FAST VERSUS SLOW AVALANCHE IMPACT DYNAMICS: INSIGHTS FROM MEASUREMENTS AT LAUTARET PASS AVALANCHE TEST-SITE, FRANCE

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ABSTRACT: The present paper describes preliminary re-analyses of field-based data on past well-documented snow avalanches that have impacted an instrumented tripod structure in one of the paths at Lautaret avalanche test-site, France. The re-analyses done include data on velocity and pressure measurements, as well as new data on flow-depth measurements. The latter data was obtained with the help of re-analyses of pressure signals. The various techniques used and assumptions made are presented and discussed, which allows us to infer how the thickness of the dense flow, and both the velocities and pressures over depth, all change simultaneously over time. The present work pays attention to the gravity-dominated flow regime occurring after the passage of the avalanche front. That regime is characterized by a mean pressure on the tripod structure that is essentially controlled by the flow thickness, unlike the inertia-dominated regime which is deemed to be driven by the square of the flow velocity during the passage of the avalanche front. Moreover, a change in dynamics is well identified during the gravity-dominated flow regime, while moving from the avalanche core to the avalanche tail.

Keywords: Avalanche dynamics, full-scale test-site, impact force, gravity-dominated regime.

1. INTRODUCTION

The force exerted by dense snow avalanches on civil engineering structures is a long-standing issue and has grown in scope since the pioneering work by Salm (1964, 1966), followed by later studies for instance conducted by McClung and Schaerer (1985) and Norem (1991), and a number of recent surveys (Ancey , 2006; Gauer and Jóhannesson , 2009; Faug et al. , 2010; Ancey and Bain , 2015). The topic has attracted much attention in the recent years because well-documented field-based measurements on avalanche test-sites (Sovilla et al. , 2008, 2010, 2016; Baroudi et al. , 2011) have raised questions regarding the methods and guidelines that are traditionnally used for the calculation of avalanche force on civil engineering structures.

In particular, the recent field-based measurements have underscored a force regime, at relatively low avalanche speed, for which the impact force does not depend on the velocity but is depth-dependent instead. Moreover, as reported by Sovilla et al. (2016) and a couple of references therein, it is observed that the mean pressure $\bar{P}$ can be several times higher than the typical hydrostatic pressure $\bar{\rho}gh$ associated with the avalanche thickness, where $\bar{\rho}$ is the flow density, g the gravity acceleration, and h the flow thickness. Note that such a flow-depth dependent force regime, or gravity-dominated flow regime, is well-known for granular flows, as reported by Faug (2015) and a number of references therein. The catastrophic collapsing of some pylon-like structures in the recent years, caused by low-speed snow avalanches that occurred in ski resorts, also contributed to increase the attention paid to the problem. A summary of two significant avalanche events and their damages, as well as a detailed cross-comparison between back-calculations from different existing (either dynamic or static) force models of the observed pressures, is available in Ancey and Bain (2015).

The present paper describes some re-analyses of data obtained from avalanches released at Lautaret pass (France) and impacting a tripod structure. The research work is here focused on that slow impact dynamics, which differs markedly from the fast impact dynamics. Section 2 shortly describes the full-scale avalanche test-site located at Lautaret pass and operated by IRSTEA Research Institute, and also provides a brief overview of avalanche database available. Section 3 presents the different measurement techniques and methods, with a particular focus on pressure measurements and re-analyses of the pressure data to extract some crucial information—which had been missing until now—on the flow thickness of dense snow avalanches. Considering the new data with flow thickness measurements allows us to clearly identify a time window, of significant duration, for which

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the regime is essentially flow-depth dependent, as explained in section 4. The present paper shows that the result is robust for two past avalanches re-analysed in the present paper. Further work will be needed to improve the methods and systematize them to the rest of the database that is available from Lautaret experiments, as discussed in the conclusion of the paper (section 5).

2. LAUTARET TEST-SITE

The Lautaret full-scale avalanche test-site (southern French Alps, $45.033°N/6.404°E$) of IRSTEA Research Institute has a long experimental history going back to 1972 (Eybert-Berard et al. , 1978; Naaim et al. , 2004; Thibert et al. , 2013). Two avalanche paths (see figure 1 in Thibert et al. (2015)) located on the southeast slope of Chaillol Mountain (max. 2600 m a.s.l.) near Lautaret Pass (2058 m a.s.l.) are surveyed on a regular basis. On path no. 1, a strong concrete foundation has been built to support equipment for tests that are focused on obstacle-avalanche interactions and impact pressure on (relatively) large structures. Avalanche dynamics is more specifically studied on path no. 2 where a 3.5 m high tripod support is located on the path to measure both velocity and pressure within the flow.

