# COMPARISON AND COMPLEMENTARITIES OF AVALANCHE PRESSURE MEASUREMENTS: PIEZO-ELECTRIC LOAD CELLS AND DEFORMATION BASED PRESSURE DECONVOLUTION

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ABSTRACT. The impact pressure of snow avalanches have been measured at the Vallée de La Sionne experimental test site using two different types of sensors. The first sensors consist of traditional piezo-electric load cells, with area of 80 cm$^2$ (diameter 10 cm), installed on the hillside of an instrumented pylon. A second "mechanical" type of sensors consist of a 125 cm$^2$ (5 x 25 cm$^2$) steel cantilever beams installed to the side of the pylon at different heights and extending into the avalanche flow. The beams are equipped with high precision strain gages to record the deformation histories during the loading by the avalanche. Pressure is extracted from measured deformations by deconvolution and the cantilever's frequency response function (FRF). The FRF is calculated from an Euler-Bernoulli beam model and validated by impact hammer in-situ tests. Pressures measured in the same avalanche by both sensors are compared and discussed in terms of sensor form, location and some other relevant parameters. As the two sensors are located at the same elevation and pair-wise close to each others having their "force sensing" surfaces differently oriented with a deviation angle of 23 degrees, it turned out that the two measurements can be combined to retrieve a rough estimate of average resultant force vector acting on a avalanche-snow control volume in the vicinity of the sensors. We estimate the modulus and the orientation of the force and discuss changes in these variables for different flow regimes.

KEYWORDS: impact pressure, piezo-electric load cells, gage-cantilever load sensor, deconvolution

## 1. INTRODUCTION

Impact pressure on structures is of fundamental importance in avalanche engineering. A correct design of structures requires knowledge of the dynamical impact pressure in time and space. This is not a trivial task since this loading is the result of complex interaction between structure and avalanche flow. Here we compare two different methods for pressure measurements: *a*) the classical use of piezo-electric load cells set-up on the hill-side of a supporting pylon (Schaer and Issler, 2001; Sovilla et all., 2008ab, *b*) and cantilever beams extending into the avalanche from the lateral side of the supporting pylon (Fig.1).

## 2. METHOD

### *2.1 Study Site and experimental set up*

Experiments are carried out at the real-scale avalanche test site of Vallée de la Sionne (VdlS), in the Swiss Alps, where natural and artificially released snow avalanches are studied. This site has been extensively described by Issler, 1999, and Sovilla et al., 2006, 2008a,b. The avalanche path is about 2700 m long with a vertical fall height of 1300 m. A 20 m high steel tower, 0.6 m wide and 1.5 m long, is located in the run-out zone. The height of the tower allows to record impact and stagnation pressures in the dense, stagnation and suspension layers. The tower is solidly anchored at its base into foundations. The mast is equipped with devices to measure impact pressure (Schaer and Issler, 2001; Sovilla et al., 2008ab), flow velocity (Kern et al., 2009), acceleration, density (Louge et all., 1997), flow height and air pressure in the aerosol part of avalanches.

The impact force is measured using two sensor types. Figure 1 shows the relative position of these two sensors relative to the pylon and to the avalanche direction.

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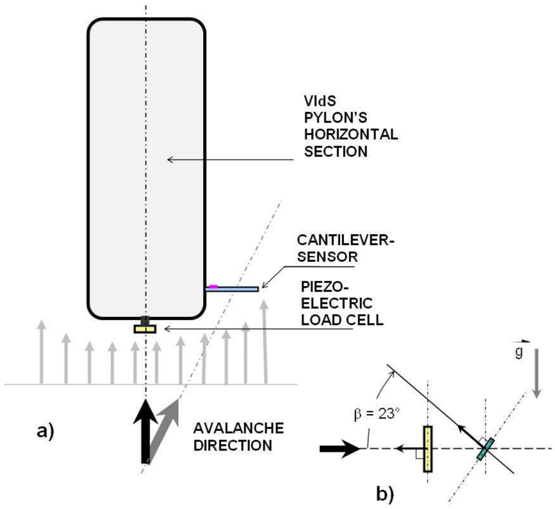



**Figure 1**: a) Pylon section indicating the position of the sensors. b) There is an angle of 23 degrees between the surfaces of the piezo-electric load cell (left) and cantilever-sensor (right).

