Acoustic sensor to measure snowdrift and wind velocity for avalanche forecasting

Bolognesi[1] R., Chritin[2] V., Gubler[3] H.

[1] *GESTER SA - Major Hazards - 35, avenue Ritz, Case Postale, CH-1950 SION 2 NORD (Switzerland) – Phone + 41 (0)27 323 15 24 – Fax + 41 (0)27 323 15 27 - bolo@gester.ch*

[2] *IAV Engineering - Noise Vibration Control & Acoustic Systems – PSE/A, EPFL – CH-1015 Lausanne (Switzerland) – Phone + 41 21 693 46 26 – Fax + 41 (0)21 693 83 93 - vincent.chritin@epfl.ch*

[3] *ALPUG - Automatic weather stations - Richtstattweg 2, CH-7270 Davos Platz (Switzerland) - Phone & Fax + 41 (0)81 416 10 19*

ABSTRACT. Wind can create even greater unstable accumulations of snow in mountainous areas than heavy snowfalls. But knowing wind conditions is not sufficient to predict these accumulations because their formations also depend on the snow quality of the snowpack surface upwind of the release zone. Consequently, assessment of snowdrift is required to improve avalanche forecasting. In accordance with this assumption, a new acoustic sensor was developed. The sensor includes a mechanical part designed to form a closed acoustic enclosure. The acoustic enclosure contains a microphone connected to an electrical amplifying and filtering device. Because the output information delivered by the instrument is proportionnal to the wind velocity and to the flux of solid particles (ice grains) drifted by the wind, the instrument is called an anemo-driftometer. Prototypes of the instrument were first tested in a wind-tunnel and then at an experimental site in the Alps. Then an operational version, called *FlowCapt*, was developped and connected to the automatic weather station at 2700 m in the Aminona ski resort (Switzerland). During the winter, snowdrift is recorded on the test site along with other meteorological parameters, and avalanche activity, to provide extensive on-site calibration and testing of the sensor. The experiment demonstrates that the instrument is a useful component of the avalanche forecasting chain.

1. A new snowdrift sensor to improve avalanche forecasting

To improve the reliability of local avalanche warning systems, parameters directly related to avalanche danger or slab stability have to be measured close to and within the potential avalanche release zones that endanger the area to be protected. Because wind can create even greater unstable accumulations of snow in mountainous areas than heavy snowfalls, snowdrift is a very predictive parameter. Wind speed measurements are not sufficient to predict these accumulations which also depend on the snow quality of the snowpack surface all around measurement stations. Knowing snowdrift by direct measurements is subsequently of high importance for avalanche forecasting.

At present time, snowdrift can be measured by ski patrol men (Fig. 1) with the so-called Driftometer (Bolognesi et al., 1995). This simple instrument makes possible quantitative snowdrift assessments, but it requires the presence of a human observer on the sites. If manual measurements are not possible, snowdrift would have to be estimated from other parameters with significantly lower reliability.

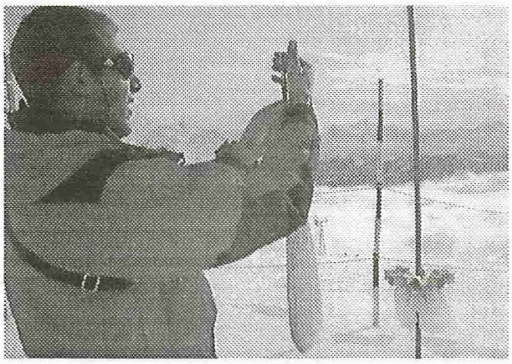

Fig. 1 : The Driftometer catches blown snow particles into a collector through a tube by the combined effects of filter and pressure fall. Weighting the collector directly gives a snowdrift index.

The new Flow*Capt* acoustic sensor gives the possibility of a continuous and automatic recording of the snowdrift ($\sim kg.m^{-2}.s^{-1}$). Installed upwind of the release zone, Flow*Capt* provides additional information on the snow accumulation process within the release zone, deformability of the forming slab and erodibility of the snow surface.