For that path no. 2 a number of detailed data on both pressure and velocity measurements are available from about 20 avalanches released since 2006. Full details of techniques and methods used to measure local pressures experienced by the tripod structure and local velocities within the avalanches are available in (Thibert et al. , 2015), in addition to other types of measurements based among other things on imaging techniques.

3. RE-ANALYSES OF PAST AVALANCHES

An important work has been conducted to improve the avalanche database and create a corresponding metadata. In particular, efforts were made to synchronize pressure and velocity measurements for each single avalanche, and to extract the thickness of the avalanche with the help of both pressure and velocity measurements. Some preliminary results on the reconstruction of flow thickness signal from pressure data are presented here. The reconstruction from velocity data and its comparison to flow-depth data from pressure data is still under developmement, and will be the scope of a future paper.

Flow thickness derivation from pressure signals consists of finding the boundaries of the dense flow at the bottom, z_b, and at the free-surface, z_{fs}, analysing in detail the activity registered by each pressure sensor along the tripod structure at any time to distinguish between real dense flow impact and any surrounding noise. As the pressure sensors are separated with a distance of 25 cm, the raw signal of both z_b and z_{fz} correspond to step functions, as shown on Figure 1.

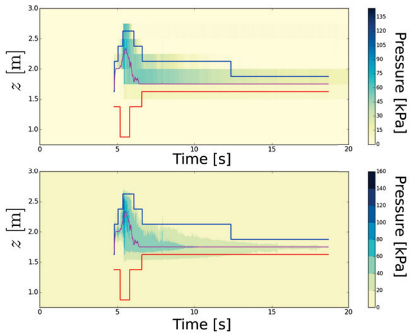

Figure 1: Example of reconstruction of flow thickness h from pressure measurements (avalanche released on 8 March 2017 that has impacted the tripod structure): h is defined as the difference between the free-surface boundary z_{fz} (blue curve) and the bottom boundary z_b (red curve). The spatial distribution of pressures is displayed using two methods by blocks in the top panel and by interpolation in the bottom panel. The curve in purple shows the position of the maximum pressure.

The flow thickness h is then extracted as the difference between the two boundaries, $h = z_{fz} - z_b$, and is also a step function. An interpolation technique is then applied to the signal to obtain a smoothed flow thickness signal. Using that flow thickness signal and all pressure measurements available at various locations across the flow thickness, the depth-averaged pressure $\bar{P}$ on the tripod structure can then be calculated at any time as:

$$\bar{P}(t) = \frac{1}{h(t)} \int_{z_b(t)}^{z_{fs(t)}} P(z,t)dz. \quad (1)$$

Because the pressure measurements show high frequency fluctuations, we considered short time windows Δt_0 and averaged over that Δt_0 in order to obtain a smoother depth-averaged pressure $\bar{P}$. The overarching aim of the present paper is to focus on the relation between $\bar{P}$ and h, as described in the following.

4. THE GRAVITY-DOMINATED FLOW REGIME

In order to seek a flow-depth dependent force regime, namely a gravity-dominated flow regime, the ratio of the depth-averaged pressure $\bar{P}$ measured on the tripod support (see section 3 for explanation about its derivation) to the typical pressure associated with the flow thickness h is defined:

$$K(t) = \frac{\bar{P}(t)}{\bar{\rho} g h(t) \cos\theta}, \quad (2)$$

where θ is the slope angle of the avalanche path. In want of any density measurements, $\bar{\rho}$ is assumed to be a constant over time, equal to 300 kg m^{-3}, considering here a density typically encountered in a dense snow flow.

Figure 2 shows the time evolution of K for two avalanches released at Lautaret pass that have impacted the tripod structure. Both signals, although they stem from two distinct events in 2009 (February 9) and 2017 (March 8), show remarkably similar features. After a short transient of about 2 s, the coefficient K defined by Eq.(2) becomes nearly independent of time over a time window of a certain duration Δt, although some fluctuations are observable. That steady state in terms of K is then followed by a gradual increase of K with time. It is worthy to note that the magnitude of the fluctuations of K are much larger for the snow avalanche in 2009 than for the one in 2017. However, the magnitude of those fluctuations should be interpreted with caution having in mind that K was derived based on Eq.(2), assuming a constant density $\bar{\rho}$, whereas density is expected to fluctuate over time as well (in particular due to the granular nature of the flowing snow, with varying grain size distribution and particle shape).

