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## Taconnaz avalanche path: pressure and velocity measurements on breaking mounds

Bellot H.\*, Naaim-Bouvet F., Naaim M., Caccamo P., Faug T. and Ousset F.

**ABSTRACT:** This paper describes the instrumentation related to velocity and pressure measurements recently set up in the avalanche protection system of Taconnaz. Previous studies on the impact pressure stemming from snow avalanches on the basis of experimental measures revealed very complex loading spectra. More particularly, open questions relative to the incident flow regime and the flow-obstacle geometry, and to how the mean pressure and fluctuations can be influenced, remain challenging issues. The Taconnaz avalanche path (Chamonix, France) is characterized by remarkable dimensions. The passive protection system has been recently improved in the framework of an expertise conducted by Irstea (formerly Cemagref). The new defence structures, retarding mounds in particular, have been equipped with sensors in order to measure the local velocity in the vicinity of those obstacles as well as the impact pressure stemming from snow avalanches, in the framework of the Alcotra DYNAVAL Interreg project. The first measurements have been obtained from the avalanche that occurred at the end of December, 2010.

**KEYWORDS:** Snow, avalanche, protection, Taconnaz, force, metrology.

### 1 INTRODUCTION

Impact pressure generated by snow avalanches represent a crucial parameter for hazard zoning and for the design of structures which are potentially endangered (buildings, protection structures, cable cars pylons, etc). This topic is complex because it concerns at the same time the behaviour of the flow around the obstacle and the behaviour of the structure impacted by the flow. Engineers usually estimate the impact pressure by using the maximum value of the mean pressure because a deterministic modelling, allowing the quantification of the entire load spectra, does not exist. However, measurements obtained from different real-scale avalanche sites indicate very heterogeneous load spectra (Schaer and Issler, 2001; Sovilla et al., 2008b,a; Thibert et al., 2008; Baroudi et al., 2011). In order to better understand the physical process governing the interaction between snow avalanches and structures, it is necessary to combine different approaches. These approaches consist of:

- analytical formulas (e.g. Naaim et al. 2008; Faug et al. 2009; Chanut et al. 2010; Faug et al. 2010);

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- small-scale laboratory models (e.g. Faug et al. 2011; Caccamo et al. 2012) and discrete numerical simulations (e.g. Faug et al. 2009; Chanut et al. 2010);
- in situ measurements (e.g. Gauer et al. 2007; Sovilla et al. 2008b,a; Berthet-Rambaud et al. 2008; Thibert et al. 2008).

In situ measurements are very expensive and time consuming and they require several years to provide reliable results. However, this approach is crucial to validate the existing models. Several real-scale experimental sites already exist: Ryggfonn in Norway (Gauer et al., 2007), Vallée de La Sionne in Switzerland (Sovilla et al., 2008a,b), Col du Lautaret in France (Berthet-Rambaud et al., 2008; Thibert et al., 2008). For years, these sites have allowed the collection of data on the dynamics of full-scale artificially released avalanches which greatly enhanced the general knowledge of avalanche dynamics.

The experimental site of Taconnaz (Chamonix, France) was equipped through the INTERREG European project named "Dynaval" by configuring the existing avalanche protection system with velocity and pressure sensors. The aims of this study is to investigate, through an experimental approach, pressures that can be exerted on structures located in the run-out zone of an avalanche path and the

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Figure 1: Global overview of the Tacconnaz avalanche path (source RTM).

influence of an obstacle on the flow behaviour in a site of remarkable behaviour.

Section 2 gives an overview on the main characteristics of the Tacconnaz avalanche path and on the previous studies that led to the improvement of the protection system. Section 3 describes the recent site equipments which allowed to collect data concerning the velocity and pressure of a full-scale, naturally released avalanche. Preliminary results are qualitatively presented in section 4. Section 5 concludes this paper and gives an insight on future works.

## 2 SITE DESCRIPTION

The Tacconnaz avalanche path (Figure 2) is situated between the municipalities of Chamonix and Les Houches (Haute Savoie, France), on the left side of the Arve river, just below the Dôme du Goûter. The morphological characteristics of the site (Table 1) such as its surface, length, and height difference, along with the presence of the Tacconnaz glacier directly above, make it an exceptional couloir.

The starting zone surface of the avalanche path, its length and the altitude drop are all exceptional features of this avalanche site. However, the immensity of the starting zone is the principle characteristic of the path. Three main starting zones can be identified (Naaim et al., 2010):

1. between the altitude of 4000 m and 3300 m a.s.l., a wide glacier area represents the first important morphological aspect. This first release area has a very irregular topography, a sur-

Table 1: Reference values, in term of velocity, pressure and volume of mobilised snow, for the experimental site of Tacconnaz (Bellot et al., 2012).