Because it was shown that snowdrift data increases the reliability of avalanche predictions (Bolognesi, 1996), this information is used by the decision support system *NivoLog*™ to establish local avalanche predictions (fig. 2).

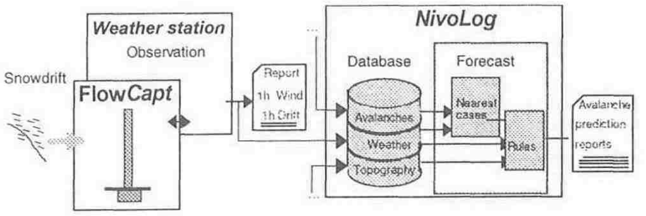

Fig 2 : The sensor can be connected to an automatic weather station. Snowdrift information is recorded into a database and computed by NivoLog to analyse the avalanche release probabilities.

2. Principle of the Flow*Capt* anemo-driftometer

The Flow*Capt* *anemo*driftometer determines both wind velocity and snow particles flux. The detection principle is based on mechanical-acoustical coupling. The sensor is composed of closed pipes containing electro-acoustic transducers and a powering, filtering and amplifying unit.

When the sensor is placed into a snow particles flux, the particles shock the sensor pipes, inducing acoustical pressure (fig. 3). The pressure is picked-up by microphones. The electrical outputs are filtered and time-averaged in given frequency ranges to provide a signal proportional to particles flux Q ($kg.m^2.s^{-1}$). The formal relation between the measured acoustic pressure and the snow particles flux Q requires the determination of the mechanical-acoustical coupling equations for the sensor, according to suitable hypothesis about particle impacts.

The wind velocity is determined on a similar principle : the wind interacts with the body of the sensor and generates acoustic pressure into air enclosures (fig. 3). Suitable sensitivity can be obtained optimising the body shape and structure to the expected wind velocities.

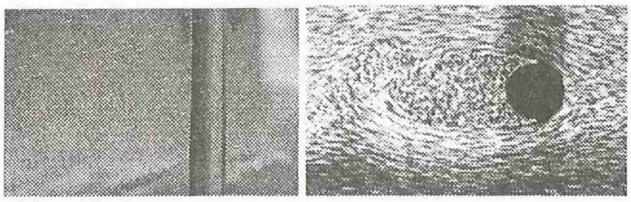

Fig. 3 : Left - Saltation ice particles shocking a pipe. (from V. Chritin). Right - Visualisation of a turbulent flux around a cylindrical obstacle. (from H. Werlé, ONERA).

Because snowdrift happens during windy periods, it is necessary that the sensor strongly discriminates wind from snowdrift. This property can be obtained by an appropriate design of the mechanical-acoustical coupling.

With no mobile components and full protected transducers (microphones inside closed cavities), the Flow*Capt* is very suitable for stringent topographical and climatic environments.

3. Prototyping of the *anemo*driftometer

Theoretical and experimental campaigns have been carried-out at the Swiss Federal Institute for Technology (EPFL) to develop Flow*Capt* prototypes (fig. 4).