*2.1.1 Piezo-electric load-cell*

Six piezo-electric load cells are installed on the pylon hillside, with 1 m spacing, from 0.5 to 5.5 m above ground (Figs. 1 and 2). Sensors have an area of 80 $cm^2$ (diameter of 10 cm). In the piezo-electric load cells, a change of volume of a loaded quartz crystal produces electrical current proportional to the load. Acquisition frequency is 7.5 kHz and the bandwidth is 2.5 kHz (Schaer and Issler, 2001).

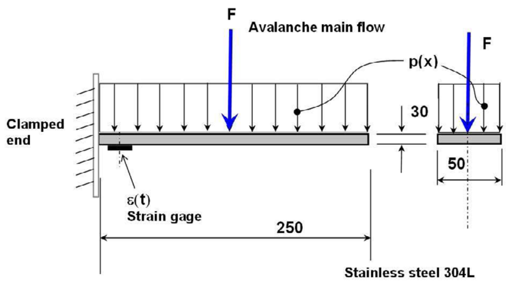
*2.1.2 Strain-gage cantilever*

The sensor devices, developed by Cemagref, are installed on the right side of the pylon, at the same height of the piezo-electric sensors, and extend into the avalanche flow (Figs. 1, 2 and 3a). The cantilever sensors are of stainless steel (grade 304L; 18% chrome and 10% Nickel) and they have area of 125 $cm^2$ (5 x 25 $cm^2$).
The dynamic loading of the avalanche on the beams induces deformations. These deformations are measured with high precision strain gages placed in the maximum bending moment area (Fig. 3b). The noise-to-signal ratio of the gages (SNR) is less than 1/1000. These beams are designed (geometry, mechanical properties) to remain in the elastic deformation domain up to 1 MPa. The acquisition frequency is 2 kHz. The effective frequency bandwidth is about 0–400 Hz after regularization.

In the cantilever-device, force measurement is obtained *via* deconvolution of measured strains. This method is validated in laboratory and *in-situ* (Berthet-Rambaud et al., 2008; Thibert et al., 2008; Baroudi et al., 2008; Baroudi and Thibert, 2009). The measured deformation is used, together with the Frequency Response Function (FRF; Fig.4) of the cantilever-sensor, to extract the history of the impact pressure.


**Figure 2**: Piezo-electric load cell are installed on the hillside of the VldS pylon. They have an area of 80 $cm^2$ (diameter 10 cm).

a) 



b)

**Figure 3**: a) Strain-gage cantilever sensor. It is designed to remain in the elastic domain up to 1MPa.

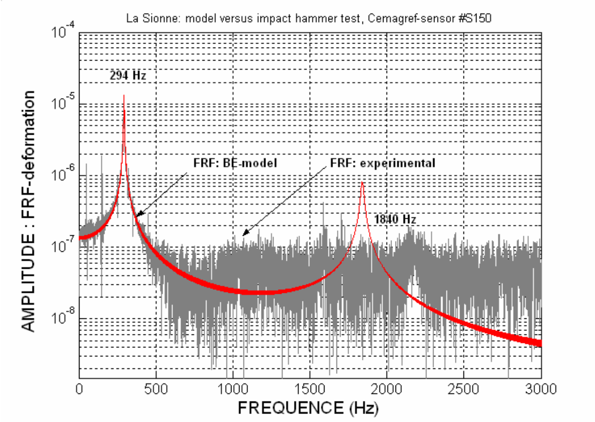



**Figure 4**. FRF of deformations of the cantilever sensor as given by *in-situ* impact hammer test (black) and Bernoulli-Euler beam model (red).

## *2.2 Methods of data analysis*

### *2.2.1 Comparison methods*

The avalanche exerts on an obstacle an external force $\vec{F}$ according to the classical Newton's 2nd law. The piezo-electric and gage-cantilever sensors are designed to measure only the normal component of the projection of this force on the normal $\vec{\mathbf{n}}$ of their loaded surface elements. The impact pressures are then defined as the ratio of such projections over the measuring surfaces. One therefore should compare the common component. This is done by projecting the pressure measured by the cantilever beam on the direction of the normal of the pylon (Fig. 1).
Beside the principle of measurements, pressure measured by the two sensors may differ for the effect of:

- ***Fluid dynamics around the pylon***: in this case the sensor position (**x**) may play an important role; i.e. lower piezo-sensors may be in pylon stagnation zone, while gage-sensors in an acceleration zone;
- ***Different size and shape (size), surface orientations (n)***. This effect may be important for different flow regimes (wet – versus dry avalanches) and different particle sizes;
- ***Boundary condition*** at the interface avalanche-sensor (**BC**): Difference in the level of the sliding surface (different sensor immersion depth) may have an influence on the flux intensity around the pylon; friction effect may play also a role;
- ***Coupled dynamics*** and structural stiffness of the supporting system (**K**): the dynamics of sensors is coupled to the avalanche dynamics. **K**, affects the mechanical coupling between sensor and avalanche flow.