<b>Type of release</b>	Natural
<b>Couloir length</b>	up to 7500 m
<b>Mean slope</b>	25°
<b>Volume</b>	1600000 m <sup>3</sup>
<b>Pressure</b>	up to 100 ton m <sup>-2</sup>
<b>Velocity</b>	up to 70 m s <sup>-1</sup>

face of approximately  $2 \times 10^6$  m<sup>2</sup> and a mean slope of 30°. The area is subject to the dominant winds which involve potential accumulation problems. The upper part of the area is delimited by a slope-braking-line generating seracs that can potentially trigger an avalanche. Considering that in this sector the cumulated height of precipitation of three days, for a return period of one-hundred years, is two meters, this single area has already the potential to generate catastrophic avalanches in terms of volume;

2. a second departure area is identified between the altitudes of 3300 m and 2800 m a.s.l.. A second long seracs line constitutes another trigger zone for avalanches. This area supplies a flowing and erosion zone characterised by a mean slope of 31°, a width of 400 m and a length of approximately 1800 m. An avalanche generated from this sector can reach, for the centennial precipitation case-scenario (cumulated on three days), a volume of  $1.6 \times 10^6$  m<sup>3</sup>;
3. at an altitude between 2600 m and 2000 m a.s.l., a third release area is 800 m long, 300 m wide, and with a mean slope of 25°. This area alone, for the centennial precipitations conditions of three days, can generate an avalanche with a volume greater than  $0.5 \times 10^6$  m<sup>3</sup>.

The couloir continues downhill at a mean slope of 30°, a length of 900 m and a mean width of 300 m. The snow volume that an avalanche can entrain in this sector, for the case-scenario conditions of centennial precipitations cumulated on three days, is more than  $0.7 \times 10^6$  m<sup>3</sup>. At 1700 m a.s.l. of altitude, the avalanche encounters a moraine of approximately 80 m of height that, in most cases, deflects the flow to the left. Regardless, fast avalanches can overflow this natural obstacle on the right side and surround it. Such a phenomenon is even more likely if the avalanche has an aerosol component because the

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powder avalanche contribution does not follow the topography. From this altitude, the couloir slope decreases uniformly until entering the run-out zone where the current defence structures are placed. The run-out zone has a mean slope of  $13^\circ$ . Historical records show that the difference between the maximum and minimum avalanche run-out distances is  $\Delta_{r.o} > 1000$  m. This is an exceptional couloir: it has a total length higher than 7500 m, a mean slope of approximately  $25^\circ$  and a width that varies with the altitude, generally around 300 – 400 m. Above 1700 m a.s.l. of altitude, this avalanche basin is covered by ice. Avalanches can entrain a part of the glacier, as observed in the deposit of the avalanche that occurred in February 1999. The ice volume of this deposit was estimated to be more than  $0.2 \times 10^6$  m<sup>3</sup>. The density, measured in the deposit few days after the event of April 2006, was higher than  $600$  kg m<sup>-3</sup>. Ice blocks of several cubic meters struck the protection structures and damaged them. Such events must be taken into account and, when designing protection structures in this area, it is very important to consider a significant increase of the flow density. Localized impacts of ice blocks transported by the avalanche can generate pressures ten times the pressure generated by a normal avalanche (Naaïm et al., 2007).

Seventy five avalanches (dense and mixed avalanches) were recorded on the Tacconnaz site between 1900 and 2000. As reported (Rapin, 2001), 21% of these episodes were released by serac calving, 61% stopped at an altitude lower than 1130 m a.s.l., and for 22% of them, the arresting altitude was even lower than 1080 m a.s.l.. Consequently, if the protection system is not considered, an avalanche reaches the village of Tacconnaz once every five years, according to statistics. Data also show that in 1937 and 1984, four avalanches descended lower than 1100 m a.s.l. during the same winter.