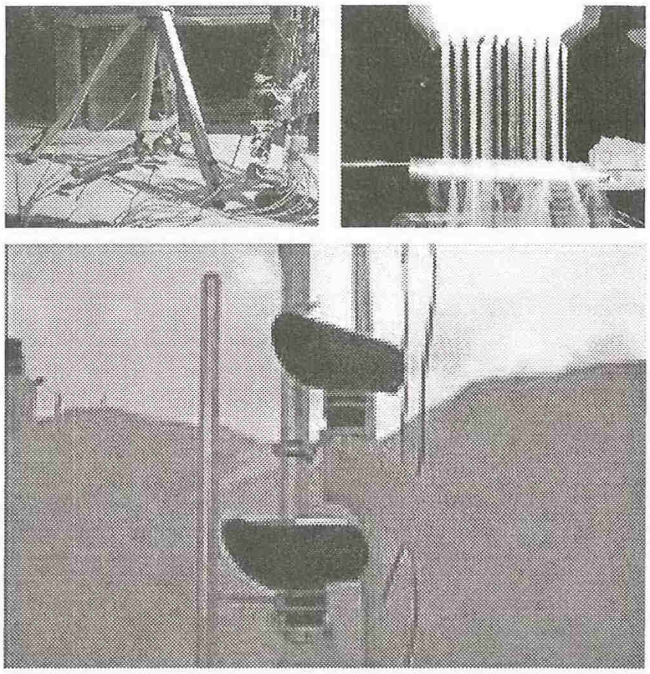

Fig. 4 : Top left - Prototypes tested in wind tunnel, at LASEN-EPFL. The acoustic response of cylindrical and spherical forms excited by wind were characterised in the 0 - 12.5 m/s range (from Th. Castelle).
Top right - Calibration with controlled particles flux on test-bench, at LEMA-EPFL. (from Th. Melly).
Bottom - Prototype tested at Anzère ski resort (2400 m). Comparison of acoustic records to manual Driftometer indexes (from Th. Melly, V. Chritin).

Results obtained from the validation experiments carried-out with a reference anemometer (fig. 5) and a reference snowdrift measuring device (fig. 6) show good accordance.

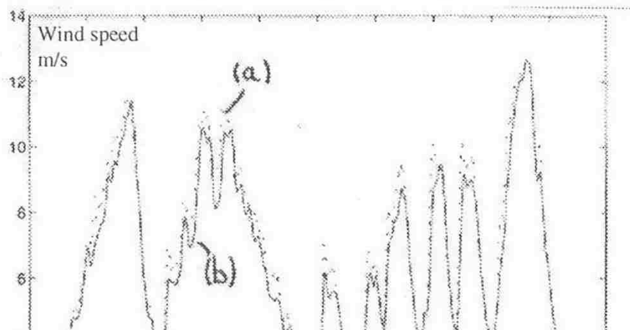

Fig. 5 : Wind velocity measurements in wind tunnel.
(a) calibrated MiniAir5™ anemometer response
(b) FlowCapt prototype response.

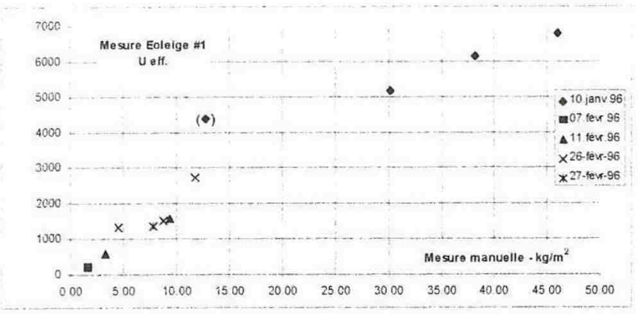

Fig. 6 : Comparison of snowdrift measured by the FlowCapt prototype and the Driftometer.

On the basis of the obtained results, the industrial development of the Flow*Capt* began. A particular attention was paid on the calibration and reliability to ensure precise quantitative snowdrift information. The sensitivity of the sensor to wind velocity is calibrated in a wind-tunnel, by comparison with reference anemometers. To calibrate snowdrift, no reference instrument exists. Thus, it is necessary to define a specific method to find the calibration parameters under various conditions (fig. 7) : (1) sensitivity measurements in bench tests, with controlled particles flux (2) continuous meteorological and snowdrift measurements for two winters on a test site (3) comparison of the Flow*Capt* response to Driftometer indexes during storms.

Fig. 7 : Left - Bench test. Center - Test site with an automatic weather station. Right - Manual driftometer measurement place (from V. Chritin).

4. Operational use

In December 1997, Flow*Capt* has been installed on a Swiss standard automatic remote station (Gubler, 1996), at Aminona ski resort (Switzerland). The station is located at an altitude of 2700m on a south facing slope of Mt. Bonvin. Values are recorded every minute (time constant =1s). Snowdrift is integrated from ground to 1m and between 1m and 1.2 m (fig. 8).