Therefore, formally, a discrepancy $\delta$, in pair-wise measurements can be expressed as:

$$\delta \approx \frac{\partial \mathrm{P}}{\partial \mathbf{x}} \cdot \mathrm{d}\mathbf{x} + \sum_{\substack{\text{size,}\\ \text{form,}\\ \text{n}}} \frac{\partial \mathrm{P}}{\partial (geom)} \cdot \mathrm{d}(geom) + \frac{\partial \mathrm{P}}{\partial (\mathbf{BC})} \cdot \mathrm{d}(\mathbf{BC}) + \ldots \quad (1)$$
$$+ \Delta \mathrm{P}(\text{coupling structure - avalanche})$$

### *2.2.2 Complementary method*

If in first analysis, we assume that all these contributions are small, and the discrepancies in both measurements, $\delta$, are merely due to deviation of the loading direction from the main flow direction (Fig. 5), one can combine pair-wise force measurements to retrieve an estimate, at least qualitatively, of a total average force vector acting on a snow control volume in the vicinity of the two sensors, even though the sensors were not originally designed for that.
Note that, only values $-67° \leq \alpha \leq 90°$ are physically meaningful. This analysis also allows to determine the instantaneous orientation of the resultant force.
In the next paragraph an example of such an analysis is shown.

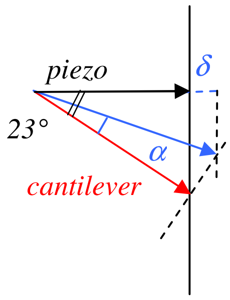



**Figure 5**. Load deviation angle, $\alpha$, from the surface orientation of the cantilever sensor, and resulting difference, $\delta$, in the pressure measured by the two sensors.

## 3. RESULTS

We analyze impact pressure measurements corresponding to avalanche n°2009_003, performed at the VdIS test site on the 4th of December 2008.

After a period of sunny and cold weather, snowfall started on the 4th of December 2008, in the afternoon. During the snowfall, there was a moderate wind from east south-east directions with speeds up to 40 m/s. The temperature was about -6℃. After an accumulation of approximately 50 cm of new snow, an avalanche released spontaneously at 12h36. This medium dimension dry avalanche had a mixed structure, with a short dilute front followed by a denser core. Measurements performed at the pylon show that the avalanche had velocity up to 20 m/s. We could estimate the sliding surface of this avalanche to be located between 0.5 m and 1 m above ground.

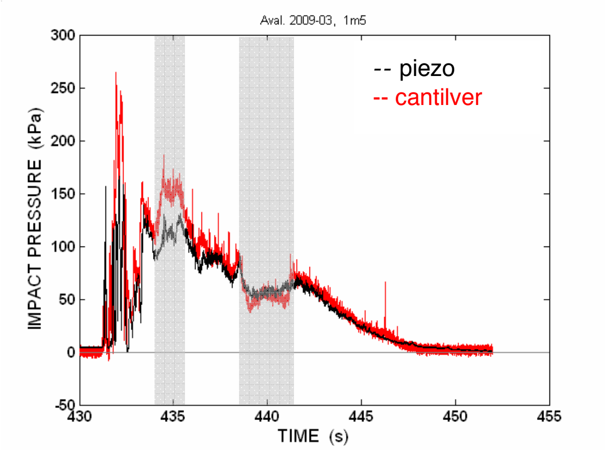



**Figure 6**. Avalanche 2009_003. Impact avalanche pressure measured at 1.5 m above ground by piezo-electric (red) and cantilever-sensor (black).

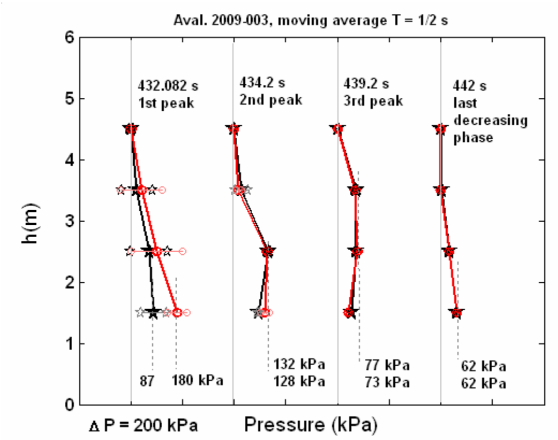



**Figure 7**. Evolution of the impact pressure profile at few characteristic times. Piezo-electric (black) and the cantilever-sensor (red). Horizontal bars are one standard deviation.