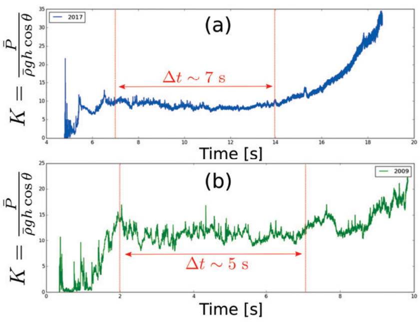

Figure 2: Ratio of depth-averaged pressure $\bar{P}$ measured on the tripod structure to pressure associated with flow thickness, $K = \bar{P}/\bar{\rho} g h \cos\theta$, as a function of time for two avalanches released at Lautaret pass on 8 March 2017 (a) and 8 February 2009 (b).

To further highlight the steady state in terms of K, figure 3 shows the mean (depth-averaged) pressure measured on the tripod support as a function of the flow thickness for the two avalanches that were released at Lautaret pass test-site in 2009 (green curve) and 2017 (blue curve), considering the time windows defined on Figure 2 for which the ratio of $\bar{P}$ to $\bar{\rho} g h \cos\theta$ was shown to be relatively independent of time. Although there are some fluctuations of $\bar{P}$ over time, the linear relation between $\bar{P}$ and h is quite clear. Interestingly, $K\bar{\rho} g \cos\theta$ is similar between both signals, as depicted by the red-colored dashed line, although the range of pressures is different between the two avalanches. During that steady state in terms of K, the avalanche in 2009 exerted higher pressures (in the range $20-65$ kPa) than the pressures from the avalanche in 2017 ($10-23$ kPa). For a constant θ (local slope at the location of the tripod structure settled in Lautaret avalanche path no. 2) and $\bar{\rho} = 300$ kg m^{-3}, this yields a typical value for K of about 10 for both avalanches (see also Figure 2). This demonstrates that the pressure on the depth-dependent force regime can reach 10 times the typical pressure associated with the flow thickness. Such values are fully consistent with previous observations on avalanches, released at Vallée de la Sionne test-site (Switzerland), as reported by Sovilla et al. (2010, 2016).

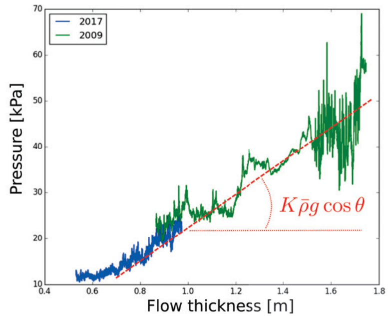

Figure 3: Depth-averaged pressure $\bar{P}$ measured on the tripod structure versus the flow thickness h, for two avalanches released at Lautaret pass in 2017 (blue curve) and 2009 (green curve).

Another interesting observation is the gradual increase of K with time after the steady state, as depicted in Figure 2. While the flow thickness decreases, the mean pressure $\bar{P}$ on the tripod structure increases. This reveals with accuracy the transition toward a flow regime for which the pressure still increases, although the flow is decelerating a lot. This dynamics is deemed to be explained by the growth of the snow mass that is settling upstream of the tripod structure. This transition is the direct signature of snow deposition which occurs at the tail of the flow when the avalanche starves, and which is enhanced by the presence of the tripod structure in the trajectory of the thinner and thinner flow.

5. DISCUSSION AND CONCLUSION

The present work was focused on preliminary reanalyses of avalanche data obtained at Lautaret test-site operated by Irstea. A method was developed to extract the flow thickness of dense flows from pressure sensors' activity measured on the tripod structure settled in path no. 2. The method still needs to be systematized and applied to the entire avalanche database and cross-compared to another method under developement based on flow thickness extraction from velocity sensors' activity (note that the velocity sensors are separated by a distance of 12.5 cm, which should improve the precision of flow thickness data). The preliminary re-analyses applied to two avalanches released in 2009 and 2017 already show interesting trends. Defining the ratio of depth-averaged pressure $\bar{P}$ to hydrostatic pressure associated with the flow thickness $p_h = \bar{\rho} g h \cos\theta$, one can clearly identify a time period during which the avalanche pressure is controlled by the flow thickness with a relatively significant amplification compared to the magnitude of hydrostatic pressure: $\bar{P} = K p_h$, where $K \sim 10$ for the two events surveyed. This result is in accordance with previous studies showing the occurrence of that depth-dependent force regime (or gravity-dominated flow regime). Moreover, the transition toward avalanche starvation is identified with precision when K is no longer constant (end of the steady state in terms of K) but starts increasing with time. Those preliminary results will need to be confirmed by systematic post-treatments of the whole database available, taking into account environmental conditions (air and snow temperature, snow quality, etc.) in addition. Work on velocity signals analysis that is under progress will help in (i) improving flow thickness measurements and (ii) identifying the transition from the velocity-squared dependent regime occurring during the passage of the avalanche front on the tripod structure toward that depth-dependent force regime. This information is crucial so that the existing analytical solutions for avalanche impact force calculation can be improved and their validity can be extended over a wider range of dense flow regimes.

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