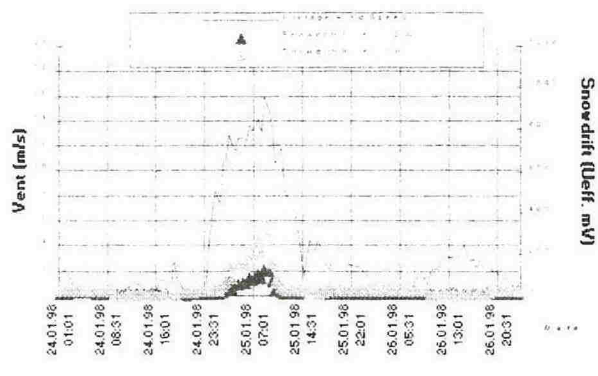

Fig. 8 : Wind and snowdrift recorded at Aminona ski resort, between January 24th and 26th, 1998.

The upper sensor additionally measures wind speed. The station (fig. 9) is equipped with a set of sensors and a number of features that allow for a significant improvement of the assessment of the actual local avalanche danger : snow surface temperature measured by a special infrared radiation thermometer, surface reflected short wave radiation, ground temperature, wind, air temperature and humidity allow for a direct onsite indexing of the formation of weak layers, one of the key parameters for the formation of dry slab avalanches (cloudiness, near surface energy flux balance, dendricity and sphericity (Brun et al, 1992) grain size of surface layer, formation of surface rime, surface melt). The snow profiler measures the snow stratigraphy at an index point within the release zone, settlement, snow accumulation, fracture height and penetration/ damming of meltwater as well as refreezing. The indication of damming of meltwater at a certain depth within the snow cover at a time resolution of about 30' improves the short term forecasting of wet slabs and surface slides. A specially prepared, low priced TDR sensor attached to the ground surface indicates the arrival of meltwater at the snow ground interface, an important parameter for the assessment of the danger from fulldepth avalanches. In the near future this sensor will possibly also provide additional information on the state of the base layer. A geophone attached to the system indicates avalanche activity and checks remote control of explosives for artificial avalanche releases. A reliable sensor for a direct measurement if initial fracturing as a precursor for slab avalanche formation is still missing but we work on it.

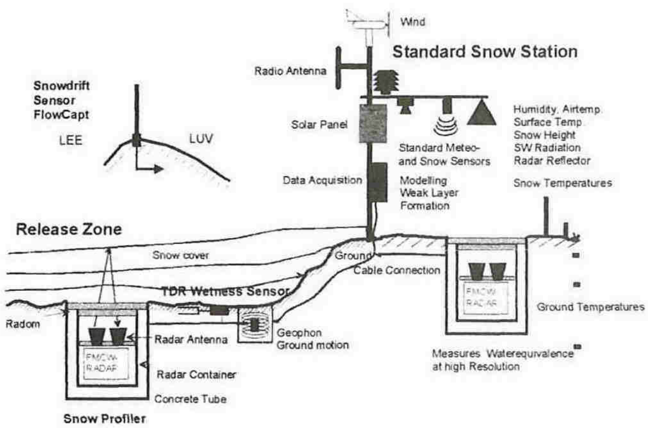

Fig 9 : Swiss Standard Remote Snow Station with additional sensors.

5. Conclusion

FlowCapt, an acoustic sensor, is the first automatic *anemo*driftometer. It can be connected to weather automatic stations located in stringent environments to provide quantitative snowdrift measurements, which are significant data to predict avalanches. Thus FlowCapt is an essential component of the automatic avalanche forecasting chain : sensor - automatic weather station - decision support system.

Acknowledgements

Ch. Wuilloud (Service des Forêts et du Paysage du Canton du Valais), J.-C. Amos and F. Meyer (Tél-Aminona SA), A. Dussex (SAREM Anzère).