Evolution of impact pressures are shown in Fig. 6 for both sensors set up at 1.5 m above ground. Both sensors experience almost the same impact pressure, both in mean and variability for the whole avalanche duration. Peak values measured by the cantilever sensor were about 1.5 higher than those measured by the piezo-electric load-cell for the first 5 s of the avalanche impact.

Figure 7 shows pressure profiles extracted from both pressure signals at times $t$ = 432.08, 434.2, 439.2 and 442 s corresponding approximately to the 1st, 2nd, 3rd peaks and the last decreasing phase after the 3rd peak (Fig. 6). A moving-average window of □ s is used to obtain mean standard deviations. We could observe that the agreement is good and the confidence intervals (one standard deviation) are narrow, suggesting that different size and shape of the sensors, their respective position in the avalanche, orientations, and structural stiffness of the mechanical supporting system have played a small role for this specific avalanche.

Nevertheless small discrepancies exist and the relative difference between both measurements is approximately ±10%. The discrepancy is remarkably small for the time windows (433-434 s; 436-438 s), and in the tail of the avalanche (443-445 s). Conversely, significant differences exist for windows (434-436 s; 439-441s) where pressure has abrupt changes (shaded area in Figs. 6 and 8).

Assuming that discrepancies between measurements are only due to the different sensor surface orientations, we can calculate the instantaneous orientation of the resultant of the total force exerted by the avalanche (Fig. 8). During the first impact (t<431.5 s) and at the end of the impact (t>446 s), the pressure measured by the cantilever is too small to identify the orientation angle $\alpha$. In the avalanche head (t<435 s), $\alpha$ is negative and changes rapidly. However, for time intervals 433–434, 436–438 and 441–446 s, the average orientation is practically zero. Therefore, the mean direction of the flow is in these cases probably parallel to the mean slope of the ground profile. For t=439-441 s, $\alpha$ is around 20° and directed horizontally. Angle variations, defined as one-time the standard deviation, and are shown in gray in Fig. 8. To verify that orientations are not in conflict with observations, one should, compare them to flow depth variations.

As a preliminary observation, we can state that the calculated orientation is at least in concordance with the pressure signal of both sensors (Fig. 6). The shaded area in Figs. 6 and 8, correspond to time-windows where significant differences exist in pressures and where the time evolution of instantaneous pressures has abrupt changes.

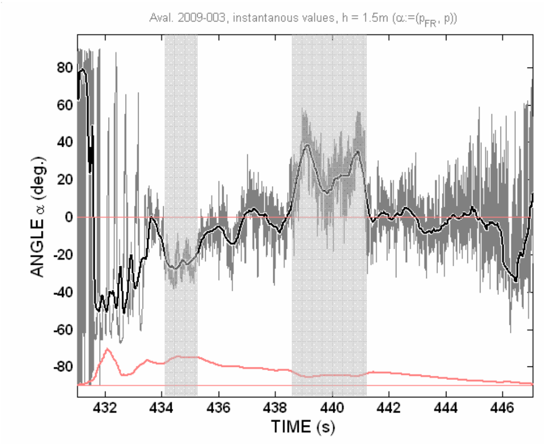



**Figure 8**: Instantaneous orientations of the resultant force at *h* =1.5 m in avalanche 2009-03. The red curve is the pressure measure by the cantilever sensor.

## 5: CONCLUDING REMARKS

Many combined factors may influence avalanche impact pressure measurements and we have shown that these effects can be quantitatively assessed. In this short example, we analyze pressure measurements from a dry-dense avalanche and we could observe that, in this regime, sensors sense practically the same impact pressures for the whole avalanche duration. We expect that this will be not the case for different flow regimes, such as the one characterizing wet avalanche flow, where slow drag processes around the pylon and the formation of force chain will completely change the dynamics of interaction avalanche-pylon. We have shown that, assuming that differences between measurements are only due to the different sensor surface orientation, the combination of two different signals may be used to retrieve the modulus and orientation of the incoming force. Our sensors have not been designed for this aim and thus the method applied to our measurements may provide questionable results. Nevertheless, we have shown that a careful sensor design, would allow the determination of the force vertical component of fundamental importance for the correct understanding of the avalanche dynamics.

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