In 1991 an avalanche protection system was constructed to preserve the village of Tacconnaz, the national road that passes below and all related structures. This defence structure, through the years, was affected by significant avalanches that overflowed and damaged it (particularly in February 1999 and April 2006), revealing the limits of the system set up in 1991. Afterwards, local municipalities decided to improve this system. Irstea (Cemagref at that time) was asked to predetermine the dense avalanche hazard at the entry of the run-out zone, to design the best combination of defence

structures capable of spreading the flow, dissipating the energy and retaining the dense reference avalanche, and to analyse the residual risk of the powder part of the avalanche. After a morphological analysis of the site, the study was realised through three main steps (Naaïm et al., 2010):

- back-analysis of the events collected in the EPA (Permanent Avalanche Survey) database, using a numerical model for dense flows, and definition of the parameters characterising the incoming avalanche at the run-out zone where protection structures are placed;
- statistical analysis of these parameters in order to define the centennial scenarios. Reference values for the Froude number ( $Fr^{100}$ ) and for the volume ( $V^{100}$ ) were calculated;
- physical and numerical modelling of dense avalanches interacting with the protection structures, in order to design the most efficient defence system. A control was necessary to verify that the structural improvements proposed could not increase the residual risk due to the powder part of the avalanche.

### 3 SITE EQUIPMENT

The detailed study led to improve the effectiveness of the avalanche protection system ended with a final solution proposing the construction of six new breaking mounds with a height of 7.5 m, an intermediate catching dam with a height of 7 m and the raising of the downhill dam up to a height of 25 m (Naaïm et al., 2010). This configuration was supposed to contain avalanches up to the centennial event characterised by a Froude number of 4.29 and a volume of  $1.6 \times 10^6$  m<sup>3</sup>. Today, five out of six breaking mounds are completed and operational and the height of the final catching dam has been raised.

After this study, a new challenge was determined and consisted of trying to monitor the avalanche path by measuring the velocity and pressure of the avalanches entering the protection system. A first trial had been run several years prior when one of the deflecting wall was equipped with two force sensors. Unfortunately, the catastrophic avalanche of 2006 destroyed the equipped wall and the two sensors were found in the storage basin once the snow had melted. In fall 2009, new velocity and pressure sensors were installed on three of the new retarding mounds. Sensors employed in the Tacconnaz site had to withstand site temperatures that can easily range between  $-30^\circ\text{C}$  and  $30^\circ\text{C}$ , resist pressures of

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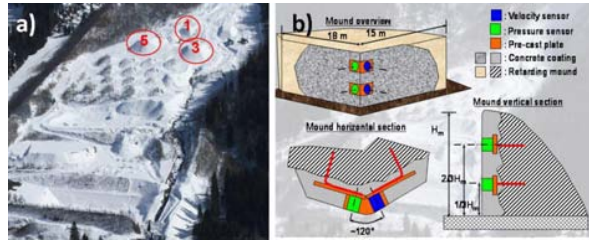


Figure 2: (a) Site overview. The three circles indicate the three breaking mounds that were equipped. (b) Typical set-up configuration of the equipped breaking mounds.

up to  $100 \text{ ton m}^{-2}$ , and be able to measure a velocity of  $60 \text{ m s}^{-1}$  (values correspond to those of the centennial event plus a security margin). The choice of the sensors had therefore to be extremely accurate. Three retarding mounds were equipped (Figure 2.a). Two pressure sensors and two velocity sensors were installed on the edge of each mound between the front and the lateral wall. For each mound, a pair of pressure and velocity sensors was placed at two different heights (approximately  $\frac{1}{3}H_{obs}$  and  $\frac{2}{3}H_{obs}$ , where  $H_{obs}$  is the obstacle height) in order to obtain the pressure measurements from the front wall, normal to the main flow direction, and velocity measurements on the lateral wall (Figure 2.b).

The signal acquisition is made by a specific unit placed in a water-proof box buried at the bottom of the mound. The three mounds' boxes are connected by an Ethernet network and, as the run-out zone is not accessible during the winter due to security reasons, they all communicate with a remote central control station. This station was installed in an underground protective chamber, approximately 300 m far from the avalanche basin where it is permanently accessible. A GSM router allows the consultation of the station from the distance, thereby downloading the recorded data. The system must be operative at any time because avalanches are naturally released and thus the acquisition units record continuously in circular memory. When an acquisition unit detects an event, it sends a signal to the unit of mound  $n^{\circ}5$  (see the numbering in Figure 2.a) which releases the recording of all the other mounds and provides their time synchronisation. When an avalanche occurs, the system records the 120 s following  $t_0$  and stores them in a specific memory space, together with the 60 s preceding the  $t_0$  signal.

The installation of the entire monitoring device was completed at the beginning of winter



Figure 3: Avalanche deposit of the event that occurred on December 29, 2010. The yellow circle indicates the presence of a person at the top of a breaking mound in order to give a dimensional reference. The inset shows the granular nature of the deposit (photo H. Bellot).