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Dynamics of two-layer slushflows

A.N.Bozhinskiy, A.N.Nazarov
Laboratory of Snow Avalanches and Mudflows, Geographical Faculty, Moscow State University, 119899 Moscow, Russia

ABSTRACT. A new mathematical model of slushflow dynamics is developed. A slushflow is treated as a two-layer flow. The lower layer consists of pure liquid phase (water) and the upper layer is a floating water saturated snow (slush). The equations of mass and impulse conservation for each layer are written. These equations include an interaction and mass exchange between the layers and between the water or slush layer and snow cover. The model equations were integrated numerically according to a developed for PC program. Series of numerical experiments for uniform slope were carried out. The structure and dynamics of slushflow were investigated. The dependencies of depths, velocities of flow and front coordinates of the upper and the lower layers on the parameters of the model are established. These parameters are the coefficient of snow entrainment, the coefficient of dry friction, the coefficients of turbulent friction, the discharge of water feeding at the rear end of flow, the snow cover thickness and the slope angle. An effect of exhaustion of the water layer is revealed. This effect is due to fast water absorption by entrained masses of snow.

INTRODUCTION

Slushflows, like debris flows and snow avalanches, belong to destructive gravitational avalanche-type flows (Sapunov, 1985; Onesti and Hestness, 1989, Perov, 1995). The mechanism of their source is basically connected with percolation of melt and/or rain water in snow cover and resultant rising of bottom channel of runoff. Slushflow generation is due to longitudinal pressure gradient of water (Sapunov, 1991; Gude and Scherer, 1995). Usually, slushflow occurence accompanies the motion of one wave-surge in channel. However, P.A.Chernouss observed the pulse motions of slushflows in Khybiny area (personal communication). The similar events were observed in Swedish Lappland (Barsch and others, 1993). Structure and dynamics of slushflows are not well studied. There were attempts to use the empirical formula (Sapunov, 1991) or the simplest theoretical estimations of slushflow velocity. For example, the formula for steady motion of snow avalanche down a uniform slope, the formula for velocity of water flow in open channels (Barsch and others, 1993) or the formula based on the estimations according to lateral inclination of free surface of flow in curved sections of path were used (Sapunov, 1991). Recently the mathematical hydraulic-type model describing the motion of slush masses in the trapezoidal cross section channel was developed (Bozhinskiy and others, 1996). The model was in good agreement with the field data in Khybiny area. At the same time slushflows are, in their nature, two-phase flows. Interaction of phases in flow transforms flow structure, changes its dynamics and leads to some effects such as pulse-motion or stratified motion.

In this paper, an attempt is made to investigate structure and dynamics of slushflow treated as a two-layer flow. In other words, the interaction of phases in the flow is approximated with the interaction of two layers. The lower layer consists of pure liquid phase, namely, water and the upper layer is a floating saturated with water snow. Phase transitions are not considered because of short slushflow release (of order several minutes). The interaction of the layers is taken into account by turbulent friction, gradient pressure on the interface boundary and mass exchange. The entrainment of new snow masses is considered. It is assumed the entrained snow instantly saturates with water and floats to the upper layer. Thus the density of the upper layer is variable. The rear end of the flow can be feeded by water accumulated in a snow basin during spring snow melting or intense rainfalls. The flow releases in a rectangular cross section channel. The model is a hydraulic-type one, i.e. all dynamic characteristics of the flow are averaged over the depth of the flow cross section.

GOVERNING EQUATIONS

Let us write the basic equations of the model.

Water layer (see Fig.1a): $x \le x_{wf}$.

The mass conservation equation is

$$(H_w)_t + (H_w U_w)_x = -\, q_b P - \theta (P - P_w). \tag{1}$$

The momentum equation is

$$(H_w U_w)_t + (H_w U_w^2)_x = -\, U_w[q_b P + \theta (P - P_w)] + g H_w \sin\psi - (g/2)(H_w^2 \cos\psi)_x - (\rho_s/\rho_w) g H_w (H_s \cos\psi)_x + k_{sw}(\rho_s/\rho_w)(U_s - U_w)|U_s - U_w| - k_w U_w |U_w|. \tag{2}$$

Slush layer: $x \le x_{sf}$.

The volume conservation equation is