-snow avalanche. *Ann. Glaciol.*, 26, 247-252.
- Faug, T., Beguin, R et Chanut, B., 2009. Mean steady granular force on a wall overflowed by free-surface gravity-driven dense flows. *Physical Review E* 80 : 021305.
- Faug, T., P. Caccamo, and B. Chanut (2011), Equation for the force experienced by a wall overflowed by a granular avalanche: experimental verification, *Phys. Rev. E*, 84, 051301.
- Faug, T., Caccamo, P., Chanut, B., 2012. A scaling law for impact force of a granular avalanche flowing past a wall, *Geophys. Res. Lett.*, 39, L23401.
- Faug, T., (submitted) Granular flows around extended objects: macroscopic drag force over a very great number Froude-number range.
- Faug, T., 2013. Granular force on objects and correlation length: Drag coefficient enhancement in low Froude number flow regimes. *AIP Conf. Proc.*, 1542, 617-621.
- Favier, L., Daudon, D., Donzé F-V., 2013. Rigid obstacle impacted by a supercritical cohesive granular flow using a 3D discrete element model, *Cold Reg. Sci. Tech.*, 85., 232-241.
- Gauer, P., Issler, D., Lied, K., Kristensen, K., Iwe, H., Lied, E., Rammer, L., Schreiber, H., 2007. On full-scale avalanche measurements at the Ryggfjonn test site, Norway. *Cold Reg. Sci. Tech.*, 49, 39-53.
- Gerardin, M., Rixen, D., 1993. *Théorie des vibrations: application à la dynamique des structures*. Masson, Paris.
- Kern, M.A., P. Bartelt, B. Sovilla, 2010. Velocity profile inversion in dense avalanche flow. *Ann. Glaciol.*, 51(54), 27-31.
- Naaim M., T. Faug, E. Thibert, N. Eckert, G. Chamon, F. Naaim and H. Bellot, 2008. Snow avalanches pressure on obstacles. *Proceedings of the International Snow Science Workshop 2008*, 21-27 September 2008, Whistler, BC, Canada, International Snow Science Workshop Canada Inc. (eds), pp. 740-746.
- Pouliquen, O., 1999. Scaling laws in granular flows down inclined planes. *Phys. Fluids.*, 11(3), 542-548.
- Rognon, P.G., Chevoir, F., Bellot, H., Ousset, F., Naaim, M., Coussot, P., 2008. Rheology of dense snow flows: Inferences from steady state chute-flow experiments. *J. Rheol.* 52(3), 729-748.
- Sovilla, B., Shaer, M., Rammer, L., 2007. Measurements and analysis of full-scale avalanche impact pressure at Vallée de la Sionne test site. *Cold Reg. Sci. Tech.*, doi: 10.1016/j.colregions.2007.05.006.
- Sovilla, B., Schaer, M., Kern, M., Bartelt, P., 2008. Impact pressures and flow regimes in dense snow avalanches observed at the Vallée de la Sionne test site. *Journal of Geophysical Research* 113(1), F01010.
- Sovilla, B., McElwaine, J.N., Schaer, M., Vallet, J., 2010. Variation of deposition depth with slope angle in snow avalanches: Measurements from Vallée de la Sionne, *J. Geophys. Res.*, 115, F02016.
- Thibert, E., D. Baroudi, A. Limam, P. Berthet-Rambaud., 2008. Avalanche impact pressure on an instrumented structure. *Cold Reg. Sci. Tech.*, 54, 206-215.
- Tikhonov, A.N., Arsenin, V.Y., 1977. *Solutions of ill-posed problems*. Wiley, Chichester (England).
- Wassgren, C.R., Cordova, J.A., Zenit, R., Karion, A., 2003. Dilute granular flow around an immersed cylinder, *Phys. Fluids* 15, 3318.