2009/2010. During the first winter, an avalanche reached the defence system but technical problems occurred. The acquisition system had memory saturation problems and National Instrument notified it later. The event was therefore not registered. These problems were fixed during the following summer and the first event was finally recorded on December 29, 2010 (during winter 2011 – 2012 two avalanches occurred, but both stopped one meter uphill from mound  $n^{\circ}1$ ). The preliminary results obtained are qualitatively presented in the following section.

#### 4 PRELIMINARY RESULTS

The first recorded avalanche occurred on December 29, 2010. It consisted of a rather dry snow avalanche with ice blocks breaking off from the glacier, which reached the storage basin and the final catching dam. The avalanche occurred during the night and thus no eye-witness testimonies were available. The event was not as powerful as other historical avalanches. A picture of the deposit is shown in Figure 3. Part of the sensors worked properly.

Thanks to the installed equipment, a complete pressure signal was recorded (Caccamo, 2012) and showed that:

- the maximum pressure reached half of the design value calculated for the centennial event ( $P^{100} = 1000 \text{ kPa}$ , see Figure 4);

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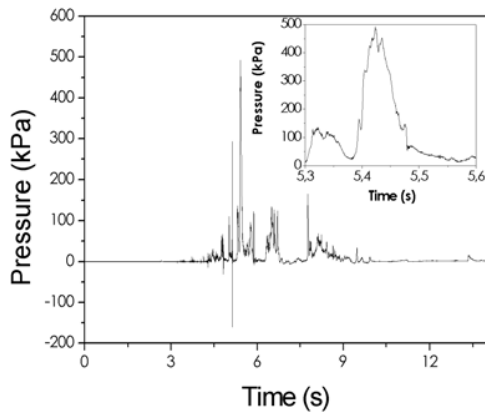


Figure 4: Pressure values versus time. The maximum peak pressure reaches a value of almost 500 kPa. The inset shows that this peak is continuous, and not a single localised value.

- very high pressure gradients were exerted by the avalanche;
- resonance effects, due to the impact of single blocks, are visible in the pressure signal. Three main vibrating modes were found, probably depending on the impact application point with respect to the sensor center. If these isolated impacts only affect the time-dependent pressure signal locally, their contribution to the total energy released by the avalanche is very significant.

And, for  $t > 5$  s, where both velocity and pressure measurements were available (see Figure 5), the data interpretation showed that:

- at low velocity regimes, high pressures can still be exerted;
- the drag coefficient  $C_d$  seems to increase when the Froude number  $Fr$  decreases. This confirms the observed behaviour from small-scale tests with grains as well as from full-scale tests at Col du Lautaret (Berthet-Rambaud et al., 2008; Thibert et al., 2008) and Vallée de La Sionne (Sovilla et al., 2008a,b).

## 5 CONCLUSION AND OUTLOOKS

The new full-scale experimental site of Taconnaz was equipped with pressure and velocity sensors on three breaking mounds, which are a part of the existing protection system. The winter season provided the first recorded event. On December

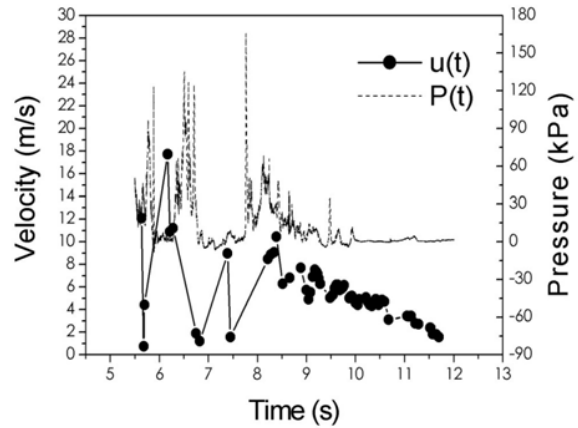


Figure 5: Velocity (left axis) and pressure (right axis) values versus time. Velocity data were obtained by processing the raw signals (Caccamo, 2012).

29, 2010, the first data were recorded by sensors, showing that the acquisition system works. Last winter, two avalanches occurred but both of them stopped 1 m uphill from the first breaking mound, without reaching the obstacles. The installation campaign represented a huge investment in terms of labour and money that only started yielding results two years later. To better understand the behaviour of extreme snow avalanches, more events still need to be recorded. The first results were treated, but they remain scarce at the present time. Thus, the main perspective is based on the hope of having as many avalanches as possible throughout future seasons in order to expand the database. This would allow the research community to further the data interpretation.

Even though the main efforts were probably centred around the start-up of the site activity, the maintenance of such a structure will be expensive and time-consuming. Regardless, the preliminary results seem to be interesting and they demonstrate that the entire system works effectively despite its complexity.

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